JÖNKÖPING UNIVERSITY
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A comparison of energy usage between LoRa 433Mhz and LoRa 868MHz

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Abstract

The number of devices connected to the internet is constantly increasing and therefore putting more weight on the importance of low energy usage. LoRa which is the physical part of the LoRaWAN communication protocol that this paper focuses on is popular in the area of IoT because of its low energy usage. The purpose of this paper was to find out how the energy usage differentiate between two of the most commonly used LoRa frequencies 433MHz and 868MHz.

LoRa is often used with battery driven components within IoT such as temperature or humidity sensors. It is of great importance to keep the maintenance cost for these devices to a minimum. And it is therefore important to find the most energy efficient solutions for communication between LoRa components.

To get an answer from the purpose of this paper, two questions were formulated, and they were in turn answered by using an experimental research method. For the experiment, two devices were set up using: one transmitter combined with a current sensor and one receiver, both of which were capable of using either LoRa 433MHz or 868MHz. The experiment was then conducted by transmitting 1000 packages for every DR and both of the frequencies.

The results were analysed in an empirical quantitative way which showed that the higher frequency of 868MHz consumed more energy in all of the experiments. One discovery that was quite interesting was that the difference could be mitigated by using different data rates.

The result in this paper is intended to increase the knowledge regarding LoRa and its energy usage. This papers result can be used as a reference when choosing between what frequency and data rate to use when working with LoRa.

Keywords: LoRa, Internet of things, Data rate, Energy usage

Abbreviations

LoRa	Long Range
IoT	Internet of Things
DR	Data Rate
SF	Spreading Factor
CR	Coding Rate
BW	Band Width
WAN	Wide Area Network
DC	Direct Current
MCU	Micro Controller Unit
I^2C	Inter-integrated Circuit
CSS	Chirp Spread Spectrum modulation
FEC	Forward Error Correction
LPWAN	Low Power Wide Area Network
ADR	Adaptive Data Rate
SNR	Signal-to-Noise Ratio
RSSI	Received Signal Strength Indication
PDR	Packet Delivery Ratio
ToA	Time on Air
NF	Noise Factor

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1: Introduction

Long-Range (LoRa) is a non-cellular long range and low power wireless technology. It is being used in both industrial and home automation where longer range, lower cost and less power consumption is of importance. There are at this point in time over 178 million LoRa devices connected to networks in 100 countries and this number is still growing. (Semtech, n.d.)

LoRa is widely used within the Internet of Things (IoT) to communicate between nodes and gateways. IoT is the communication that connects everyday objects like sensors or vehicles to each other and to the internet. This can be explained with an example of a battery driven temperature sensor which is located outdoors and, is transferring data wirelessly to a device that in turn can display the current temperature to the residents. With IoT a sensor can send data directly to the user application through the internet or save it in the cloud for ease of use at a later occasion.

There have been studies in how LoRa and Long-Range Wide Area Network (LoRa WAN) can be used to increase energy efficiency and decrease costs in several areas. In one of these studies the focus was on increasing energy efficiency for streetlights. By using LoRa to monitor the streetlights energy efficiency and change configurations remotely, energy savings obtained for one year reached 2,615.635 kWh which is a quite significant number (Cano-Ortega & Sanchez-Sutil, 2021). In another study the focus was to keep the ordinary network cost down, and the proposition to do this was to use LoRa. This was then done by developing a long-distance communication architecture for medical devices (Gaitan, 2021). LoRa works well in applications like this because of its low power consumption and long range, which in some cases can go up to and over 10 km.

In this paper the focus will be on two frequencies in LoRa, namely 433MHz and 868MHz, then a comparison will be made regarding their energy usage and effectiveness. The reason why this study has its focus on LoRa, is because it is an interesting technology that have been on the uprise for a couple of years, and that there exist several papers about the subject that could be built upon.

This work is done because of how important energy effectiveness is when working with LoRa and is done in cooperation with Combitech.

1.1 Problem statement

When making the choice of which frequency to use, there is possibility that the frequency will be between 433MHz and 868MHz which are the two most common ones. According to the study led by Bratt and Carlbäck (2018) the choice between 433MHz and 868MHz is not obvious. In their study data loss was analysed, it was discovered that depending on the environment and circumstances both frequencies had their advantages and disadvantages. While the results point towards 433MHz as the better choice in most situations, it does not however account for the energy usage between the frequencies.

LoRa is often used with battery driven components within IoT such as temperature or humidity sensors. A reason could be to keep the maintenance cost for these devices to a minimum. It is therefore important to find energy efficient solutions to make the communication between a gateway and a node more effective. There are several factors that have an impact on how much energy is being used, such as number of transmissions and size of data sets which was proven in the paper by Fareby and Olofsson (2020). In their study they only tested the frequency 868MHz.

The reason for this study is to continue these earlier works and to help LoRa users make the most energy effective choice. This study will compare the energy usage between LoRa frequencies 433MHz and 868MHz to find out how they differ from each other.

1.2 Purpose and research questions

Drawing on the problem statement, it is evident that further research within LoRa energy consumption is necessary and important to develop more efficient solutions. Consequently, the purpose of this study is:

To conduct experiments to collect empirical data on the two different frequencies energy usage. To compare the frequencies and see if there is a marginal difference in the energy consumption between the two frequencies. Which will help further projects to decide which frequency is the most appropriate one to use.

To answer the purpose, it has been broken down to two research questions.

I. How does the energy usage differ between nodes that uses LoRa 433MHz and LoRa 868MHz?

The LoRa modulation has different configurations that affects the energy consumption, in this study the configuration of spreading factor, bandwidth and coding rate will be examined to analyse the energy difference. To answer the first research question, it has been broken down to three sub-questions.

i. How does the spreading factor affect this energy difference?
ii. How does the bandwidth affect this energy difference?
iii. How does the code rate factor affect this energy difference?

II. How is the percentual difference in energy usages affected when changing data rate and is the difference linear between the two frequencies 433MHz and 868MHz?

By finding out how the percentual difference is presented between using 868MHz and 433MHz when using different DR values, the LoRa user can easier make more energy effective choices between what DR values and the frequencies to use in their specific cases. To answer the second research question, it has been broken down to three sub-questions.

i. How does the spreading factor affect the percentual difference?
ii. How does the bandwidth affect the percentual difference?
iii. How does the code rate factor affect the percentual difference?

1.3 Scope and limitations

An experimental study will be conducted to collect data which will be analysed in the empirical research. The data in this case will be the amount of energy that is being used when the LoRa device is transmitting. The two different setups had the same precondition, and all experimentation will be done in the same way, meaning no deviation between the setups occurred. The results will then be used to get an average from the two frequencies that answered the research questions.

Experiments will use a set distance for both frequencies. These tests will not look at data loss differences between the two frequencies and will be conducted indoors in room temperature. The equipment and code will be adapted to this study.

1.4 Disposition

The remainder of the report consist of six additional chapters. The second chapter contain the methods that are being used and how they are implemented. Chapter three describe the earlier work that exist and how the research question and method is connected. In chapter four the analysis of the empirical data, where presentations of tables and graphs are presented. The fifth chapter handles the analysis of the test results. Chapter six contains the discussions about what the test results and analysis has answered and if not, how it could be answered. The seventh and last chapter present what answers the study led to and what could be a good area for future research.

2: Method and implementation

To achieve the research purpose and answer the research questions, an experimental study was conducted. The experiment compared two different setups, one setup tested the energy usage with 433MHz, and the other setup tested the 868MHz energy usage. Each setup contained a LoRa receiver and transmitter, two microcomputers and an electronic device that measured how much energy was used. It was a quantitative experiment where data were collected from the two experiment setups. The collected data was used in an empirical research where the data was analysed to answer the research questions. To analyse the collected data, electrical theory was implemented and used to calculate the results with correct formulas.

2.1 Connection between research question and method

I. How does the energy usage differ between nodes that uses LoRa 433MHz and LoRa 868MHz?
II. How is the percentual difference in energy usages affected when changing data rate and is the difference constant between the two frequencies 433MHz and 868MHz?

To answer the research questions two test units was developed. One LoRa 433/868MHz transmitter and one 433/868MHz receiver. The experiment compared how much energy the frequency 433MHz consumed compared to 868MHz. To measure the energy usage another test unit was built with a current sensor which enabled the collection of data in terms of energy usage. The collected data from the experiment was used to get an average of how much energy was used by the two frequencies.

2.2 Design

Two identical units were set up, to help answer the research question. With these units the experiment was conducted. The parameters in the experiment were energy usage for 868MHz and energy usage for 433MHz.

The test setup was built with the following components, two LoRa RF click modules that use RN2483 which is capable of using both 433Mhz and 868Mhz, three Arduino Uno Rev3 cards, four antennas with two of them being ¼ Wave Flexi Antenna 433MHz SMA and two being ¼ Wave Flexi Antenna 868MHz SMA and lastly one INA219 current sensor as seen in Figure 1.

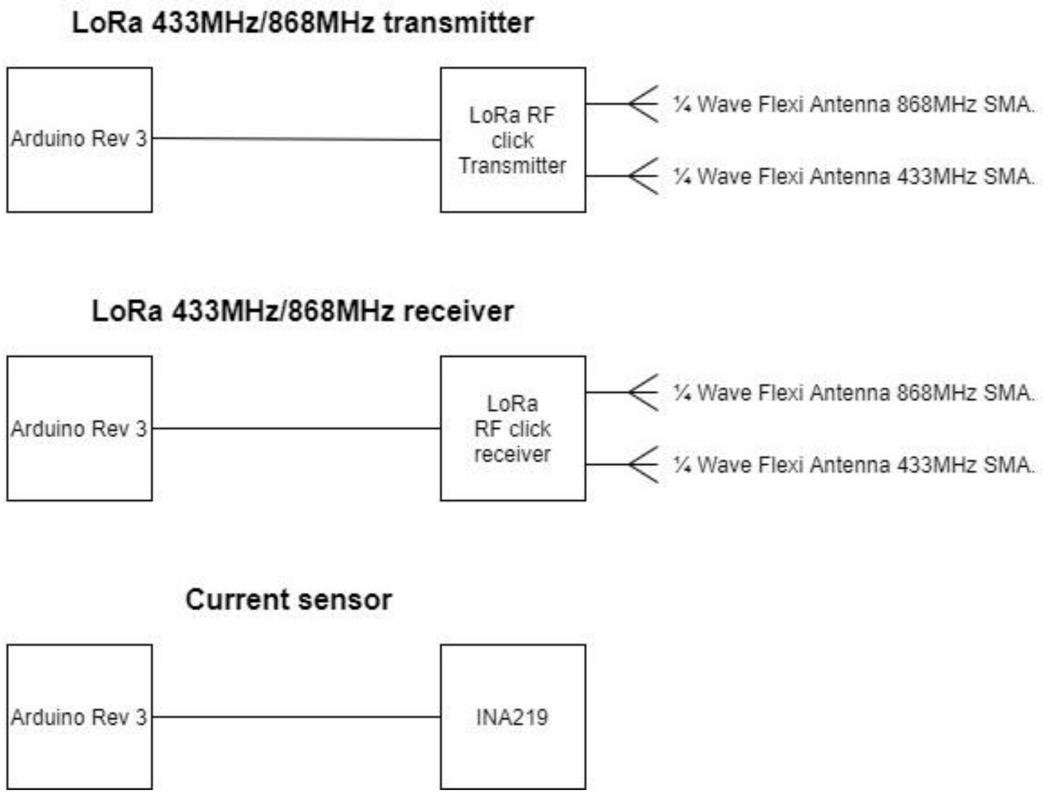

Figure 1. Illustration of test components.

Setup for LoRa receiver was one Arduino Uno connected with one of the LoRa RF click modules and this was running code which makes this LoRa component the receiver. For the LoRa transmitter the setup also included INA219 current sensor which was connected to the LoRa components high side and was being run by a separate Arduino Uno.

2.3 Data collection

2.3.1 Current sensor - INA219

For the experiment, the current sensor INA219 was used. The sensor can measure both high side voltage and DC current draw with 1% precision. To read the data over I^2C the sensor needs to be connected to an MCU like an Arduino. The sensor will send voltage, current and effect.

This sensor was used to measure the voltage and current to be able to calculate the energy usage. To ensure that the sensor is reliable and gives correct data it was connected to a 100Ω resistor in circuit with 9V using a Velleman PS 613 bench power supply. The resistor was measured to 96,4Ω with a multimeter. By using Ohms law in a mathematical expression, the current can be calculated and should theoretically be 93,36mA, as shown below.

$I_{theoretical} = V / R \Rightarrow 9/96{,}4 = 0{,}09336A = 93{,}36mA$

To test the sensor, ten output measurements were sampled. The average current from the sensor was 93,97mA. With the values divided, a precision within 99% was accomplished and this proves the reliability of the sensors return data.

$I_{theoretical}/I_{average}$ = 93,36/93,97 = 0,99 = 99%

2.3.2 Experiment

The experiment was conducted in one of Jönköping University's laboratories. The INA219 sensor was calibrated in the code to have 16V and 400mA as a maximum value, with this calibration the sensor gave a higher precision on the voltage and ampere. The code was retrieved from the manufacturers GitHub website. (Adafruit Industries, u.d.)

The two LoRa-components were set approximately one decimetre apart since the experiment would only investigate the energy usages and not data loss or data packages. Each LoRa module were connected to an Arduino, one module acted as a receiver and the other as a transmitter. The LoRaWAN part of the modules was deactivated since the experiment will only investigate and compare how much energy the transmitting module is using with the two different frequencies. When the LoRaWAN part is deactivated, the modules becomes either a LoRa radio frequency receiver or a LoRa radio frequency transmitter, there is no communication with a gateway which would give access to the internet.

The sensors Vin+ was connected to the Arduinos 3,3V output and the Vin- was connected to the LoRa transmitters 3,3V input. The DR Tx/Rx will either send a high or low signal from the Arduino sensor to the Arduino TX/RX. The measure on/off will either send a high or low signal from the Arduino TX to the Arduino sensor. All components were connected to the same ground as seen in Figure 2.

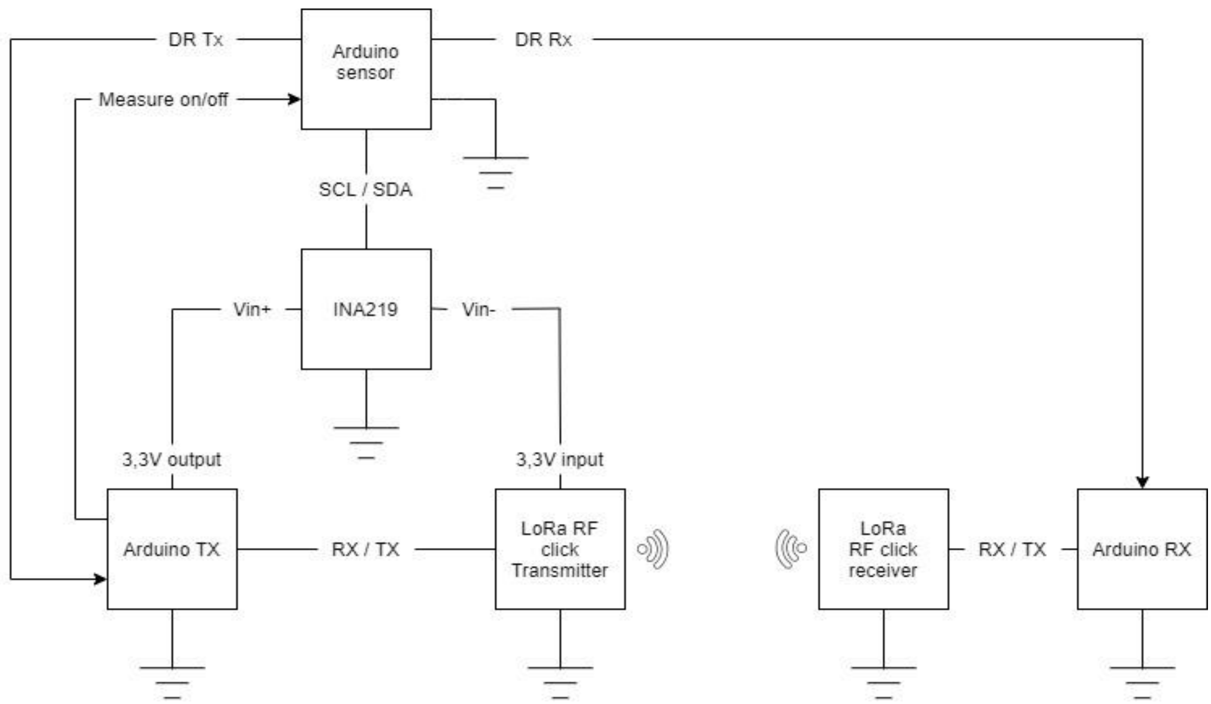

Figure 2. Circuit scheme for test environment.

The sensor only took measurements when the transmitter transmitted data to avoid measurements when the components went idle. This was solved by sending a signal via the cable Measure on/off from the Arduino TX to the Arduino sensor every time when transmitting. To get valid data the sensor measured 1000 samples for each data rate and calculated the averages value. The experiment was systematically done where every test started with DR0-868MHz then DR0-433MHz and so on up to DR10. All the DR are shown in chapter 2.4 in Table 1.

The code was written in such way the test could be completely autonomous. When 1000 samples were collected for one DR, the Arduino sensor would send a signal via the cables DR Tx and DR Rx to the Arduino TX and Arduino RX. When this signal was received both cards would change configuration and change either DR, frequency, or both.

The code that was sent for each transmission was the hexadecimal value "48656C6C6F" which is in ASCII is "Hello". The messages' size was then 5bytes for each transmission.

The data which was of most importance was that of microwatt used and this had to be converted over to microwatt-hours. This conversion is necessary because the standard unit for measuring energy in electronics is watt-hours (Wh) or kilowatt-hours (kWh). This conversion was done by taking the time for each transmission and multiplying it with the wattage.

t_h = time in hours

P_w = Watts

E_{Wh} = Energy

$$t \times P = E$$

Or in our case

$$h \times \mu W = \mu Wh$$

2.4 Data analysis

The analysis method that was used in this study was the collection of empirical quantitative data. The collection of data was grouped up between data rates and frequencies. To answer the first research question, the two frequencies 433MHz and 868MHz energy usage were compared with the frequency configuration plans DR0-DR10 as seen in Table 1. DR0 to DR5 changes the SF value which ranges from 7 to 12. The LoRa modulation only has theses 6 SF as changeable parameters. DR5 to DR7 changes the BW values 125kHz, 250kHz and 500kHz. These BW are used when using LoRaWAN and therefore are compared in this study. DR5, DR8, DR9 and DR10 changes the CR values 4/5, 4/6, 4/7 and 4/8. These values are tested since the RN2483 component that is used in this study is able to change them. (LoRa Developer Portal, n.d; The Things network, n.d)

Table 1. Data rates that were tested for 868MHz and 433MHz.

Data rate	SF	BW	CR
DR0	12	125	4/5
DR1	11	125	4/5
DR2	10	125	4/5
DR3	9	125	4/5
DR4	8	125	4/5
DR5	**7**	125	4/5
DR6	7	250	4/5
DR7	7	500	4/5
DR8	7	125	4/6
DR9	7	125	4/7
DR10	7	125	4/8

This analysis method was chosen because of how relatively easy the collection of big amounts of data would be. The reliability of the results is also strengthened by using greater amounts of data.

2.5 Validity and reliability

The experiment has been performed in the same location under the study and with the same room temperature. The sensor was tested to make sure it was accurate in the measurements. During the experiment, the two Arduinos were swapped between the two LoRa components to make sure the cards provided the same voltage and current. By this manufacturing deviations or faulty cables are taken into consideration. The two LoRa components were used as transmitters and receivers to confirm that the difference in energy usage between the two cards were within an acceptable range, in this case a difference of 3,3%. By sampling 1000 measurements for each frequency and data rate the data becomes more reliable and accounts for deviation if such should occur as seen in Figure 3. There were small deviations on the 433MHz frequency but since there was only 15 deviations out of 1000 samples which translates to 1,5%, they were not taken into consideration and were deemed to be negatable. The data which was chosen to be used in this paper’s figures and tables was from the card that had the smallest fluctuations in energy usage.

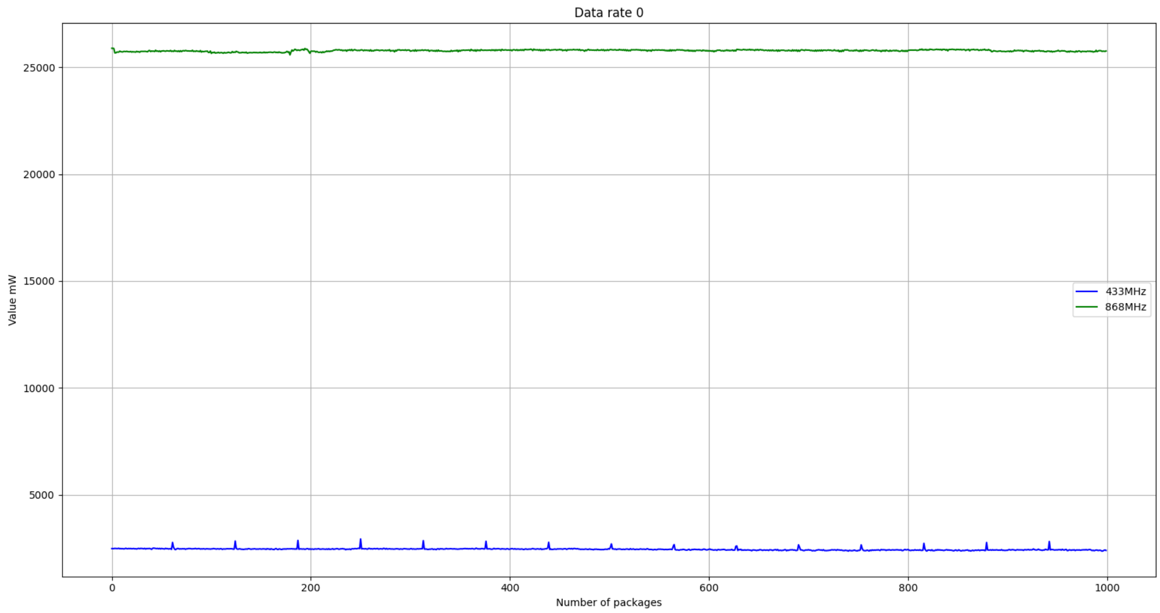

Figure 3. Shows data collected from 1000 transmission using DR0 comparing 868MHz and 433MHz.

The procedure of the experiment and its component is well documented so the experiment can be replicated. The codes for the experiment have been adapted for the experiment and only necessary code for configuration and measurement has been used.

The LoRa component was chosen since it can transmit both 433MHz and 868MHz. With this the components becomes more identical and uses the same Microchip RN2483 that is the LoRa module. The radio frequency transmitter power output was set to 10dBm due to regulation for 433MHz has 10dBm as the highest allowed value (Microship).

3: Theoretical framework

3.1 Connection between research question and theory

To give a theoretical foundation to the research questions *How does the energy usage differ between nodes that uses LoRa 433MHz and LoRa 868MHz?* and *How is the percentual difference in energy usages affected when changing data rate and is the difference constant between the two frequencies 433MHz and 868MHz?* following areas are described in the theoretical framework: Electronic formulas, LoRa and IoT. The Electronic formulas described for the calculation for electrical energy, current and Ohm's law. LoRa is addressed to give a basic understanding of the technology behind LoRa. Internet of Things is addressed to give a basic understanding of how the Internet of Things is build up.

3.2 Electronic formulas

To answer the research question where energy usage is of interest an electronics formula will be used, called Ohm's law. Ohms law is a formula that is used to calculate the relationship between voltage U in volts (V), current I in ampere (A) and resistance R in Ohm (Ω) in an electrical circuit.

$$R \times I = U$$

U_V = Volt
R_Ω = Ohm
I_A = Current

The effect formula is used to calculate the relationship between power P in watts (W), voltage U in volts (V) and current I in ampere (A).

$$U \times I = P$$

P_w = Watts
U_V = Volts
I_A = Current

The energy E in watt-hours (Wh) is equal to the power P in watts (W), times the time period t in hours (h).

$$t \times P = E$$

t_h = time in hours

P_w = Watts

E_{Wh} = Energy

3.3 Mathematical formulas

When analyzing the collected data, it was of interest to find out the percentual change in energy usage and this was calculated using the formula below. Percentage change equals the change in value divided by the absolute value of the original value, multiplied by 100.

$$\frac{a-b}{|b|} \times 100 = c$$

a = value one

b = value two

c = percentual change

3.4 LoRa

LoRa is the interface between different devices that enables IoT and smart cities. It uses license free narrowband radio frequencies such as 433MHz, 868MHz and 915MHz. Using LoRa opens new possibility for IoT since it has a range of 15km on the countryside and 10km in an urban environment, its energy usage is low and could support up to 10 or more years of battery life. (ambiductor, n.d.)

3.4.1 LoRa Modulation

LoRa is a spread-spectrum modulation technology with a wider band which is usually 125KHz or more, the technology is based on the Chirp Spread Spectrum modulation (CSS). CSS uses both up-chirps and down-chirps, e.g., an up-chirp starts with a low frequency and increases in the frequency as depicted in Figure 4. LoRa uses orthogonal Spreading Factors (SF) which allows optimizations of individual nodes to preserve battery. If a node would be close to a gateway, then it could have a lower spreading factor which will preserve battery, if it would been further away or there is more disturbance the use of a higher SF is optimal. (LoRa Developer Portal, n.d.)

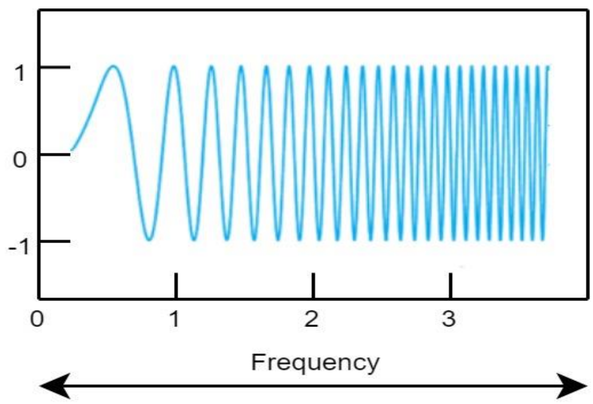

Figure 4. Example of an up-chirp

3.4.2 Data rate - Spreading factor, Bandwidth and coding rate.

SF decides how many chirps that are sent per second. The SF ranges between 7 and 12, for each jump up it takes the double amount of time to send the chirp. Lower SF means that more chirps are sent per second and needs less airtime. Airtime is the transmission time, which means that the modem is active and consumes energy. If a transmission with SF12 would send the same amount of data like a transmission with SF7, it would need more Time on Air (ToA) to do so. See Figure 5. (The Things network, n.d.)

Bandwidth (BW) – In LoRa the bandwidth of either 125kHz, 250kHz or 500kHz is most used, the choice of BW is depending on the region it is used in or the frequency plan. Increasing the bandwidth from 125kHz to 250kHz allows two times more bytes to be sent in the same airtime. Using 125kHz with 868MHz means that the chirps frequency moves between 867,9375MHz and 868,0625MHz where 868MHz is the centrum frequency. (The Things network, n.d.)

Coding rate (CR) – LoRa modulation uses Forward Error Correction (FEC). This means that redundant bits are added to a transmission so that errors or interferences can be detected and corrected. When using the CR 4/6, only four bits are containing information while the two is redundant bits. CR 4/8 has a higher degree of error-handling than CR 4/6 but will increase the airtime. (TechTarget Contributor, 2007)

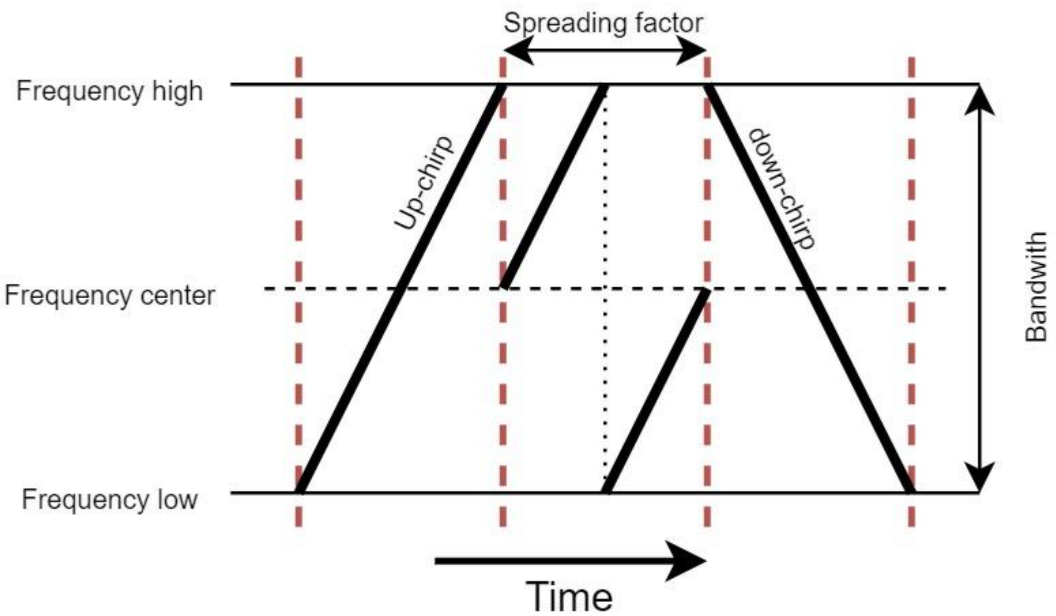

Figure 5. Graphical example of chirps and SF.

3.4.3 Frequencies

LoRa uses license free frequencies which has the perks of being free to use. The free license frequencies standard differs in different regions: Europe uses the 868MHz and 433MHz, while America uses 915MHz and Asia uses 433MHz. Despite those standards LoRa is not locked to these frequencies but can use other registered frequencies. (ambiductor, n.d.)

3.4.4 LoRaWAN and LoRa

While LoRa is the physical layer of communication, LoRaWAN is the protocol used with LoRa and provides seamless interoperability between devices. The protocol standard of LoRaWAN is driven by the LoRa Alliance which is a non-profit association. (Semtech, n.d.)

3.5 IoT

IoT is the communication that connects everyday objects like sensors or vehicles to each other and to the internet. IoT architecture consist of three different layers, perception layer, network layer and the application layer. The application layer is like the physical layer, its main task is to perceive physical properties of things around us that are a part of IoT. The received data from the perception layer is processed by the network layer and then transmitted to the application layer via various networks technologies. The processed data from the network layer is used by the application layer to constitute the front end of the whole IoT architecture. (Mohammed, Djamel, & Romdhani, 2015)

3.6 Related research

There already exist a great amount of research papers and studies regarding LoRa, many of which at the least mention energy consumption.

In the paper *LoRaWAN-uppkopplade smartcyklar* the authors Befwe and Ferm (2019) was investigating how well LoRaWAN works with smart bicycles. One of the research questions examined is how the energy consumption differs when sending different sizes of data with different intervals. In their paper the LoRa configuration is not changed meaning that the SF, BW, CR and frequency (868MHz) were the same during the whole experiment. The paper deemed that LoRaWAN is relevant when used with smart bicycles. The authors also mentioned in further research that a higher SF could be used if packages needed to be sent less frequently, how this would affect the signal coverage and the energy consumption.

Another paper that looks at energy consumption compares the energy consumption of two different types of LPWAN (Low Power Wide Area Network) devices that uses either LoRa or Sigfox. During the experiment, the frequency that was being used was 868MHz and to analyse the energy consumption, different SF and CR was used. One of the parameters which could be used to optimise energy efficiency was the bitrate which is decided by the LoRa modulation. (Eriksen, 2019) The experiments in this paper as mentioned above, focused on how the energy consumption differs between LoRa 868Mhz and Sigfox.

This other study presents an architecture, communication protocol and a data analysis algorithm for wastewater treatment system intended for irrigation. LoRa is used for the communication between the nodes and gateways. In the study a simulation was used to choose the most suitable LoRa configuration. The simulation compared different combinations of BW and SF on the frequency 868MHz. In the simulation the frequency 433MHz reached the maximum theoretical distance with all settings. The selected configuration used the frequency 868MHz with the BW 125kHz and SF 8, with the transmission power of 13dB this configuration had the theoretical power consumption of 92,4mW/h. The result of the study shows that the proposed system using

LoRa can transmit the necessary information and alerts with a low bandwidth generation. (Jimenez , o.a., 2021)

In another paper a smart irrigation system based on LoRa/LoRaWAN IoT nodes and gateways are proposed. Their system was told to be able to exchange data with local fog computing nodes and with a remote cloud. The study compared the frequency 868MHz and 433MHz. The different setups for the two frequencies had different microcontrollers which essentially affects the power consumption. During collection of data using LoRaWAN the transceivers by default made use of an ADR (adaptive data rate) which adjust the configuration of BW, SF and transmission power. While LoRa do not execute ADR the configuration is static, during the collection of data the SF was set to 12 and power transmission set to 20dBm. The authors concluded that if larger areas were monitored and controlled by irrigation nodes, 433MHz were the most suitable choice. This because of the better radio propagation the frequency achieved. (Froiz-Míguez , o.a., 2020)

One paper compares the two frequency 868MHz and 433MHz inside a multi-story building. The study measured the parameters SNR (Signal-to-Noise Ratio), RSSI (Received Signal Strength Indication), PDR (Packet Delivery Ratio) and Packets received. The parameters were measured at 8 different floors to see how effective the frequencies were in the building. During the experiments, the SF was changed from SF7 to SF12 on the two frequencies and the signal strength were measured. The frequency 433MHz gained a stronger signal when increasing the SF but the frequency 868MHz showed higher percentage of received packets. The authors concluded that 868MHz with SF10 is better to use in a nine-story building with concrete floors. (Bobkov, Rolich, Denisova, & Voskov, 2020)

And then there is a paper that compares the frequencies 433MHz, 868MHz and 915MHz performance in terms of signal strength and energy requirements using MATLAB and Simulink. The experiment was completely tested in a simulation using MATLAB and Simulink special purpose wireless simulation environment. To calculate the energy usages the author uses a mathematical formula that calculates the maximum sensitivity which is measured in dBm. The parameters BW, NF (noise factor) and SNR was used in the formula. During the simulation, the dBm is converted to watts using standards equations and tables. The energy consumption and data loss were calculated between the different SF for 24 hours. It was concluded in the paper that "It was observed that packet data-loss increases with increase in distance between transmitter and receiver." And increasing the SF to correct distance between the LoRa transmitter and receiver could solve the data-loss but with a compromise in power consumption. (Alset, Kulkarni, & Mehta, 2020)

4: Experiment design

This chapter gives an overview of the empirical collected data that is the foundation of this study and is used to explain the data and to help answer the research questions. All data rates have been sampled 1000 times on both frequencies and the averages for each data rate has been used in the tables and graphs below. All data in this chapter was measured, calculated and saved in text files using the Arduino-sensor setup. The different settings for all tests where automatically changed as explained in chapter 2.3.2.

The sub headlines Spreading factor, Bandwidth and Coding rate shows the results from different DR. Spreading factor compares from DR0 to DR5 since the only changed parameter in these DR are the SF. Bandwidth compares from DR5 to DR7 since the only changed parameter in these DR are the BW. Bandwidth compares DR5, DR8, DR9 and D10 since the only changed parameter in these DR are the CR. These DR are explained in chapter 2.4 and are displayed in the Table 1.

4.1 Spreading factor

4.1.1 Collected data from different SF on frequency 868MHz.

Table 2 Displays the Watt, microWatt-hour, ToA and the current for one transmission on the frequency 868Mhz when changing the spreading factor from 7 to 12.

Table 2. Collected values when changing spreading factor on the frequency 868MHz.

Data rate	Power (W)	Energy (uWh)	ToA (ms)	Current (A)
DR0 $_{SF12}$	25.76	6211.00	876.99	8.03
DR1 $_{SF11}$	15.48	2320.43	539.48	4.82
DR2 $_{SF10}$	7.84	631.36	289.84	2.45
DR3 $_{SF9}$	4.02	185.84	166.40	1.25
DR4 $_{SF8}$	2.16	60.58	103.11	0.67
DR5 $_{SF7}$	1.15	23.45	73.12	0.36

4.1.2 Collected data from different SF on frequency 433MHz.

Table 3 Displays the Watt, microWatt-hour, ToA and the current for one transmission on the frequency 433Mhz when changing the spreading factor from 7 to 12.

Table 3. Collected values when changing spreading factor on the frequency 433MHz.

Data rate	Power (W)	Energy (uWh)	ToA (ms)	Current (A)
DR0 $_{SF12}$	24.71	597.49	870.57	0.75
DR1 $_{SF11}$	1.53	229.58	538.61	0.46
DR2 $_{SF10}$	0.89	71.15	289.10	0.26
DR3 $_{SF9}$	0.55	25.42	166.03	0.17
DR4 $_{SF8}$	0.40	11.38	102.93	0.12
DR5 $_{SF7}$	0.31	6.36	73.02	0.10

4.2 Bandwidth

4.2.1 Collected data from different BW on frequency 868MHz.

Table 4 Displays the Watt, microwatt-hour, ToA and the current for one transmission on the frequency 868Mhz when changing the bandwidth between 125, 250 and 500.

Table 4. Collected values when changing bandwidth on the frequency 868MHz.

Data rate	Power (W)	Energy (uWh)	ToA (ms)	Current (A)
DR5 $_{BW125}$	1,15	23,45	73,12	0,36
DR6 $_{BW250}$	0,68	10,67	56,49	0,22
DR7 $_{BW500}$	0,44	6,14	49,78	0,14

4.2.2 Collected data from different BW on frequency 433MHz.

Table 5 Displays the Watt, microwatt-hour, ToA and the current for one transmission on the frequency 433Mhz when changing the bandwidth between 125, 250 and 500.

Table 5. Collected values when changing bandwidth on the frequency 433MHz.

Data rate	Power (W)	Energy (uWh)	ToA (ms)	Current (A)
DR5 $_{BW125}$	0,31	6,36	73.02	0.10
DR6 $_{BW250}$	0,28	4,46	56,44	0,09
DR7 $_{BW500}$	0,26	3,54	49,75	0,08

4.3 Coding rate

4.3.1 Collected data from different CR on frequency 868MHz.

Table 6 Displays the Watt, microwatt-hour, ToA and the current for one transmission on the frequency 868Mhz when changing the coding rate from CR4/5 to CR4/8.

Table 6. Collected values when changing coding rate on the frequency 868MHz.

Data rate	Power (W)	Energy (uWh)	ToA (ms)	Current (A)
DR5 $_{CR4/5}$	1.15	23.45	73.12	0.36
DR8 $_{CR4/6}$	1.24	25.05	72.97	0.38
DR9 $_{CR4/7}$	1.27	26.89	76.34	0.40
DR10 $_{CR4/8}$	1.36	30.02	79.33	0.42

4.3.2 Collected data from different CR on frequency 433MHz.

Table 7 Displays the Watt, microwatt-hour, ToA and the current for one transmission on the frequency 433Mhz when changing the coding rate from CR4/5 to CR4/8.

Table 7. Collected values when changing coding rate on the frequency 433MHz.

Data rate	Power (W)	Energy (uWh)	ToA (ms)	Current (A)
DR5 $_{CR4/5}$	0.31	6.36	73.02	0.10
DR8 $_{CR4/6}$	0.30	6.21	73.04	0.09
DR9 $_{CR4/7}$	0.33	7.00	76.36	0.10
DR10 $_{CR4/8}$	0.33	7.29	79.68	0.10

5: Analysis

5.1 Research question 1

To answer the first research question “How does the energy usage differ between nodes that uses LoRa 433MHz and LoRa 868MHz?” the empirical data was analysed. To answer the research question, it was broken down to three sub-questions that compared energy difference when either changing SF, BW or CR.

I. How does the spreading factor affect this energy difference?

When the different data rates were compared with different SF it shows in Figure 6 that DR5 had the lowest energy difference and DR0 had the highest one. The energy difference keeps increasing from DR5 on every DR up to DR0. As described in chapter 3.4.2 when increasing the SF, a transmission will need more airtime. Which is reflected in the measured amount of energy consumed during the experiment.

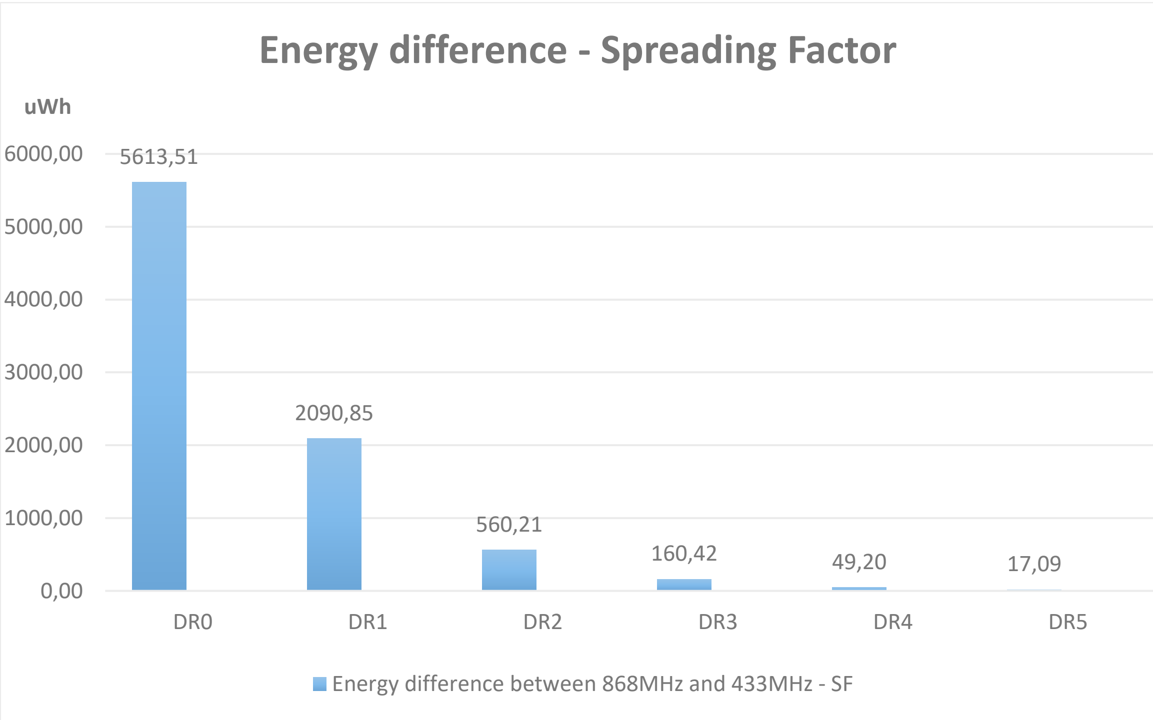

Figure 6. Energy difference between the 433MHz and 868MHz when changing SF.

II. How does the bandwidth affect this energy difference?

When the different data rates were compared with different BW it shows in Figure 7 that DR7 had the lowest energy difference and DR5 had the highest one. The energy difference keeps decreasing from DR5 on every DR up to DR7. As described in chapter 3.4.2 when increasing the BW, it allows more bytes to be sent under the same airtime. Which is reflected in the measured amount of energy consumed during the experiment.

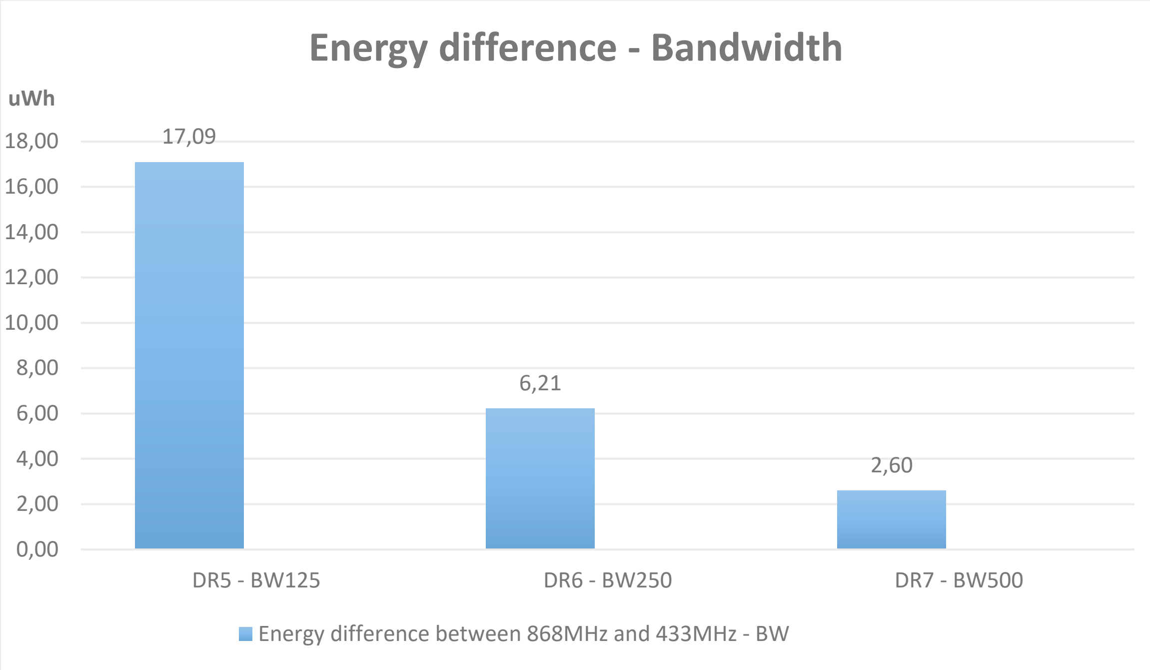

Figure 7. Energy difference between the 433MHz and 868MHz when changing BW.

III. How does the code rate factor affect this energy difference?

When the different data rates were compared with different CR it shows in Figure 8 that DR5 had the lowest energy difference between frequencies and DR10 had the highest one. The energy difference keeps increasing from DR5 on every DR up to DR10. As described in chapter 3.4.2 when changing the CR, the transmission is given either a higher or lower degree of error-handling and this will in turn affect the ToA.

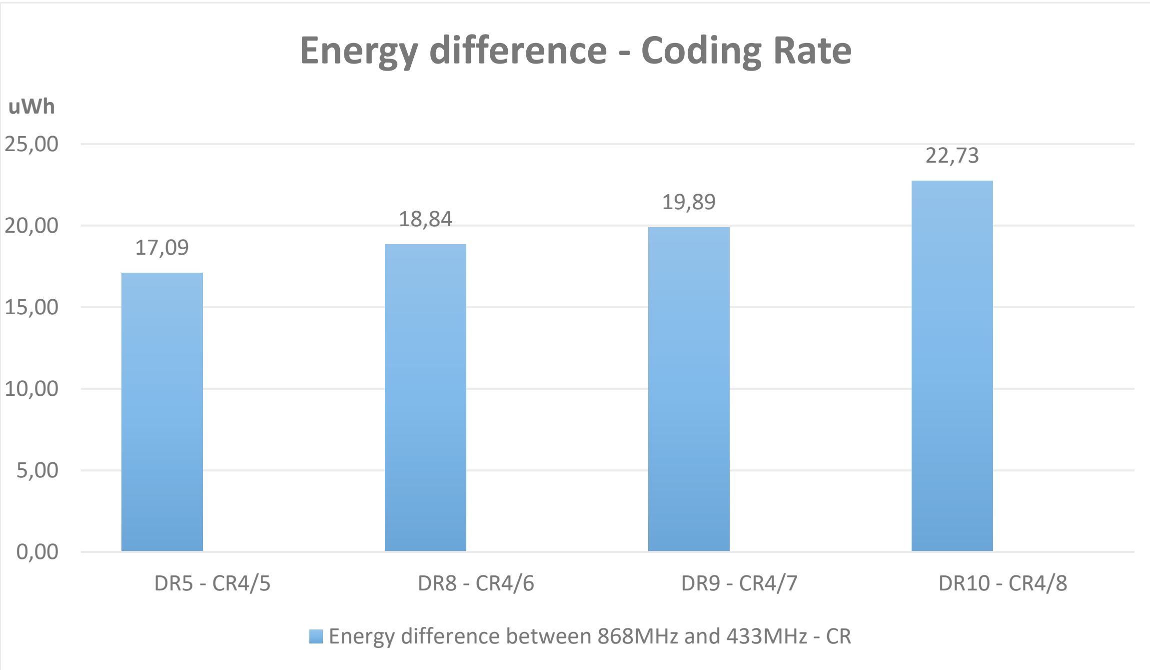

Figure 8. Energy difference between the 433MHz and 868MHz when changing CR.

5.2 Research question 2

To answer the second research question "Is the percentual difference in energy usage constant between the two frequencies when using different data rates?" the empirical data was analysed and by using a simple math formula shown in chapter 3.3 the percentual change could be calculated. When the percentual change was calculated using the formula mentioned above, the *b* variable was given the collected data value of 868MHz and the *a* variable was given the collected data value of 433MHz for each DR. The value of *c* which contains the percentual change was then used to show the percentual difference between the different DR values. And to help answer the research question, it was broken down to three sub-questions that compared energy difference when either changing SF, BW or CR.

I. How does the spreading factor affect the percentual difference?

When the different data rates were compared with different SF it shows in Figure 9 that DR5 had the lowest percentual energy difference between frequencies and DR0 had the highest difference. The percentual energy difference keeps increasing from DR5 on every DR down to DR0, where DR5 has 73.88% and DR0 has 90.38% which makes the percentual difference 16.5%. The biggest increase with 8.3% is between DR5 and DR4 and the second biggest increase with 5.11% is between DR4 and DR3.

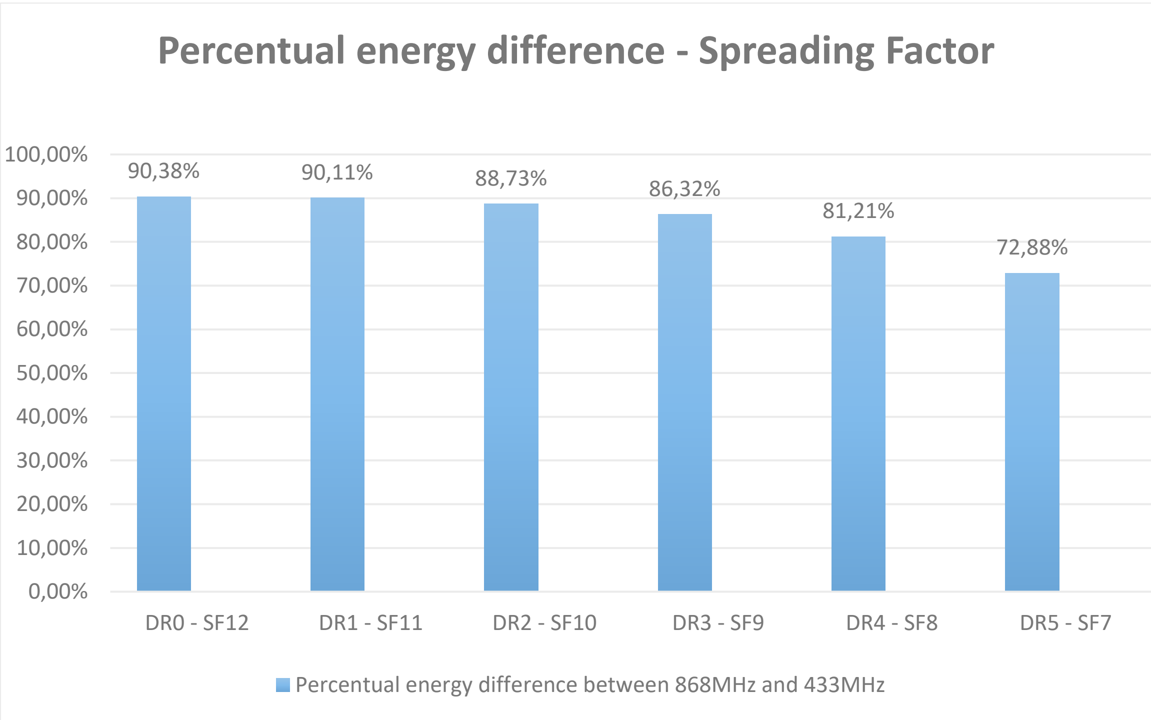

Figure 9. Percentual energy difference between the 433MHz and 868MHz when changing SF.

II. How does the bandwidth affect the percentual difference?

When the different data rates were compared with different BW it shows in Figure 10 that DR5 had the highest percentual energy difference between frequencies and DR7 had the lowest one.

In turn, the overall difference between the DR5 and DR7 is 30,53%. With a difference of 14,68% between DR5 - DR6 and a difference of 15,85% between DR6 – DR7.

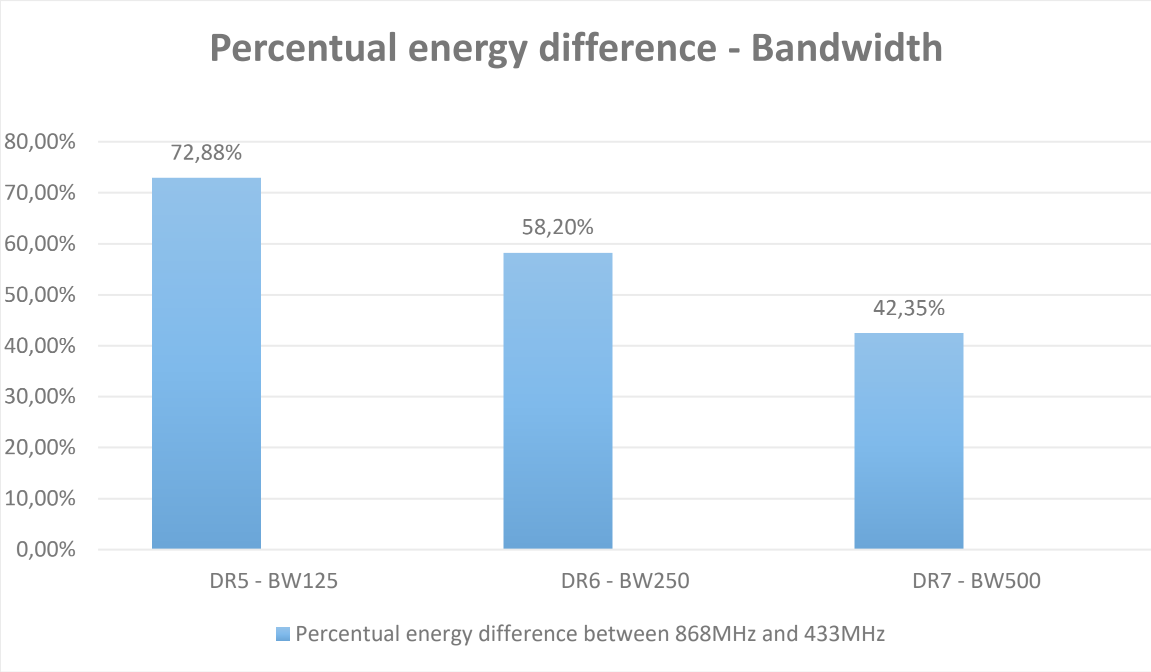

Figure 10. Percentual energy difference between the 433MHz and 868MHz when changing BW.

III. How does the code rate factor affect the percentual difference?

When the different data rates were compared with different CR it shows in Figure 11 that DR5 had the lowest percentual energy difference between frequencies and DR10 had the highest difference. The energy difference in the case of CR-values was quite small and had small fluctuations.

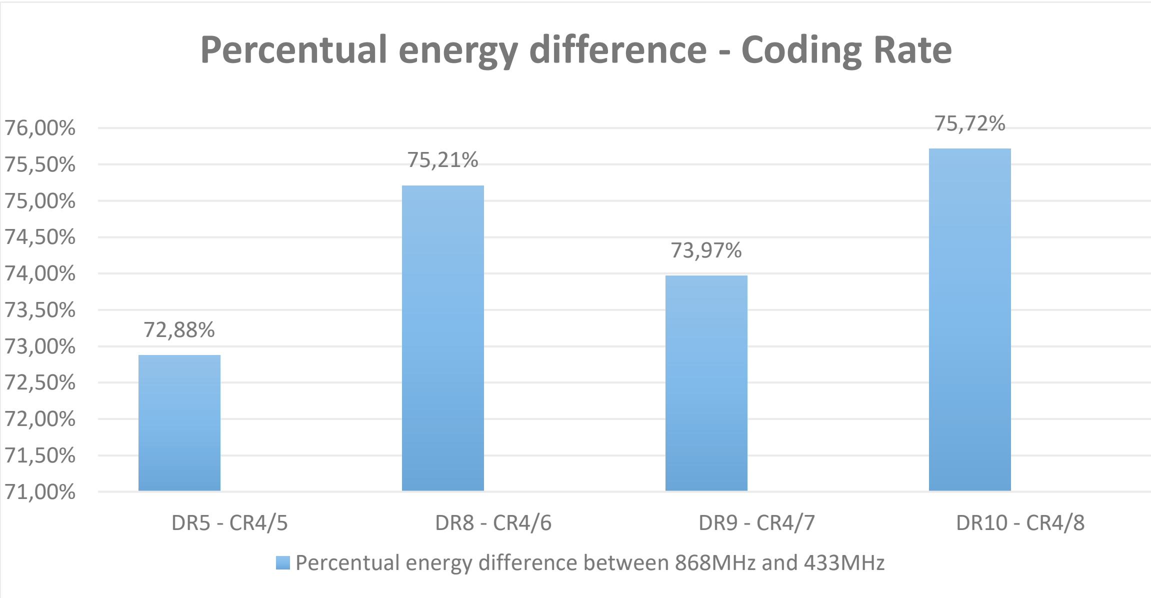

Figure 11. Energy difference between the 433MHz and 868MHz when changing CR.

6: Discussion

This chapter will cover a discussion about the methods, experiment results and what implications and limitations they have.

6.1 Result discussion

The purpose with this study was:

To conduct experiments to collect empirical data on the two different frequencies energy usage. To compare the frequencies and see if there is a marginal difference in the energy consumption between the two frequencies. Which will help further projects to decide which frequency is the most appropriate one to use.

To answer the purpose two research questions with sub-questions were created.

I. How does the energy usage differ between nodes that uses LoRa 433MHz and LoRa 868MHz?

II. How is the percentual difference in energy usages affected when changing data rate and is the difference constant between the two frequencies 433MHz and 868MHz?

The frequency 868MHz will in all cases in this study consume more energy than the 433MHz frequency when increasing SF. It is showed in the collected data in Figure 5 that increasing the SF will also increase the difference in energy consumption between the two frequencies, it will become greater for every increment in SF. The increase in percentual energy difference can be seen in Figure 8 and can be perceived as a nonlinear change. As described in chapter 3.4.2 when increasing the SF, a transmission will need more ToA. In the study by Alset (2020) similar results were retrieved and show that the frequency 868MHz consumes more energy than 433MHz on all different SF. Increasing the CR has the same results as increasing the SF, the energy consumption differential and percentual differentiation will increase for every incremental in CR. As described in chapter 3.4.2, when increasing the CR, more bytes need to be sent which will create increased ToA. A previous study (Eriksen, 2019) only measured data on the frequency 868MHz and can consequently only partially be compared with our study. But data of the frequencies that correlate between these two papers are still relevant. In the result of the study by Eriksen, it is displayed that increasing the CR will increase the energy consumption which agree with our papers results. Increasing the BW will decrease the ToA which leads to less energy consumption and at the same time decrease the percentual differentiation as seen in Figure 9. As described in chapter 3.4.2 when increasing the BW, it allows more bytes to be sent under the same ToA. The sampled data implies that the longer ToA will lead to more energy consumption and greater energy consumption difference between the frequencies 868MHz and 433MHz.

6.2 Method discussion

To answer the research questions an experimental study was conducted to collect empirical quantitative data that could been analysed. This method is suitable to answer the research questions since it collects real-practical data and no theoretical data. With real-practical data real life variations could affect the experiment and alter the expected results which could lead to new discoveries. With this method complications can occur since there are multiple factors that could affect the experiment such as bad connections, differentiation in the modules and so on. Simulated experiment could be more effective while practical experiment could take longer time and more resources. The execution must be systematically and thoroughly described so that others can replicate and get the same result.

With this method the purpose and research questions were answered and fulfilled to a satisfactory degree. The experiment was well documented and was done in such way that it can be replicated, and the result can be reproduced. By following the methods explained in the previous chapters others should be able to see the same results. Before the experiment, the test equipment was tested to make sure it gave reliable and valid data.

7: Conclusions and further research

This chapter will present a conclusion of the work and briefly go over what possible implications the result could have.

7.1 Conclusions

After the study, it appeared that the most significant factor affecting the energy consumption and difference between 868MHz and 433MHz, are the ToA. When increasing the SF, which subsequently will increase the ToA, the difference in energy consumption also increases. This also implies on increasing the CR which have the same effect as increasing SF. When increasing the BW, the ToA will lower because of higher BW can send more bytes on the same ToA. The percentual difference is not linear but instead shows a decreasing difference value and a stagnation when moving up through higher SF values. When going through the BW values it instead showed a slight increase in percentual difference when moving up to higher values. It was a bit harder find a similar increase or decrease in difference when looking at CR values as they have greater fluctuations.

With the percentual difference in energy usage, LoRa users can decide which DR is the most optimal and energy efficient. This could help users to decide to either use 433MHz or 868MHz in a certain situation. Or to decide if there are any benefits to change from 868MHz to 433MHz or vice versa in a specific DR. Since this report has examined the energy difference with different LoRa modulation configuration to help decide which is the best for different situations the reports' purpose is considered fulfilled.

7.1.1 Implications

Despite that this study only investigated the difference in energy consumption on the LoRa extension card LoRa Click RF that uses the LoRa module RN2483, it is still applicable to other LoRa modules. The result is still valid to understand the difference between the two frequencies. This study contributes to increased understanding when it comes to the differentiation between 868MHz and 433MHz frequencies and its energy usages.

7.2 Further research

For further research following topics are relevant:

- The experiment could compare the energy consumption in different weather environment and humidity to investigate how this affect the energy consumption.
- The experiment could compare the frequencies 433MHz, 868MHz and 915MHz to investigate how this affect the energy consumption.
- Test different LoRa modules and compare them to each other to investigate how this affect the energy consumption.

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