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LoRaWAN-Based Communication for Autonomous Vehicles: Performance and Development

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Abstract

Automotive technology in the future continues to develop with a variety of sophistication, especially in vehicles that can move on their own, this research is new from previous developments, intelligent vehicles can be seen from various system developments ranging from the ability to find parking positions, have the right navigation system, and are equipped with various artificial senses such as LiDAR, Smart Camera, Artificial Intelligence, and various components for telecommunications. A small part that will be discussed in this research is in terms of data communication. The development of intelligent vehicles in a broader scope can be included in one of the categories to build a Smart City. In the analysis system, this research develops in terms of analyzing the possibility of data collisions or how to avoid them, with various methods that can be developed and approached comprehensively using LoRaWAN, so that a method can be determined using LoRaWAN Communication and LoRa Modules that can have an important impact in the development of intelligent vehicles or autonomous vehicles for Smart City. In this paper, the LoRa data transmission approach is to use the GPS Module, the GPS Module data is sent from each car to the nearest LoRaWAN Gateway, the car can automatically select the nearest Gateway for data optimization, reducing Packet Loss and Signal Attenuation due to LoRa data communication in the NLOS area, This article still uses data transmission simulation using MATLAB and is planned to be applied to Smart vehicles directly, the contribution of this research is the discovery of a new method in terms of LoRaWAN-based multi-point data transmission that can avoid data collisions from the position of intelligent vehicles in Mobile or moving, in building Smart City technology in the future.

Keywords: Artificial Intelligence; Future of Automotive; LoRaWAN; Smart City; Telecommunication.

Introduction

Intelligent vehicle systems have been developed by several world-level automotive developers and companies such as Tesla and BMW, as well as other manufacturers that continue to provide extraordinary innovations. One of the vehicle modes or city cars that continue to be developed at BRIN, for example, is a vehicle based on Battery Mode as a source of energy, to develop a future culture of Renewable Energy, which no longer uses petrol fuel with its various variants. The vehicles developed by BRIN include Wuling, which needs to be developed from various sides, including autonomous systems, or vehicles that can walk alone [1]–[6] can avoid precisely if there is an obstacle, or can find parking alone. This paper discusses comprehensively about intelligent vehicles on the mechanical side, but also the telecommunications side of the data. The telecommunication system has many variants that have been developed whether using Wi-Fi, Li-Fi, or lower power devices such as LPWA or Low Power Wide Area which only has a data rate of 5 kbps, with a transmitting power of only 25 mW or 14 dBm and 100 mW or 20 dBm. LoRa module is one example of LPWA technology besides Sigfox, NB-IoT, and other LPWA devices. Previously developed LPWA devices use LoRa and its variants depending on the frequency used such as 433 MHz, 866 MHz, 915 MHz, or 923 MHz which is actually in the Frequency Wave in Ultra High Frequency (UHF). In this case, it also has a lot of parameters that need to be comprehensively calculated in two types of measurements, namely Simulation and Practice. In terms of simulation, there are parameters of Coding Rate or Chip Rate (CR), Bandwidth (BW), Spreading Factor (SF), Bit Rate (RB), and other parameters. All of these parameters determine the performance of LoRa and LoRaWAN which can transmit data properly, without data collisions that cause Packet Loss or small data Throughput (bytes per Second) at the Receiver. Several types of data results can be analyzed, using several approaches from many methods, including Adaptive Data Rate (ADR) with various complex variants e.g., Static ADR, Network Server Controlled ADR, Device Controlled ADR, Hybrid ADR, and Event-Driven ADR. The complete data of SF, BW, and Bit-Rate can be seen in **Table 2**. **Table 2** proves that the values of SF, and BW of LoRa determine the Bit-Rate. The autonomous vehicle [7]−[13] developed in this paper is an approach from the LoRa communication system developed in cars or mobile devices, the car that will be tested is a car in BRIN which is comprehensively developed from various sides, starting from the battery (kW), and telecommunication devices, and smart navigation [14]−[19]. Moreover, **Table 3**, tells about the Range of LoRa Spreading Factor with the Time on Air (ms) [20]−[25] . From **Table 3** it can be seen that the greater the Spreading Factor (SF), the greater the Time on Air (ms) required for electromagnetic waves to travel from the Transmitter to the Receiver. In other words, the greater the SF, the longer the time or Time on Air (ms) or the time required by LoRa through electromagnetic waves emitted from the LoRa Transmitter to the LoRa Receiver. Broadly speaking, the specifications of the types of GPS, and other devices in the Mobile Node can be seen in **Table 3**. It can be the difference in data bytes requirements that can be generated from the types of tools or hardware specifications on the mobile Node or Car.

Furthermore, In previous research on communication systems in intelligent vehicles, it has been discussed but continues to need improvement, some of which do not have the ability to perform automatic handover by looking at the parameters used in LoRaWAN. This is one of the new discoveries as shown in **Figure 6**. Normally it is like **Figure 5**, but the development is to **Figure 6**. Moreover, in the process of research development in the field of LoRaWAN utilization in autonomous vehicles, the Research Gap is very important to show the difference, the Research Gap can be from various autonomous vehicle development technologies or V2V or V2X Communication. As shown in Reference [26], that this research builds mmWave communication and also looks at various parameters such as low-light situations and also takes into account infrastructure, this research produces detailed analysis for example on Throughput, and in this research uses 70 GHz and 100 GHz bandwidth on Carrier Communication, development on the simulation side is also carried out such as the use of NetSim software for comprehensive analysis results. Moreover, The development of autonomous vehicle communication systems can also be seen in reference [27] which develops on the side or Autonomous Connected Vehicles (ACVs), in this research analyzed in detail from the V2X Communication side and also the system or control mechanism. In the development of communication concepts in autonomous vehicles can also be seen from the development of layers such as in reference [28], in the research analysis explains comprehensively on realtime decisions specifically on the security system that can be applied to autonomous vehicle communication systems. Next is reference [29] about the Traffic Load Generator System used in the V2X system. And in this research analyzes in detail from the actual equipment side. Furthermore, research [30] also uses ALOHA software and mechanisms to analyze autonomous vehicles, from this research an Authonomous Vehicles use real-time ALOHA communication system is obtained.

Furthermore, the autonomous vehicle communication system is developed by means of a V2X-based Parallel Surface System [31], from this system a detailed analysis of hotspot offloading is obtained, as well as facilitating multiple antenna signal transmission and high-precision positioning. The development of communication media other than LoRaWAN for V2X is also based on 5G such as research analysis [32], by analyzing MCSV, and from the analysis can precisely analyze the driver safety system. However, in driving an autonomous vehicle, it cannot be separated from blind spots and unreachable areas, so research [33] discusses and solves this problem by demonstrating blind spots using V2X, which will be very important in driver safety and avoiding collisions or hitting certain objects. From various experiments, a system is also needed that is not only in a limited area, but also in a complicated location and mixed traffic, references [34] simulates and analyzes the mixed traffic situation in great detail. And also the communication system continues to be developed not only autonomous vehicles on land but also intelligent vehicles that can move on the seabed or in water. Parameters that need to be discussed include Horizontal and Vertical flux, from research or experiment [35] obtained DC-DC efficiency of 94.12% and also realized full-duplex communication.

Method

In determining the method used, we first describe the differentiators of LPWAN with WiFi and LTE technologies.Why this research discusses LoRaWAN or LPWAN as one of the telecommunications technologies offered to build telecommunications systems in autonomous vehicles, some of the points that are featured are Range or Distance, Energy Consumption, Scalability, and Infrastructure implementation. It is not significant that all are superior on all fronts, but some of these indicators state super reliable performance, especially in terms of range, very wide, LPWAN or LoRa Module can reach a distance of >15 km in Line of Sight (LoS) Condition, but the bit-rate is low so it is necessary to do a special algorithm in sending or transmitting image data for example. In terms of power consumption, the LoRa module is also low at 25 mW to 100 mW during transmission, Scalability excellent means that it is able to connect multiple autonomous vehicles at a distance. The most important thing is the cost of installing the tool, LPWAN is guaranteed the easiest and does not require complicated and expensive infrastructure. In detail, **Table 1** has explained more comprehensively.

Table 1. Advantages of LPWAN for autonomous vehicles compared to WiFi and LTE

Features/Expects	LPWAN	WiFi	LTE
Range Distance	Very wide range, ideal for communication between autonomous vehicles and infrastructure and devices outside WiFi range	Limited range, suitable for communication within connected areas such as parking lots or nearby neighborhoods	Wide coverage, supporting communication over long distances and between vehicles and infrastructure
Energy Consumption	Very low, suitable for sensor and communication devices that require high energy efficiency	Relatively high, it requires more power, which can be a constraint for devices that require energy efficiency	Moderate to high, the device must be recharged frequently or have a stable power source
Data Capacity	Limited, more suitable for periodic transmission of small data (e.g. sensor status) than video or heavy data	High, can handle large data transmission and high bandwidth, suitable for streaming video and heavy data	High, supporting high data rates and large capacity, ideal for real-time communication and heavy data
Latency	High, not ideal for applications that require real-time response such as vehicle control or navigation	Low, good for applications that require fast response, such as real-time communication in the immediate environment	Moderate, suitable for applications that require real-time communication with fairly low latency
Scalability	Excellent, can support thousands of devices efficiently, suitable for applications with many autonomous vehicles and sensors	Limited to the access point area, not ideal for large scale or wide areas	Good, supports a large number of vehicles and can be customized for larger scales
Mobility	Limited, more suitable for communication outside the WiFi area with wide coverage than high mobility	Excellent within WiFi coverage area, but not designed for high mobility	Excellent, supports high mobility and stable communication on the move
Interference and Signal Quality	Tends to be better for wide coverage and low interference outside dense environments	Vulnerable to interference from other devices and physical obstructions, which may affect signal quality	Affected by interference, but LTE is designed to overcome interference and maintain good signal quality
Infrastructure Implementation	Easy and cheap, often utilizing existing network infrastructure such as telecommunication towers	Requires multiple routers and access points, as well as maintenance in each required area	Requires complex and expensive telecommunications infrastructure for coverage and signal quality

Table 2. Relationship between Spreading Factor, Bandwidth, and Data Rate of LoRa

Spreading Factor (SF)	Bandwidth (BW) (kHz)	Data Rate (kbps)
SF7	125	5.47
SF8	125	3.13
SF9	125	1.76
SF10	125	0.98
SF11	125	0.54
SF12	125	0.29
SF7	250	11.0
SF8	250	6.25

Spreading Factor (SF)	Bandwidth (BW) (kHz)	Data Rate (kbps)
SF9	250	3.51
SF10	250	1.95
SF11	250	1.08
SF12	250	0.58
SF7	500	21.8
SF8	500	12.5
SF9	500	7.03
SF10	500	3.91
SF11	500	2.15
SF12	500	1.17

Table 3. Range of LoRa Spreading Factor

No	Specification			
	Spreading Factor	*Bit Rate (bps)*	*Range (km)*	*Time on Air (ms)*
1	SF10	980	8	371
2	SF9	1760	6	185
3	SF8	3125	4	103
4	SF8	5470	2	61

Furthermore, LoRaWAN communication is divided into three classes, including class A, class B, and class C communication types. This class A type is a communication type consisting of alternating Uplink and Downlink Frames, while class B has a Downlink extension or there are several Downlink processes. Class C is a Uplink process consisting of Downlink Continues. Class A is certainly effective for remote monitoring that requires a small data rate, small power consumption, and long-range such as the LoRa module. Class A is very appropriate for monitoring data from temperature and humidity sensors, heart rate sensors, and so on. So the power consumption for class A is smaller than that of class C which has a continuous Downlink. This class of parameters can be divided into several including Downlink Receptions, Uplink Transmission, Energy consumption, applications, data delivery delay, battery usage, and response speed. **Figure 1** is a Classes in LoRaWAN, and **Figure 2** is a **Figure 2** is a LoRaWAN Communication Stack.

Table 4. Bit-Rate of End Node Sensor Car

Times (s)	Specification (bytes per second)				
	GPS Neo-6M 10 Hz	*Radar uses an ultrasonic sensor of 10 Hz*	*IMU Sensor*	*OV7670 camera*	*Speed Sensor*
1	66 bytes	20 bytes	2,76 kb	3,84 Mb	3 kb
60	3,9 kb	1,2 kb	165, 6 kb	230,4 Mb	180 kb

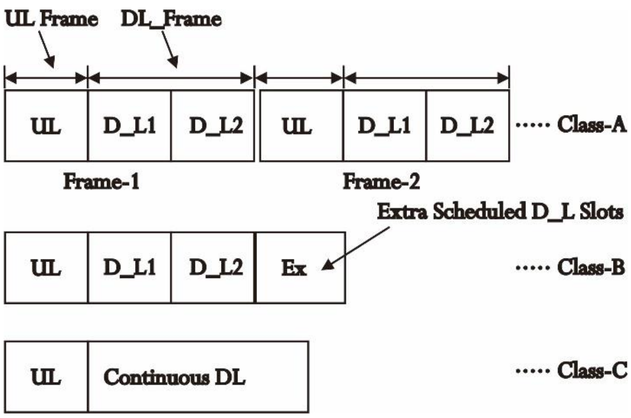

Figure 1. Classes in LoRaWAN

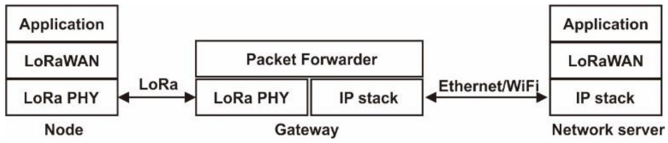

Figure 2. LoRaWAN Communication Stack

Figure 2 shows a communication system consisting of a Node, Gateway, and Network Server, on the Node side there is Application, LoRaWAN, and LoRa PHY, on the Gateway side, including Packet Forwarder, LoRa PHY, an IP stack, and from Node and Gateway this communicates using LoRa, then on the Network server side, consisting of Application Server, LoRaWAN, and IP Stack, which communicates with Ethernet or WiFi. Moreover, LoRa is included in one type of Low Power Wide Area (LPWA) networking Protocol devices besides Sigfox and NB-IoT. LoRa was developed in the LPWAN-based Internet of Things communication system called LoRaWAN. There is a modulation system on LoRa called GFSK and Chirped-FM-based LoRa modulation. This development was done by Semtech Corporation. The typical bandwidths are 125 kHz, 250 kHz, and 500 kHz, which are comprehensively explained in this manuscript, and the resulting example signals. Karakteristik dari LoRa technology is a low data rate, low cost, long battery life, and long-range communication. **Figure 3** is a LoRa Uplink and Downlink PHY Structure

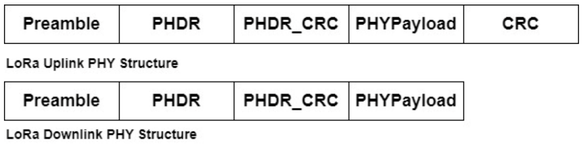

Figure 3. LoRa Uplink and Downlink PHY Structure

Some methods or algorithms, and data communication designs on Autonomous Vehicles developed from previous research can be seen in Algorithm 1 and Algorithm 2, in Algorithm 1 is a LoRaWAN data communication system from one car to another car that moves together, while Algorithm 2 is a LoRa data communication system on the car to the LoRa Gateway. Equations 1, 2, 3, and 4 are the basic formulas of essential LoRa communication, to calculate the data bit-rate, sensitivity of LoRa, and Packet data received, to determine the quality of the data transmission process of LoRa Communication. Equation 1 shows in detail the data that will be processed during communication, and this bit-rate can be obtained theoretically like Equation 1 and also tested in the field [20], [36]–[40]).

$$Rb_{car} = \frac{\frac{4}{4+CR}}{\frac{2^{SF}\ car}{BW}} 1000 \tag{1}$$

$$S = -174 + 10\ Log_{10}BW + NF + SNR \tag{2}$$

$$P_{rx_{car}}(dBm) = P_{rx_{car}}(dBm) + G_{car_{system}}(dB) - L_{car_{system}}(dB) - L_{car_{Channel}}(dB) - M(dB) \tag{3}$$

$$P_{rx_{car}}(dBm) = P_{rx_{car}}(dBm) + S_{car}(dBm) \tag{4}$$

Algorithm 1 *ADR_Node_on_CAR [Mobility Node]*

1. *ADR_CAR_ACK_LIMIT* ← *64* [Depend with SF Value or CAR Position]
2. *ADR_CAR_ACK_DELAY* ← *32* [Depend with SF Value or CAR Position]
3. *ADR_CAR_ACK_CNT* ← *0* [Depend with SF Value or CAR Position]
4. **If** *uplink transmission,* **then**
5. *ADR_CAR_ACK_CNT* ← *ADR_CAR_ACK_CNT* +1
6. **If** *ADR_CAR_ACK_CNT* == *ADR_CAR_ACK_LIMIT* **then**
7. **Request response from network server** [27, 28]
8. **if** *ADR_CAR_ACK_CNT* ≥ *ADR_CAR_ACK_LIMIT* + *ADR_CAR_ACK_DELAY* **then**
9. increase SF [Car moves at a point away from GW]
10. if downlink transmission is received then
11. ADR_ACK_CNT ← 0

Algorithm 2 *ADR_on GW*

1. *SNRm* ← *max* (SNR of last 20 frames)

2. *SNRreq* ← demodulation floor (current data rate)
3. *deviceMargin* ← 10
4. *SNRmargin* ← (SNRm – SNRreq - deviceMargin)
5. *steps* ← *floor* (SNRmargin / 3)
6. **while** steps > 0 **and SF** > SFmin **do**
7. *SF* ← *SF* – 1 [Movement of End Node or Car Position]
8. *steps* ← *steps* -1
9. **while** steps > 0 **and** TP > TP min **do**
10. *TP* ← *TP* – 3
11. *steps* ← *steps* – 1
12. **while** steps < 0 **and** TP < TP max **do**
13. *TP* ← *TP* + 3
14. *steps* ← *steps* + 1
15. **end**

Details can be seen in **Figure 1**, **Figure 2**, and **Figure 3**. **Figure 1** is a communication system between cars that uses different SFs because the SF position of Car 1, 2, and so on is different from GW LoRa resulting in different data rates (bps). **Figure 2** is a LoRa communication car uplink and downlink system 1, 2, and so on, and **Figure 3** is a Data Switching System on LoRa Car 1, 2, and so on based on the distance of the car and the nearest GW, in other words, the car data transfer automatically.

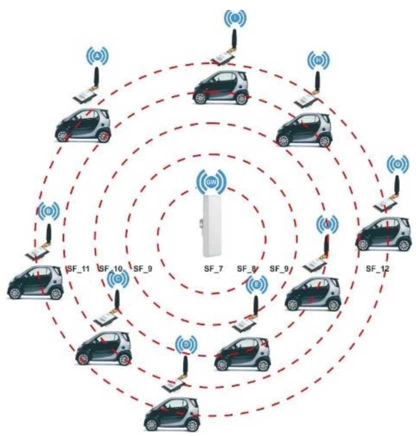

Figure 4. The communication system between cars uses different SFs because the SF position of Car 1, 2, and so on is different from GW LoRa resulting in different data rates (bps).

Furthermore, in general, the method starts from the conditions in **Figure 4**, the car that is between the Gateway is distinguished by its position and SF settings, there are SF7, SF8, SF9, SF10, SF11, and SF12. From each different SF, it produces different performance in transmitting data, in this case the GPS data sent, in the SF7 position the resulting bit-rate is greater than SF12 (kbps). However, the system to be built will maintain that the bit-rate must remain maximum in these different positions. So there is a method described as **Figure 5** and especially clear auto handover as in **Figure 5**. The results of this condition can be seen in **Figure 23** to **Figure 26**. In the simulation results there is a regular movement in the car, and random and random movements, we can see the right Gateway and SF retrieval, this is the pattern of the LoRaWAN Handover Gateway to ensure that the data bit-rate from the GPS Module can be sent properly and avoid large packet loss.

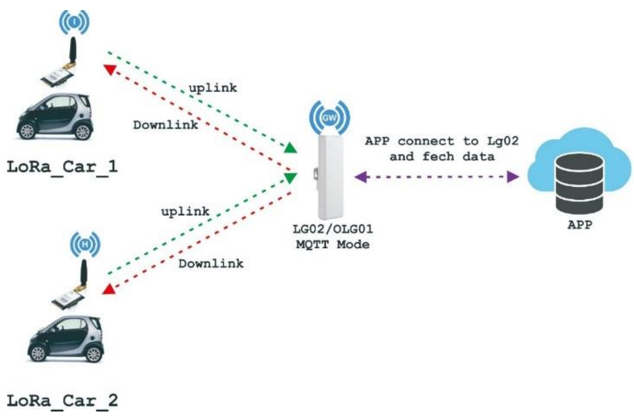

Figure 5. LoRa communication car uplink and downlink systems 1, 2, and so on

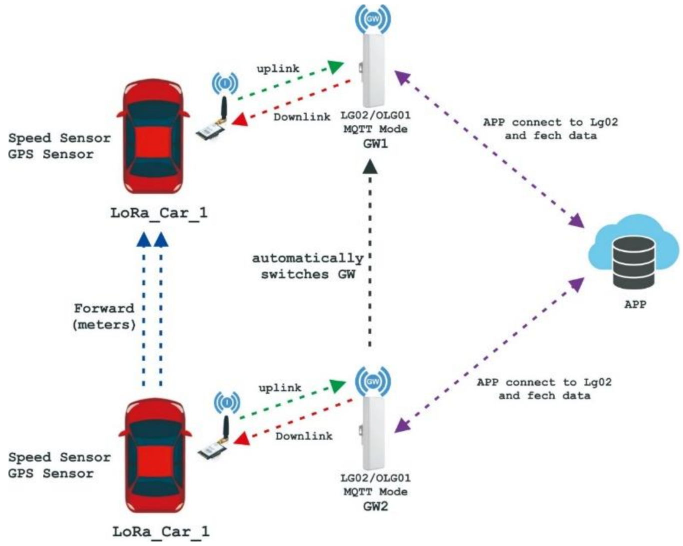

Figure 6. Data Switching System on LoRa Car 1, 2, and so on based on the distance of the car and the nearest GW, in other words, the car data transfer automatically

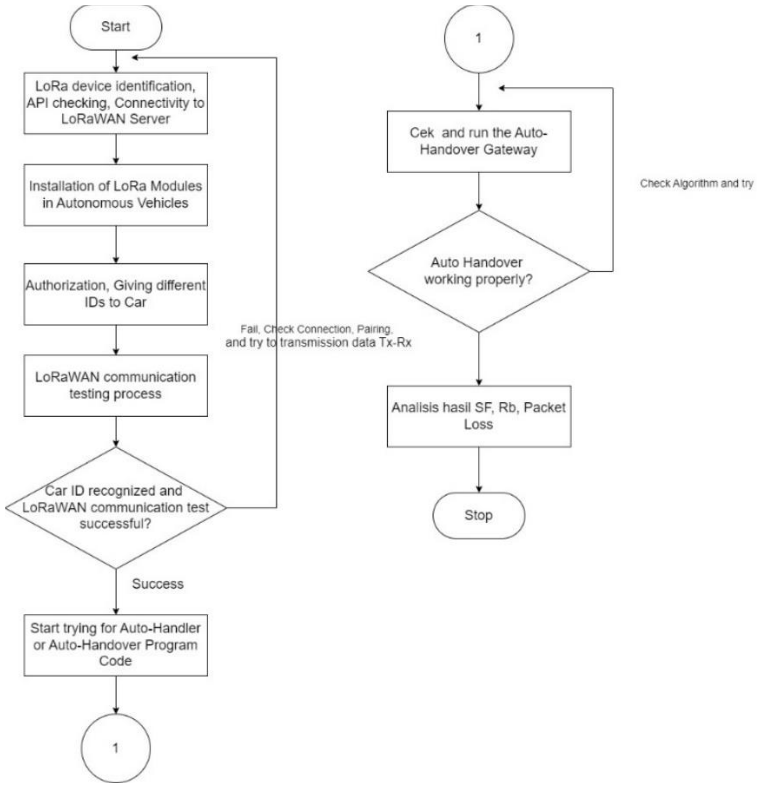

Figure 7. Flowchart system in this research

Results and Discussion

In building a LoRaWAN communication system in intelligent autonomous vehicles, improvements are needed on various sides, including algorithms that can be developed such as the Auto-Handover Gateway LoRaWAN that can be applied, this research discusses only on the simulation side and does not rule out the possibility of being developed into practice in the field directly. So in this result and discussion I started with how LoRaWAN works starting from its modulation. That is Chirp Spread Spectrum (CSS). This modulation is like FSK which works in conditions that if it is close to the object then the high frequency or signal will be docked, otherwise if it is at a distance away from the object then the resulting wave is also a little wide or not docked as in the radar work system. so that in LoRa it is known as Up chirp and Down Chirp, which is a condition where if Up then the frequency rises and the signal is docked, while if Down chirp the signal weakens or widens. Can be seen in the analysis mentioned in **Figure 8**, **9**, and so on. **Figure 7** shows a detailed overview of the system built in this research.

A. Chirp Spread Spectrum (CSS) with different Bandwidth

In terms of signals, autonomous vehicle communication can use several bandwidths such as 125 kHz, 250 kHz, and 500 kHz, with the forms of Chirp signals can be seen in the following CSS image series. Which is seen in **Figure 8, Figure 9**, **Figure 10**, **Figure 11**, **Figure 12**, and **Figure 13**. This chirp on the autonomous vehicle is to show the pattern or reaction of the transmission process, whether it is close to the Gateway or far away, the closer the vehicle position means that it is closer to the Gateway and Automatic Handover will work if the SF used is still SF10, then immediately change to SF7.

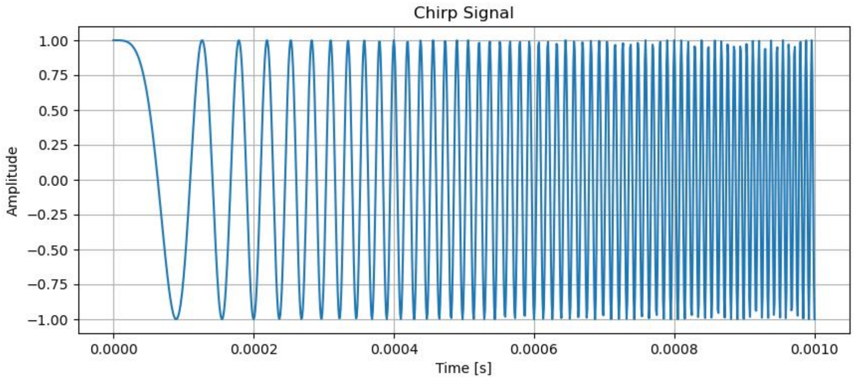

Figure 8. Chirps Spread Spectrum (CSS) of LoRa 125 kHz BW

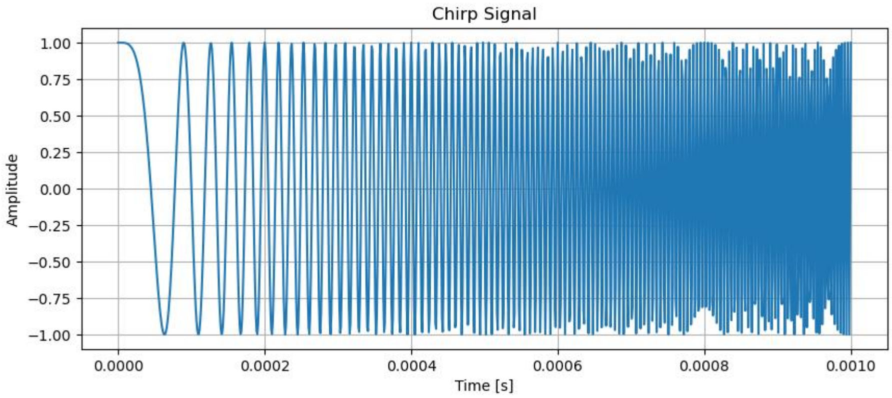

Figure 9. Chirps Spread Spectrum (CSS) of LoRa 250 kHz BW

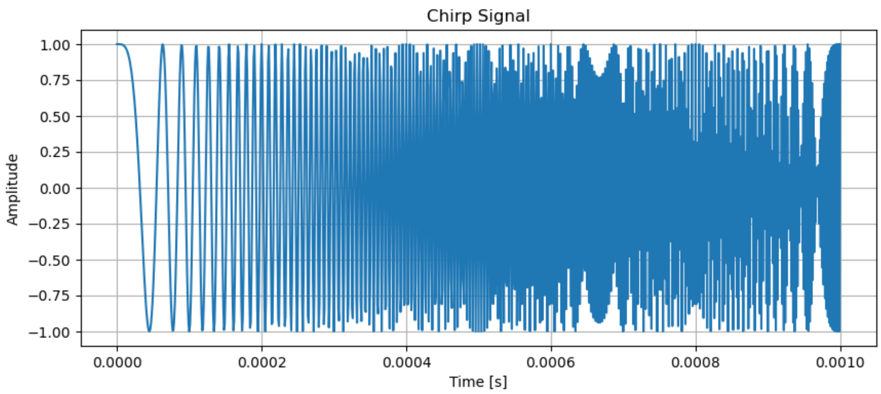

Figure 10. Chirps Spread Spectrum (CSS) of LoRa 500 kHz BW

Furthermore, the signal demodulation process according to the different LoRa Bandwidth Frequencies can be seen in the following Signal.

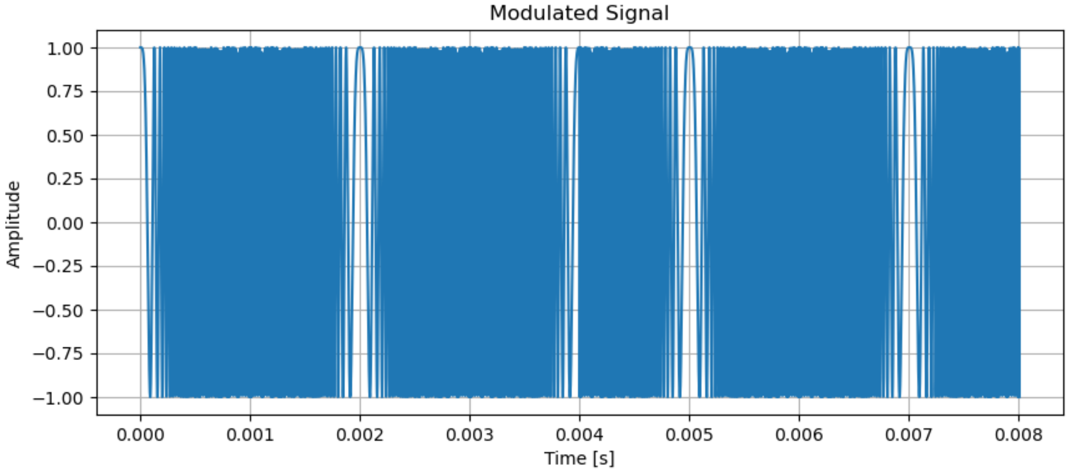

Figure 11. Modulated Chirps Spread Spectrum (CSS) signal of LoRa 125 kHz BW

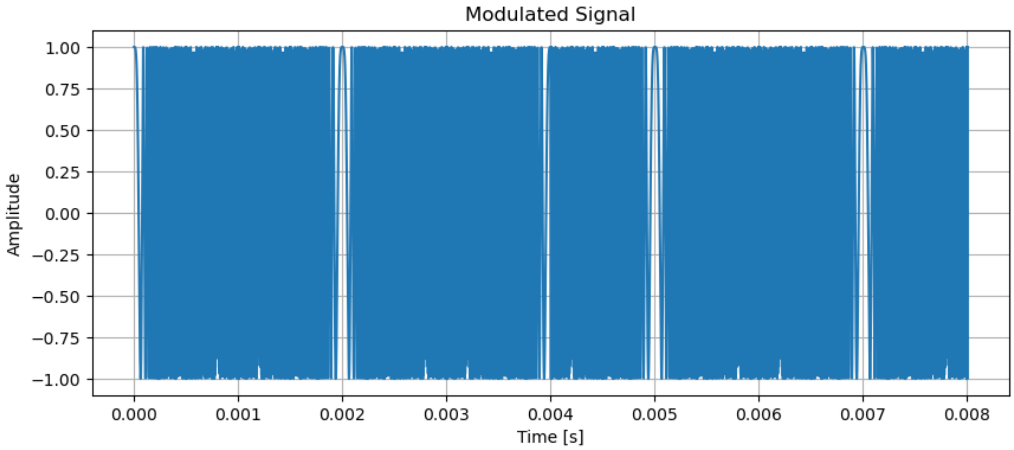

Figure 12. Modulated Chirps Spread Spectrum (CSS) signal of LoRa 250 kHz BW

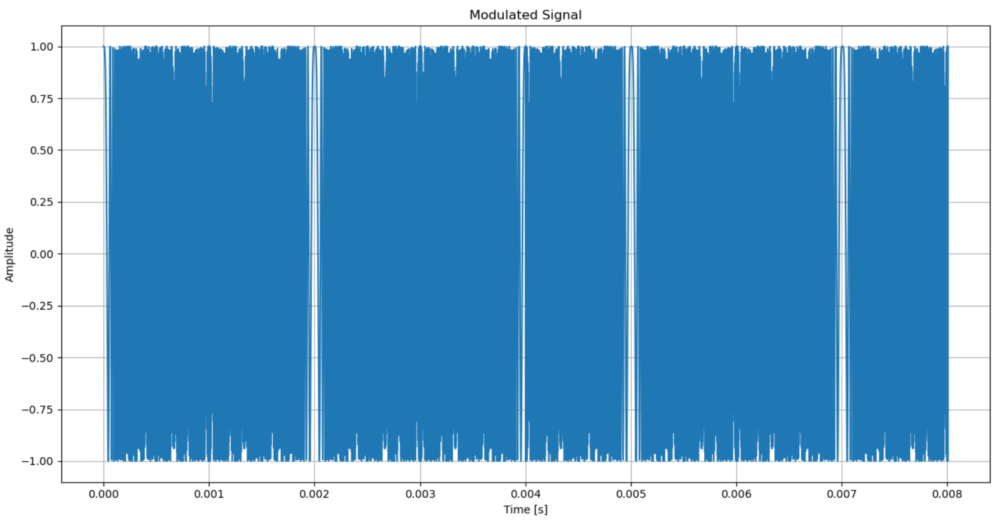

Figure 13. Modulated Chirps Spread Spectrum (CSS) signal of LoRa 500 kHz BW

Furthermore, with different bandwidths producing different received bits, at 125 kHz, 250 kHz, and 500 kHz the Modulated signal results in Received same Bits: [0, 1, 0, 1, 1, 0, 1, 0], which is shown in Figure 13.

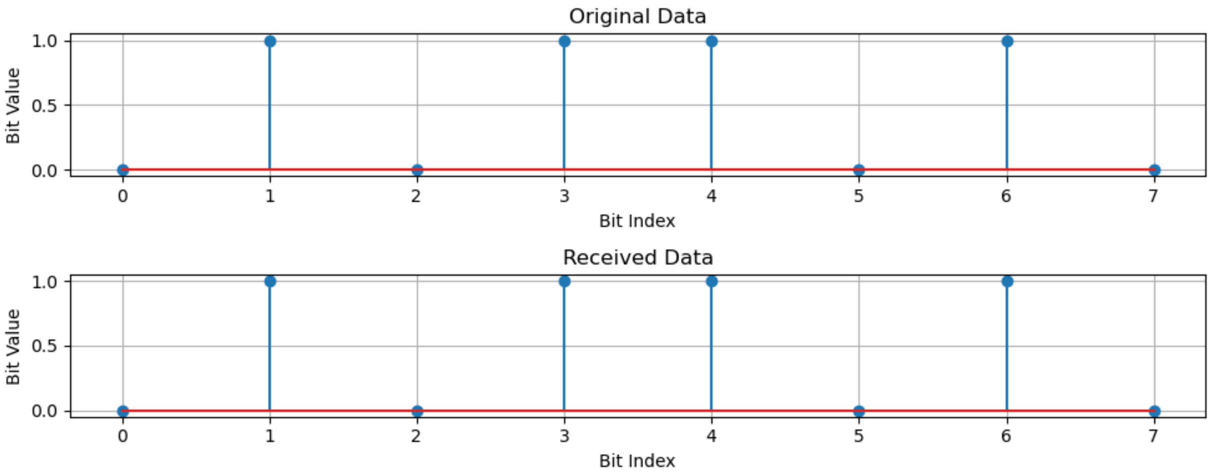

Figure 14. Original Data and Received Data of Chirps Spread Spectrum (CSS) signal of LoRa 125, 250, and 500 kHz BW

B. Data Rate (kbps), Power Output, LoRa Bandwidth, and ADR and Car Prototype

Some analysis results can refer to the LoRa communication system that looks at many sides, including Comparison of Data Rate (kbps), Power Output, LoRa Bandwidth, Static ADR, network-controlled ADR, Device Controlled ADR, Hybrid ADR, and Event-Driven ADR comparison with Data Rate (kbps) and Power Output (dBm), and data collisions that can be seen from a simulation using Python and MATLAB. Moreover, **Figure 17** is a LoRaWAN Nodes example. For autonomous vehicles can be seen in **Figure 14**, while **Figure 15** is a Comparison of Data Rate (kbps), Power Output, and LoRa Bandwidth. Moreover, **Figure 16** is a Static ADR, Network Server Controlled ADR, Device Controlled ADR, Hybrid ADR, and Event-Driven ADR comparison with Data Rate (kbps) and Power Output (dBm). Figure 21 is a example of LoRa signal below the noise floor.

Figure 15. Prototype Autonomous Vehicle with LoRa module device in the future

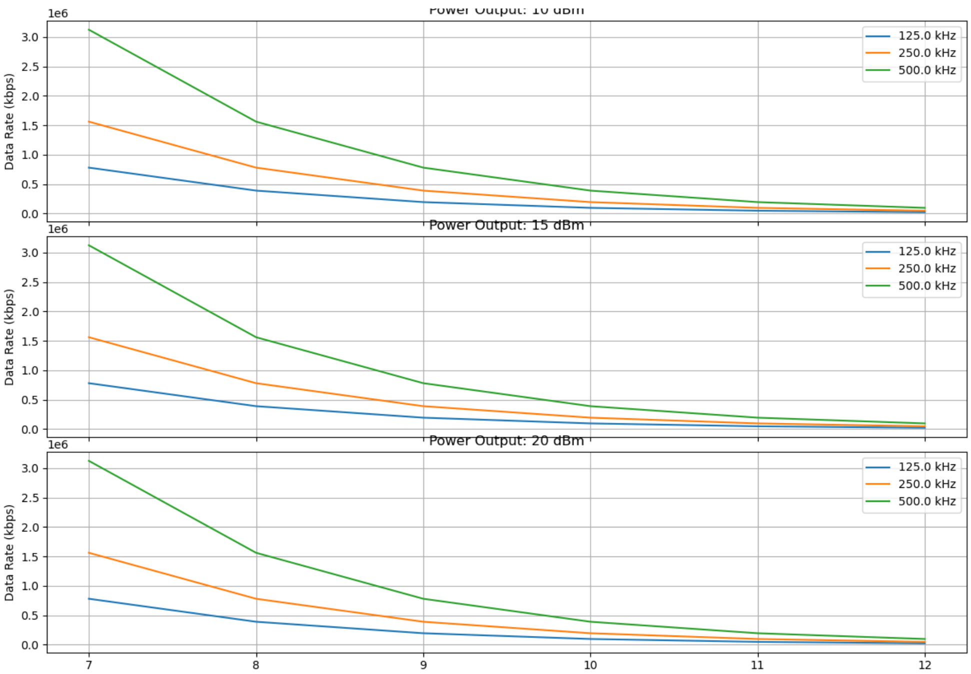

Figure 16. Comparison of Data Rate (kbps), Power Output, and LoRa Bandwidth

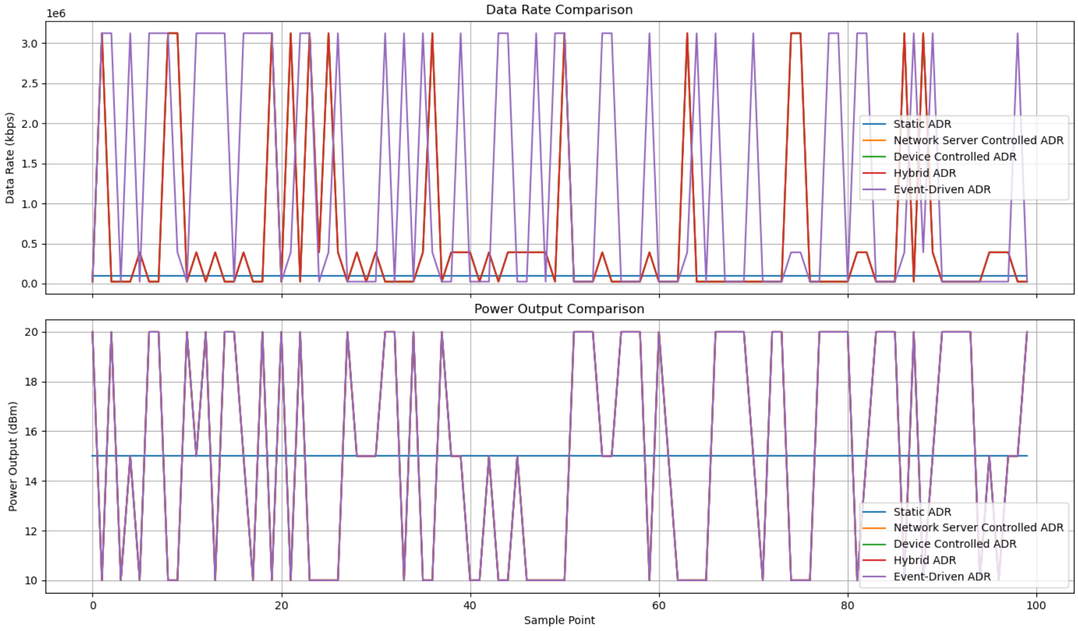

Figure 17. Static ADR, Network Server Controlled ADR, Device Controlled ADR, Hybrid ADR, and Event-Driven ADR comparison with Data Rate (kbps) and Power Output (dBm)

Figure 18. LoRaWAN Nodes example

C. Collision LoRa Data Analyzes

In this section, we will comprehensively analyze the LoRa collision with the essential parameters of LoRa, namely Spreading Factor, and Packet Error Rate (%) caused by LoRa data collision on the car. In this research, the analysis is carried out by looking at collision data comprehensively from SF 7, SF 8, SF 9, SF 10, SF 11, and SF 12.

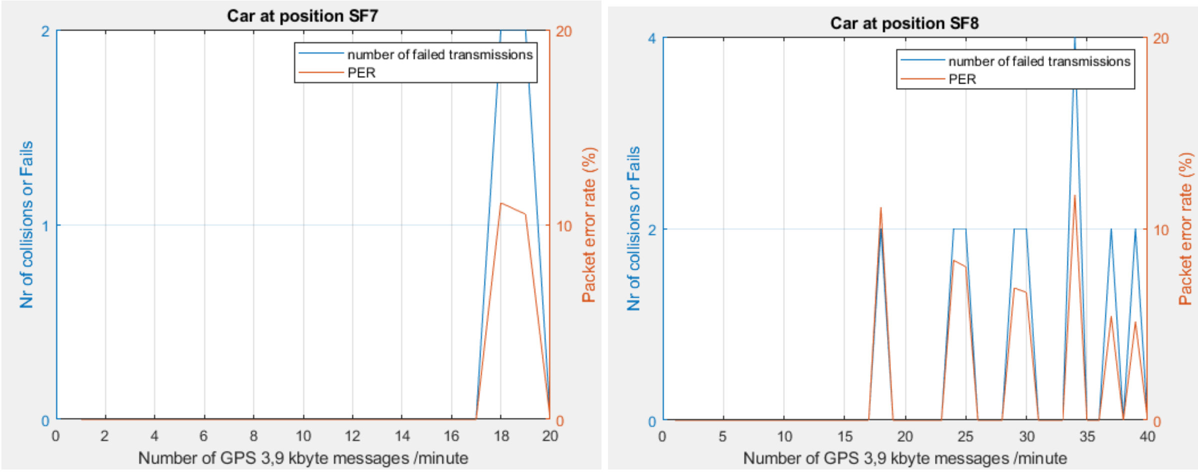

Figure 19. Collision Prediction of Car in different SF (SF7 and SF8)

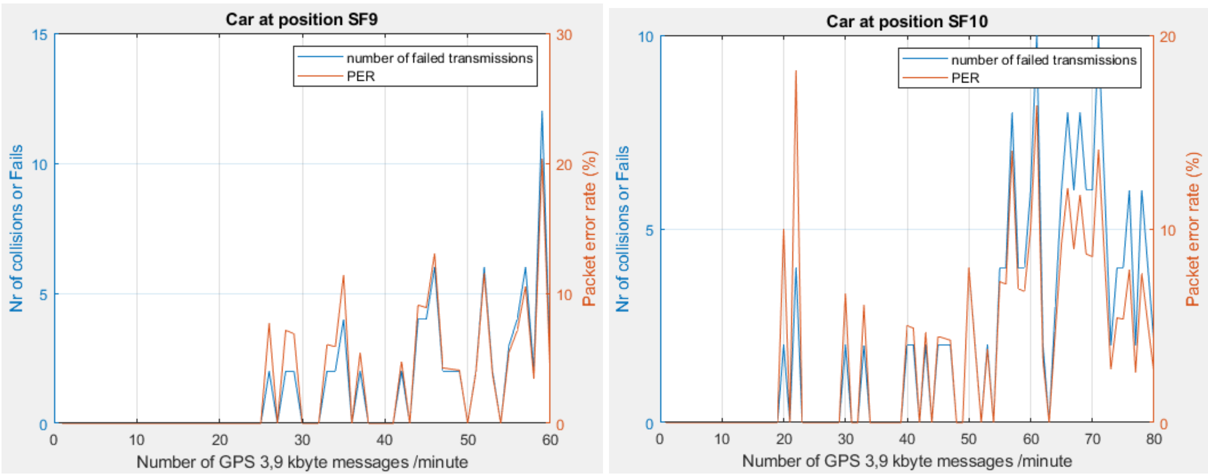

Figure 20. Collision Prediction of Car in different SF (SF9 and SF10)

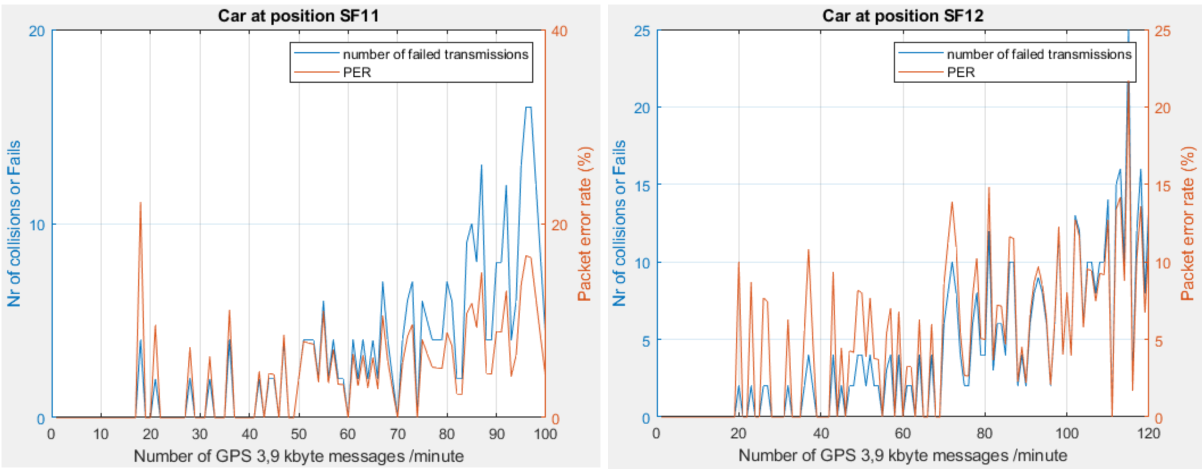

Figure 21. Collision Prediction of Car in different SF (SF11 and SF12)

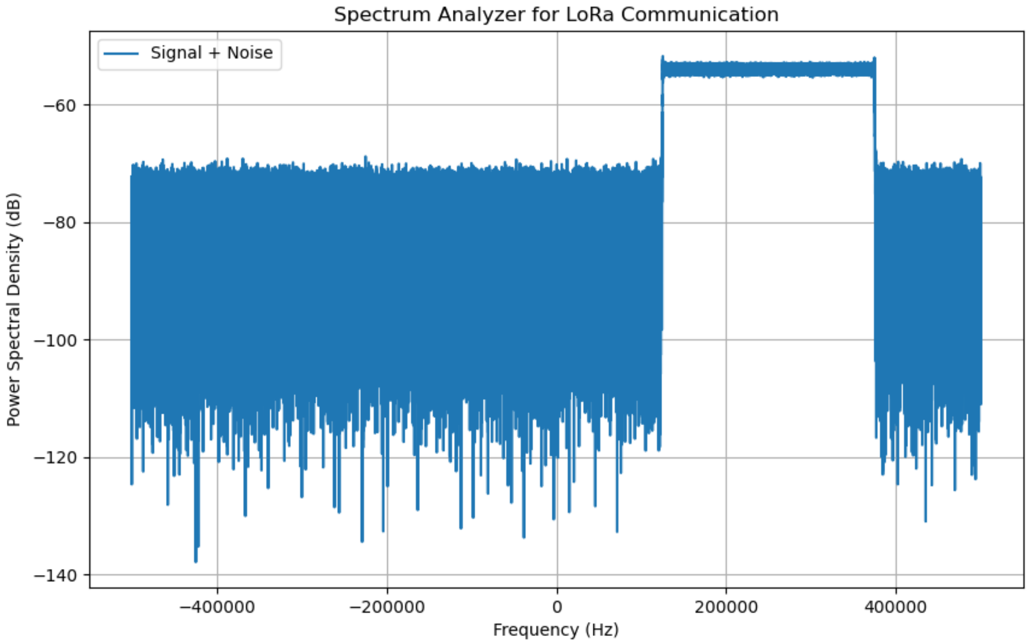

Figure 22. example of LoRa signal below the noise floor

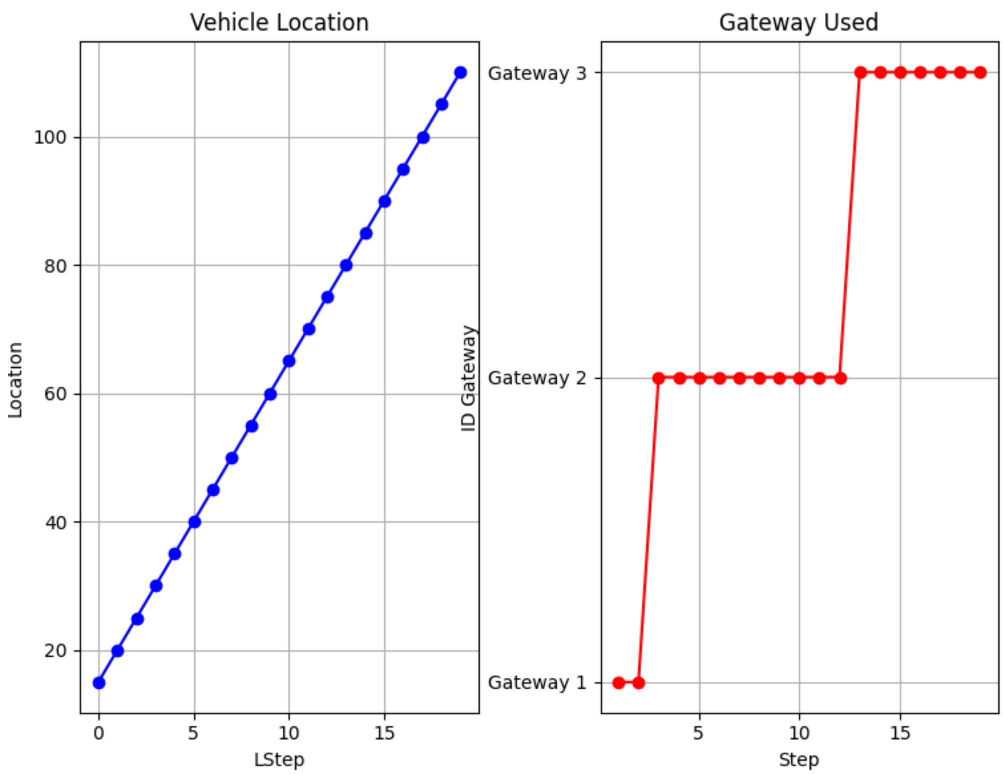

Figure 23. Gateway LoRaWAN Auto Handover

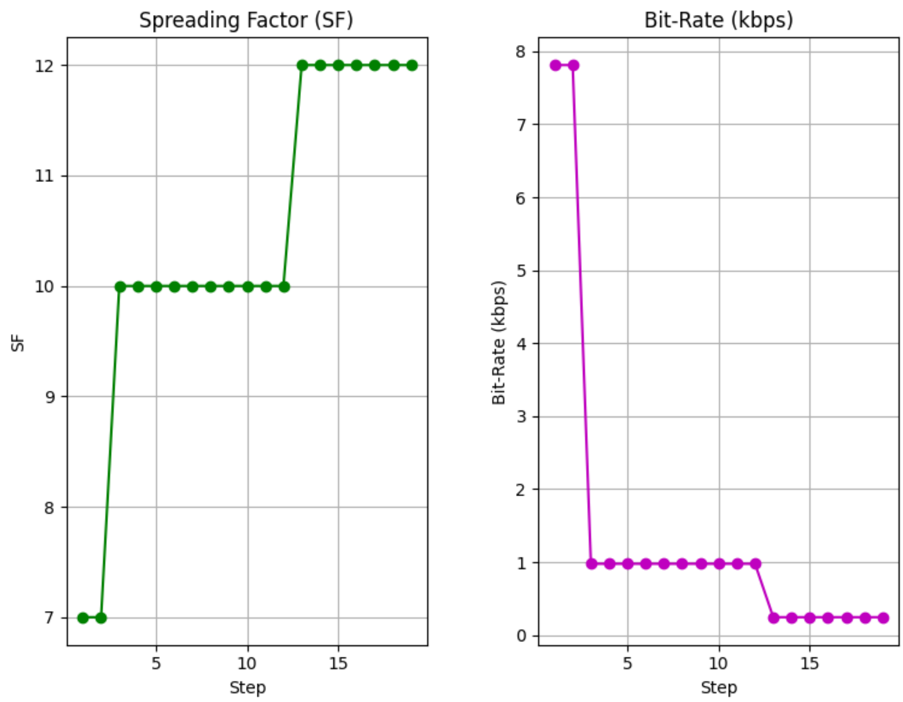

Figure 24. SF and Bit-Rate parameter conditions on GW LoRaWAN Auto Handover

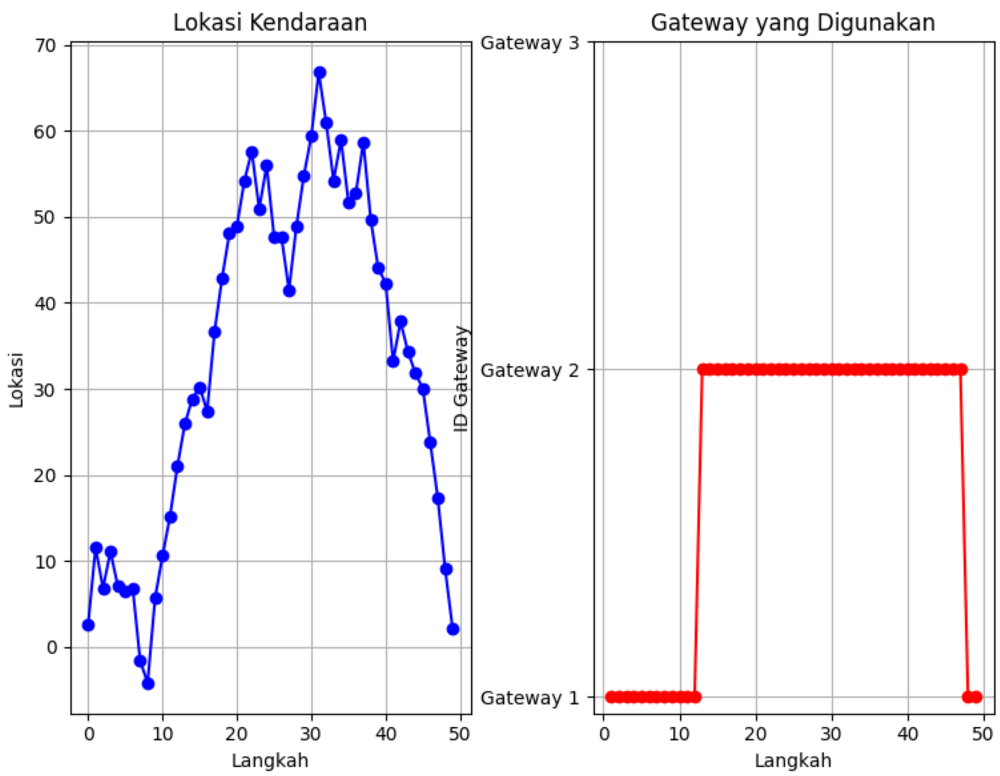

Figure 25. Gateway LoRaWAN Auto Handover on more random and dynamic car conditions

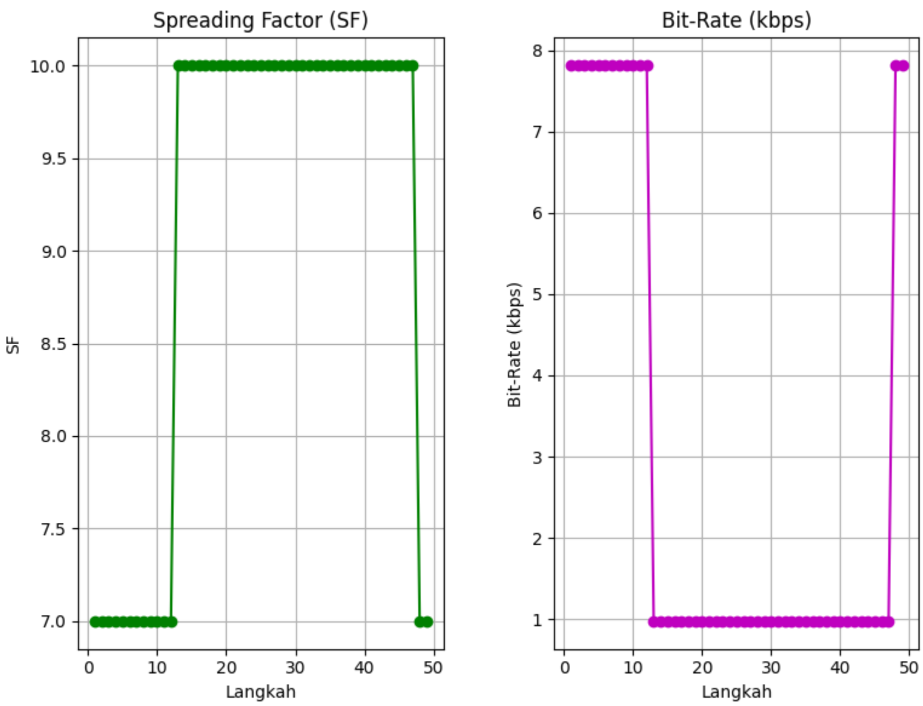

Figure 26. Gateway LoRaWAN Auto Handover on more random and dynamic car conditions

We also describe in detail the future challenges that will be faced if LoRaWAN is applied to intelligent vehicles, which until now have been working in a limited environment, in the end we will also approach the future environment if it is applied to rural and urban areas as shown in **Table 6**.

Table 6. Challenges of applying LoRaWAN to autonomous vehicles in rural and urban areas

Challenge	Rural	Urban
LoRaWAN Network	- The gateway coverage is greater due to the large area and lack of interference.	- The gateway range is shorter due to the presence of many buildings and signal interference.
Gateway Availability	- The number of gateways may be limited, resulting in more frequent handovers.	- The number of gateways is usually greater, reducing handover frequency but increasing the risk of interference.
Signal Interference	- Low signal interference due to open area.	- The signal interference level is higher due to many interference sources such as electronic devices and buildings.
Vehicle Density	- Vehicle density is usually low, so lane management is simpler.	- Vehicle density is high, requiring complex and fast lane management systems.
GPS Quality	- GPS quality is generally good with little reflection and multipath.	- GPS quality can be affected by multipath and reflections from tall buildings and other urban structures.
Energy Availability	- The availability of energy resources may be better and more stable in more open areas.	- Energy availability may be interrupted due to the large number of energy-using devices and infrastructure.
Data Capacity	- LoRaWAN's data capacity is sufficient for applications with low to medium data transmission.	- Data capacity should be well considered due to the high data potential in urban areas.
Network Speed and Latency	- Network latency is usually low due to lack of traffic.	- Latency can be high due to traffic density and possible signal conflicts.
Bandwidth Requirement	- Bandwidth is usually sufficient for autonomous vehicle applications with low data transmission.	- Bandwidth requirements can be high if the application requires real-time transmission of large data.

Challenge	Rural	Urban
Resource Management	- Resource management is simpler due to less complex environmental factors.	- Resource management must be more careful due to the many sources of interference and higher network load.
Signal Quality	- Signal quality is usually more stable due to the lack of physical obstructions.	- Signal quality may fluctuate due to physical obstructions such as tall buildings and other structures.
Security	- Network security may be less prominent because the physical risk is lower.	- Security is an important concern as the potential risk of hacking and cyberattacks is higher in crowded environments.
Adaptation to Environmental Change	- A stable environment allows for slower network adjustments.	- Dynamic environments require rapid network adaptation and responsiveness to changing conditions.
Installation and Maintenance Costs	- Costs may be lower due to the need for less dense infrastructure.	- Costs can be higher due to more complex infrastructure requirements and frequent maintenance.

Conclusion

From the simulation results, transmitting LoRa data using Mobile Node or Car which is more flexible in terms of data rate (bytes), and with sample data from GPS of 3.9 kbytes, different estimated data collisions are obtained, the greater the Spreading Factor (SF), the greater the N of Collisions of Fails although the value is not significant. One of the strategies to improve the Quality of Service (QoS) of LoRa placed on Car, is to automatically change the SF side to change automatically so that the resulting data rate is greater, reducing or even eliminating packet loss (%). This research continues to be developed by placing the LoRa module on a moving car and placing the LoRaWAN Gateway on the roadside, so that the car will automatically switch to the next Gateway according to the closest one to the car. One of the characteristics of LoRa modulation is that the LoRa signal condition is below the noise floor.In the end, in conducting research and applying LoRaWAN to autonomous vehicles, seeing from various sides of its advantages and weaknesses and its prospects in the future, that LoRa is an LPWAN device that is easy to apply and build but is also very weak in terms of latency which is still high and also a small bit-rate or data-rate, so it needs to be improved by utilizing algorithms that can help in sending larger data later. And in terms of range, LoRaWAN is very powerful, able to reach very long distances, >15 km in Line of Sight (LoS) conditions and also supported by Antennas that have high Gain (dB)**,** also other parameters that support LoRa data transmission**.** In other cases, such as Automatic Handover needs to maximize its performance, in this research it is still in simulation but needs to be improved more comprehensively, and applied to autonomous vehicles. The strategy is to place autonomous vehicles according to the ID that has been set and if the vehicle approaches a certain gateway, it immediately changes the SF, so that it will maintain the bit-rate value, and also minimize packet loss (kbps).

In the future, this technology needs to add gateways at various corners of the city, where smart cities will be built, and specialized for intelligent vehicles. Automatically the infrastructure will be improved and upgraded more appropriately for these autonomous vehicles to run. For now, we can start with a narrow and limited scope.

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