Improving Channel Efficiency in LoRaWANs using Novel Channel Sensing Mechanism

By

Shahzeb Ahsan

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Supervisor

Dr. Syed Ali Hassan

Department of Electrical Engineering

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Approval

It is certified that the contents and form of the thesis entitled "**Improving Channel Efficiency in LoRaWANs using Novel Channel Sensing Mechanism**" submitted by **Shahzeb Ahsan** have been found satisfactory for the requirement of the degree.

Advisor: **Dr. Syed Ali Hassan**
Signature: ______________

Date: ______________

Committee Member 1: **Dr. Hassaan Khaliq Qureshi**

Signature: ____________________

Date: ____________________

Committee Member 2: **Dr. Fahd Ahmad Khan**

Signature: ____________________

Date: ____________________

Committee Member 3: **Dr. Arsalan Ahmad**

Signature: ____________________

Date: ____________________

Abstract

Low Power Wide area network (LPWAN) technology is being widely adapted in different Internet of things (IOT) services. Long Range Wide are Network (LoRaWAN) is most used in private outdoor applications. LPWAN technology works in a star topology which is easy to construct as compared to complex multi-hop network. Considering LoRaWAN in dense networks, we have to have an efficient channel access mechanism to improve efficiency and robustness as compared to old ALOHA protocol. Little work has started to implement channel mechanisms in this technology, but it is yet to be tested in multiple devices under the limit of duty cycle. In our work we will develop new method to use channel sense in efficient way to improve channel efficiency and to reduce the collisions in LoRaWAN.

Dedication

I dedicate this thesis to my parents. Without their constant prayers, this day might never have come.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

Author Name: **Shahzeb Ahsan**

Signature: ________________

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List of Abbreviations

LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
LPWAN	Low Power Wide Area Network
IoT	Internet-of-Things
IIoT	Industrial Internet-of-Things
ToA	Time-of-Arrival
MAC	Medium Access Control
CSMA	Carrier Sense Multiple Access
DCF	Distributed coordination function
BEB	Binary Exponential Back-off
CAD	Channel Activity Detection
BEH	Binary Exponential Hybrid
BED	Binary Exponential Delay
RSSI	Received signal strength intensity

Chapter 1

Introduction

Internet-of-things (IoT) devices are growing considerably and expected to reach 31 billion by 2020 [4]. Lots of work is being done on IoT and industrial IOT currenlty [5] [6]. A big chunk of these IoT devices constitute the low power wide area network (LPWAN). Specifically, the technologies such as LoRa [7], weightless [8], and Sigfox [9] are efficient in low power and long distance communication. Long range wide area network (LoRaWAN), network protocol of LoRa has been widely used in private outdoor applications such as smart cities, industrial, health care, agriculture. LPWAN operates in a star topology which is easy to manage, whereas the multi-hop network is relatively complex. In LPWAN, numerous devices are connected to a very few sink (gateway) devices. It is required to connect the maximum number of end nodes to a sink node, therefore, exposing to the risk of a large number of devices and their consequent output sharing the same medium.

Wireless medium is capable of very limited capacity in the presence of noise. Whereas, demand of wireless communication is increasing dramati-

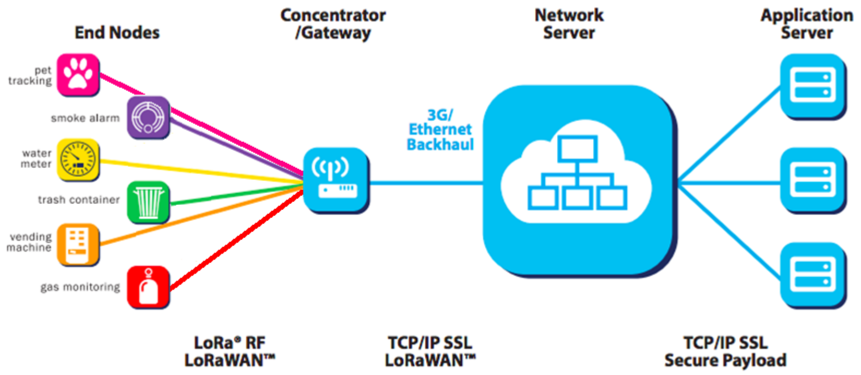

Figure 1.1: LoRaWAN Network Architecture [1]

cally. Therefore, due to increase in demand, devices needs to communicate in the shared wireless medium. Thus increasing the chance of interference among the devices. Figure 1.1 shows LoRaWAN setup where each end device is talking to the gateway. A set of rules called Medium Access Control (MAC) protocols should be followed in order to communicate to mitigate any interference from other devices. There are many MAC protocols in Wi-Fi but only few are implemented in Long Range (LoRa) network. Typical LoRaWAN uses pure ALOHA [10] to communicate among devices. Other protocols are Carrier Sense Multiple Access (CSMA) [11], Packer Reservation Multiple Access (PRMA) [12], Time Division Multiple Access(TDMA) [13], Code Division Multiple Access (CDMA) [14], and Orthogonal Frequency Division Multiple Access (OFDMA) [15] have been studied.

LoRa is derived from LPWAN [16] network, which comprises of long range communication with low power and less data rate. LoRa uses Chirp Spread Spectrum (CSS) [17] to modulate its data, therefore it carries data to large distances. LPWAN networks are defined by the IEEE 802.11.4 standard, this standard is mostly used for Device to Device (D2D) communications. Therefore, LoRa has its own wireless MAC standard, which is developed by LoRa Alliance.

LoRa networks enables IoT scenarios by using distributed sensors which talks to the single or multiple LoRa Gateways (GWs). Therefore, it mitigates the complex communication protocol of multi-hop network. LoRa have been used in many industrial indoor or outdoor applications such as industries, agriculture, smart-homes [18].

1.1 Internet of Things and 5G

IoT is connecting devices over the network for communication without the use of human interaction. it is D2D or Machine to Machine (M2M) communication [19], where these devices could be used in any applications. Advancing the M2M communication method, IoT became a network with billions of devices connected over the network and communicating its data to the applications which collects or shares or even controls it.

Mostly IoT have an application which controls and gathers all the data of connected sensors and other devices through which it can control or give specific instructions in real time. The end devices or sensors have embedded processors with some communication hardware to communicate, these end devices sends the data of their surrounding environment to the gateway or a server. In some cases these end devices communicate with each other and act according to the data they collect. Usually all these communications are without human intervention, but human can interact with end devices or gateways/servers to give specific tasks. IoT is a necessity in many industrial and household applications to ease up our lives. From automation of our homes to overlook all the machines in the industry, IoT enables us to get aware of every machine or device operating in our surroundings. It touches manufacturing, retail, finance, health care and all other industries. It is used in farming to help reduce the time and to gain maximum output from crops and cattle. It is used in smart cities to help reduce the energy consumption and the excessive waste [20].

Usually IoT system comprises of three steps which is to collect data using sensors, to collate and transfer data using micro controllers and communication module, to analyze and take action using application servers.

5G network are being used universally in rural and urban environments [21]. 5G gives friendly platform to IoT, not only it provides high data-rates but also low latency of just 1 millisecond [22]. IoT is exploiting full 5G capabilities and providing many utilities to the industry. such as, self driving cars, where many sensors generates data such as weather, GPS, temperature, thus high speed communication with low latency is necessary which is provided by 5G to send this data for monitoring in real-time. Healthcare services such as remote surgery needs almost no latency and feedback of every movement of the machine, as it is movement critical. Furthermore it is used in Logistics, smart cities and retail services which is only possible due to 5G services.

5G and IoT are making possible to connect billions of devices to the internet. Some products needs to be connected constantly for real time monitoring but some others needs to send data only on occurring of some events. The current wireless network is not capable of handling these many products on the network [23], therefore it is only possible due to 5G.

1.2 Introduction to LoRa and LoRaWAN

Communication is important aspect of IoT, that is how the devices can be connected to the Internet. There are tonnes of communication protocols but none of that exactly fits to the IoT as every application have different needs. Major drawback of communications are range and power consumption. Communication radios of devices such as Zigbee [24], BLE [25], WiFi are for lower range and are power hungry. 3G and 4G have good range but also consumes a lot of power, thus decreasing battery life of the devices. That is where LoRa comes in, with long range and power efficient devices whose battery can last much longer depending on the application [26].

1.2.1 LoRa

LoRa network is derived from CSS which uses spread spectrum modulation which is developed by Semtech [27]. It is combination of low power consumption with higher range, which is only possible due to its CSS modulation technique. Typically LoRa comprises of Line of Sight (LoS) and Non-Line of Sight (NLOS) communication which ranges up-to 13- 15Km. Therefore one Gateway of LoRa can provide service to multiple towns, and few gateways can cover whole city.

The major part of LoRa radios are its modulation techniques which is CSS, it provides significantly high range due to the frequency chirps while using low power. CSS uses chirp pulses to encode the data, which is increase or decrease in frequency over the time similar to Frequency Shift Keying (FSK) [28]. CSS were mainly used in majority of military and space applications, LoRa makes it possible to use in industrial low cost applications [29].

LoRa radios uses unlicensed low-frequency bands for their communication, there are sub-GHz bands which are available around the world, which can vary in different countries. Such as, Europe uses 868MHz for communications, whereas, North America uses 915MHz. There is not much difference in technology due to the change in frequency. These lower frequencies enables to communicate much farther than that of in WiFi devices which uses 2.4 or 5.8GHz frequencies [26].

There are different Bandwidths (BW) which LoRa uses, which is also different in different regions. Europe uses 125/ 250KHz for up-link (UL) and 125KHz for down-link (DL). Whereas, North America uses 125/ 500KHz for UL and 500KHz for DL. LoRa comprises of 6 spreading factor (SF) range from (SF7-SF12) where SF12 have lowest data rate but longest reach whereas SF7 has highest data-rate but less reach. We can get Adaptive data rate by using combination of SF and BW, which are chosen according to the link conditions [30]. Thus Lower SF increases data rate of the transmission but decreases the sensitivity and transmission range.

There is also adaptive power level which can be used by LoRa radios. Transmission power can be adjusted in the range of The transmission power (TP) can be adjusted from -4 dBm to 20 dBm. It depends on different factors like link conditions and data rate. We increase transmission power near to maximum for fast communications or for long range communications and vice versa [31]. By varying power level of transmission we can optimise

$Mode$	SF	BW (kHz)	ToA_{max} (ms)
1	12	125	9019.39
2	11	125	5001.22
3	10	125	2295.81
4	9	125	1250.30
5	8	250	353.54
6	7	250	199.81

Table 1.1: ToA_{max} using different settings of SF and BW

power consumption of the battery.

The time-on-air (ToA) is the time needed for a LoRa packet to transmit, and is given as [32],

$$ToA = T_{\text{pr}} + T_{\text{pl}}, \tag{1.1}$$

where preamble time, T_{pr}, and payload time, T_{pl}, can be calculated as follows

$$T_{\text{pr}} = (n_{\text{p}} + 4.25)T_s \tag{1.2}$$

$$T_{\text{pl}} = \big(8 + max[\,]\delta(CR + 4), 0\big)T_s \tag{1.3}$$

$$\delta = \left(\frac{8PL - 4SF + 16CRC - 20H + 28}{4(SF - 2DE)}\right), \tag{1.4}$$

where T_s is symbol time which is equal to $2^{SF}/BW$. Table 1.1 is constructed using above equations by using different combination of SF and BW. Other parameter in above equations are, the number of included preambles, n_{p}, payload, PL, cyclic redundancy check, CRC, implicit header mode, H and low data-rate optimization, DE.

1.2.2 LoRaWAN

LoRaWAN is a standard designed by LoRa Alliance for LoRa devices. It is Long range, high capacity LPWAN standard. It comprises of bi-directional communications protocol which performs different services such as, reliable message delivery, location and multi-cast capabilities and end to end security. LoRaWAN is MAC protocol which is above physical layer of LoRa. It comprises of system architecture and communication methods for the network. These functions determines quality of service, network capacity, battery life of a node and other security applications which is provided by the network. There are other MAC protocols but LoRaWAN is most popular [1].

LoRaWAN uses star topology in which end devices are connected to a gateway, rather than being in mesh network where each end device can send data to another end device. Therefore, star network is much easier and do not require routing algorithm to send or receive data. Also, each end device will not be in always on state to conserve energy as LoRa devices are battery powered. LoRa devices will only communicate with the gateway when they want to communicate, in the other time it will be put to sleep. This is big contribution to the low power feature which ends up in longer battery life. LoRa architecture can be seen in the figure 1.1.

The LoRa network consists of different parts which includes End Devices (ED), LoRa Gateways (GW), Network Server (NS) and an Application Server (AS) as shown in the figure 1.2.

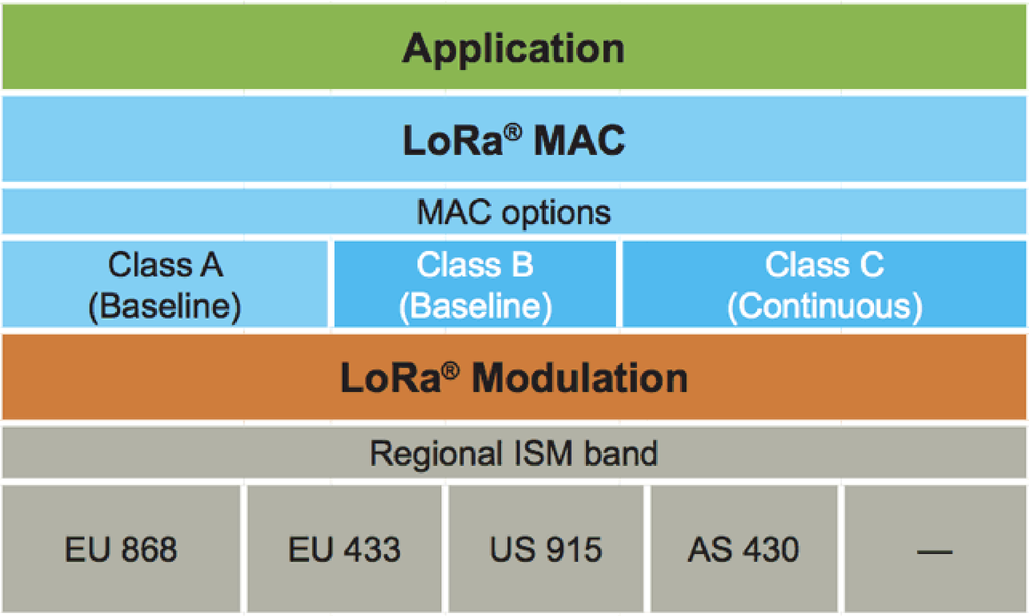

Figure 1.2: LoRaWAN Network Layer [1]

End Devices

End devices could be any actuator or sensors working at the edge of the network. Different applications have different types of end devices which serves different requirements according to the need. There are three different type of classes according to fulfill different needs, there are different trade-off between battery life, latency and down link communication for different applications. Following are the three different classes

- Class A: In this class there is an immediate down link communication from the server after the up link communication from the gateway. There is 2 slots for DL communication after the UL communication. DL communication can vary in the form of getting a delivery message or some updates. Second window of DL communication depends on the first window DL communication, whether it is success full or not. By this communication technique DL communication is set to be minimum as one Gateway has to overlook many other EDs. Therefore, it is used for the devices which needs longer battery life and much power saving.

- Class B: These devices have scheduled DL communication in addition to the class A properties. Every device will have their own extra DL window at scheduled time. These consumes little extra power than the class A devices and have low battery life than class A.
- Class C: These devices have their receiving window always for a DL communication. therefore, server can send data to any ED whenever it wants. But these ED will consume much energy and it should need other source of power than the battery to keep it running.

Gateways

Gateways are the devices connected to the network using LAN by using IP connection. It relays message to and from the ED to the NS. Therefore LoRa gateway acts as a transparent bridge and receives data from the ED and deliver it to the NS using IP communication and vice versa. Gateways can do multi casting and are capable of two way communication. Gateways are even capable of updating EDs over the air. Gateways are connected to the power source as it needs much power to communicate with every device.

Network Server

Network server are connected to gateways and the application servers. Network server duplicates the data and sent it to relative application server. It can communicate both ways to the GW and the AS. Network server can be in the form of cloud based solution, these consists if a Router, Handler and a Broker. It ensures of no duplication of data packets and it schedules different acknowledgements and manages ADR.

Application Server

These comprises of different IoT servers which differentiates according to the application. The data from the ED are used here to overlook and control the network according to the need of an application.

1.3 Thesis Motivation

Considering LoRaWAN in dense networks, the sink and the end nodes are using combinations of different parameters such as transmission frequency, transmission power, spreading factor and coding schemes to gain maximum diversity. These parameters are selected randomly depending upon few circumstances (e.g., path loss), to avoid collisions and to perform more robust communication. Given that the conventional LoRaWAN operates on a simple ALOHA protocol, the performance of this protocol dramatically declines, as the number of nodes approaches a few thousands. Therefore, it is recommended to substitute the conventional ALOHA protocol with an efficient channel access mechanism that increases efficiency and adds robustness while mitigating the risks the system was previously exposed to.

1.4 Thesis Contribution

In this paper, we discuss the Listen Before Talk (LBT) channel sense mechanism that a LoRaWAN could use to identify whether the channel is 'idle' or 'busy'. We also propose channel access mechanisms using the aforementioned sensing technique that help reducing the large number of collisions and optimising the channel utilization, such that maximum number of nodes can be connected to the gateway. We apply our protocols on large scale LoRaWAN network to study scalability of the proposed approach.

1.5 Thesis Organization

Thesis is organised as follows. Chapter 2 highlights important concepts and literature review of the topic, with all the work already being done. In chapter 3, a system model for many LoRa end devices to sense and then access the channel. Chapter 4 addresses the the performance analysis of the proposed system in terms of thousands of devices. Chapter 5 shows desired results found during the performance analysis of the proposed model. Finally, chapter 6 presents the conclusions and further proposes the future work.

Chapter 2

Literature Review

2.1 MAC protocols

Talking about MAC protocols, there are many protocols through which devices are made to talk to each other by making sure data is not collided or lost. There are many protocols of Multiple Access Methods in WiFi which are not yet implemented in LoRaWAN, some of the protocols are discussed as below

ALOHA

ALOHA is the very first protocol for communication for a shared frequency channel [10]. In ALOHA protocol node do not sense the data and sends it regardless of the state of the channel. The very first ALOHA was implemented in radio broadcasting system, which later also being used in satellite communications. This is the easiest protocol and does not require much processing to sense channel before sending the data. There are two types of ALOHA which are discussed as below.

- Pure ALOHA: In Pure ALOHA, the node sends the data whenever it wants to send it. but if two nodes sends data at the same instant, it collides and data from both the nodes is lost. Pure ALOHA needs acknowledgment of sent data to not to retry of sending it again. If acknowledgement is not received the node will assume that the data is not delivered, hence the node will send data again after random timeout period. When two nodes will send data at the same time, there will be a collision and both have to send that data again. Chances of collisions in pure ALOHA is significantly high.
- Slotted ALOHA It is improved version of ALOHA where nodes will start sending its data from the start of the slot. Single slot will carry only one frame and if data is large the node will use multiple slots to send its data. The probability of collisions in this algorithm reduces to half than that of pure ALOHA, but still data collides when two or more nodes send data in the same slot [33].

Carrier Sense Multiple Access (CSMA)

In CSMA, same frequency channel is share among different end devices, every end device first scans the channel and look for the absence of the traffic. If the channel is not busy the ED will transmit its data to the AP otherwise it will wait until the channel becomes idle again. In this protocol if one device is talking to the AP, all other devices could listen i.e., EDs opens their receiving window and check if signal on specific frequency is above the threshold then the channel is busy and vice versa.There are further different types of CSMA protocols [34] which are,

- 1-persistent: In this algorithm node sense the channel for idle or busy. if idle it transmits immediately, otherwise it waits and transmits data as soon as channel become idle again. If collision happens node waits for random amount of time and starts the procedure again.
- Non-persistent: In non-persistent CSMA algorithm, the node starts to sense the channel and send data if it is idle. If channel is busy it waits until channel is idle again to send data. If collision happens it waits for random amount of time, but in that time it do not sense the channel again, then it starts the whole procedure again after that random time.
- P-persistent: In this algorithm, the node senses channel similar to above methods. Thus, when channel is idle it sends data with p probability. if channel is not idle, it keep sensing the channel until it becomes idle and then send data with p probability. The probability that node will not transmit is $1 - p$.
- O-persistent: In this algorithm, every node is assigned transmission order by the AP. Nodes will transmit their data according to their assigned time slot. Every node will change their assigned slot by sensing every detected transmission. This is similar to queue system where top packet gets to send first and all other waits for their turn in the queue.

Distributed Coordination Function (DCF)

In DCF, network consists of single , all the EDs operates in single AP frequency in distributed manner to talk to the AP. Therefore, they follows DCF protocol to send data to the AP. DCF uses CSMA/CA protocol with Binary Exponential Back-off (BEB) [35]. In this algorithm every node whose packet is in the queue runs Clear Channel Assesment (CCA) to check whether the channel is idle or busy. If the channel is occupied then it has to wait until it becomes idle. if channel is sensed idle for DIFS amount of period then the node starts its back-off time and sends data as soon as its back-off time has finished. Random back-off time is assigned according to the number of collisions of the packet of specific node. This back-off time is selected from a specific window which is called as Contention Window (CW). The back-off time reduces by one with every slot, as there is constant time for each slot which is predefined. Therefore because of this algorithm, multiple nodes can transmit data with very less possibility of collision.

Every time when two nodes sends data simultaneously, it collides and thus receiver AP does not receive the correct data and both the nodes have to go into BEB condition and select another time from bigger CW. If after collision the AP successfully retrieve the information of high power node, this phenomenon is knows as capture effect. Through capture effect, data from one of the node can be successfully recovered, while other node goes into back-off state. This increases the overall packet delivery ratio (PDR).As number of nodes starts to increase in the network, probability that other node will send data at the same instant increase, thus increasing the collision probability. This drops the throughput of the network significantly.

Various other methods for Collision Resolution

various techniques have been studied for collision avoidance and for collision resolution, to improve energy efficiency and spectral efficiency with fair and efficient algorithm for all the nodes. Recently more dynamic techniques are being defined based on DCF, such as Early Back-off Announcement (EBA) [36]. In EBA a node announces its back-off time to the AP, which then broadcast to all other nodes, then the nodes excludes that back-off time and chose some other if same. Therefore, the system will be collision free, if all the devices will chose different back-off time. Only drawback in this algorithm is, if any neighbouring node will not hear the back-off time and will select the same as other, which can cause collision.

Another algorithm which achieves zero collisions is call Zero Collision Random Back-off (ZC-RB) [37], it work similar as Reservation ALOHA (R-ALOHA). In this algorithm there are fixed number of active nodes, but when number of nodes changes, algorithm needs adjustment which is time costly. Some recent algorithm in which AP tells the back-off time to every node, one of them is called Semi-Random Back-off (SRB) [38]. This back-off mechanism which is deterministic in nature, is based on basic DCF protocol. In case of collision the algorithm shifts to basic DCF protocol. The drawback of this algorithm is that maximum number of nodes which will be in contention free state are just the half the number of size of CW. Therefore, to include more number of devices in collision free state, CW size should be increased accordingly.

There is another algorithm which is Centralized Back-off (CRB) [39] for collision free network. In this the AP generates the random back-off for every node which is attached and convey them using a reply message. At start every node is randomized and will not be in contention free state, so it needs time for every node to converge into collision free state. After every node is into contention free state, there will be no collisions unless more nodes will try to join the network.

2.2 Related work

A lot of work has been done in improving MAC layer of LoRa, most of the work is done on scheduling of the packets to make it collision free [40]. In scheduling AP will know all the information to schedule the nodes, but nodes can not know information about other nodes. As down link communication in LoRa is very costly therefore this procedure is difficult to apply practically. A little work has been started on LBT, but it is yet to be researched in detail. LBT usually takes more power than usual because of sensing the channel around them, therefore they have to open their receiving window for some time, which consumes power and drain the battery more fast. We have to find a better way so that less power is consumed without much collisions.

Scalability and capacity of LoRa has been a topic of keen interest in the field. Augustin *et al*. [41] simulated LoRa regarding its channel capacity and collision ratio for large number of devices by increasing the channel capacity. They elaborated that LoRa channel capacity usage is similar to Pure-ALOHA (P-ALOHA) having a maximum throughput of 18%. Adelantado *et al.* [42] address different limitations of LoRa in large scale networks and provide answers to questions such as the number of maximum devices a gateway can support without deteriorating the performance significantly; and how the throughput and collisions of nodes varies as the network size increases, respecting the duty cycle limitations. Haxhibequiri *et al.* [43] addresses scalability issue in large networks and introduced packet scheduling using low overhead header. Where time slots are been assigned to every node when it should transmit its message. This method use very less battery as compared to send message again if collision happens.

juha *et al.* [44] performed practical of LoRaWAN using highest transmission power and SF12 and found out that data can reach up to 30km in distance on water. they also performed mobile communication in which a car travels up-to 40km/hr where the LoRa modulated signal exceeds the coherence time. Bor *et al.* [45] designed algorithm to select best parameters to transmit LoRa packet. He found out that by using different Sf, BW, TP and CR there could be 6720 possible transmission settings through which a LoRa packet can be transmitted. They ensured to select perfect parameter to ensure minimum energy consumption and with minimum packet loss to make much reliable system according to the requirements. Mahmood *et al.* [46] illustrated the degradation in coverage probability, because of co and inter-SF interference as devices increase in a single cell large scale network. They explained that Sf are not fully orthogonal and that some packets overlap due to this interference resulting in packet loss.

Duda *et al.* in [47] proposed carrier sense multiple access $CSMA - x$ protocol with LoRaWAN and simulated on NS-3 where they sense channel

10 ms before sending every packet. Using this approach, they improved the collision ratio whereby utilising a sample of large number of devices. Their protocol also consumes less energy as compared to LoRaWAN, while using more than 5000 devices in a network. Kouvelas *et al.* [48] developed p-CSMA protocol on NS-3 where they sense channel and send packets using different persistence values. They have also taken hidden devices into account for showing the results on a small scale LoRaWAN network. Results shows improvement as compared to current LoRaWAN and persistence values changes as the number of devices changes in the network. C. Pham [2] introduced listen-before-talk (LBT) mechanism on hardware and proposed $CSMA_{new}^{LoRa}$ protocol by using channel activity detection (CAD). He explained CAD reliability issues and how it can be adopted to LoRaWAN. He used two devices to show the performance of $CSMA_{new}^{LoRa}$ and discussed the increase in energy consumption with respect to CAD while using LBT mechanism. Whereas the collision between packets can be reduced to much extent. Pham shows no collisions but only with 2 devices, whereas, if devices increases the situation can be different and there should be some other techniques to adapt to overcome the collisions.

Chapter 3

System Model and Performance Analysis

3.1 ALOHA protocol in LoRaWAN

LoRaWAN MAC is based on pure ALOHA protocol. It is asynchronous ALOHA, in which a node wakes up and sends data regardless of any channel sensing or synchronization with the gateway, making it vulnerable to collisions. If any collision occurs, the node has to re-transmit the data, thereby decreasing the channel capacity and consuming more energy. Using pure ALOHA, the nodes can achieve maximum throughput of 18% of the channel capacity, if all nodes in the network are using same parameters [41].

LoRaWAN gets channel diversity by using different parameters, i.e., frequency, SF, BW and CR. This is achieved by using different combinations of these parameters which are orthogonal to one another. Increase in number of end nodes enhances the possibility of two nodes selecting non-orthogonal

SF	No. of symbols	*CAD* time (ms)	False detection %	*CAD* consumption (nAh)
7	2	2.67	0.17	2.84
8	2	5.39	1.27	5.75
9	4	19.15	1.90	20.44
10	4	38.74	1.00	41.36
11	4	78.40	0.09	134.55

Table 3.1: *CAD* information [3]

parameters, hence results in collision. While using 1000 end nodes per gateway LoRaWAN losses are upto 32%, whereas pure ALOHA will have 90% losses in similar case [43].

3.2 Chanel Activity Detection (CAD)

CAD is a process to detect a LoRa signal, as LoRa signals are mostly below noise floor which make them hard to detect. After activating *CAD* mode, the device receiver scans the channel depending upon the duration of time provided. If it senses the activity on that channel, i.e., capture of symbols which are correlated successfully, it gives an interrupt with the *ChannelActivityDetected* flag.

It is very important to keep the settings correct to rule out false detection during CAD. Semtech evaluated the performance of *CAD* using SX1261/2 node [3]. They have provided the optimal settings for different *SF* and *BW* as shown in Table 3.1. Furthermore detection of single LoRa symbol is not effective, as false detection rate is very high. Also performing multiple *CAD*

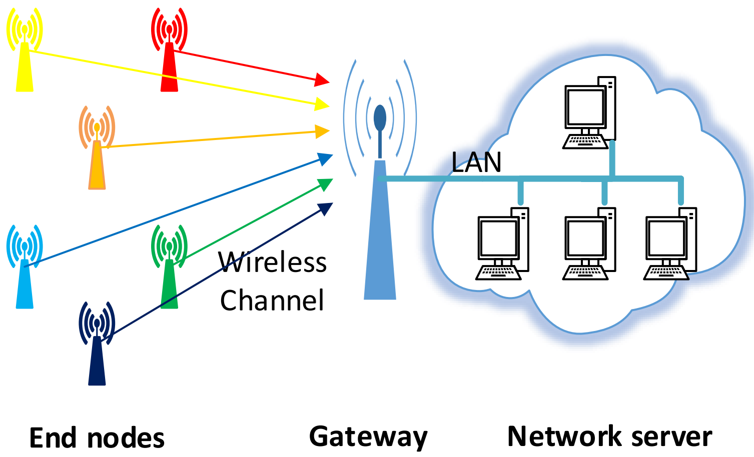

Figure 3.1: Network structure

for single LoRa symbol do not yield good results. Therefore, we need to detect more than one LoRa symbol to make CAD reliable. They also have shown that by detecting two symbols for SF 7, 8 and four symbols for SF 9-11 using BW 125 KHz, the false detection rate remain less than 2%, thus making CAD much efficient. Whereas, by detecting more symbols, more energy is consumed. Therefore, energy considerations should be taken into account.

3.3 Proposed Channel Access Approach

The scope of our design is to make a compatible protocol for LoRaWAN, related to, distributed coordination function (DCF) [35] from where we will adopt binary exponential back-off (BEB) algorithm into LoRa. We consider N number of nodes connected to a gateway. The nodes are randomly distributed around gateway with wireless channel between them as shown in Figure 3.1. The main goal is to avoid the collisions which happen when Lo-

RaWAN nodes select settings that are not orthogonal to each other. Therefore, we need LBT mechanism to minimize the loss of transmitted data. The functionality of our proposed protocol can be summarize as

- Sensing channel using CAD method to find if the channel is idle or not.
- If channel is busy, the algorithm will find how much it should wait to sense channel again.
- If channel is idle, the algorithm will find when the node should transmit data.

The proposed algorithm runs on end nodes, calculating the time when node should transmit its data with respect to the channel condition.

Following are the assumptions we make while designing the protocol.

- All nodes are considered to be stationary and spread equally around the gateway.
- Path loss is ignored, which implies that gateway will receive every packet above its sensitivity level.
- There is only up-link (UL) traffic, i.e., gateway is not sending acknowledgements to the nodes.
- Hidden nodes are ignored. All nodes are considered to know the channel conditions by using CAD.

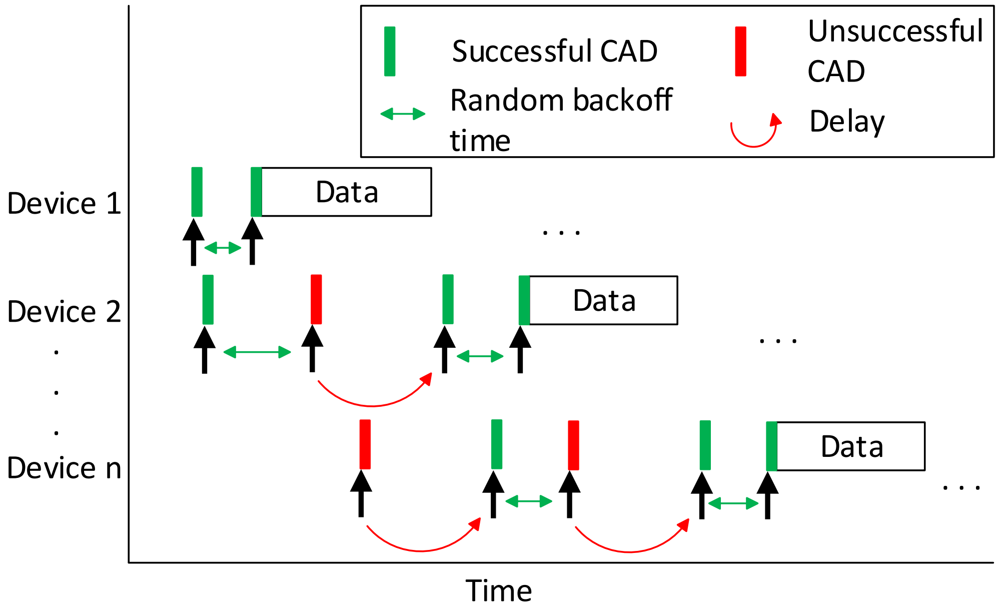

Figure 3.2: Principle of LoRa-BED using n number of devices

- All nodes are assumed to use same settings, i.e., same frequency, channel, SF, BW and CR. This is to ensure a collision based environment to check the performance of the proposed protocol.

3.3.1 LoRa-BED

In LoRa-BED, we use binary exponential delay (BED) technique. If node n wants to transmit the data, first it will start CAD process on the channel and wait till T_{CAD} i.e., wait for $ChannelActivityDetected$ flag interrupt. T_{CAD} value is given in Table 3.1 for different SFs. If the flag interrupts in selected T_{CAD} time, it will be called Unsuccessful CAD (UC), which implies a busy channel. If interrupt does not occur in T_{CAD} time, it will be called Successful CAD (SC), which means channel is idle. If the channel is busy, the node goes into delay state, where it defers the transmission for time

D_{CAD} (Delay) which is exponentially decreasing with increasing number of UC. For every UC, D_{CAD} is calculated using equation given below, until the channel becomes idle again,

$$D_{\mathrm{CAD}} = (2^{-i}) ToA_{\max}, \tag{3.1}$$

where i is a counter which increases by one for every consecutive UC and it resets when channel is found to be idle. The counter i has maximum limit of 7, such that the minimum delay time $D_{\mathrm{CAD}min}$ with $i_{\max}$ is greater than T_{CAD}, to give the node enough time to perform CAD. If channel is idle, then the node goes into back-off state where the node selects its back-off time, T_{RB}, randomly from [0, $ToA_{\max}$], before getting into transmission state. It is necessary to include a random back-off time to prevent the nodes sending data at the same time instant, which then results in collusion between the data packets. The proposed approach is shown in Figure 3.2.

3.3.2 LoRa-BEB

This protocol is based on binary exponential back-off (BEB), similar as in DCF in which window size (W) increases exponentially with every collision. In $LoRa-BEB$ we increase the W exponentially with every UC. Whenever node n wants to send data and channel is busy, the node goes directly into back-off state, in which it selects T_{RB} randomly from [0,W], where W can be calculated as,

$$W = (2^{j}) ToA_{\max}, \tag{3.2}$$

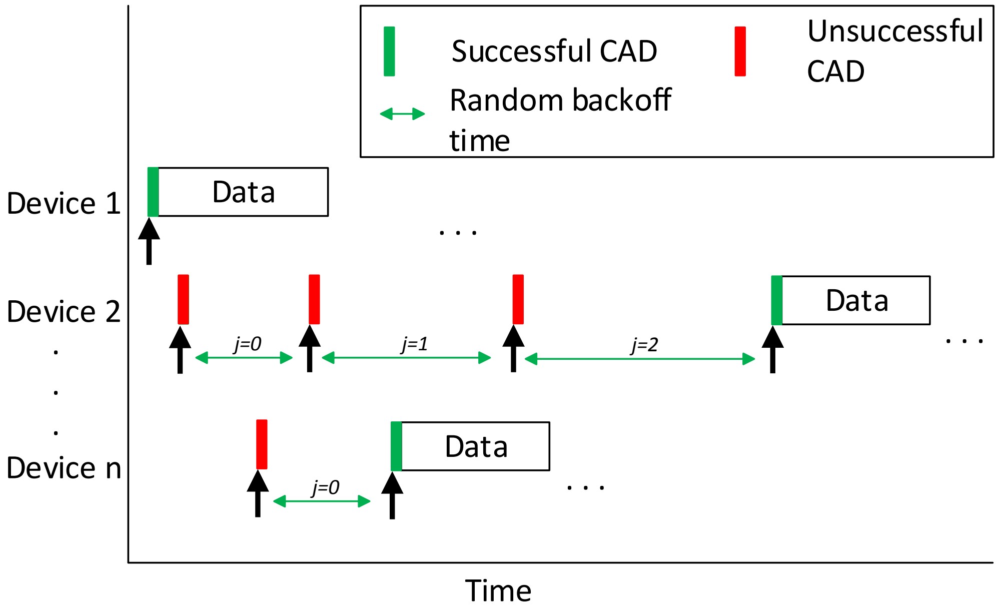

Figure 3.3: Principle of LoRa-BEB using n number of devices

where j is counter which starts from zero and increases by one for every UC, it will not reset unless the node sends the packet. As it can be seen in Figure 3.3, after first UC the value of j starts from 0 and it increases for every UC. If channel is found to be idle, the data is transmitted instantly without any wait.

3.3.3 LoRa-BEH

LoRa-BEH (binary exponential hybrid) is the combination of both BEB and BED techniques. Whenever node finds busy channel, it will go into delay state for the time D_{CAD} (Equation 3.1) and stays in this state until it finds idle channel. If node finds idle channel, it will go into back-off state where it will back-off for time T_{RB} randomly from $[0, W]$ and W is calculated using Equation 3.2. After T_{RB}, if the node finds the channel to be idle it will go into

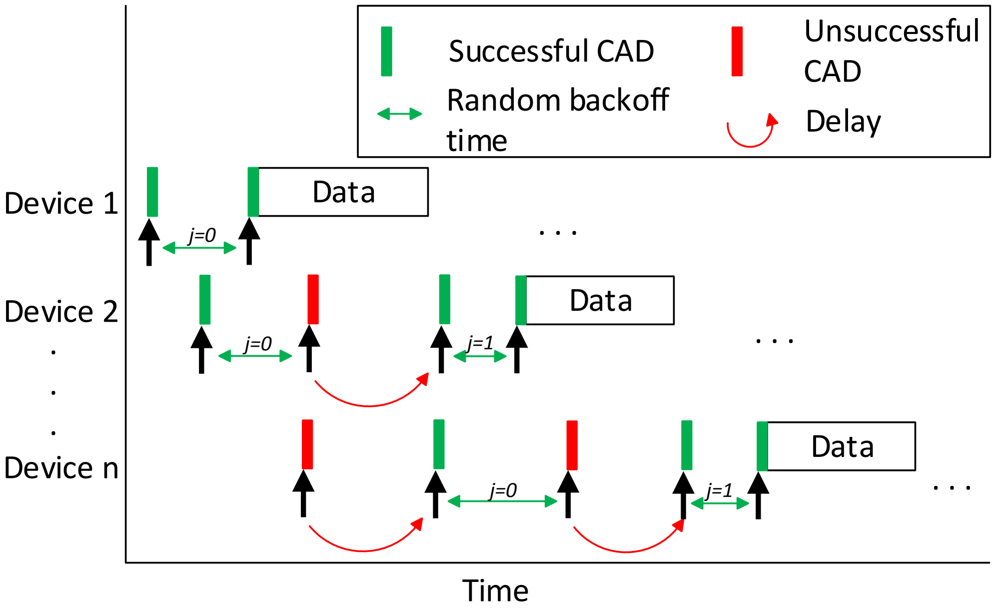

Figure 3.4: Principle of LoRa-BEH using n number of devices

transmission state and will transmit instantly, otherwise it will go again into delay state as shown in Figure 3.4. Algorithm 3.1 presents the pseudo-code running on each end node using one of the above three methods.

Algorithm 3.1 Pseudo code of operation on end node using LoRa-BED, LoRa-BEB and LoRa-BEH as mode 1, mode 2 and mode 3 respectively.

```
$mode$, $i_{\max}$ , $T_{\text{CAD}}$, $ToA_{\max}$ $fl \leftarrow 0$, $i \leftarrow 1$, $j \leftarrow 0$, $k \leftarrow 0$
while Data is not transmitted do
    Start $CAD$

    Wait $T_{\text{CAD}}$ milliseconds
    if Channel is idle and ($fl = 1$ or $mode = 2$) then
        Start transmitting data
    end
    else if Channel is idle and $fl = 0$ and $mode \neq 2$ then
        if $mode = 1$ then
            $T_{\text{RB}} \leftarrow randi[0, ToA_{\max}]$

        end
        else if $mode = 3$ then
            $T_{\text{RB}} \leftarrow randi[0, (2^k)ToA_{\max}]$
            $k \leftarrow k + 1$

        end
        Wait $T_{\text{RB}}$ milliseconds

        $fl \leftarrow 1$, $i \leftarrow 1$

    end
    else if Channel is busy and $mode = 2$ then
        $T_{\text{RB}} \leftarrow randi[0, (2^j)ToA_{\max}]$
        Wait $T_{\text{RB}}$ milliseconds
        $j \leftarrow j + 1$

    end
    else
        $D_{\text{CAD}} \leftarrow (2^{-i})ToA_{\max}$

        Wait $D_{\text{CAD}}$ milliseconds
        if $i < i_{max}$ then
            $i \leftarrow i + 1$

        end
        $fl \leftarrow 0$

    end
end
```

Chapter 4

Results and Discussions

The results have been obtained by MATLAB simulations using the parameters specified in Table 4.1, as payload size of the packet is variable and randomly chosen from specified values. CAD time is taken from Table 3.1 for SF 11 using 4 symbols, which is the most reliable CAD among all as seen in that table. That means Every time when CAD will start, it will sense 4 symbols on the channel to make sure if there is data ongoing on the channel or not. We have take simulation interval of one hour, that means every node will be assigned a random time within one hour to transmit its data. Every node chooses its random packet sending time, P_t, from the interval of an hour. Every node will have random length of packet, as shown in the table from 5 to 255 bytes. Every node will have constant header size as only thing which can vary is the payload data. Each node will send only one packet in the above defined interval without any retry, if collided. A packet is assumed collided if some node starts transmitting in between the CAD time of other node. That means both nodes transmit data at the same time,

Parameter	Value
Simulation interval	1 hour
PL	5-255 Bytes
n_p	8 Symbols
SF	11
BW	125 KHz
CAD time	78.40ms
DE	1
H	0
CRC	1

Table 4.1: Simulation parameters used to obtain results

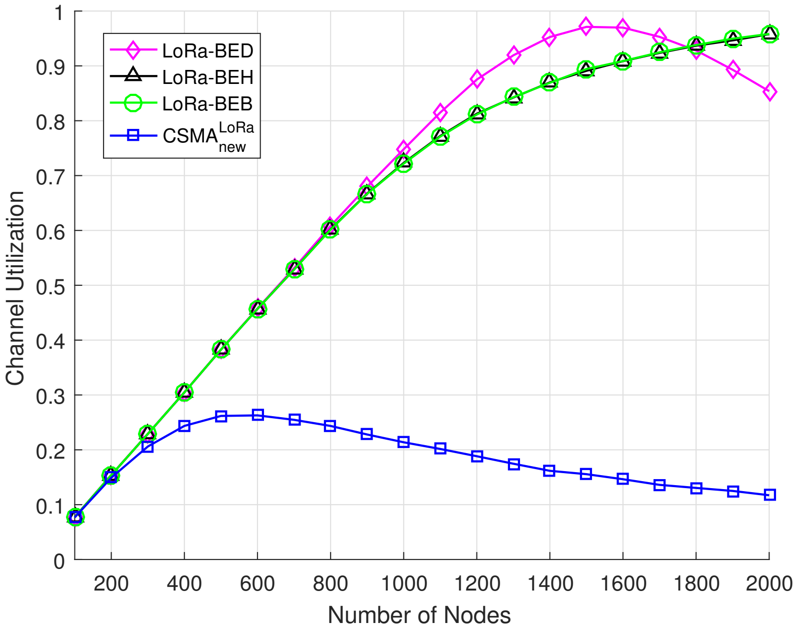

Figure 4.1: Channel utilization vs. number of nodes for $LoRa-BED$, $LoRa-BEH$ and $LoRa-BEB$ with comparison to $CSMA_{new}^{LoRa}$ [2]

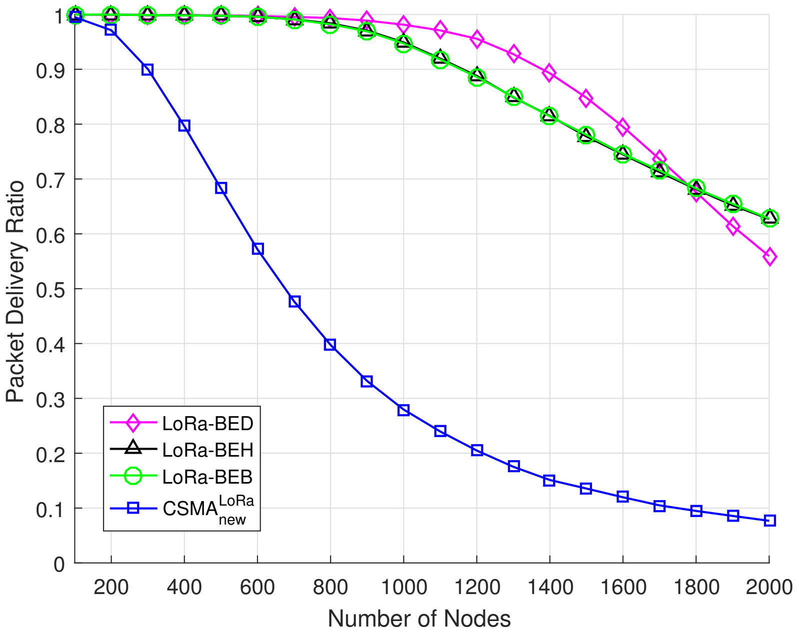

Figure 4.2: Packet delivery ratio vs. number of nodes for $LoRa - BED$, $LoRa - BEH$ and $LoRa - BEB$ with comparison to $CSMA^{LoRa}_{new}$ [2]

therefore, data of both nodes is received to the gateway which can not be demodulated. Channel load is measured as the number of nodes that want to send data within T_s. If we increase number of nodes, channel load also increases. We have shown the results for channel load less than 1%.

Figure 4.1 shows the channel utilization which is seen to be reaching upto 95% for all three proposed approaches. We see that LoRa-BED increases more abruptly than the other two approaches and then starts to decline due to collision as the channel load increases. This shows that LoRa-BED utilizes channel better for less number of nodes whereas LoRa-BEB and LoRa-BEH work better for greater number of nodes. Figure 4.2 shows the number of packets delivered in an hour for every protocol by increasing the number of nodes. All curves starts to drop after specific number of nodes because of

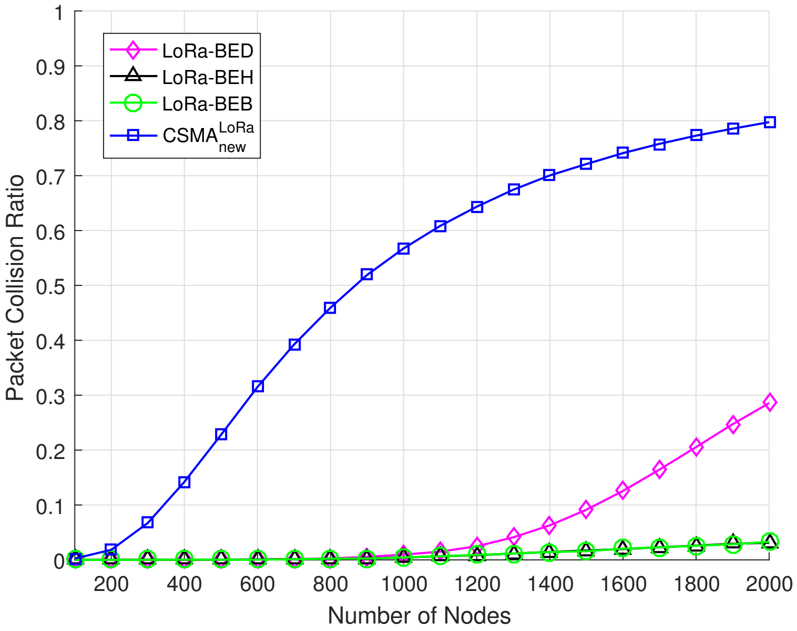

Figure 4.3: Packet collision ratio vs. number of nodes for $LoRa-BED$, $LoRa-BEH$ and $LoRa-BEB$ with comparison to $CSMA_{new}^{LoRa}$ [2]

reaching saturation point of maximum packets that can be send per hour. LoRa-BED sends most packets in an hour due to less jumps of back-off time as compared to others. It sends about 800 packets in an hour out of 2000 devices with one packet each. Whereas other protocol such as LoRa-BEB and LoRa-BEH sends about 700 packets in an hour. Therefore, LoRa-BED have more throughput but it decreases dramatically when channel load increases due to increase in collisions as back-off window does not increase with an increase in the number of nodes as it have constant delay window.

Figure 4.3 shows that LoRa-BED is more prone to collisions as the number of nodes surpasses 1000, and with 2000 nodes the packet loss reaches around 30%. Whereas, other two proposed protocols have very gradual increase in the number of collisions and with same number of nodes, the loss is only

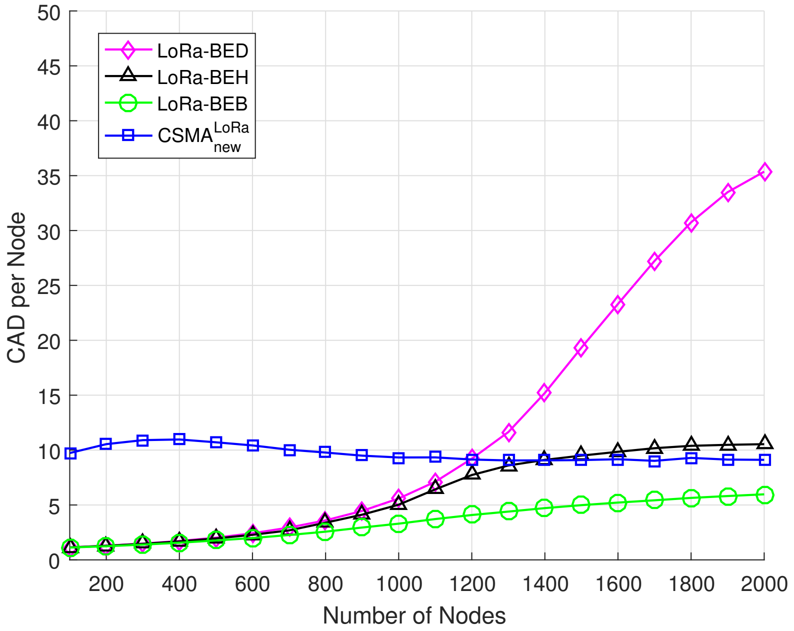

Figure 4.4: CAD per device vs. number of nodes for $LoRa-BED$, $LoRa-BEH$ and $LoRa-BEB$ with comparison to $CSMA^{LoRa}_{new}$ [2]

around 3% and 2% for LoRa-BEH and LoRa-BEB, respectively. Figure 4.4 shows energy perspective of all the protocols, where LoRa-BEB is using least amount of CAD per node with respect to others as more number of CAD consumes more energy. With 2000 nodes LoRa-BEB needs on average of 6 CAD per node. Energy consumption per CAD is shown in Table 3.1 for SF 11.

From all figures, LoRa-BEB which uses binary exponential back-off just like DCF, works better than every other algorithm. In terms of channel utility, Packet delivery ratio, Packet collision ratio or CAD per device. This is because it does CAD only when it has to send packet after its back-off time, and makes decision according to that. Also because its back-off window increases with every collision which reduces the probability of next collision.

Whereas, other algorithm such as LoRa-BED does CAD after back-off delay time which are after very short intervals. Which results in an increase of energy consumption. Also, as the delay window for BED algorithm is constant therefore after specific increase of the load on channel this algorithm starts to behave badly which results in many collisions and CAD per every device which has to send the packet. Therefore BED algorithm only works good where there are less number of devices. On the other hand BEB and BEH controls the traffic well, and packets does not results in collisions if traffic increases. This is due to bigger window size with every collision which not only saves energy consumption but also control the collisions.

Chapter 5

Conclusion & Future Works

In this Thesis, we investigated how LBT can be adopted in LoRaWAN. We investigated the best settings for CAD channel sensing technique for which it has maximum reliability. We proposed three channel access protocols using novel channel access techniques which can be adopted in LoRaWAN. As a result we showed an improve in channel utilization and decrease in number of collisions with little increase in energy while sensing the channel. More importantly, LoRa-BEB has excelled among all the proposed solutions with having minimum energy usage (CAD per device) and less number of collisions.

In future this work can be extended to be implemented on LoRa end nodes. By using same settings of every end node in the network i.e., same frequency, SF and BW, so that maximum throughput at the same channel can be determined. It can also be further tested with all possible settings which can co-exist. Which probably will not be the worst case scenario which we discussed in our thesis, therefore that network simulation will have better results as probability of 2 devices selecting the same settings is not much high, but it increases as the number of nodes per gateway increases.

We can also consider putting these algorithm in LoRa gateway instead of the end nodes. As gateway have unlimited supply of power and energy consumption is not an issue. But as The down-link traffic is much smaller in size i.e. 10% of the up-link traffic, also the down-link traffic will be depending on the up-link traffic therefore this algorithms will not be saving much of the collisions. Another consideration can be taken into account where it can only be implemented in class C devices where they have unlimited power supply and can open their receiving window all the time. Therefore every time a node has to send packet it can do channel sensing i.e. CAD and then takes decision according to that.

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