Master's Thesis

Priority-Group based Link Scheduling over Duty-Cycle Constrained LoRa Network

Fatou Williams

September 12, 2019

Graduate School of Information Science
Nara Institute of Science and Technology

A Master's Thesis
submitted to Graduate School of Information Science,
Nara Institute of Science and Technology
in partial fulfillment of the requirements for the degree of
MASTER of ENGINEERING

Fatou Williams

Thesis Committee:

Professor Youki Kadobayashi	(Supervisor)
Professor Minoru Okada	(Co-supervisor)
Professor Keiichi Yasumoto	(Co-supervisor)
Associate Professor Yuzo Taenaka	(Co-supervisor)

Priority-Group based Link Scheduling over Duty-Cycle Constrained LoRa Network*

Fatou Williams

Abstract

Long range (LoRa), being non operator-based, has been one of the most innovative LPWANs (Low Power Wide Area Networks) technology offering long range and low power capability. It has proved to be excellent in remote and rural area deployments. With LoRa's low data rate property, small payload sensor nodes are mainly deployed with LoRa. However, the integration of large data transmission such as images along with small payload size data, can contribute to realizing the goals of improved productivity and reduced management cost for various IoT ecosystems.

LoRa wide area network (LoRaWAN) does a random channel selection of usable channels, to transmit data. This introduces multiple scenarios where nodes make channel selections that usually ends up affecting the data delivery times of other transmissions, especially of large data nodes. Also, LoRa network operates in the sub-GHz bands where duty-cycle regulation is imposed on the frequency channels and time offs from frequency-use need to be adhere to. As we experience multiple frame transmissions for large data, the airtime to transmit data increases. Coupled with the time-off periods and transmission time limitation due to the duty-cycle, further delay is introduced.

In this thesis, we tackle these two problems by scheduling channels on time slots for data transmission of nodes that minimizes the data delivery delay specifically for large data (images) sensor nodes in a LoRa network. We propose a priority-group based and link scheduling methodology using a combined knowledge of the network for informed channel selection instead of a random channel

*Master's Thesis, Graduate School of Information Science, Nara Institute of Science and Technology, September 12, 2019.

selection. Our simulation results on a LoRa Network Simulator (LoRaSim) indicates an increase in successful data frame reception rates of large data delivered, at data delivery times more than 10 times faster than typical LoRaWAN, while adhering to the duty-cycle limits imposed.

Keywords:

IoT ecosystem, LoRaWAN, large data transmission, priority-traffic, delay-constraint, channel selection, duty-cycle, data delivery delay

Contents

List of Figures

List of Tables

1. Introduction

1.1 Background

The rapid evolution and success of the Internet of Things (IoT), has brought along innovative network enablers such as low-power wide-area networks (LPWAN). There are various types of LPWANs. Some of these are Sigfox[3], LoRa[9], LTE-M, EC-GSM-IoT[12] and NB-IoT. All of these LPWANs differ by the data rate used, the bandwidth, the frequency channels they operate on, the range achieved, power consumption and even the cost of operating the technology. In this research, we focus on long range (LoRa) because it is non operator-based. Thus, LoRa supports private deployments and it is excellent for ad-hoc deployment scenarios. However, due to its low data rate (50 kbps at most), achieving long range and energy-saving properties, LoRa is mainly used in the transmission of periodic small payload data size of IoT sensors such as temperature, humidity and soil moisture etc. These sensor payloads can range from 1 to 22 bytes of data. As such, there is a lack of study related to integrating periodic and delay constraint large data (images of up to 2100 bytes, size based on results in section 5) with small payload data in a LoRa network. This has various important application use-cases as it employs IoT visual sensing. Visual sensing plays a vital role in the management of smart cities as the eyes of businesses. Some few application use-case scenarios are in video surveillance, real-time object tracking, motion detection, alerts for situation awareness and visual verification of details for a lot of IoT ecosystems.

In this research, we envisioned an environment incorporating small payload sensors and visual sensors transmitting on the same established LoRa network as in Figure 1.1, where end-devices send data to gateways with particular spreading factors (SF that determines communication distance), which are relayed to the cloud and to application servers using Ethernet. The image sensors and small payload data sensors in such systems can be periodic as well as event-triggered. Our research focus is on enabling visual sensing on LoRa Networks. Hence, we work with images. Images are usually stored in high bytes of data (from kilo bytes to mega bytes) making it a large data. As LoRa maximum packet size is 255 bytes, to transmit images over LoRa, it needs to be packetized into multiple

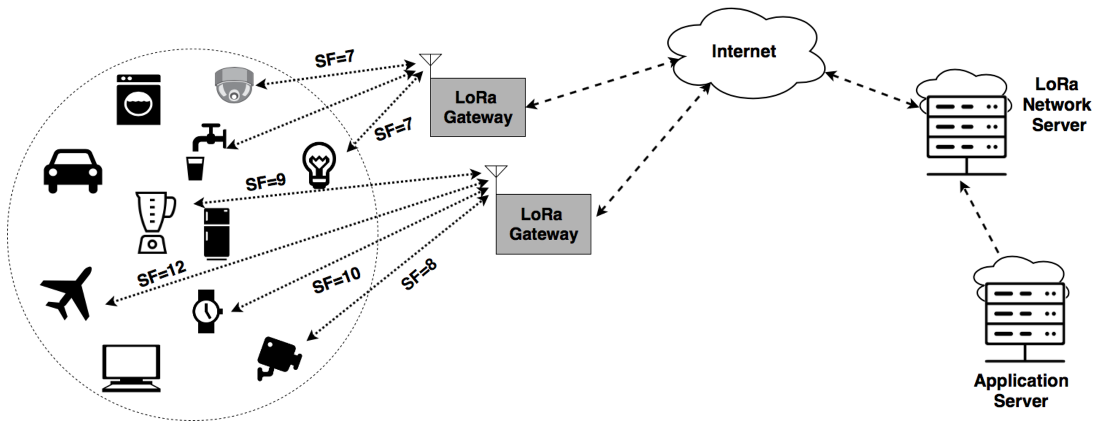


Figure 1.1. LoRa network for IoT applications transmissions [19].

packets. The transmission of these packetized data with large payload on LoRa, has higher resource demands which results to increased airtime and thus longer time to transmit. Also, sending images over LoRa being periodic and delay-constrained, requires a timely data delivery duration to be reassembled on the gateway.

The properties that make LoRa great for IoT applications, also challenge the transmission of large data. Firstly, LoRa operates in the unlicensed sub-GHz band where coexistence and frequency band sharing for different kinds of wireless technologies exist. To ensure fairness of spectrum use, a duty-cycle limit is imposed on the bands. The duty-cycle defines the total time on air allowed for a node to transmit on the frequency channel. With 24 hours in a day, a 100% duty-cycle implies being allowed to send data anytime, which is 86400 (60 x 60 x 24) seconds. LoRa devices are allowed a duty-cycle of only 10% to 1%. This implies that devices using LoRa have a limited amount of time per hour to transmit on the bands. This is the first fundamental problem that this research focuses on. The duty-cycle reduces the throughput and induces a lot of delay in large data transmissions. As a result of the duty-cycle, time-off periods where the devices are restricted from further transmitting on the channel is observed. However, devices can transmit on other available channels while they wait for the time-offs on other channels to expire as long as the duty-cycle is adhered to.
Secondly, LoRa transmissions use pure ALOHA mechanism which introduces high

probability of collision. It also exhibits random channel selection. The LoRa network only provides a set of available channels from which nodes make their channel selection arbitrarily. This means that a node can use the same channel in succession as long as it is available. Nodes random selection of channels on time slots can have a huge effect on the transmission time of other nodes. This causes a problem especially for large payload nodes (as they experience longer transmission time) because they require longer time-off periods on channels due to the duty-cycle. Thus, while the large payload node is not able to transmit on certain channels due to the duty-cycle time-off, the available channels that it can transmit on, can be randomly selected by other nodes. The small payload data nodes selecting such channels can introduce delay that could have been avoided if calculated and informed channel selection was carried out. This is the second fundamental problem because delays in the transmission of multiple frames that make up an image means application desired data delivery times are not satisfied.

There have been studies related to transmitting images over LoRa [18], [28], that considers image encryption and compression to tackle packet loss of large data transmission. However, these studies, [18], [28], did not address the implications of the duty-cycle limit on data transmission over LoRa. Recently, firmware updates of IoT end devices over LoRa was explored, however the scope of the implementation is mainly for downlink multicast large data. The adaptive data rate (ADR) command [23], in LoRa usually handles suggestions of available channels to end device. However, the ADR does not further provide any information on best channel sequence in which the channels might be more efficient to choose from. Thus, introducing the random channel access by nodes. For works related to addressing the duty-cycle limitations, an activity sharing scheme [29], that introduces an aggregated network duty-cycle was proposed. However, LoRa works with node and channel based duty-cycle, not aggregated network duty-cycle. Islam et al. [16] proposed a link scheduling algorithm for LoRa that considers the urgency of the packets as well as the availability of the channels for duty-cycle constraint real-time data but only small payload bytes were considered. Other studies [5], [36], on bulk data transmission in LoRa are designed for collective small payload size data for non-critical applications without time delay constraints. In summary, most of the related works to large data (image) transmission either fail in addressing the duty-cycle limit or their solutions do not capture the complex and true nature of the IoT ecosystem for LoRa with regards to accommodating large data size (images) and small payload data size applications together.

A complete IoT ecosystem involves applications that send data for various sizes, as shown in the end-devices in Figure 1.1. In this research, we seek to enable and harmonize such a diverse network for LoRa. Since most of these sensors send data periodically and few others, especially the small payload data, send in a non-periodic way, we propose a channel selection based on status of the channels and scheduling mechanism to enable smooth transmission of multiple data frames of images as priority to reduce the image delivery time and data frame drops of such delay constraint data, and fit in small payload application data whenever they are ready to send while complying with the duty-cycle time limitation.

1.2 Motivation and Purpose

Our motivations towards our research are:
1) To enable smart and periodic visual sensing in LoRa, which has many application use-cases.
2) There is a lack of study in integrating small payload data and large data transmissions in LoRa.
3) To introduce a more efficient channel selection and recommendation for data transmissions in LoRa as typical LoRa channel selection is arbitrary.
4) The scheduling in LoRa is a new class of channel scheduling as duty-cycle is imposed on both nodes and channel.

Our purposes for this thesis are:
1) To create a cooperative and well-balanced integration of large data (image) transmission and small payload sensory data transmission in a LoRa IoT ecosystem.
2) To improve the data delivery time at the gateway that is delayed by the duty-cycle and inefficient channel selection in LoRa ALOHA-like transmissions.

3) To enable delay-constraint IoT systems meet application-specific delivery times for better productivity.

1.3 Contributions of this Thesis

In this research, we provide solutions for two challenges that forestall the transmission of images over LoRa. The duty-cycle limitation on the sub-GHz bands will always be present and imposed, thus, finding better ways to overcome such to enable innovative IoT applications is important. Also, the advantage of the simplicity of LoRa ALOHA-like transmissions, can be inefficient to serve large data transmissions with huge time-offs. With this, our contribution towards this thesis are:

1. We provided priority-traffic and an informed channel access mechanism that will be beneficial in LoRa application implementation and deployment.
2. The channel selection mechanism observes the node time-off periods on all channels, thus enabling a duty-cycle aware scenario.
3. Achieving efficient transmissions (low-delay, meeting satisfactory application data delivery times) to enable a flexible sensor network for both large and small payload data in LoRa.
4. We illustrate the feasibility of using LoRa for image transmission in an already established LoRa network.
5. We added support for large data transmission on the LoRa simulator that enables and supports multiple IoT applications with different payload sizes.

1.4 Organization

This thesis is organized as follows: Chapter 2 gives an overview of LoRa technology as an IoT enabler, the effects of LoRa properties on large data transmission as well as the application use-cases focus of our research. We also formulate the main problems that causes delay in LoRa transmissions and limit large data transmission over LoRa. In Chapter 3, we describe the most relevant related works towards large data transmission, the formulated problem and the technology towards our proposed approach. Chapter 4 describes our proposed method and algorithm. In Chapter 5, we illustrate the experimental analysis and simulations to verify our proposed method performance. Finally, Chapter 6 summarizes our research with a conclusion and future research related to our research theme.

2. LoRa and Large Data Transmission

In section 2.1, we introduce the LoRa technology in detailed. Section 2.2, throws a light on the application use-cases and focus of our research. We formulate the problems we seek to address in this research in section 2.3.

2.1 LoRa Technology

In the following subsections, we first give an overview of LoRa's characteristics and talk about the LoRa network from the physical layer to the MAC layer and the frequency channels it operates on. We also explain a few important properties and parameters effect on data transmissions, essential for our research.

2.1.1 Overview

LoRa [2] short for 'Long Range' defines the physical layer of a low power wide area network (LPWAN) that offers an excellent solution for battery-powered IoT sensors, attaining long range for city-wide network coverage. LoRa devices can send data that travel distances to up to 14 km with energy-saving capability that allows batteries to last for 5 to 10 years [7]. This is possible as LoRa uses low data rate of 0.3 to 50 kbps [9]. LoRa uses a chirp spread spectrum modulation to transmit data. The chirps, which are frequency varying sine wave signals, enables LoRa to traverse long distances and resilient to channel noise, multipath fading and doppler effects. LoRa has gained recognition as an IoT enabler due to these properties discussed above. It is favored among LPWANs, as it can be deployed privately and works well for ad-hoc deployment scenarios.

The MAC layer communication protocol, that uses LoRa modulation at the physical layer, is called LoRaWAN. Thus, LoRa can be mapped to the first layer of the OSI model while LoRaWAN, to the second and third layer of the OSI model [23]. Together, LoRa and LoRaWAN form the LoRa network. Figure 2.1 shows the structure of the LoRa network as mapped to the OSI layer structure. It also illustrates the relationship between LoRa and LoRaWAN.

LoRaWAN exhibits a one-hop star of stars topology thus, avoiding complex and costly relay nodes. LoRaWAN adopts the pure ALOHA channel access mech-

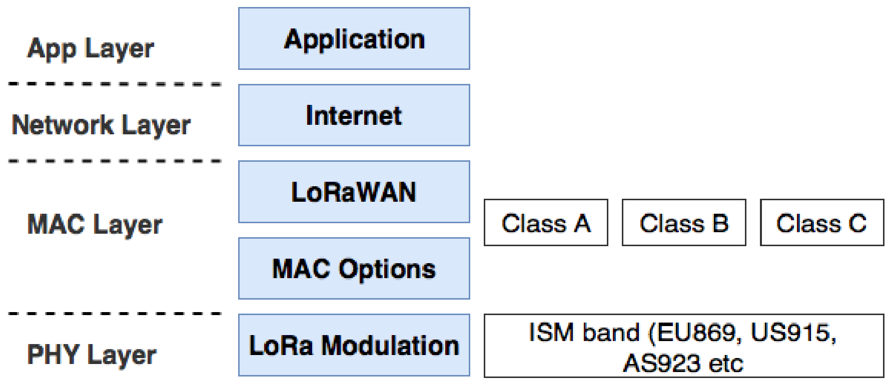


Figure 2.1. LoRa network structure as mapped to OSI layer

anism that has well-known performance limitations [25]. The combination of ALOHA scheme with LoRa physical layer enables multiple devices to communicate at the same time but using different channels and/or orthogonal codes known as spreading factors. LoRaWAN enables three main device classes: A, B and C. As described in [9], Class A devices support bi-directional communication between a node and a gateway while achieving the lowest power consumption. Class B devices expand on Class A by providing the network with the ability to schedule receive windows for downlink messages using periodic network-synchronized beacons. Class C devices add on to supporting bi-directional communication while providing the lowest latency at the cost of more energy. This is achieved by keeping the receive windows open unless they are transmitting.

In this research, we work with Class A devices as it is the baseline and default class that is supported by all LoRa nodes. The LoRaWAN MAC layer imposes a duty-cycle limit on devices and channels on the LoRa network. LoRaWAN also implements and makes use of some standard high-level MAC commands used in downlink and uplink transmissions.

LoRaWAN operates in the unlicensed sub-GHz ISM bands and has frequency/ channel plans as shown and explained in Table 2.1. Each of these bands are made of sub-bands or channels. Each band represents a frequency plan of a region of the world.

The LoRa network is formed by end-devices and gateways as in Figure 2.2. This implies, our research focuses on the physical and MAC layer properties

Frequency Band	Region	Channels
EU863-870	Europe	9 Uplink and 10 Downlink
EU433	Europe	No plan yet
US902-928	USA, Canada and South America	9 Uplink and 8 Downlink
CN470-510	China	8 Uplink and 9 Downlink
CN779-787	China	-
AU915-928	Australia	9 Uplink and 8 Downlink
AS920-923	**Japan, Malaysia, Singapore Indonesia**	**10 Uplinks and 11 Downlinks**
AS923-925	Brunei, Cambodia, Hong Kong Laos, Taiwan, Thailand, Vietnam	10 Uplinks and 11 Downlinks
KR920-923	Korea	7 Uplinks and 8 Downlinks
IN865-867	India	3 Uplinks and 4 Downlinks

Table 2.1. LoRaWAN frequency plan over regions of the World

of the network. The LoRa network is equivalent to a bigraph similar to how most communication networks are modelled. Sensor nodes such as humidity, temperature and camera nodes represent the nodes(N) in the graphs. Data is transmitted through the channels which represent the edges (L) in the graph as communication links. Communication goes through links between nodes and gateways (M).

2.1.2 LoRa Properties and Parameters Effect

LoRa allows the use of different parameter configurations when transmitting. These configurations can increase the probability of successful transmission of a frame at the cost of more transmission time, higher energy consumption or shorter range. Some LoRa network properties that have an effect on large data transmissions are described below. Table 2.2 summaries the network properties and their range of set values:

- Duty-cycle: This represents the percentage of total time on air a device can transmit on a channel. With 10% duty-cycle, a device can occupy the channel for 10% of 24 hours which is 8640 seconds. With large data such

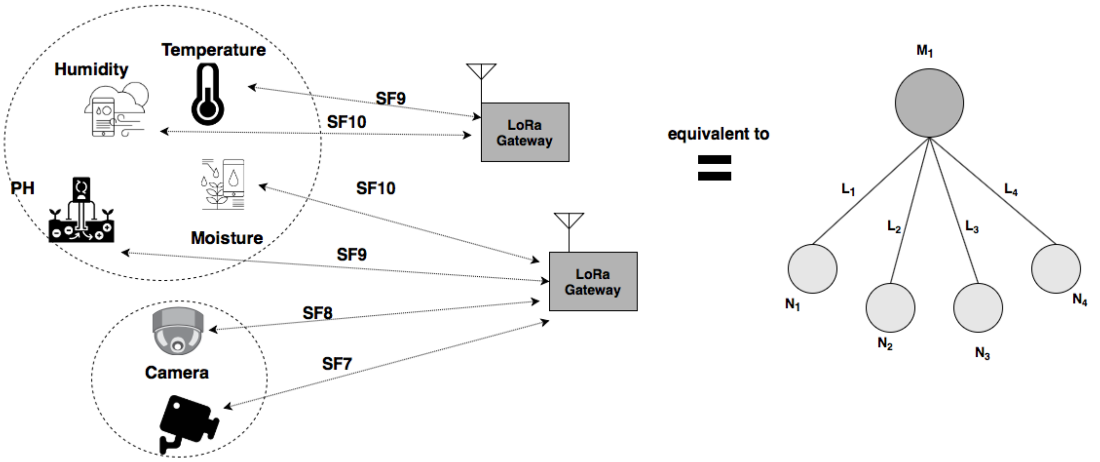


Figure 2.2. LoRa network formed by nodes and gateways with links to carry data transmissions modelled as a bigraph.

as an image, it means few captured images can be sent in a day.

- Time on Air (ToA): This is the duration of transmitting a LoRa message. The time on air can increase with larger payload size.
- Spreading Factor (SF): This defines the duration of chirp in the LoRa modulation. The values of SF ranges from 6 to 12. Each step up in SF doubles the time on air to transmit the same amount of data. Thus, the higher the SF, it means longer time on air but at the advantage of longer range. For large data transmission, we seek to use less time on air to not deplete the limited duty-cycle allowed.

Orthogonal Spreading Factor : One important capability of LoRa is that the spreading factors are orthogonal. This means that concurrent data transmissions can occur on the same channel with nodes and we can separate the network using different spreading factors. Other parameters used in LoRa message transmission are: Transmission power (T_xP), Bandwidth (BW), and Coding rate (CR).

Capture Effect : This occurs when one data transmission with higher transmission power interferes with a data transmission of weaker power on the same

Parameter	Values	Effect on
Spreading Factor	6 - 12	Range achieved; ToA; SNR; Sensitivity
Duty-Cycle	0.1%; 1%; 10%	Throughput; Scalability;
Transmission power	2 to 20 dBm	Range; RSSI; Link reliability
Channel bandwidth	125, 250, 500 kHz	ToA; Bit rate; Receiver sensitivity
Coding rate	4/5; 4/6; 4/7; 4/8	ToA; Packet Error Rate
Payload	1 to 255	ToA
ALOHA-Like MAC	-	Collision

Table 2.2. LoRa network parameters and properties for data transmission

channel, even when they use different spreading factors. The capture effect shows that SFs are not quite as orthogonal. The nodes with higher SFs (further away from the gateway) are usually affected more when the capture effect happens. Thus, reducing greatly the performance of such nodes. In our simulation in later chapters, we do consider the capture effect.

2.2 IoT Visual Sensing in LoRa : Application Focus

The first subsection discusses an IoT application use-case for LoRa large data transmission linked to periodic visual sensing. In the second subsection, we made analysis on the traffic model of LoRa data transmissions and of various application use-cases.

2.2.1 Use-Case Scenario : Monitoring Soft-Shell Crabs

The use of LoRa for IoT visual sensing can be very helpful in the special case of monitoring the molting process of Soft-Shell Crabs. In an already established LoRa network ecosystem for crab farming, where an IoT-based water quality monitoring [26] is carried out by various small payload sensors to gather enough knowledge of the water environment to improve crab survival rate, integration of visual sensors that use LoRa to capture and send images is a vital innovation.

Such visual sensing will be periodic and event-triggered based on motion. Most species of soft-shell crabs molt at most six times in one year, thus, making it, a periodic event. The molting process can last for about 10-15 minutes in each of these molting periods. However, after molting, it takes only one hour before the shell of the crab turns hard again. The goal of such system is to be able to detect and capture when these molting processes are happening so as to harvest these crabs while the shell is still soft. Thus, such application requires a deadline for data transmission. Since the scenario is a periodic event that can be over a long duration, we need low-cost camera sensors that can stay in the field for years without battery change by going into deep sleep mode and capturing these events when sufficient motion is detected.

To carry out this task with other power-hungry IoT enablers can be costly and less productive. Enabling the use of LoRa for such large data transmission cases is excellent as it will help reduce management cost, especially when the LoRa network is already in place for such an IoT system.

Visual sensing with LoRa can be applied to other use-cases such as: pest detection and outbreak prediction, detecting ripening of farm products and even in LoRa-enabled GPS tracker that requires a location with images.

2.2.2 LoRa Traffic Modelling

The traffic of images over LoRa compared to the traffic from small payload size sensors, have different characteristics which are among the motivation of our research. The knowledge of the traffic helps in the implementation of the scheduling mechanism and the LoRa network simulator. Table 2.3 summarizes the different characteristics of these different payload sizes.

Through a series of surveys, we furthermore modelled LoRaWAN traffic for different IoT applications. We evaluate various sensor devices that LoRa can enable. Our main aim was to have a knowledge of the exact payload sizes these diverse LoRa network application use. We evaluated our survey for data payload size, frequency of transmission and number of nodes with respect to area covered.

We also consolidated the traffic model for image sensors in a LoRaWAN network. Table 2.4 gives a summary of LoRaWAN traffic modelling for different IoT use-cases.

Image Transmission	Small Payload Sensor Transmission
Predictable traffic	Random traffic
Readily buffered data	As it is available
Data size varies with camera used and environment	Usually fixed data size for a node
Long transmission time	Short transmission time*
Duty-cycle limit on transmission time	Not much effect

Table 2.3. Difference between large data and small payload data LoRa transmission

*If they are assigned the same bandwidth, transmission power and SF.

From Table 2.4, it can be seen that small payload size sensors have data size ranging from 1 to 22 bytes. Visual sensors with image compressed and suitable to be sent over LoRa can have a maximum data size of 2100 bytes (based on results in section 5). The transmission (T_x) control interval which signals the frequency of nodes transmitting data is also summarized for each sensor.

2.3 Problem Formulation

In these subsections, we give a detailed formulation of two issues that are a challenge in transmitting large data over LoRa. The two problems are: the regulated duty-cycle and the channel selection mechanism in LoRaWAN.

2.3.1 Duty-Cycle Time-Off Delay

The duty-cycle is defined as the percentage of time a device can transmit on a channel. It can also be evaluated as the fraction of time on air (ToA) of LoRa payload data. A 100% duty cycle means a device can transmit data at any time on any channel without any pause or time-off, (T_{off}), period. The time-off is the period of wait where a device has to wait for a certain period of time before it can send data again on the same channel. However, with LoRa, a device can send data on other channels while it waits for the time-off period to expire on the

Use case	**Device Type [sensors]**	**Data size [bytes]**	**T_x Control interval**	**Node density/km**
(i) Water quality Monitoring (ii)Soil Monitoring (iii) Irrigation	Temperature Moisture Humidity pH Salinity	17 [26] 5	10 secs 60 secs 10 mins 60 mins	-
GPS Tracker	Accelerometer	22	10 mins	-
Traffic [27]	Lights	1	60 secs	~ 39,000
Home security[27]	Motion	20	10 mins	~ 12,000
Weather conditions	Rain Wind speed	16 5	15 mins	-
Visual sensing	Camera	Max. 2100 for this research	(i)180 secs (ii)15 mins (iii)Change detection	-

Table 2.4. LoRa-enabled IoT application traffic modelling

channel. The T_{off} duration [7] is calculated as shown in equation 1.

$$T_{off} = \frac{ToA}{dutycycle} - ToA \tag{1}$$

The duty-cycle is imposed on the unlicensed 1-Sub Ghz frequency bands in the frequency spectrum. Due to coexistence operations in these bands, channels are shared with various other wireless technologies. Thus, the need for duty-cycle limits to ensure fairness of channel-use by network transmitters.

Depending on the region of the world you are in, every device operating in the sub-GHz frequencies should comply with the rules of its usage. In most regions of Europe, EU863 frequency, the duty-cycle is 1% per day. This means that only 864 seconds per day per device (aggregated duty-cycle) is allowed to transmit on the frequency band. However, there are regions and countries, including those in Africa, the Caribbean, Asia and even Europe, that do not have any duty-cycle

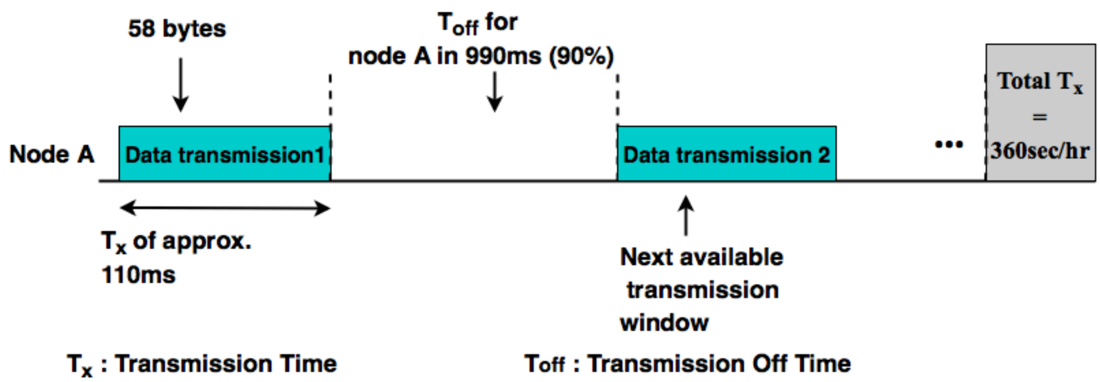


Figure 2.3. Ideal node and single-channel imposed 10% duty-cycle transmission for a 58 bytes packet.

regulations imposed on these frequency bands.

The AS923 frequency band used in Japan, is also used in Malaysia, Indonesia and Singapore. The duty cycle is 10% per day in Japan. This is because the AS923 does not allow a bandwidth of 500 kHz, and only one channel allows a value of 250 kHz. For the scope of this research, we focus on the AS923 frequency band standard.

According to the Standard Technical report (STD-T108) [17] from the Association of Radio Industries and Businesses (ARIB) in Japan, using a single channel, a device can transmit 360s per hour at most in the current AS923. However, this does not imply that a device can actually use up all the 360s per hour. There are additional regional rules and standards in using the band as imposed by ARIB [17]. We illustrate a single channel with data transmissions and the imposed duty-cycle limit in Figure 2.3. Node A has data frame transmission of 58 bytes that would require approximately 110 ms of transmission time (T_x) or ToA under a set BW, CR and SF. After each completion of a frame transmission, the node has a time-off period (990 ms) before it can attempt to send data again on the same channel. A node with a smaller frame transmission of 17 bytes with T_x of about 49 ms and using the same transmission parameters will have a shorter time-off of 441 ms.

The additional regional regulation on the bands allow for a default dwell time (transmission time) of 400ms with a maximum of 4 seconds. For such transmission

Channel Frequency	**Carrier Sense**	**Transmission Time**	**Wait Period**	**Total Transmission Time**
920.5 - 923.4 MHz	5ms or more	4s or less	50ms or more	None
920.5 - 928.1 MHz	128us or more	400ms or less and more than 200ms ------------- 200ms or less	10x of transmission time ------------- 2ms or more	Time of 360 sec or less per hour

Table 2.5. Specification on carrier sense, data sending controls and duty-cycle for LoRa channels on the AS923 in Japan with antenna power of 13 dBm or less

on a single channel, after every packet sent, a device has a waiting period of at least 50ms before it can send data again on the channel. However, these are meant for devices that perform listen-before-talk and use carrier sense multiple access (CSMA) scheme in transmitting data over LoRa. The unreliability of adapted CSMA for LoRa is described in [29]. Such listen-before-talk scheme adoption is defined and applied on channel frequencies in the upper half of Table 2.5. With a transmission power of between 1 mW to 20 mW (which corresponds to 13 dBm), the lower part of Table 2.5 illustrates the sending controls with duty-cycle for recommended LoRa transmission.

The duty-cycle is also imposed on wireless sensor network (WSN) node. However, a major difference in this research with regards to LoRa compared to wireless sensor network(WSN), is that, the duty-cycle of WSN is defined as the sleep-awake ratio of nodes. It is not imposed on both nodes and channel.

With the T_{off} coupled with the aggregated duty-cycle per one hour duration allowed, the duty cycle limits the amount of time, sensor nodes can transmit which increases the data delivery delay and adds to network latency. It also reduces the throughput of IoT applications, as more data is being sent from nodes. This means that at a certain point when the duty-cycle limit is reached, no more data can be sent from the application until the limit expires. The duty-

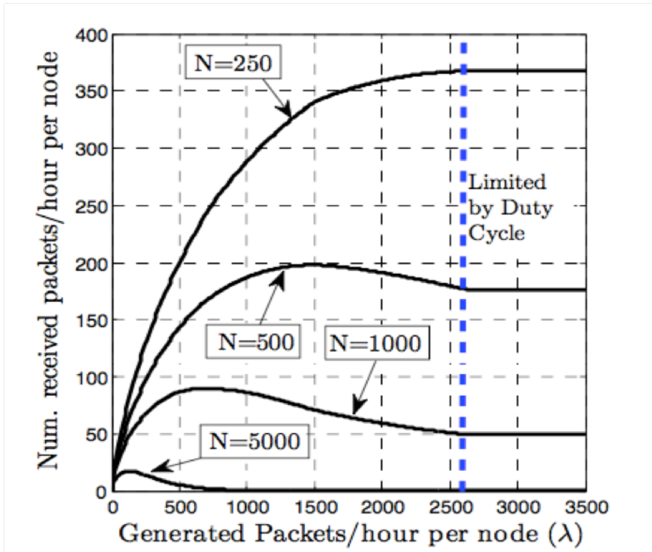


Figure 2.4. Effect of the duty-cycle as node and packet transmission increases [7].

cycle constraint has a huge effect on the efficiency and scalability of the LoRa network. In [7], Adelantado et al. analyzed the limits of LoRaWAN and showed how the duty-cycle affects data throughput as in Figure 2.4.

An important point to note is that, exceeding or violating the regulations of duty-cycle limit is punishable by the law of the region and IoT applications are required to track and record transmission times to adhere to the duty cycle rules.

Image transmission requires sending multiple packets over the LoRa network. This kind of traffic will use up the aggregated (combined from all the channels/sub-bands used) duty-cycle quite fast which can cause incomplete transmission of the whole image. This can cause missing of important events from the nodes and not being able to report them to the gateway. Another issue with the duty-cycle limit is not being able to recover and collect the whole image on the gateway to satisfy application delivery times for delay constraints IoT applications which is the application focus for our research.

The main requirements to solve the duty-cycle issue is to ensure the large data has enough time to send complete image packets. We should also adhere to the fairness characteristics of using the channels. This means imposing the T_{off} periods for every link data transmission.

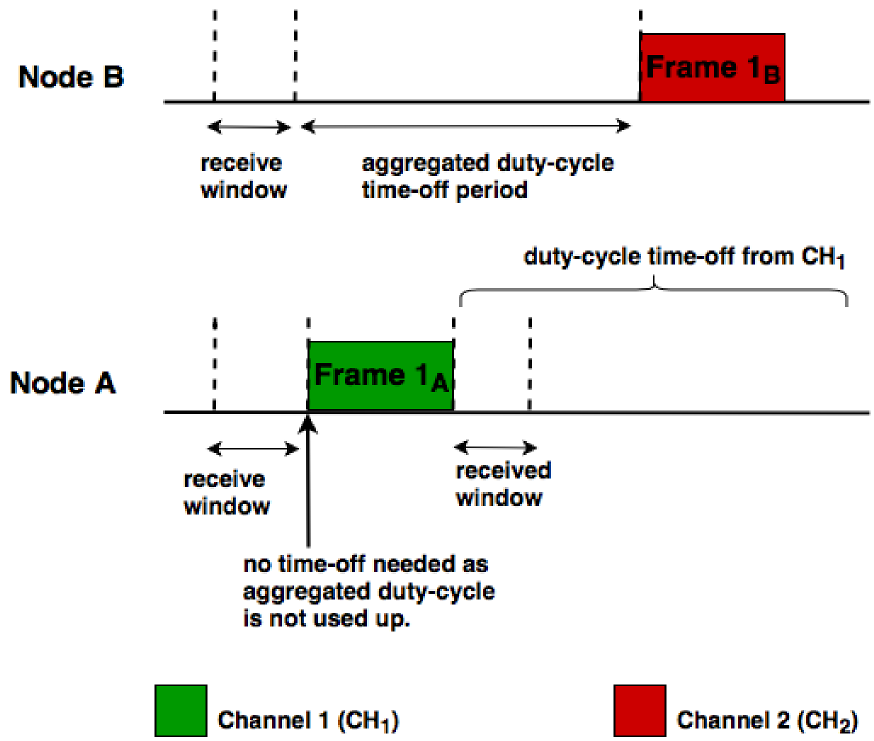


Figure 2.5. Mechanism of LoRa data frame transmissions

2.3.2 Inefficient Random Channel Selection in LoRa Transmissions

LoRa transmissions are uniformly random as no other condition (except for when a channel is not supposed to be available due to duty-cycle) is imposed on how or what channel is selected for what data frame transmission. This means that under any condition where one or more sensor nodes wants to send data on one or more channels, the assignment of a channel for data transmission from any of the nodes is arbitrary. For nodes having data to send, the following steps are applied to select a channel :

1. The nodes wait for the end of any receive window as in ALOHA-like data transmissions.

2. The nodes wait for any time-off due to the aggregated duty-cycle limitation.

3. The nodes check for available channels. These are channels that are not unavailable due to duty-cycle regulations. For this step, either of these two

routes are taken:-

(a) A channel is selected uniformly randomly from the set of channels in all available channels.

(b) If there is no free channel, the transmission is queued in the first free channel.

In Figure 2.5, Nodes A and B each wait for receive window from previous transmissions first. Node A did not have to wait for the aggregated duty-cycle time-off as it has not depleted the amount of time per device in the hour/day yet. Thus, it can check for the available channels and randomly selects one (in this case CH_1) to transmit $Frame1_A$. Node B, however, after waiting for the receive window has to wait for the aggregated duty-cycle time-off period before it is able to choose an available channel to transmit on (CH_2 was chosen).

Adaptive data rate scheme in LoRaWAN

The adaptive data rate (ADR) controls and adapts the transmission parameters for uplink LoRaWAN transmissions. The command can be enabled or disabled by nodes. The adaptive data rate command in LoRaWAN, *LinkADRReq* [23], basically controls the transmission power and the data rate. It also gives recommendation on the available channels for uplink transmission to the nodes, if the channels operate on the data rate the nodes are using. This command gives a list of available channels as in Step 3 of the LoRa data frame transmission discussed above. The ADR provides information on data rate change and channel available list. However, it does not provide information on the channel selection to avoid the selection from being random. With the introduction of the random channel selection by the nodes, which as we will further explain below, delay of other (important, delay-constrained) data frame transmissions are experienced.

Considering a scenario where we use slotted ALOHA-like LoRa transmissions where data frames are transmitted in time slots. We demonstrate the problem this research focuses on. We assume a small payload sensor node and one large payload (visual) sensor node that has a captured image data to be sent.

Figure 2.6 illustrates the effect of the two main issues in transmitting large data among small payload data. The problem occurs as follows:-

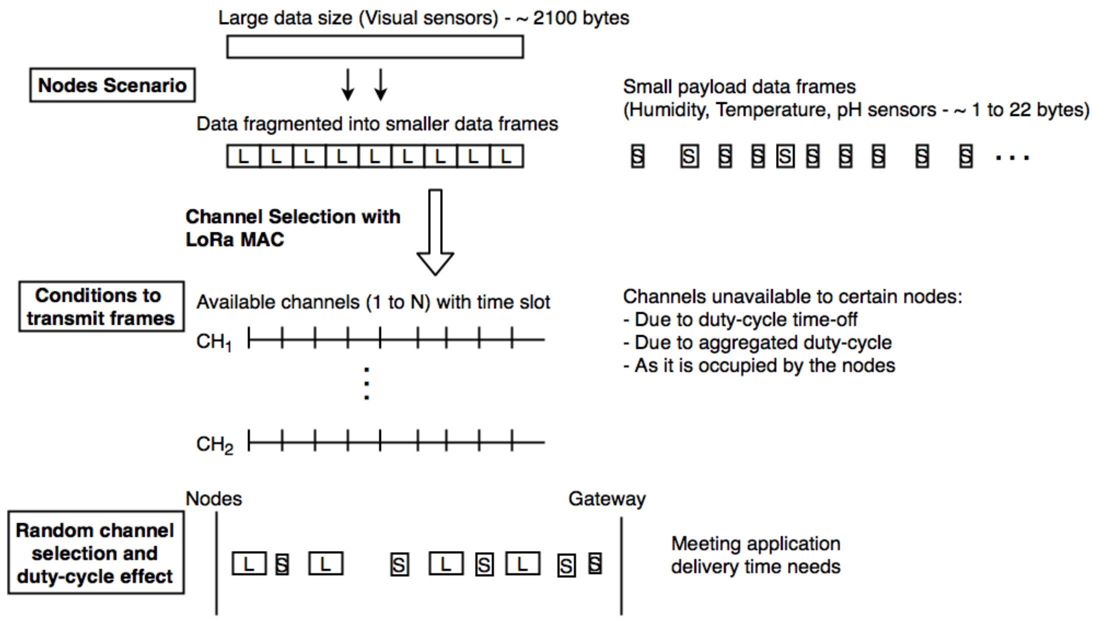


Figure 2.6. Relationship of the two issues of inefficient random channel access and duty-cycle

- We have a node scenario where an image data and small payload data are to be transmitted. The image data is divided into multiple data frames according to the LoRa limited frame size (255 bytes maximum). The small payload data are small enough (1 to 22 bytes) to be sent in one transmission.
- The LoRa MAC (LoRAWAN) random channel selection explained in section 2.3.2 is used by both nodes' transmissions.
- In the random channel selection and duty-cycle effect stage, delays are introduced in two main ways:-
  1. Larger frames having longer time-offs and wait period on channels.
  2. Small payload data affecting the transmission time and causing delays on the large data transmission by randomly selecting channels that could have been selected by the large data nodes. This is illustrated in Figure 2.7.
     - The first frame transmissions, S_1 and L_1, of small payload node

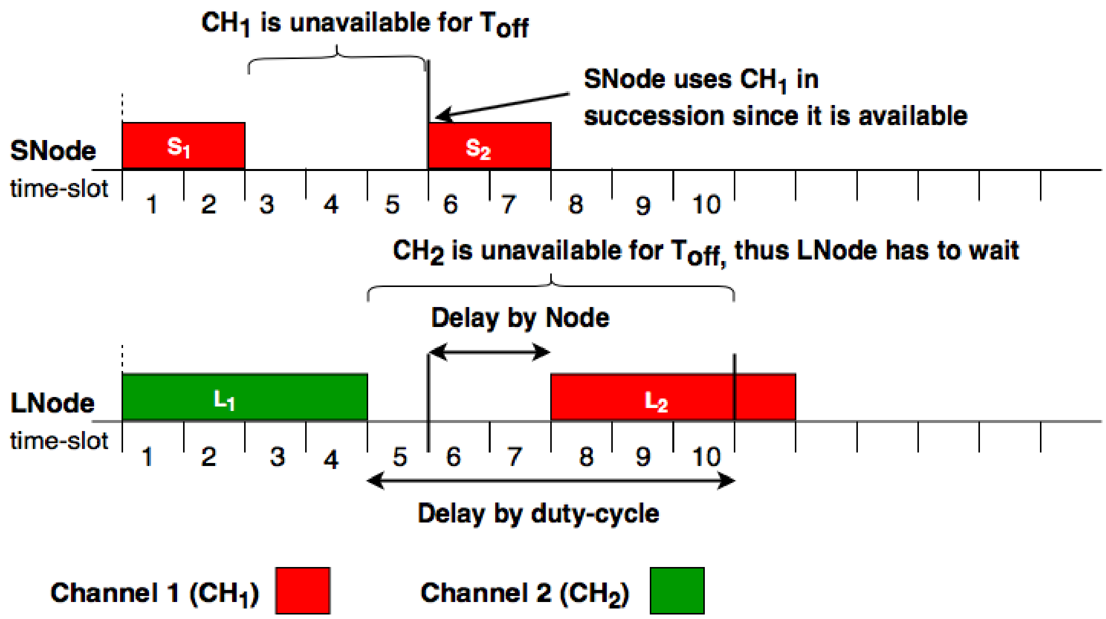


Figure 2.7. Data delivery delay of Large data node affected by Other nodes transmissions and the duty-cycle

(SNode) and large data node (LNode) used CH_1 and CH_2 respectively.

- Adhering to the duty-cycle, each node is not able to use the same channel again for a period of time-off. LNode experiences longer time-off than SNode (6 slots).
- When SNode is ready to send data again S_2, with random channel access, since CH_1 is available, it uses CH_1 again.
- Since LNode cannot use CH_2 at time slot 6, it has to wait until S_2 completes before it can use CH_2.
- The choice of channel selection of SNode and lack of priority, caused a delay in L_2 that could have been avoided if SNode chose CH_2 at slot number 6.

As mentioned in our application focus, delivery of images is delay-constrained as they have deadlines and delivery times where a certain image or collection of images is required to be received to meet the needs of the application. Hence, this brings up the question: Is there a particular best channel selection sequence or rank that will avoid the delays caused by small payload nodes and adhere to the duty-cycle regulations? In summary, due to channels not carefully scheduled and randomly accessed, large data payload transmission can be further delayed, thus increasing the data delivery time on the gateway. This problem of random channel selection in LoRaWAN is also mentioned in [16] but on a smaller scale considering only small payload data bytes/ nodes.

Our goal is to schedule channels in such a way that the selection of channels for all nodes' data transmission will not affect the large payload sensor node data transmission, that will cause further delay in delivery time at the gateway. We want the method to meet application delivery time limits as much as possible, especially for the large payload size data. Thus, we propose priority scheduling of channels and time slots with the image data transmission frames being highest priority among other small payload data transmissions. The gateway is responsible for recommending the channel sequence to the node using a series of network status knowledge such as: received signal strength indicator (RSSI) of nodes, channel availability, and channel saturation.

3. Related Work

In this chapter, we discuss current methods used to solve the problems we formulated in the previous chapter. Section 3.1 discusses related researches on LoRa. We mention the main trends in most studies towards LoRa. Section 3.2 discuss the existing studies on large data transmission in LoRa networks. Section 3.3 entails, works on addressing duty-cycle issues, channel access and scheduling in LoRa, as our proposed approach involves scheduling of channels for data transmission. Finally, in Section 3.4 we surveyed studies on ALOHA frame reservation and priority reservation of slots to show the new context of study with LoRaWAN.

3.1 LoRaWAN Scalability

One of our research goals is to expand the applications LoRa can enable by integrating periodic image transmission in LoRa, alongside the small sensor payload data from temperature sensors, humidity sensor, etc. Recent studies [7] towards LoRa scalability has shown that LoRa is not able to scale well due to its MAC layer transmission protocol that is ALOHA-like. Other related studies on LoRa are based on analyzing its limits, scalability, merits and demerits from a technical perspective [13], [15]. These studies mentioned that LoRaWAN does not scale well due to increased collision and limitation by the duty-cycle when the number of nodes and transmission increases. Although these studies were practical, they lack a general and more theoretical approach of IoT applications, where different payloads of data are being transmitted, extending LoRa to different innovative technologies for future implementation. Furthermore, as stated in [20], ALOHA's scalability issue can be a bottleneck for the success of IoT, thus giving a need to provide modification and improvement in its channel access mechanism to accommodate for large data transmissions.

3.2 Large Data Transmission in LoRa Network

Large data transmission in traditional wireless networks had to consider complex multi-hop communication and costly relay nodes. However, in LoRa networks, having the advantage of a single-hop star topology, do not have to deal with such complexities but there are challenges mainly because of the already discussed LoRa properties in Chapter 2. Thus, there has been studies related to transmitting images over LoRa. Jebril, Akram, et al. [18] contributed in addressing the challenges of the limited bandwidth by proposing an image encryption scheme where images are encrypted as hexadecimal data and then split into packets for transfer. The study focused on image transmission in the physical layer only. In [28], Pham et el. built an off-the-shelf image sensor that uses a packet loss tolerant and an optimized image compression scheme. The study employs the use of CSMA for LoRa. Thus, these studies did not address the implications of the duty-cycle limit on data transmission over LoRa MAC layer.

Recently, a study on firmware updates of IoT end devices over LoRaWAN was explored [8]. Updates are a critical part of IoT devices which supports security and integrity. In the study, a fragmented data block transport specification was added to LoRaWAN which enables sending an application layer messaging package to end devices either through unicast or multicast. However, the scope of the over-the-air firmware update was for downlink messages(from servers to end-nodes).

3.3 Channel and Data Transmission Scheduling In LoRaWAN

For works related to addressing the duty-cycle limitations, Congduc Pham in [29] approached reducing the effect of the duty-cycle by proposing an activity sharing scheme where sensor nodes with higher ToA activity requirements borrow activity time from other nodes. This is to globally satisfy the duty-cycle. However, LoRaWAN duty-cycle is imposed on a node and channel and not aggregated for a network. The main reason for the duty-cycle was to ensure fairness of channel-use by all end-devices. Thus, this renders the approach impractical. Islam et al. [16] proposed a duty-cycle aware link scheduling algorithm for LoRa that considers the urgency of the packets as well as the availability of the channels. The approach to enable real-time link scheduling was to choose a channel that has been most unavailable to a node. The work [16] randomly selects SF which is a key parameter that can highly affect network reliability and scalability, thus requires careful and calculated selection. The approach also considers just small payload data sizes of 1 to 5 bytes of data.

Due to the poor scalability of LoRaWAN, there have been researches towards scheduling communication links to improve the performance in terms of collision, data latency and energy efficiency. First, we have baseline scheduling algorithms of least laxity first (LLF), earliest deadline first (EDF) and deadline monotonic (DM), as scheduling policies [32], that are used in various kinds of technology, specifically in allocating CPU resources. Although, applicable in a lot of scenarios, some have the disadvantages of huge computation for each time instant of scheduling. EDF also exhibits high overheads and poor performance is experienced in LLF when more than one task has least laxity.

Scheduling large data has not been explored fully in LoRaWAN which is one of our motivation. The few works [5], [36], and [37], towards large data transmission scheduling, handle small payload data nodes, that have collected data over a period (refer to as bulk data collection of small size data) and which are to be transmitted at regular intervals with temporal gateways. These collective data can amount up to 2KB per node. The related studies are not for delay-constraint application with desired application delivery times or for continuous large data such as images. Also, some of the works [36], [5] used frequent long downlink messages during scheduling which can drain the limited duty-cycle resource in LoRaWAN and cause overhead.

3.4 Reservation Frame Slotted ALOHA and PR-ALOHA

With LoRaWAN exhibiting an ALOHA-like transmission, and thus, using a random channel access and selection, there has been studies and research related to reserving time slots and prioritizing traffic for ALOHA protocol. Frame Slotted ALOHA (FSA) was proposed for scenarios where the network is saturated due to multiple devices accessing the channels simultaneously which is common in IoT device traffic as well. It works with time, organized into access slots. However, time slots are randomly selected which introduces collision and this is continued for every packet transmission. Also, FSA has only been proven to be efficient for devices, with as few packets as one, to transmit. As described in [35],[34], Reservation Frame Slotted ALOHA (RFSA) is an evolution of FSA as random selection is only done for the first few unsuccessful transmission, after a successful transmission on a time slot, that slot is reserved for the rest of packets of the device. This forms a repeated slot allocation. RFSA works best for long messages with multiple packets [34]. Both FSA and RFSA, although an improvement of Pure-ALOHA in terms of time slot allocation, does not address the priority of nodes or traffic. Reservation ALOHA (R-ALOHA) [21] was proposed to improve the performance of slotted-ALOHA in times of delivery delays and channel utilization. The MAC protocol is suitable for ad hoc wireless networks similar to LoRaWAN and it is simple to implement. In R-ALOHA, a time slot is temporarily reserved by a device that successfully used it and after completion of transmission, it is used by other nodes. However, due to the lack of prioritizing traffic, thus delay of important messages, Priority Reservation (PR) ALOHA was proposed. PR-ALOHA [11], [10] reserves specific time slots for high-priority messages and it increases the number of slots that a high-priority message may compete for thus decreasing its delay.

All these variations of ALOHA work under certain scenarios. However, for LoRa Network traffic, they fail to address the duty-cycle constraints that come with most radio receivers that use the MAC protocol under the IEEE 802.15.4. The duty-cycle in LoRaWAN as mentioned earlier is of another class as it is not merely the on and off period of a node. Duty-cycle is imposed on both channel and node. Secondly, the discussed MAC protocol still exhibit random channel access and as such are not able to solve the issue of delayed transmission of large data due to the choice of channels and time slot by small payload data nodes.

In summary, the related works do not address the need for a well integrated large data and small payload data transmission to show the diverse and realistic nature of IoT applications for LoRa Networks. Unlike previous works, in this research we explore the capability of transmitting images as a large data, not just a collective buffered bulk data of small payload data, over LoRaWAN. Such a study has not been explored yet. Scheduling such traffic is important to not overload the channels as coexistence with small payload nodes is required. We also need to respect LoRa duty-cycle, imposed on both nodes and channels, introducing time-off intervals which are not addressed in most of the related works. We schedule the delay-constrained large data to improve its data delivery time performance at the nodes, using essential network information gathered by the gateway, to meet application-satisfactory delivery times.

4. Priority-Group-Based Link Scheduling

In this chapter, we describe our proposed approach to reduce the data delivery delay caused by the channel selection mechanism and duty-cycle regulation of the LoRa channels in transmitting large data. Section 4.1 discusses the channel structure and a quick summary of our approach. Section 4.2 discusses in detailed the mechanism ran on the nodes and gateway to enable the scheduling and selection of the channels for the node transmission.

4.1 Slotted Channel Access

The channel access selection mechanism in original LoRaWAN is unslotted (refer to section 2.3.2) as nodes access channels at random times. Due to nodes selection of channels being arbitrary and uninformed, large data transmissions are delayed. Since Slotted ALOHA has been proven to have a better performance than pure ALOHA in terms of data frame collisions [30], we assume time-slotted channel access for LoRaWAN throughout our research. The reason we utilize the ALOHA slotted-channel access for LoRaWAN is because transmissions will experience severe collisions in pure ALOHA state that will be impractical for delay-constrained data.

In our approach, each slot holds a data frame transmission and one or multiple data frames make up a large data (image) or a small payload application data. The length of a time slot is the length in time (milliseconds) of the frame plus two guard times length. We use the guard times to account for any overlap in time synchronization between the network and the nodes. We define a round as the time from when the current node starts transmitting data to the complete transmission of all frames. We give a formula for the round length ($RLen$) for each individual node as in Equation 2. We use the maximum data size to estimate the number of data frames ($NrFrames$) to be scheduled and thus, the length of the round. This is estimated with the duty-cycle time-offs (T_off), the time on air

(ToA), based on the spreading factor used, and the number of channels ($NrChs$).

$$RLen = \left\lceil \frac{NrFrames}{NrChs} \right\rceil * (ToA + T_{off}) - (T_{off} - (NrFrames \bmod (NrChs) * ToA)) \quad (2)$$

We illustrate the structure of the channel for uplink transmissions in Figure 4.1. It entails a series of data transmissions by nodes and a downlink at the end of every round. The downlink transmission provides information for the next transmission when there is a change in number of nodes and channel availability.

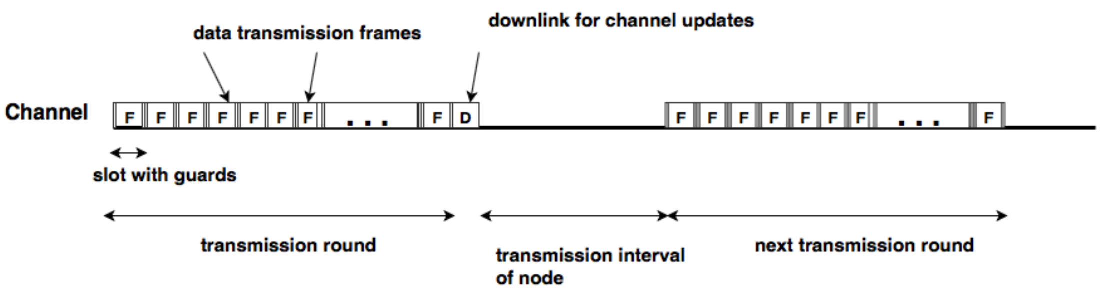


Figure 4.1. Time slots, frame and round with the channel transmission structure.

We define a link as the communication path that is used by a node to transmit a data frame, expected to reach a gateway under a ToA duration. Data frame transmissions are facilitated by LoRa transmission parameters of SF, bandwidth (BW), coding rate (CR), transmission power(T_xP) and channel. Thus, we define the parameter combination on a link as $L_i = \{SF, BW, CR, T_xP, CH\}$. Our scheduling mechanism ensures that the best parameters for reduced data delivery delay are allocated to all data transmissions.

With the issue of random channel selection in LoRaWAN and the time-off imposed on data transmission as illustrated in the previous chapters, our main goals towards our scheduling algorithm are:-

1. Delivery of large data at the gateway to meet application-satisfactory delivery times.

2. Ensure the transmission of small payload data does not affect high priority large payload data transmission.

To enable such implementation, our requirements are :-

1. Divide nodes and their frame transmissions into priority groups based on the data size.
2. With slotted communication, synchronization between nodes and gateway is essential. However, there should be considerations to minimize the size of the downlink traffic to meet duty-cycle limitations.
3. Nodes should have sufficient knowledge of channel status to ensure its data transmission reception.

The main concept and idea behind our approach came as a result of the root problem explained in section 2.3.2. Instead of nodes choosing randomly from a set of available channels, it would be best for the gateway to also suggest to nodes, the availability and best channel selection with the goal of reducing the delay for especially the large data nodes. Also, as we want to achieve fast data reassembling and delivery of the large node's transmissions, we introduce priority-traffic for the large nodes in addition to the channel status information.

Thus, we propose a link scheduling algorithm where gateways broadcast channel status update messages that hold information about channel availability for each of the priority groups and SF while sending timing of network for synchronization. The scheduling of channels and time slots by gateways, enable the nodes to make a better decision on channel parameters for data frame transmission. Figure 4.2 shows a flow-chart of the complete process.

4.2 Proposed Method : Improve Data Delivery Time

In our proposed link scheduling, we organize how channels and transmission parameters such as the SF and the slot number are selected by the channel for the node to achieve our goals of the research. Nodes are provided important scheduling information of channel status by the gateway to choose the best fit transmission parameters to achieve fast data delivery and successful data frame transmission.

Here, we explain and illustrate the tasks carried out on both the nodes and the

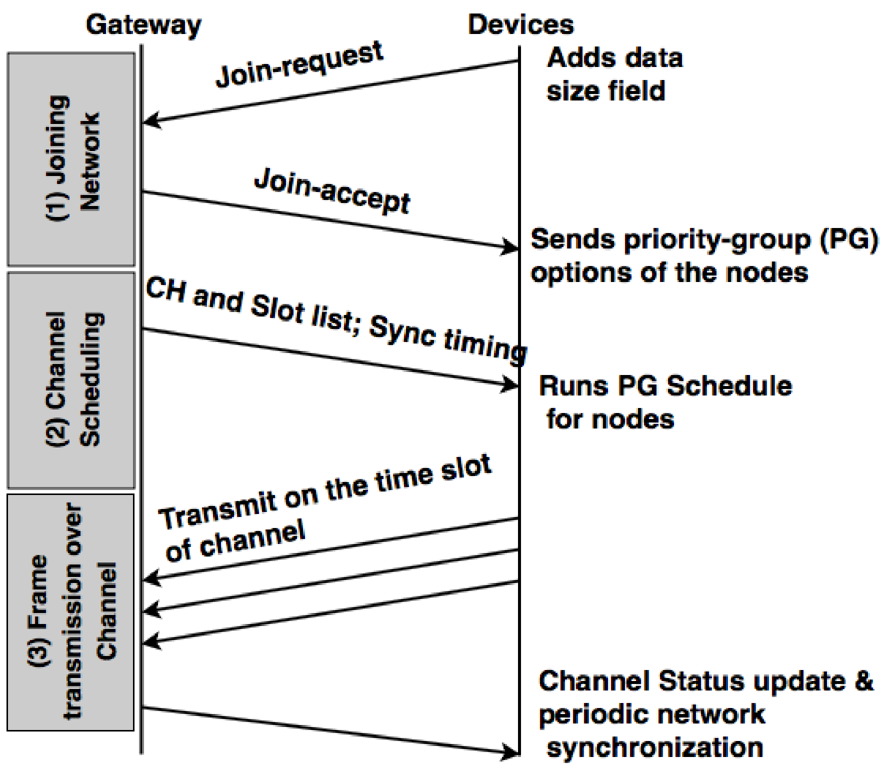


Figure 4.2. Flow of the data transmission in LoRaWAN with the proposed scheduling

gateway for the process of the link scheduling and channel selection. We first explain the process of joining the network when a node has data to send. We further discussed the algorithm design considerations. Finally, we illustrate the channel and slot selection mechanism to rank channels and the node data transmission after getting the channel status update from the gateway.

4.2.1 Network Joining and Priority Group Assignment

The link scheduling is initiated by the nodes. A node having data to send, as in typical LoRaWAN, sends a $join-request$ to the gateway. During this process, we modify the $join-request$ message structure by adding the data size of the end-device sensor node. We first present the $join-request$ process, then gateways processing the priority groups of nodes and sending back a $join-accept$.

Table 4.1. Join-Request Message Structure

Field	**JoinEUI**	**DevEUI**	**DevNonce**	**DataSize**
Bits	**64**	**64**	**16**	**24**

Table 4.2. Join-Accept Message Structure

Field	**NetID**	**DevAddr**	**DLSettings**	**RxDelay**	**PriorityGP**
Bits	**24**	**32**	**8**	**8**	**2**

1. Sending join-request : Table 4.1 shows the structure of the $join-request$ process as defined and implemented in LoRa MAC [23]. For this step, we add the data size of the sensor nodes as modelled in Table 2.4 of Chapter 2. For large payload data , the size is usually about 2100 bytes and the small payload data ranges from 1 to 22 bytes of data. The $join-request$ is sent on any available channel as explained in the LoRaWAN MAC specification [23]. The purpose of this technical step is to be able to estimate the number of frames and thus the duration of transmission for a round. After a successful join-request, the gateway sends back a $join-accept$ adding on the payload a two bit (00 or 11) priority-group(PG) of the nodes based on the data size information.

2. Priority Group(PG) : The priority-group is to specify and separate the importance of the messages to be transmitted from the nodes. The reason for this stage is to reduce delay of important messages, especially for large data node. In the channel selection mechanism on the gateway, the PG is used to dedicate specific channels for the nodes. The PG is represented in two bits of data. Bit 00 represents small payload data nodes with typical data size less than 110 bytes. Bit 11 signifies a large payload data node with data size ranging from 110 bytes to 2 KB. We represent the PG in two bits to reduce the amount of downlink data bytes sent. The $join-accept$ message sent by the gateway to the device is shown in Table 4.2. The fields are the same as implemented in the LoRaWAN specification [23]. We simply added the $PriorityGP$ field to signal communication and channel priority for the different nodes.

3. Network Join-accept : The $join - accept$ message structure at the gateway is as it is illustrated in Table 4.2. On receiving the particular node's datasize, the gateway decides the priority group it belongs to, with one of the two bits options already described.

4.2.2 Algorithm Design Considerations

1. **Frame length**

   The size of the frame to be sent can have an effect on the time on air used for the data to reach the gateway. With different transmission parameters, the transmission time can change, thus the data delivery time. We seek to use a frame length that will take the least time to transmit the data. To make the best selection on frame length for each SF transmission (as LoRa allows simultaneously transmission on the same channel when different SF are used: Section 2.1.2), we first analyze the time on air at the different frame length using Equation 3 as defined in [33]. T_{frame} is the time on air; $T_{preamble}$ as the duration of the preamble and $T_{payload}$ as the duration of the payload of the data frame. As the LoRa MAC headers can introduce overhead in our data transmission due to sending data of different sizes (accommodating large and small payload data nodes), to reduce the overhead, we propose to use variable frame length for the different SF.

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

   To calculate the $T_{preamble}$ and the $T_{payload}$, we use the formular in equation 4 and 5. $n_{payload}$ and $n_{preamble}$ defines the number of payload symbols and preamble length respectively.

   $$T_{preamble} = (n_{preamble} + 4.25) * \frac{2^{SF}}{BW} \tag{4}$$

   $$T_{payload} = n_{payload} * \frac{2^{SF}}{BW} \tag{5}$$

   We used values of the bandwidth and coding rate as 125 kHz and 4/5. We used a frame length ranging from 1 to 255 as LoRaWAN's applicable

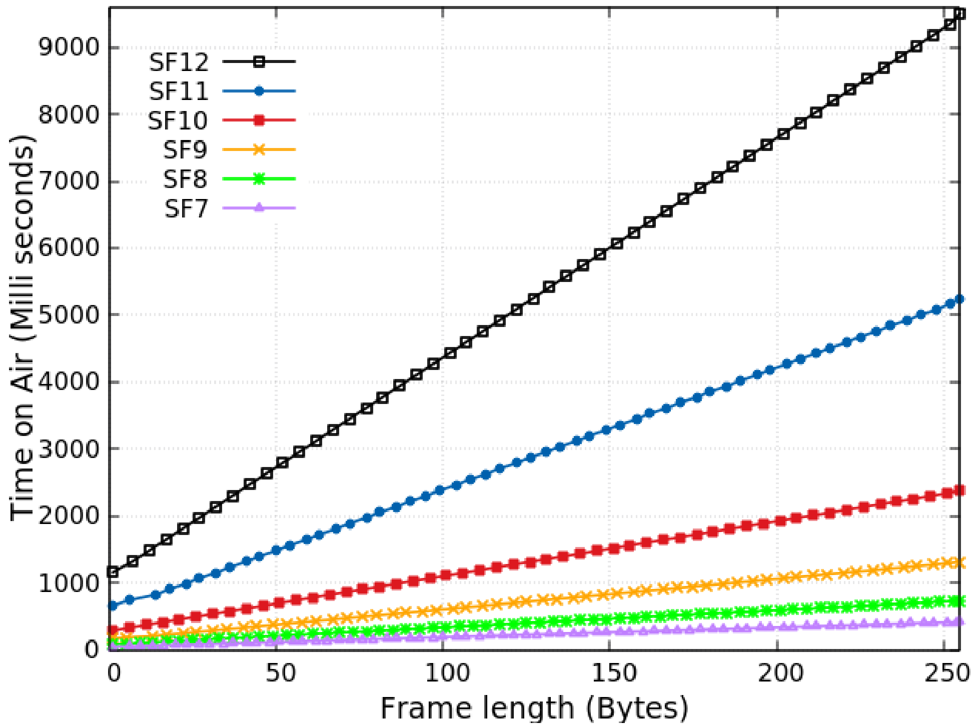


Figure 4.3. Time on air for variable frame length for the different SF.

payload values. We added the default MAC header of 13 bytes to each of the frame length. The time on air implementation for the graph 4.3 is added in the Appendix 7. It simply calculates the preamble and payload length in time, of a data frame transmission. Figure 4.3 shows that as the frame length increases, the ToA using each SF increases. The ToA for the frame lengths, doubles with every increase in step of the SF. The steps on the graphs for each SF indicates that for a small range of payload length, the time on air is constant. A frame of size 50 bytes will take different amount of time to be transmitted using the different SF, with SF 12 taking the longest time. We use the graph to determine a suitable frame length of each SF to be used.

2. **Spreading Factor**

   As stated earlier in Table 2.2 of Chapter 2, the SF can affect the values of the ToA , the range achieved and sensitivity of receiver. SF effect on

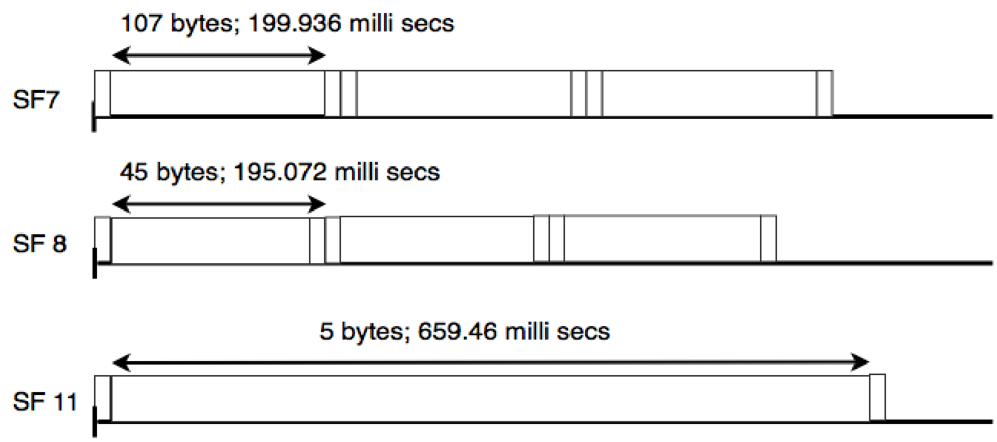


Figure 4.4. Variable data frame size per SF for (SF 7,8 and 11)

the ToA can be seen in Figure 4.3. As the SF increases, the transmission time of the data frame increases. Most related works randomly select an SF [16] and others select the SF based on the RSSI of the channel. In this work, we select SF based on the size of the data frame being sent that corresponds to the priority group of the node. With the goal and aim of reducing data delivery time of large data and using as less time to transmit the whole large data, we assign lower SF for larger frame size and higher SFs, which takes a longer time to complete transmission, for smaller frame sizes. Figure 4.4 shows the frame sizes allocated to the different SFs. From SF 7 to SF 12, we used frame lengths: 107, 45, 22, 11, 5 and 1 in bytes respectively. For fragmented large payload data nodes, we use SF7 starting with 107 bytes of data frame transmissions, as it takes the fastest time. Since LoRa transmission supports concurrent transmission, we can have up to six transmissions at a time corresponding to SF 7 to SF 12 on a single channel. Thus, the algorithm considers use of different SF on the same channel by nodes to transmit simultaneously. It also considers same SF but in different channels or different time slots.

3. **Channel Selection** In the current implementation, we consider six concurrent transmissions for a channel. These are mapped to the six spreading factors used. However, most LoRaWAN gateways, only support a maximum

of 8 transmission for all channels used. Some gateways are single-channeled while others have 3 to 8 channels. This work accommodates for the maximum of 8 simultaneous transmissions over any combination of channels. However, as shown in [31], use of all 8 transmission paths might not be suitable for all application scenarios. Thus, we measure and check the capture effect and effect of the imperfect orthogonality of LoRaWAN in the simulator.

4.2.3 Channel Selection Mechanism

After the gateway sends join-accept to the nodes, it broadcast downlink messages called channel status updates (CSU) to the nodes which contain a list of available channels and their scores, favouring high priority groups, and the SF to use. The information of time slot number to indicate when to transmit on the recommended channels is added as well. We employ the use of channel status updates to enable informed channel selection instead of random channel selection.

We score each available channel based on a series of parameters that has an effect on the performance of the transmissions. These parameters are updated as the gateway learn more about the status of the network, nodes and channels. These parameters can provide essential knowledge of the network for a node's higher success rate of frame transmission and fast data delivery. The channel selection for nodes, criteria are as follows:

1. **RSSI :** It defines the received signal power in milliwatts and is measured in dBm. It is an indicator for how well the gateway can hear the signal from the node on a channel. RSSI values range from -30 to -120 dBm. For the implementation, we check and compare the RSSI value to the receiver sensitivities (as stated in table 5.4) on the channels. When the RSSI is greater than the receiver sensitivities at a particular SF, frame transmissions can be successfully received by the gateway. This indicates the SF to avoid on the channel list. The RSSI is affected by the distance of the node to the gateway. Knowing the distance of the node from the gateway, we estimate the RSSI using log-shadow.

2. **Channel Availability:** This checks for the last time channel was used.

Parameter Effect	**RSSI**	**Channel Availability**	**SF**	**Delivery Time**	**Channel Saturation**
Reduce Collision	✓	✓	✓		✓
Good Link Indicator	✓				
Faster Delivery time			✓	✓	

Table 4.3. Effect of the parameters for best channel selection

This parameter enables the nodes to avoid using the same channel consecutively. We use the duty-cycle time-off calculation (equation 1) as a value and decrement the value after every frame transmission for each channel and node.

3. **Delivery Times:** With the unpredictable nature of wireless transmissions, the location and distance of transmission or even external conditions can alter the data delivery times. Thus, this criteria helps us estimate the data delivery times, the channel has achieved thus far. We use the air-time cost (equation 3) to estimate the delivery times based on the SF and payload of the transmission. We also check for the fastest delivery time achieved on the channel and under what SF and transmission power.

4. **Channel Saturation :** This is used to indicate how many of the concurrent SF transmission were used in the previous transmission time slots. We check for each slot to be scheduled, the number of processed frame transmissions. As most LoRaWAN gateways can only demodulate at most 8 frames simultaneously, and any additional frame when gateway is in full capacity, will be dropped, thus, this information gives us more light on channels to avoid for a period.

Table 4.3 illustrates the different parameters considered for the channel selection and the effect it has on three important characteristics we need to achieve. A channel score will let a node know what sequence of available channels, SF and slot time and number to use for its data frame size and priority-group.

Algorithm 1 illustrates our proposed channel selection and ranking mechanism. It takes as input the total number of channels, number of nodes, the frame

Algorithm 1: Channel Selection and Slot Allocation

Input: data size; number of nodes; list of channels; framelength_per_SF

Action:

```
1    Loop through channels to analyze for rank;
2        Evaluate RSSI of node transmission
3        Sort: longest availability to node
4        Best delivery times achieved
5        Concurrent transmission at gateway
6    Generate channel sequence based on network parameter effects;
7    Estimate number of frame transmissions with data size and frame length per SF;
8        Select best SF for each channel;
9    Calculate length of round;
10       Verifies nodes priority group ;
11       Assign slot number for node data frames
```

Output: channelListScore in sequence; SF per CH; slot number

lengths per SF, and data size and outputs a list of channels in sequence, SF per CH, and slot number to start data transmissions. Lines 1 to 6 does the channel selection analysis based on the criteria discussed and place channels in a sequence for transmission. Line 7 and 8 select and assign an SF for each channel. Line 9 to 11, allocates the slot number, indicating start of transmission for the node.

4.2.4 Synchronization :

Since we are using time-slotted channel access, we need to allow the timing of the gateway to concur with the nodes. We perform synchronization when sending downlink channel status updates (CSU). The CSU for nodes contains the slot number. This indicates the time nodes can wake up and send on the recommended channels based on channel score. We add guard times to each frame transmission to ensure the transmission does not extend along the next transmission. The nodes use the slot number and number of channels to estimate the duty-cycle time-off interval before transmitting again. After the end of each time-off interval, the channel schedule is repeated until the end of a round for a node. We illustrate

Algorithm 2: Data Transmission from Nodes

Input: channelList; slot number;

Action:

1 If PG is L_N:

2 Fragment dataSize using the lowest SF frame lengths into frames.

3 Else:

4 Use SF frame length closest within datasize

5 Use suggested SF of channel

6 Loop through frame transmissions at slot number time

7 Loop through channelListScore

8 If channel available

9 Sends frame

10 Else:

11 Rearrange channel rank sequence

12 Track duty cycle with frame ToA and time-off

13 Next frame transmission

the data transmission for a node in Figure 4.5. This is further explained in the following section. The gateway sends an updated downlink CSU after every end of round only if nodes have data to send or there is a change in channel status. This is to reduce the amount of downlink transmissions in the network as more downlink traffic is introduced in addition to uplink, the network performance drops with regards to successfully received data transmissions [31].

4.2.5 Data Transmission :

Assuming the gateway has provided, the list of channels in sequence of best fit for the data transmission of the node and the SF, and slot number, the node sleeps and then wakes up on the time of the slot number to send data with the respectively suggested parameters. The algorithm to transmit data takes in as input, the output of the channel selection mechanism. Lines 1 to 4 prepares the payload data for transmission. Lines 6 to 12 loops through all frame transmissions and send the frames accordingly while tracking the timings.

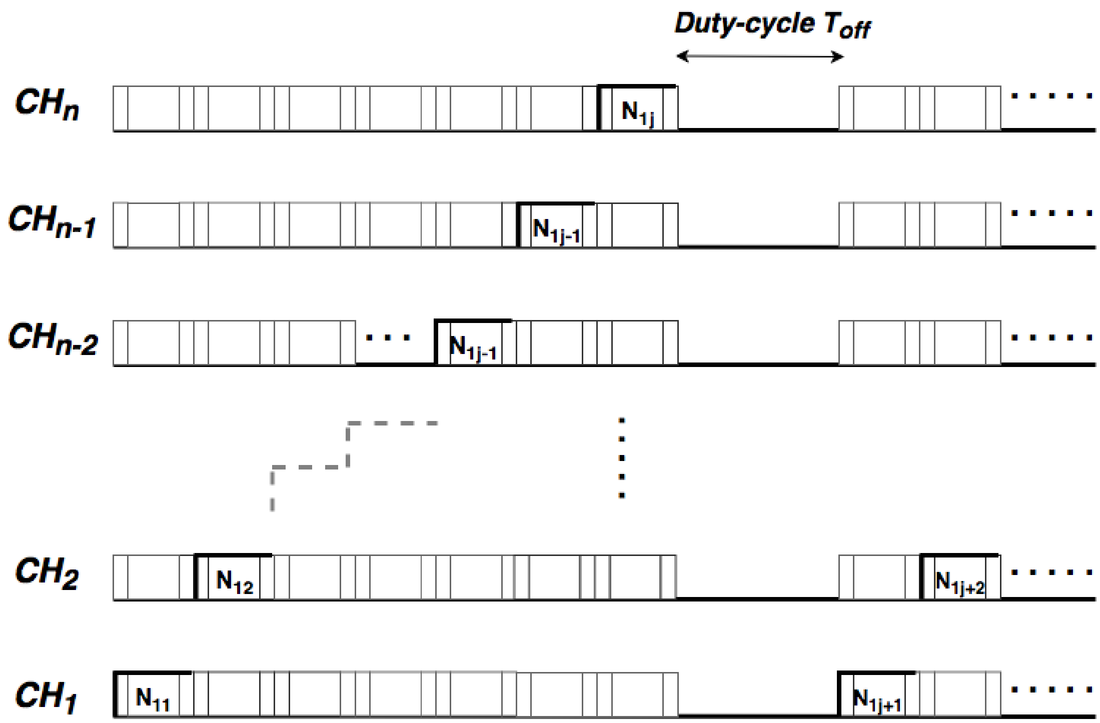


Figure 4.5. Data transmission for a node in a multi-channel gateway

Figure 4.5 shows the data frame transmission for our proposal on a channel list in sequence for a node. The node follows the rank of channels as suggested by the channel selection mechanism to transmit data (N_{ij}). After the end of the selected frame transmissions on all channels, depending on the remaining duty-cycle time-off, there is a wait period before the node can continue and repeat the channel list schedule suggested by the gateway as in frame N_{1j+1}. After all frame transmission end, the round is completed. Then, nodes wait for the average control transmission interval or whenever they have data to send, before attempting to connect and transmit to the gateway again.

5. Performance Evaluation

In Section 5.1, we first made a feasibility test to transmit large data over LoRa physical layer. We built a real system using LoRa nodes and experimented sending multiple images for a period of one hour. Results were analyzed based on packet loss and reception ratio of images. In section 5.2, we explain about the simulation environment, LoRaSIM, that is used and contributions we made towards the simulation environment. Section 5.3 , shows the performance analysis of our proposed approach to enable large data transmission among small data payload nodes aiming to reduce the data delivery delay. Finally, we made a discussion on challenges, improvement and extension of the proposal in section 5.4.

5.1 Image Transmission Feasibility Test

In this research, we first carried out an experiment to show the feasibility of sending images over LoRa. Our main goal was to illustrate the conditions in sending images over LoRa physical modulation with inter-packet transmission delay. We also wanted to know how well LoRa modulation handles image transmission with the challenges of low data rate and large image size. Furthermore, the physical layer has no restriction of the duty-cycle as it is simply sending data from LoRa nodes over radio waves.

5.1.1 System Setup and Process

Towards our feasibility test, we setup a LoRa network consisting of two LoRa-enabled nodes, and two personal computers (PCs) to analyze the packets.

The main device used in our experiment as our sender and receiver node is the low resource LoRa Mini Development board [22]. The LoRa mini dev is based on the SX1276/SX1278 transceiver standard that enables long range transmission, low power consumption and secure transmission capability of LoRa while exhibiting high resilience to interference. It is readily available and easy to use for beginners and provides a good challenge for programmers wanting to work on low-resource IoT nodes. The specifications of the LoRa Mini dev are summarized in Figure 5.1.

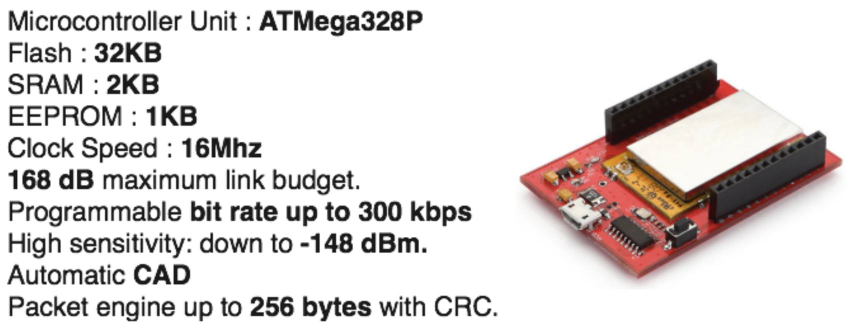


Figure 5.1. LoRa Mini development board

For our implementation, we utilized frequency channel 923.4. This channel is among the ten uplink LoRa channels stated in table 2.1.

Figure 5.2 illustrates the experimental setup. Each of these nodes are connected to a PC using a USB cable. This helps to view the serial monitor that shows the packet data being sent and received on either side. Both PC have the Arduino Integrated Development Environment installed and that is where we programmed our sender and receiver node solutions. The image data flows from the PC connected to the LoRa sender node through the serial interface and then the image is sent in packets using LoRa Modulation on channel, 923.4.

We used a spreading factor of 7, coding rate of 4/5 and bandwidth of 125kHz. These physical layer properties of LoRa are chosen as they give the least time on air for the given payload size. The packets received by the LoRa receiver node (gateway), were then transferred to the second PC to be reassembled as an image. The experiment was carried out in an enclosed environment with node 1 to 5 meters apart. Table 5.1 gives us a summary of the experimental parameters used. A detailed explanation of each step carried out in the experiment as shown in Figure 5.2 is as follows:

- **Uploading images to LoRa sender node**

  Images of crabs are collected and processed by converting them to grayscale and of size 128 x 128 pixels. This compresses the size to a much more desirable and acceptable size for transmission. The image format used is identical to low-cost cameras format. We used the PySerial library[1] to

Parameter	Value [Unit] and Comments
Devices	2 LoRa Transceivers
Region	AS923
Frequency Band	923.4
Coding Rate	4/5
Bandwidth	125 kHz
Transmission Power	13 dBm
Payload length	58 bytes
Preamble Length	8 bytes
Channels	1 Uplink
Spreading Factor	SF7
Exp. Periodicity	1-hour
Max. Image Size	2067 bytes

Table 5.1. Image transmission feasibility experiment parameters

send the images as byte array packets over Universal Asynchronous Receiver/Transmitter (UART) at a baudrate of 9600 bits per second.

- **Sending packets over LoRa** As data is being received over the serial connection, packets of 58 bytes payload size are formed and encoded. From the LoRa sender node, we send these packets over the LoRa modulation. Radio parameters are set on the nodes and channel sensing is performed before sending of any packet. Delays are inserted between packets to increase the probability of packets reaching the receiver node. The radio head library, RH_RF95 library [24] is used in sending the data to the gateway.

- **Receiving packets over LoRa** The LoRa receiver node continuously listens for connection on the 923.4 frequency. After arrival of packets, there is verification to check node source address. Then, packets are decoded and sent to the second PC for reconstruction and analysis using pyserial. The gateway calculated the packet's transmission SNR, RSSI as well as the total bytes per packet received.

- **Packet assembling**

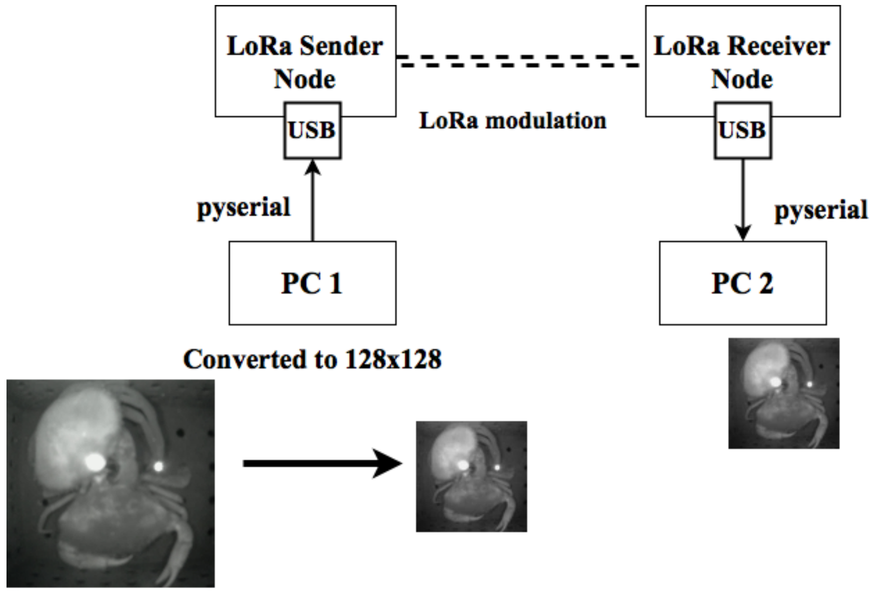


Figure 5.2. The LoRa network experiment setup with two LoRa nodes.

On the PC connected to the receiver node, a python script listens to the serial connection and reassembles the packets.

5.1.2 Experimental Results

To demonstrate the feasibility of a critical one hour multiple image transmission, we transmitted six images that were captured and collected from an IoT Soft-shell crab farming system test bed. With the transmission parameter as in Table 5.1, we sent an image after every two minutes for the duration of one hour. We were able to transmit and receive 27 images in a one hour duration. These images have an average byte size of 1997 and an average overall transmission time of 15.192 seconds.

Table 5.2 shows the different sizes of the six images sent, the number of packets sent and received and the time elapsed in cases when we had a successful image transmission without any packet loss. The elapsed time includes: time used to send the image through serial connection to sender node, time used to read the image, time used to packetized and transmit, and time the receiver node retrieved all packets of the image.

Image Size in bytes	No. of packets sent/received	Time elapsed in seconds
2067	37	15.71
2009	36	15.29
2059	37	15.69
1927	34	14.66
1923	34	14.61

Table 5.2. Image transmission sent and received packets with the tracked elapsed time of transmission.

Packet loss/ Packet Reception Ratio :

We experienced packet losses towards the end of the one hour duration of transmission. However, overall, it was not very significant. Only one out of the 27 images sent had a high packet loss percentage of 19%. 23 of the images transmitted, experienced no packet loss. Two images had packet loss of 2.9% (as a result of 1 packet drop) and 5.4% (as a result of 2 packets drop). For a total of 27 images, a total of 963 packets were transmitted, and 953 were received at the gateway.

Figure 5.3 shows the packet reception ratio over the one hour duration for the 27 images sent. The packet reception ratio was as its best for almost all the images received over the one hour duration study.

Image Size :

During the feasibility test, we compressed large size of images to less than 2 KB to be able to send the data in a format that corresponds to low-cost cameras [6], [4]. These images have size of 128 x 128 pixels. Image data more than 2 KB, when sent over LoRa tend to introduced a lot of packet loss. Thus, we used the optimal image size of less than 2100 bytes for our research.

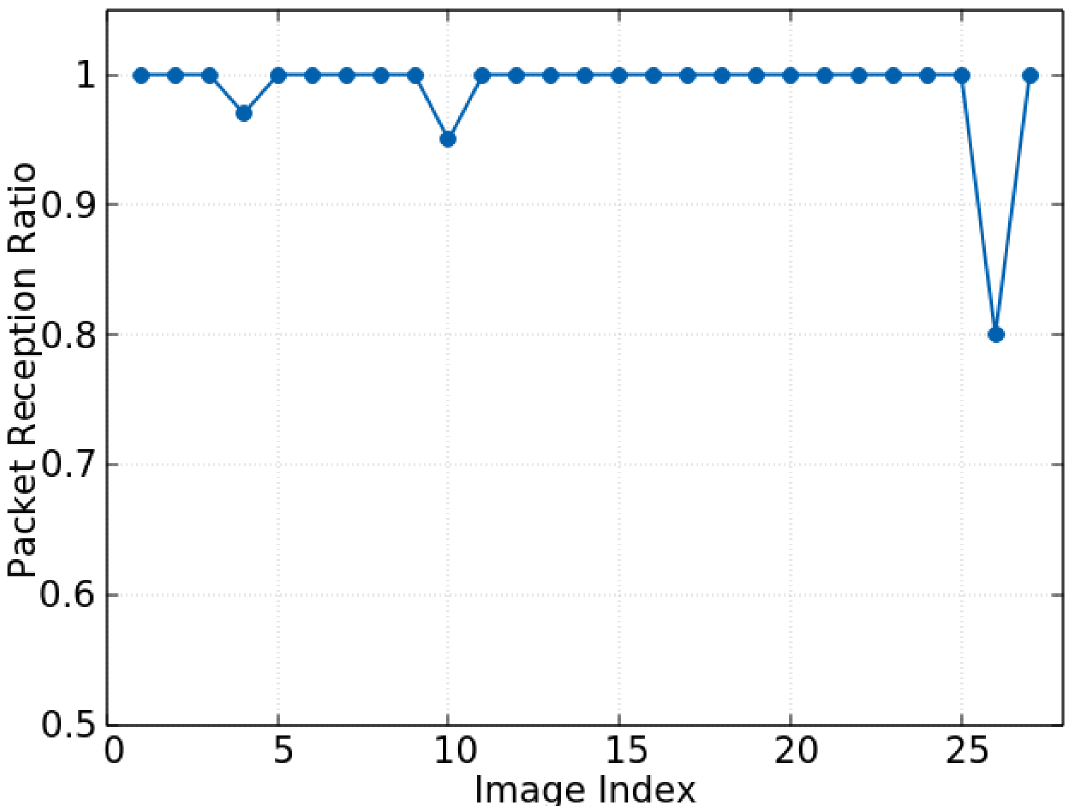


Figure 5.3. The packet reception ratio for the images received.

5.2 Simulation and Evaluation Metrics

We performed simulation experiments on the performance of the channel selection and link-scheduling algorithm based on uplink transmissions made, data frame reception ratio and data delivery time. We compared the results with slotted ALOHA LoRaWAN.

We made assumptions on the simulation environment. We assume that large data size sensor nodes (L_N), buffer data frames and fragmentized the large data into sizeable frame sizes . We assume a real LoRa network environment enabling multiple nodes and channels with periodic traffic. The L_N generates delay constraint data. We also enable concurrent data transmission using different SF which is controlled by the scheduling algorithm. We do not consider mobile sensor devices, thus the gateway is stationary. We assume that the data size sent will be constant for every node and will slightly vary for image sensor nodes.

5.2.1 Simulation Environment : Improved LoRaSIM

In this research, we utilize and extend the LoRaSIM network simulator [13], which uses a log-distance path loss model obtained from a real environment. This means the simulator produces a good quality of prediction. There are research works that have used and extended LoRaSIM [31], [5] for their study purpose. The current LoRaSIM does not accommodate multiple applications with variable frame length. Thus, to improve the LoRaSIM for our research, we added the following functionalities:

1. Both large data node and small payload data node support that can perform simultaneous data transmission in the same simulation period.

2. Large data fragmentation into sizeable data frames.

3. Base station network information collection and analysis for channels status updates.

4. Node channel selection and slot scheduling for reduced data delivery time in LoRaWAN for large data transmission.

Our simulator model and workflow is illustrated in Figure 5.4. Our simulation starts with creating channels at the base station. We assume a single gateway/base station. Then, we create the nodes with random distances between each other with the log distance path model. Priority groups are assigned and number of frames estimated based on the data size of nodes transmissions. We create the frames with the various transmission parameters and carry out the scheduling of the channels and slot numbers. Lastly, we transmit frames according to their schedules while checking for collision, frames processed, sent and yielding timings for duty-cycle tracking.

1. **Receiver Sensitivity**
   In the simulation, to ensure that LoRa receivers/gateways pick up the data frames being sent, we use the LoRa device receiver sensitivity calculation in [33]. This means that when a data transmission's RSSI is less than the

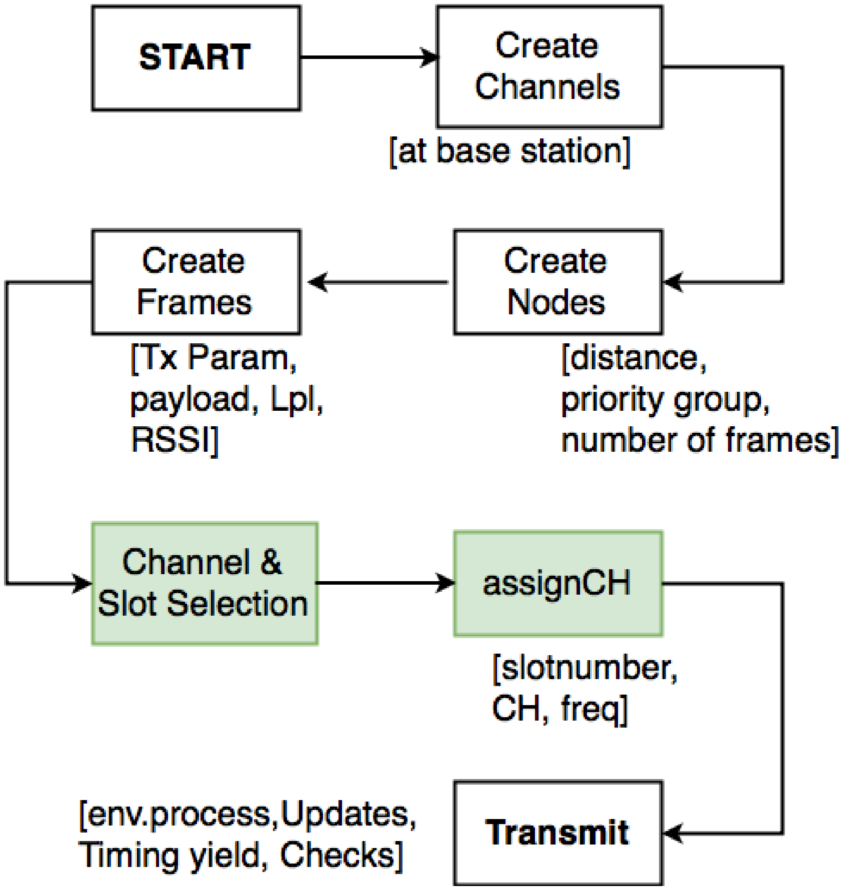


Figure 5.4. LoRa Priority Scheduling (LoRaPS) Simulation Model

sensitivity calculated, the data frame will not be received by the gateway. Equation 6 is the formula for calculating the LoRa receiver sensitivity (S) where BW is the bandwidth in KHz, NF is the noise figure of receiver in dB and SNR as the signal to noise ratio limit for a specific SF as listed in [33]. The NF is fixed for a given hardware implementation and the value 6 dB is given for current LoRa end device transceivers SX1272 and 1276. Table 5.4 shows the calculated values for bandwidth 125, 250 and 500 corresponding to the different spreading factors used in the simulation as reported in the LoRaWAN datasheet [33]. Although higher bandwidth means faster data rate, it causes a deterioration in receiver sensitivity, thus

SF7	**SF8**	**SF9**	**SF10**	**SF11**	**SF12**
-7.5dB	**-10dB**	**-12.5dB**	**-15dB**	**-17.5dB**	**-20dB**

Table 5.3. Required SNR

SF	125 kHz	250 kHz	500 kHz
7	-123	-120	-116
8	-126	-123	-119
9	-129	-125	-122
10	-132	-128	-125
11	-133	-130	-128
12	-136	-133	-130

Table 5.4. LoRa receiver sensitivity for different bandwidth and SF.

reducing link robustness.

$$S = -174 + 10log_{10}BW + NF + SNR_{limit} \quad (6)$$

Typical LoRa's SNR values range from -20dB to +10dB. Higher values mean the signal is less corrupted. Table 5.3 shows the required SNR for the different SF, for LoRa to demodulate signals. This is used in equation 6 to calculated the receiver sensitivity.

2. **Non-orthogonality and Capture Effect of SFs**
In the simulation, we also consider the non-orthogonality of SFs in LoRa transmissions. This basically translates that two or more transmissions from nodes using same or different SF can overlap in time, frequency or power causing overpowering and collision within the frame transmissions. The capture effect between the different SFs are calculated as the isolation threshold [14]. To check if collision or overpowering between transmissions has occurred, we can compare the difference between the RSSI of the two transmissions and the isolation threshold at the two SFs of the transmissions. For the simulation, we use the values of the isolation threshold as in [14].

3. **Simulation Parameters**

   Table 5.5 gives the simulation parameters used in the simulation experiment. We ran simulations up to a 1000 nodes with data to send. With each simulation, we have a balanced ratio of small payload data nodes of 1 to 22 bytes and large data nodes of up to 2100 bytes. These ratios were chosen to reflect LoRa IoT application scenarios modelled and studied in table 2.4. We assume a 10% duty cycle limit (which translates to 360 seconds per hour) as in the AS923 band but using limited bandwidth of just 125kHz as per regional recommendation [17]. We assume a maximum of 8 channels of a single gateway is available for data transmission. We used a guard time of 2 ms at beginning of a frame transmission and at the end to accommodate for synchronization timing with the gateway. The guard times also help with avoiding timing collision between packets.

Parameter	**Value [Unit]**
Devices	6 - 1000
Ratio of Sensor nodes (Small to Large)	5:1; 10:1; 50:10; 100:10;
$S_N : L_N$	150:20; 500:100; 1000:100
Region	AS923
Duty cycle	10%
	per node
Channels	3 - 8
Spreading Factor	7 - 12
Code Rate	4/5
Bandwidth	125 kHz
Transmission (T_x) Power	13 dBm
MAC Header	13 bytes
Guard Time (GT)	0 - 5 millisecs
Traffic	Unconfirmed
Small Data Payload (SP)	1 - 22 bytes
Max. Image Size	2100 bytes

Table 5.5. Simulation Parameters

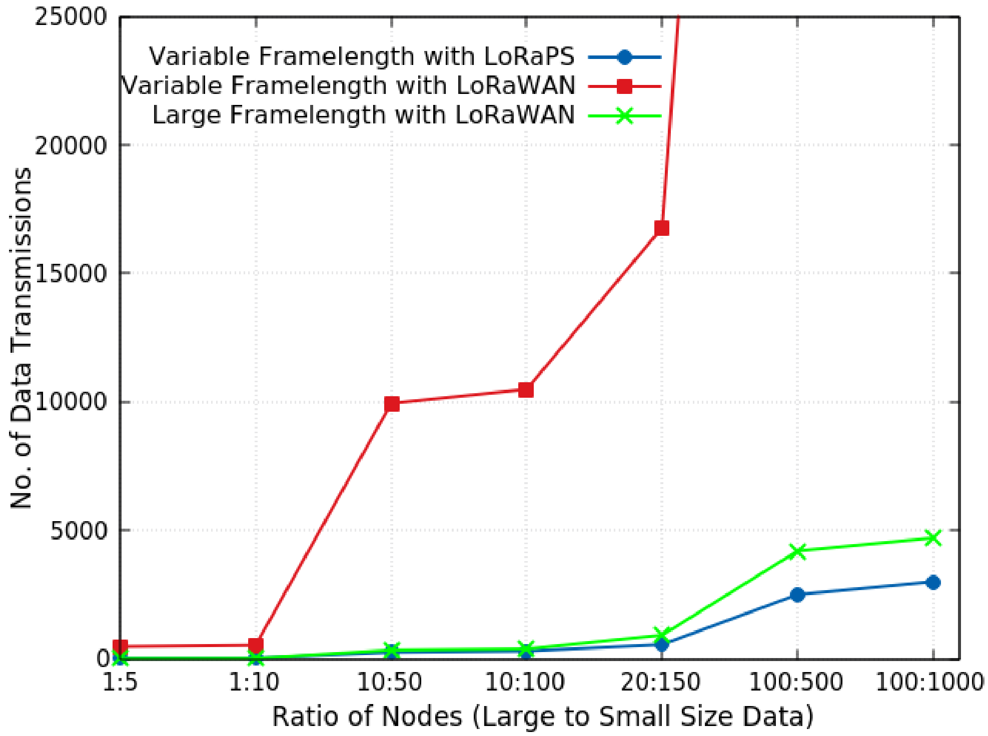


Figure 5.5. Uplink transmission of data frames

5.3 Simulation Results: Link Scheduling

We evaluated our scheduling mechanism with regards to the amount of uplink traffic made, the data delivery times achieved by nodes, the frame reception ratio for successfully received data frames as the number of nodes increases and the achievable delivery time of various IoT application scenarios. Through this evaluation, we refer to the priority-group based scheduling method as $LoRaPS$. The variable framelength referred to in the analysis is discussed in Chapter 4 of subsection 4.2.2. We also used in the evaluation, large frame length sizes for the different spreading factor ranging from 242 to 246 bytes of data on the LoRaWAN. This is to reduce the impact of MAC overhead that results from smaller data frame sizes.

5.3.1 Uplink Transmission of Nodes

The number of uplink frame transmissions reflects on the efficiency of the method. Higher transmissions means data was sent in multiple smaller frames, thus longer transmission time and delay. With the utilization of the variable frame length and mapping the frame payload size to the SF used to transmit data, our method (*LoRaPS*) is able to achieve fewer data frame transmissions to be scheduled compared to slotted Aloha LoRaWAN as illustrated in Figure 5.5.

As high priority nodes use the SF with the least delay, the data frame sizes used are larger. This allows the data size (example, image) to be fragmented into fewer packets. With node ratio of 10:100 (total of 110 nodes), LoRaPS was able to transmit as few as 300 data frames while LoRaWAN using variable framelength, fragments the data into over 10,000 frames. This is because typical LoRaWAN favours using higher SF (longer delay) and smaller frame sizes. Thus, as the number of nodes increases, the amount of data transmissions increases significantly. Using large frame lengths in LoRaWAN significantly reduced the amount of data frames transmitted as large data is fragmented into large frame sizes, thus fewer frames to send. This works for large data, however, considering that the application scenario combines sending both small and large data nodes, the drawback is using a 242 bytes frame to carry a 5 bytes data of a node.

5.3.2 Various Application Node Scenario

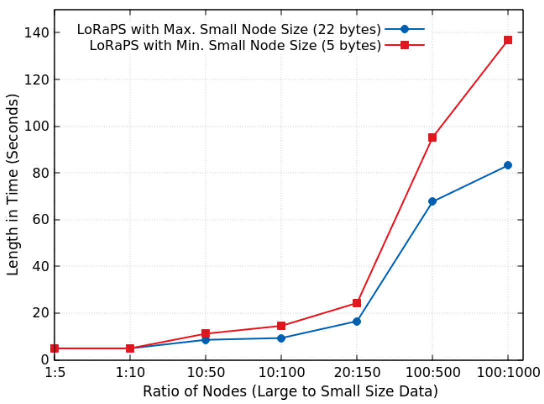
Since our study is application-based focused, we also considered and analyzed a few real-world scenarios of using different combinations of large data nodes and small data nodes. These IoT application network includes Soft-Shell Crab Harvesting, Smart Irrigation and Home Security. For Soft-shell crab harvesting, we consider a small-sized pond with 3 water quality sensors of 17 bytes and 10 visual sensors sending data to a gateway. For each round of data transmission of all nodes, with LoRaPS, sending data on multiple channels, data sent can reach the gateway in less than 9 seconds. This time was achieved by simulating 10 large size nodes and 3 small payload size nodes of 17 bytes. Table 5.6 shows the different application scenarios considered and the achievable data delivery time with scheduling.

No. of nodes	Large data nodes	Small data nodes	Application view	Data delivery time in ms
13	10 Cameras 2100 bytes	3 Water Quality (Salinity, pH, Temperature) 17 bytes	Soft-Shell Crab Harvesting (1) Water Quality (2) Visual Sensing	8565.312
60	10 Cameras 2100 bytes	40 Moisture 5 Temperature 5 Humidity 5 bytes	Smart Irrigation (1)Soil Quality (2) Moisture Level (3) Plant Visuals	11203.152
15	5 Cameras 2100 bytes	10 Motion Detectors 20 bytes	Home Security	4894.464

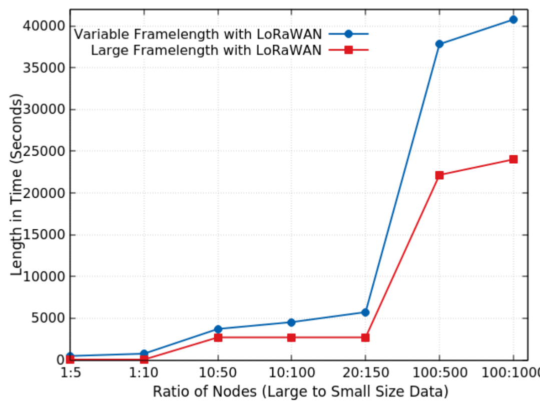
Table 5.6. Various application scenario

5.3.3 Data Delivery Time (DDT)

One of the main goal of this research is to improve the data delivery time of large nodes by giving them channel selection priority. We also consider the duty-cycle time-off of nodes on channels. As such, we analyze the length of time to send data from multiple nodes. During simulation, LoRaPS showed better timing compared to typical LoRaWAN. Figure 5.6 shows two graph plots of using LoRaPS and using typical LoRaWAN for the different ratio of nodes combination. Large frame length on LoRaWAN transmit data faster that using variable size LoRaWAN as in Figure 5.6 (a). However, both methods still incurred a lot delay for both large and small nodes compared to LoRaPS. Since LoRaWAN methods obtained longer data delivery times compared to LoRaPS, we separated the graphs into Figure 5.6 (a) and (b). LoRaPS as shown in Figure 5.6 (b) performs in the lower ranges of seconds to transmit data, thus we made comparison of using a maximum of 22 bytes of small node data and a minimum of 5 bytes of data. It takes longer time to send the smaller bytes of small payload data node than the maximum byte size of 22 as seen in Figure 5.6 (b). This illustrates prioritizing nodes with larger data sizes. Smaller payload bytes such as 5 bytes uses higher SF (in this case SF 11). This is further explained in Chapter 4. Thus, overall, LoRaPS scheduling



(a) Using LoRaPS



(b) Using Typical LoRaWAN frames

Figure 5.6. Data delivery time achieved on the different node data payload sizes

mechanism works in reducing the delivery time of both large and small data nodes compared to typical LoRaWAN.

Large payload Data Node DDT : We also made analysis on the average time large nodes can send and successfully transmit to the gateway. With LoRaPS, each node has a slot start time that it starts to send to the gateway, with time on air considered and time-off from the channels. Figure 5.7 shows the minimum and maximum amount of time with respect to the total number of nodes scheduled for transmission on the gateway, that a large data size node can send all data frames to the gateway. The plot in 5.7 shows the upper and lower limit of delivery time for large data nodes (an image). With the plot, for a total node of 300 nodes with 100 large size data and 200 small payload size nodes, the least amount of time for an image to be transmitted and reach the gateway is within 4.894 seconds and the longest time is 53.431 seconds. We can notice in the graph that for equal amounts of large data nodes, the range of delivery times is equal. LoRaPS prioritizes large data node traffic to small payload data nodes. Thus, an increase in small payload data nodes, does not affect the range of time to transmit for high priority nodes. The graph shows the effectiveness of the scheduling and priority traffic especially for large payload data nodes

Small Payload Data Node DDT : We further made similar analysis of the delivery time of small payload nodes to show that LoRaPS ensures small payload data reach the gateway within a reliable time frame. Similar to Figure

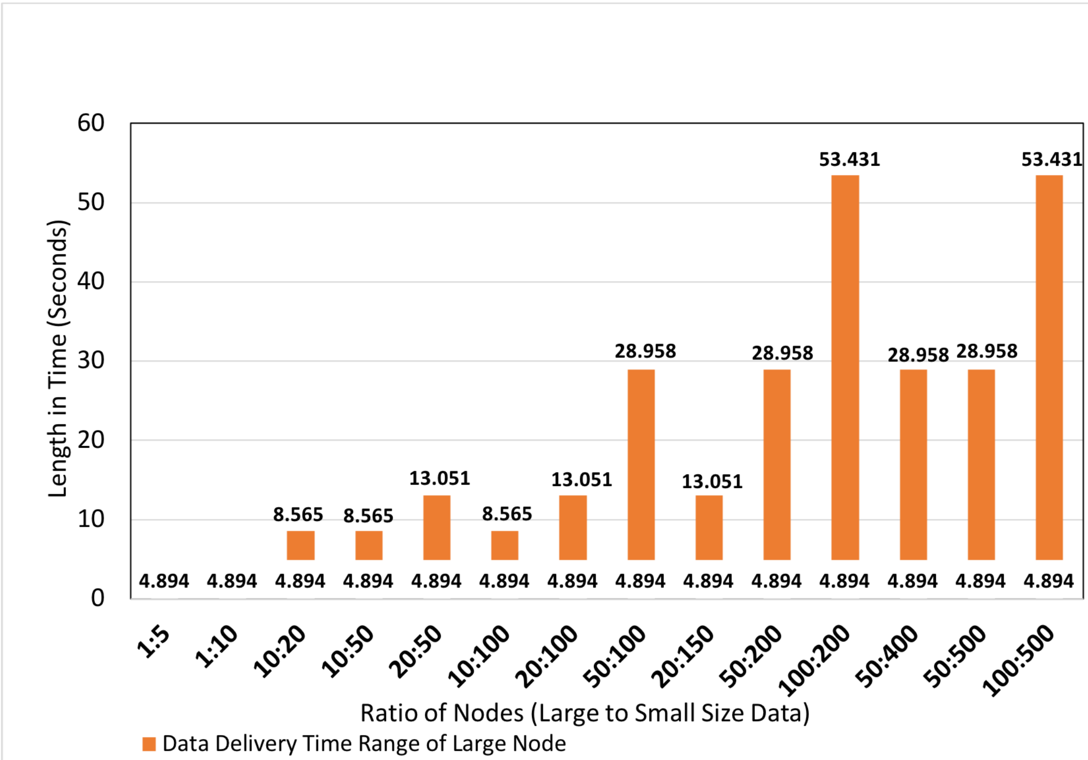


Figure 5.7. Analysis on the average time Large payload data nodes can be successfully transmitted to the gateway.

5.7, we illustrate in Figure 5.8 the least amount of time to transmit data of a small data node and the longest duration of time considering other nodes. The plot graph differs from figure 5.7 as, not equal amount of nodes means similar time duration to transmit. Transmission duration depends on the number of high priority nodes. From the figure 5.8, with 170 nodes, and 150 of them being small nodes, the minimum time is within 7 seconds and the maximum is with 17 seconds. But, for 150 nodes, with 100 nodes of small payload data bytes, the least amount of time translates to 23 seconds. This is due to the amount of higher priority nodes, in this case, large data nodes.

5.3.4 Frame Reception Ratio

The ratio of frames received at the gateway to transmissions made by the nodes is evaluated. This shows how well the mechanism avoid data frame drops. Figure

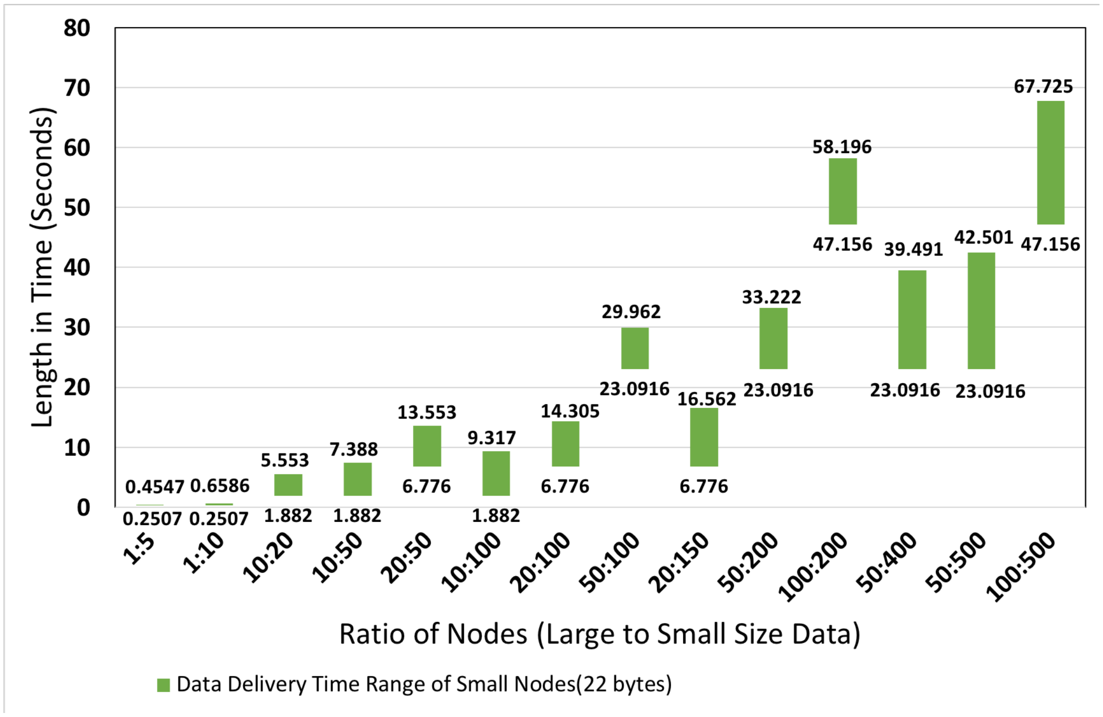


Figure 5.8. Analysis on the average time Small payload size nodes can be successfully transmitted to the gateway

5.9 illustrates the frame reception ratio for every total combination of nodes. The worst performance was experienced with LoRaWAN using large frame length. Although, it shows good performance with the number of uplink transmissions, and data delivery time, it showed some data frame lost or collision with other nodes. Figure 5.10 (a) and (b) illustrated the performance of the three mechanisms with regards to collision and data frame loss respectively. LoRaPS experienced the least collision and frame loss among the other methods evaluated. LoRaWAN with the variable frame length, performed good(as in frame reception ratio, Figure 5.9), in successfully receiving the data frames at the gateway even though it exhibits the longest delay on data traffic as seen in figure 5.6. This is due to the fact that, LoRaWAN with variable frame lengths sends smaller size uplink data and achieves low number of collisions and data frame loss as such.

LoRaPS compare to the typical LoRaWAN performed better in data frame reception, as shown in Figure 5.9. But, the mechanism did experience some frame

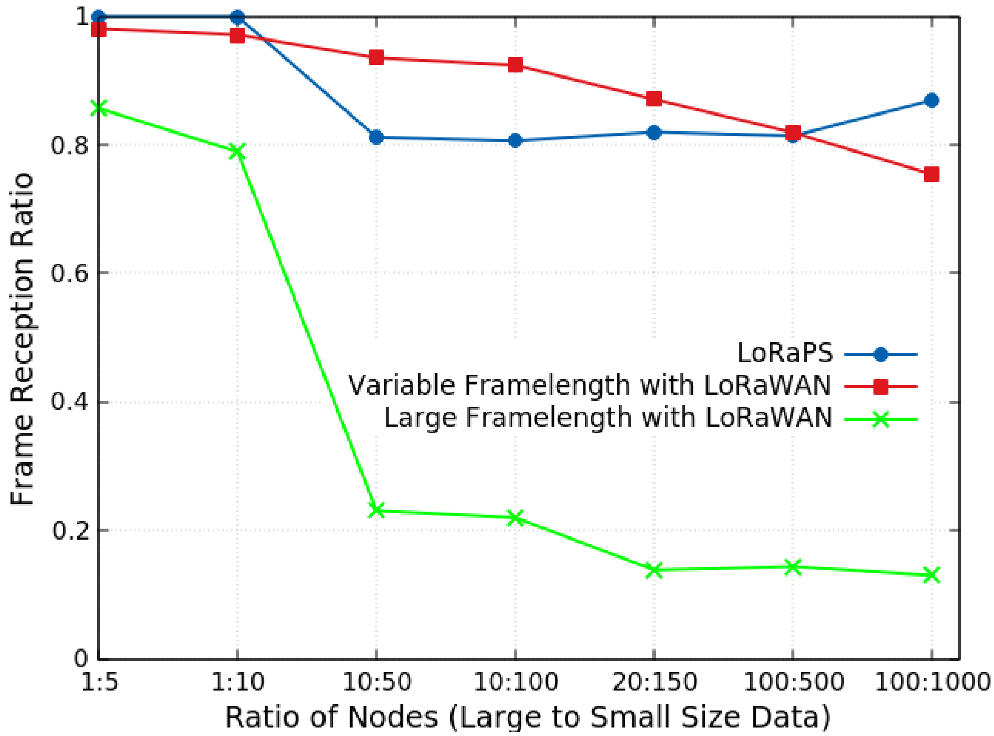
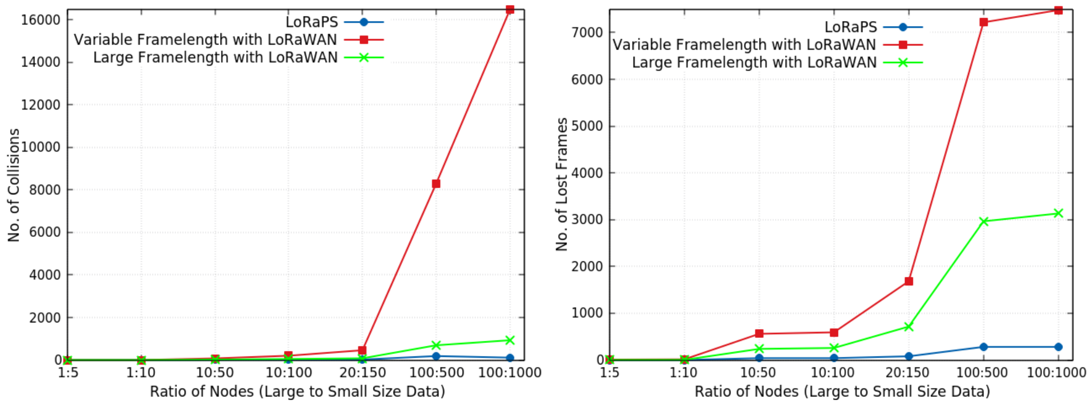


Figure 5.9. Frame reception ratio of nodes

loss and collision between nodes due to timing. Due to the scheduling of channels and time slots, frequency and SF collision were avoided, however, there were few timing collisions caused by data frames being too late and colliding with the preamble of the following data frame.

The simulator [13] analyzes data frame transmission with respect to: collision at base station due to more than the maximum number of data transmission being executed, collision between data frames of different nodes as a result of using same frequency channel or transmitting with same SF, power collision (RSSI and Isothreshold explained in Section 5.2.1) and timing collision as frames overlaps with other frames. In Figure 5.10, despite experiencing some collision and loss, overall LoRaPS performed better than the typical LoRaWAN in successful frame transmissions while achieving the least delay with duty-cycle time-offs.



(a) Data Frame Collision

(b) Data Frame Loss

Figure 5.10. Data Frame collision and loss

5.4 Discussion

In this section, we highlighted some of the areas of improvement of the priority-based link scheduling algorithm. Our research demonstrates a reliable scheduling of channels among large data payload nodes and small data payload nodes. Fast data delivery times were achieved for the delay constrained image transmissions compared to LoRaWAN. However, some considerations should be made in some areas of the performance.

5.4.1 Downlink Transmissions

The link scheduling mechanism introduces downlink traffic to send the channel status updates. The total bytes of the CSU is 16: four (4) bytes of channel rank, four (4) bytes of spreading factor suggested for each 8 (number of maximum concurrent transmission for LoRaWAN) links and eight (8) bytes that holds the slot number. On LoRa gateways, during downlink traffic, no other node can send data to the gateway and duty-cycle regulation is also imposed on the gateway downlink traffic as it is a network transceiver. We did not consider the duty-cycle of the downlink traffic and how it affects the overall data delivery time of transmissions. Since the downlink traffic is affected by the duty-cycle as well, thus, the base station can only transmit for 360 seconds per hours. Analyzing how the 16 bytes of channel status update affects the data delivery time and duty-cycle is interesting.

5.4.2 External Interference

Our simulation does not consider the transmission of other devices of probably the same or different technologies. In a real test bed deployment scenarios, frequency channels might be in use by other devices. However, the network simulator uses timeouts to adhere to the duty-cycle regulations of channel use. Also, in real-world scenarios, not all channels might be available to be used and there are are some gateways that allows just a single channel use. The simulation assumes a maximum usage of all channels. Thus, considering these scenarios, it will be useful to analyze LoRaPS performance in a real-world testbed.

5.4.3 Extension of Proposal

We have thus far showed the performance of LoRaPS in application scenarios that use the integration of large data nodes (visual sensors) and small payload data nodes. The main goal was in transmitting delay-constrained application data that sends data periodically. LoRaPS introduces the priority traffic for LoRaWAN in such application scenarios. Such priority-traffic scheduling in LoRaWAN has the unique context that LoRaWAN has duty-cycle imposed on both channels and nodes. We started the research aiming to ensure reliable large data transmission over LoRaWAN with the challenge of the small node transmissions affecting the data delivery time of the large data nodes.

Thus, apart from improving on the frame reception ratio and the technical challenges discussed, we can extend our proposal to developing a network deployment model towards reduced data transmission. With LoRaPS, we use channel status updates that take a few parameters of data transmissions to get information of the channel use. We can further propose machine learning models for data-oriented networks and focus on answering the question, how do transmit less but accurate data using network traffic knowledge.

5.4.4 Proposal's Compatibility with pure ALOHA LoRaWAN

Typical LoRaWAN uses Pure ALOHA for its data transmissions. In [30], Polonelli et al., made an analysis of slotted ALOHA on LoRaWAN and basically built the slotted ALOHA variant on top of the LoRaWAN standard without the need of changing for any pre-existing libraries or command. Most other related works use the standard LoRaWAN and create an extension to maintain compatibility. In this research, we used the same concept and added functions of separating traffic by prioritizing and channel recommendation to solve our research problems. In our solution on section 4.2.1, we added some fields in the message structure to achieve our desired outcome. As future work, already stated, verifying the compatibility of the functions in a real-test bed with LoRa devices will be explored.

5.4.5 Admissible Delay On Application

As our research focuses on reducing the delay caused by small payload nodes to large data nodes, there are application requirements that provides a measure of the delay in time that can be tolerated or managed. The admissible delay refers to how much delay can be considered as minimal for efficient data transmissions. In our research, this depends on the application transmission control interval mentioned in Table 2.4 and the maximum duty-cycle limit per node (360 seconds/ hour in Japan) according to the regional regulations. A summary of the transmission control intervals for small payload data nodes are: 10 seconds, 60 seconds, 10 minutes and 60 minutes. As for large payload data nodes, we have: 180 seconds, 15 minutes and when there is environment change detection. Our main focus with our experiments was on reducing the delay for the large data node transmission. With our approach , we were able to achieve the optimal transmission control interval with respect to the large payload data nodes.

5.4.6 Scalability and Usability: Application Scenarios for Proposal

The application focus for our research is towards small payload and large payload data nodes transmission with large payload data nodes having delay-sensitive information such as images. Recently, the Ministry of Internal Affairs and Communications (MIC) in Japan is considering deregulation of duty cycle to 720 seconds/hour/station in the case of using multiple channel as stated in IEEE document 802.19-18/0084r0. This will contribute in scaling the use of our method with regards to availability of more time to schedule nodes frame transmission.

With IoT networks being diverse and accommodating a variety of applications, thus unique traffic models, our priority scheduling scheme can be applied in multi-class heterogenous network ecosystem with differentiated services. The different classes can be given different priority levels and scheduled accordingly.

Our method is also applicable in data collection scenarios where gateways are available temporarily and nodes carry out bulk data sensor collection. Nodes with bulk data can be scheduled and considered as high-priority messages to be delivered to the gateway with as less delay as possible.

We can also apply the informed channel selection and priority scheduling in satellite communications where nodes usually transmit long messages containing multiple packets. Our method can reduce delay while making maximum use of the channels.

6. Conclusion and Future Research

6.1 Conclusion

Enabling easy and effortless integration and coexistence of large payload nodes with the typical small payload nodes in a LoRa Network is of great importance for the IoT community. LPWAN, such as LoRa, provides the basic communication requirements of low power and wide network coverage for smart city applications.

Due to the challenges of the time-offs experienced with the duty-cycle limitations and the LoRAWAN MAC layer protocol channel access and selection mechanism, data delivery delays are introduced on sensor nodes, especially worst in large payload sensor nodes such as images which require fast data delivery to the gateway.

In this thesis, we examined the problems of transmitting large data size among small payload data nodes in LoRaWAN. We proposed a modification of the MAC layer mechanism to handle delay constraint large data such as images, improving their data delivery time. In the proposed link scheduling mechanism, the gateway recommends available channels sequence based on the knowledge of the network and important transmission parameters. The gateway further divides the sensor nodes by the size of their message payloads into priority groups. Image sensors are given higher priority in the channel and time slot selection to ensure fast data delivery and successful frame transmission. We first made feasibility tests of transmitting large data over LoRa network. Results showed that images can be successfully sent over LoRa, although, with the ALOHA-like transmissions, packet loss will be experienced. We then, made performance evaluation of the scheduling algorithm in improving the data delivery time and in IoT application scenarios. The priority-based link scheduling achieved faster data delivery times for nodes compared to LoRaWAN.

6.2 Future Research

In this research, our main goal was to improve the channel selection mechanism in ALOHA-like LoRa to reduce the data delivery delay caused when nodes randomly selects channels which affect other important nodes (large payload size) transmission. The large data we refer in this research is mainly images, but it can be applied in bulk data collection of small payloads as well. We carried out simulations on our proposed delay improvement link scheduling. In the future, it will be important to do a real-world deployment of the system in a test bed. Our performance evaluations focused on uplink transmissions, data frame reception, data delivery times achieved and ensuring the duty-cycle limits are adhered to. Since this research is geared towards using LPWAN, it will be a good addition to evaluate range and energy consumption of the network, as LoRa is a technology for low power, remote but city-scale IoT applications.

Acknowledgements

First and foremost, I would like to thank God the Almighty (Allah SWT) for giving me the strength, knowledge, and opportunity to undertake this Master study. Without His blessings, this achievement would not have been possible.

I would like to sincerely thank my supervisor, Professor Youki Kadobayashi for his guidance and for providing me with an excellent atmosphere for doing research. It is an honor for me to be one of his students in the Laboratory for Cyber Resilience. I will also like to thank Professor Yuzo Taenaka for his support and contribution with regards to suggestions and advice towards my research. I am sending special gratitude to Assistant Professor Shigeru Kashihara and Assistant Professor Doudou Fall for their invaluable guidance, patience, and persistence in ensuring i work hard on my research. They have been my rock throughout my research and without them, it would have been twice as challenging. Special thanks to all the members of IPLab who also supported and helped me in daily life.

I send my deep gratitude to MEXT for sponsoring my studies and life in Japan. This was a once in a lifetime opportunity. I give my gratitude to the staff of the International Student Affairs Division of NAIST and Information Science office for their help regarding some administrative matters during my stay in Japan. Last but not least, I thank my family in the Gambia that has been there for me throughout my studies in good and hard times. I was very much motivated by their continuous encouragement.

References

[1] PySerial-PyPI. https://pypi.org/project/pyserial/, Jan 2019.

[2] Semtech LoRa Technology Overview. https://www.semtech.com/lora, Jan 2019.

[3] Sigfox. https://www.sigfox.com/en, April 2019.

[4] 4D Systems. 4D Systems uCAMIII. https://www.4dsystems.com.au/product/uCAM-III, Jan 2019.

[5] Khaled Q Abdelfadeel, Dimitrios Zorbas, Victor Cionca, Brendan O'Flynn, and Dirk Pesch. FREE-Fine-grained Scheduling for Reliable and Energy Efficient Data Collection in LoRaWAN. *arXiv preprint arXiv:1812.05744*, 2018.

[6] Adafruit. Adafruit ttl serial camera. https://learn.adafruit.com/ttl-serial-camera/overview, Jan 2019.

[7] Ferran Adelantado, Xavier Vilajosana, Pere Tuset-Peiro, Borja Martinez, Joan Melia-Segui, and Thomas Watteyne. Understanding the limits of LoRaWAN. *IEEE Communications magazine*, 55(9):34–40, 2017.

[8] LoRa Alliance. LoRaWAN Fragmented Data Block Transport Specification v1.0.0. https://lora-alliance.org/sites/default/files/2018-09/fragmented_data_block_transport_v1.0.0.pdf, Sep 2018.

[9] LoRa Alliance. About LoRaWAN. https://lora-alliance.org/about-lorawan, Jan 2019.

[10] Nesreen Alsbou, Daniel Henry, and Hazem Refai. R-aloha with priority (pr-aloha) in non ideal channel with capture effects. In *2010 17th International Conference on Telecommunications*, pages 566–570. IEEE, 2010.

[11] Nesreen Alsbou, Sylvain Prigent, and Hazem H Refai. Analysis of priority r-aloha (pr-aloha) protocol. *Wireless Communications and Mobile Computing*, 15(4):716–725, 2015.

[12] GSM Association. EC-GSM-IoT. https://www.gsma.com/iot/extended-coverage-gsm-internet-of-things-ec-gsm-iot/, April 2019.

[13] Bor, Martin C and Roedig, Utz and Voigt, Thiemo and Alonso, Juan M. Do LoRa low-power wide-area networks scale? In *Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, pages 59–67. ACM, 2016.

[14] Daniele Croce, Michele Gucciardo, Stefano Mangione, Giuseppe Santaromita, and Ilenia Tinnirello. Impact of lora imperfect orthogonality: Analysis of link-level performance. *IEEE Communications Letters*, 22(4):796–799, 2018.

[15] Orestis Georgiou and Usman Raza. Low power wide area network analysis: Can LoRa scale? *IEEE Wireless Communications Letters*, 6(2):162–165, 2017.

[16] Md Tamzeed Islam, Bashima Islam, and Shahriar Nirjon. Duty-Cycle-Aware Real-Time Scheduling of Wireless Links in Low Power WANs. In *2018 14th International Conference on Distributed Computing in Sensor Systems (DCOSS)*, pages 53–60. IEEE, 2018.

[17] ARIB Japan. Association of Radio Industries and Businesses(ARIB) STD-T108 Version 1.0. https://www.arib.or.jp/english/html/overview/doc/5-STD-T108v1_0-E1.pdf, 2012.

[18] Akram Jebril, Aduwati Sali, Alyani Ismail, and Mohd Rasid. Overcoming Limitations of LoRa Physical Layer in Image Transmission. *Sensors*, 18(10):3257, 2018.

[19] Alexandru Lavric and Valentin Popa. Performance evaluation of LoRaWAN communication scalability in large-scale wireless sensor networks. *Wireless Communications and Mobile Computing*, 2018, 2018.

[20] Andres Laya, Charalampos Kalalas, Francisco Vazquez-Gallego, Luis Alonso, and Jesus Alonso-Zarate. Goodbye, aloha! *IEEE access*, 4:2029–2044, 2016.

[21] Te-Kai Liu, John A Silvester, and Andreas Polydoros. Performance evaluation of r-aloha in distributed packet radio networks with hard real-time communications. In *1995 IEEE 45th Vehicular Technology Conference. Countdown to the Wireless Twenty-First Century*, volume 2, pages 554–558. IEEE, 1995.

[22] LoRa. LoRa Mini Wiki. https://wiki.dragino.com/index.php?title=LoRa_Mini, Oct 2018.

[23] LoRa Alliance. LoRaWAN Specification v1.03. https://lora-alliance.org/sites/default/files/2018-07/lorawan1.0.3.pdf, Sep 2018.

[24] Mike McCauley. Radiohead - rh rf95 class reference. https://www.airspayce.com/mikem/arduino/RadioHead/classRH__RF95.html, Jan 2019.

[25] Randolph Nelson and Leonard Kleinrock. The spatial capacity of a slotted ALOHA multihop packet radio network with capture. *IEEE Transactions on Communications*, 32(6):684–694, 1984.

[26] Muhammad Niswar, Sonny Wainalang, Amil A Ilham, Zahir Zainuddin, Yushinta Fujaya, Zaenab Muslimin, Ady Wahyudi Paundu, Shigeru Kashihara, and Doudou Fall. IoT-based Water Quality Monitoring System for Soft-Shell Crab Farming. In *2018 IEEE International Conference on Internet of Things and Intelligence System (IOTAIS)*, pages 6–9. IEEE, 2018.

[27] Juha Petäjäjärvi, Konstantin Mikhaylov, Marko Pettissalo, Janne Janhunen, and Jari Iinatti. Performance of a low-power wide-area network based on LoRa technology: Doppler robustness, scalability, and coverage. *International Journal of Distributed Sensor Networks*, 13(3):1550147717699412, 2017.

[28] Congduc Pham. Low-cost, low-power and long-range image sensor for visual surveillance. In *Proceedings of the 2nd Workshop on Experiences in the Design and Implementation of Smart Objects*, pages 35–40. ACM, 2016.

[29] Congduc Pham. Enabling and deploying long-range IoT image sensors with LoRa technology. In *2018 IEEE Middle East and North Africa Communications Conference (MENACOMM)*, pages 1–6. IEEE, 2018.

[30] Tommaso Polonelli, Davide Brunelli, Achille Marzocchi, and Luca Benini. Slotted aloha on lorawan-design, analysis, and deployment. *Sensors*, 19(4):838, 2019.

[31] Alexandru-Ioan Pop, Usman Raza, Parag Kulkarni, and Mahesh Sooriyabandara. Does bidirectional traffic do more harm than good in lorawan based lpwa networks? In *GLOBECOM 2017-2017 IEEE Global Communications Conference*, pages 1–6. IEEE, 2017.

[32] Bran Selic and Sébastien Gérard. *Modeling and analysis of real-time and embedded systems with UML and MARTE: Developing cyber-physical systems.* Elsevier, 2013.

[33] Semtech. SX1276/77/78/79 - 137 MHz to 1020 MHz Low Power Long Range Transceiver. `https://www.semtech.com/uploads/documents/DS_SX1276-7-8-9_W_APP_V6.pdf`, Jan 2019.

[34] Francisco Vázquez-Gallego, Luis Alonso, and Jesus Alonso-Zarate. Modeling and analysis of reservation frame slotted-aloha in wireless machine-to-machine area networks for data collection. *Sensors*, 15(2):3911–3931, 2015.

[35] Francisco Vazquez-Gallego, Jesus Alonso-Zarate, Anna Maria Mandalari, Orazio Briante, Antonella Molinaro, and Giuseppe Ruggeri. Performance evaluation of reservation frame slotted-aloha for data collection m2m networks. In *European Wireless 2014; 20th European Wireless Conference*, pages 1–6. VDE, 2014.

[36] Dimitrios Zorbas, Khaled Q Abdefadeel, Victor Cionca, Dirk Pesch, and Brendan O'Flynn. Offline Scheduling Algorithms for Time-Slotted LoRa-based Bulk Data Transmission.

[37] Dimitrios Zorbas, Patrick Maillé, Brendan O'flynn, and Christos Douligeris. Fast and Reliable LoRa-based Data Transmissions. 06 2019.

7. Appendix

Time on air calculation as in [33] and as implemented in LoRaSIM simulator [13].

```
def airtime(sf,cr,pl,bw):
    H = 0 # implicit header disabled (H=0) or not (H=1)
    DE = 0 # low data rate optimization enabled (=1) or not (=0)
    Npream = 8
    if bw == 125 and sf in [11, 12]:
        # low data rate optimization mandated for BW125 with SF11 and SF12
        DE = 1
    if sf == 6:
        # can only have implicit header with SF6
        H = 1
    Tsym = (2.0**sf)/bw
    Tpream = (Npream + 4.25)*Tsym
    # print "sf", sf, " cr", cr, "pl", pl, "bw", bw
    payloadSymbNB =
        8 + max(math.ceil((8.0*pl-4.0*sf+28+16-20*H)/(4.0*(sf-2*DE)))*(cr+4),0)
    Tpayload = payloadSymbNB * Tsym
    return Tpream + Tpayload
```