UNIVERSIDAD DE VALLADOLID

ESCUELA DE INGENIERIAS INDUSTRIALES

Máster en Ingeniería Industrial

Cooperative transport communication in AGV groups using Omni-Curve Parameters

Autor:
Quevedo Martínez, Miguel

Responsable de Intercambio en la Uva:
Rogelio Mazaeda Echevarría

Universidad de destino:
Universität Stuttgart

Valladolid, septiembre de 2023.

TFM REALIZADO EN PROGRAMA DE INTERCAMBIO

TÍTULO:	Cooperative transport communication in AGV groups using Omni-Curve Parameters
ALUMNO:	Miguel Quevedo Martínez
FECHA:	23 de agosto de 2023
CENTRO:	Institut für Fördertechnik und Logistik (IFT)
UNIVERSIDAD:	Universität Stuttgart
TUTOR:	Carolin Brenner

Institut für Fördertechnik und Logistik (IFT)

Masterarbeit

Cooperative transport communication in AGV groups using Omni-Curve Parameters

Miguel Quevedo Martínez

Course of Study:	Maschinenbau
Examiner:	Prof. Dr. Robert Schulz
Supervisor:	Carolin Brenner, M.Sc.
Commenced:	March 6, 2023
Completed:	August 22, 2023

Abstract

The concept of Omni-Curve Parameters (OCPs) is used in the context of Automated Guided Vehicles (AGVs). It allows a group of vehicles to move as if they were one and, for example, carry a load together (cooperative transport). Its aim is to be universal, which means that any vehicle could use it regardless of their chassis configuration or number of wheels. To achieve this, the concept calculates the direction and speed of each wheel knowing their constant relative position in the group and the planned trajectory. For each instant of the trajectory, there can be different values for the OCPs, which are three: floating angle, nominal velocity and nominal curvature.

This work focuses on discerning how best to ensure that the AGVs update the values of the OCPs. First, some communication technologies are studied and compared. Robustness and low latency are some of the most desired features. Then, the most appealing ones are used to build a communication system capable of sending and receiving this parameters, as well as some concepts are developed to optimize the information flow of the OCPs through the group. Finally, technologies are compared and tested and conclusions are drawn.

Key words

AGVs, cooperative transport, Omni-Curve Parameters, communication systems.

Contents

List of Figures

List of Tables

1 Introduction

1.1 State of the Art

This work is based on a concept for an intuitive control of omnidirectional industrial trucks with any wheel configuration developed by André Colomb and Carolin Brenner at the IFT [BC22; CB20]. Currently, the AGV groups that operate with this concept perform smooth and accurately, as if they were a unit. However, every information exchange is made through a wire between AGVs, which impedes the goal of having a flexible and autonomous system.

1.1.1 Similar approaches

Some approaches use cooperative transport with AGVs as a way to carry heavy loads . They explore the way the load is attached to the vehicles [HL19; SG04] or use other approaches for the mechanical concept [FWH+22; RLS20].

These examples consist of cooperative AGVs systems which are conceived to work that way and for an specific task. However, the aim of the OCP concept is to be universal and to be used in any kind of vehicle, regardless the chassis configuration, number of wheels, size...

1.1.2 Centralized or decentralized?

This is one of the first questions that come to mind when thinking about designing a communication system. Centralized ones offer the advantage of streamlined coordination and decision-making, which can be better in scenarios with a limited number of vehicles and well-defined tasks. However, they are susceptible to bottlenecks, communication failures, and reduced adaptability to dynamic changes. It would consist of a central control or coordinator sending information to all the vehicles, whereas a decentralized system would not require to communicate to all of them, but there should always be a central device communicating with at least one vehicle. Of course, there is an infinite amount of possibilities in between this and centralized. For example, communication can happen just between some specific vehicles and the central device and the rest would get the trajectory information in other way such as secondary communication from the vehicles that already have the information or through distance controlling.

1.2 Objetives

This work aims to conceive, design and build a small distance communication system for groups of AGVs with different chassis configurations working cooperatively using the OCP parameters. To achieve this, theory of AGVs steering and motion and the OCP concept are first studied. Then the different types of communication technology available for industrial robots are studied and compared. Afterwards, the most suitable types of communication are chosen, built and tested. Finally, conclusions are drawn on the work as a whole.

2 Omni-Curve Parameters

In this chapter, the Omni-Curve Parameters (OCP) concept is summarised. This concept is a method of defining the movement of vehicles with intuitive Parameters that is valid for any type of chasis and number of wheels, and also has low computational effort and is free of singularities at any driving situation. Once the movement is as independent as possible from vehicle geometry and performance, it is possible to group different vehicles together to act as a single one with as many wheels as the sum of the wheels of the vehicles making up the group.

The three Omni-Curve Parameters are called:

- β: floating angle,
- v_n: nominal specific velocity and
- κ_n: nominal curvature.

It works this way: the vehicles, knowing already their relative position (or more specifically, their wheels relative position) in the formation, just need the input of these three parameters to calculate the direction and velocity of each wheel. This means that the OCP are the same for every element in the formation, and the output just depends on their relative position. The necessary concepts to understand the meaning of the OCP and how they are obtained are explained below.

2.1 Kinematics

To begin with, it is assumed that the movement takes place on a plane, and this leaves three degrees of freedom of movement: two translational and one directional. Then, the motion can be expressed by a movement vector whose components are v_x (forward direction), v_y (lateral direction, orthogonal to v_x) and ω (rotation around z axis). This vector starts from the reference point of the vehicle, which is called K. These are depicted in Figure 2.1.

Translational components form the instantaneous velocity vector $\overrightarrow{v}$ would be the exact derivative of the x and y absolute position components (with respect to K), while rotational velocity is the derivative of the orientation, ψ (between the space and the coordinate system attached to the vehicle). **Floating angle** β is the angle between the forward direction axis x and instantaneous velocity vector $\overrightarrow{v}$.

Velocities v_x, v_y and ω can always be calculated, regardless of different number and type of wheels depending on the chasis configuration. However, the degrees of freedom of the vehicles can be reduced when there are kinematic constraints in the chasis (bounded system). The most extreme example would be a vehicle on rails, which would only have one degree of freedom.

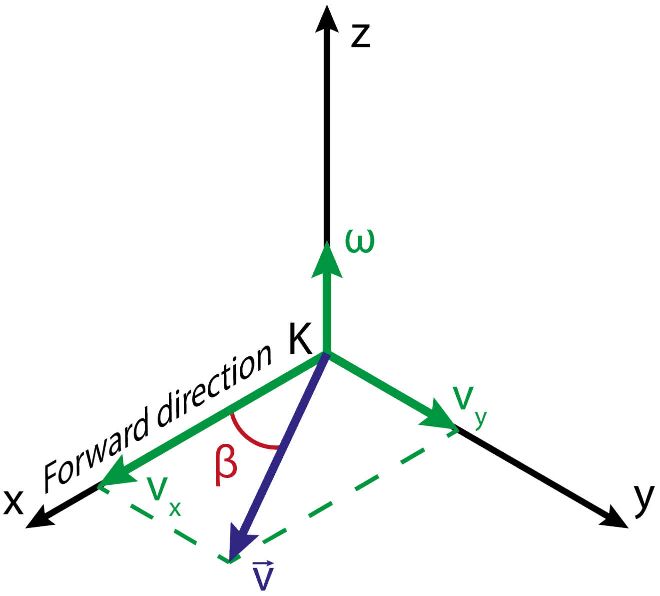


Figure 2.1: Coordinate system relative to vehicle xyz, reference point K, velocities v_z, v_y and $\overrightarrow{v}$ and floating angle β.

In a wheels, there is a dependence betweent the geometric alignment and the direction of the velocity vector that implies a non-holonomic constraint. A system is holonomic when the number of controllable degrees of freedom is equal to the total degrees of freedom. This can be expressed as: $f(q_1, ..., q_n, \dot{q}_1, ..., \dot{q}_n) = 0$, which means that all the constraints are integrable in the positional constraints.

Due to the complexity of the contact between the wheel and the floor, all slippage is assumed to not exist in the model (in the direction of velocity and in its ortogonal direction). In practice, slippage does occur, specially when turning. This is a problem to be solved later.

2.2 Types of movement

It is necessary to previously describe the possibilities of movement depending on the type of chasis in order to understand the other two Omni-Curve Parameters: V_n and κ_n. There are two kind of vehicles according to their behaviour:

- Line-mobile vehicles, with two degrees of freedom. They are able to follow any curvilinear trajectory but the direction of movement is restricted to this direction by the chasis arrangement of the vehicle. This means there is a constraint due to the dependency between the orientation ψ and the direction of the velocity vector.
- Surface-mobile or omnidirectional vehicles, with three degrees of freedom. They can occur in several ways, differing by their non-holonomic constraints:

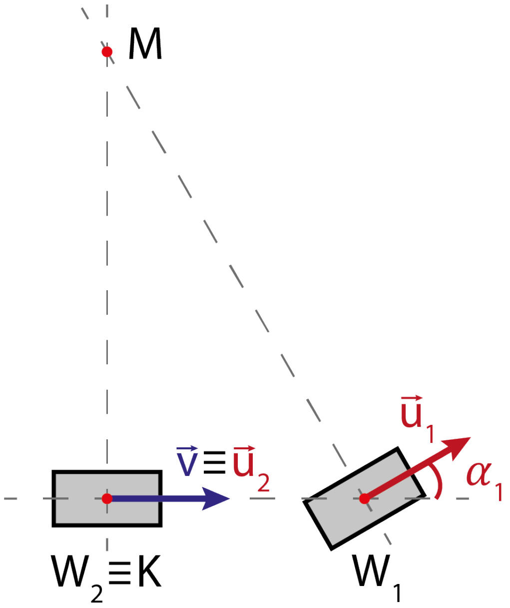


Figure 2.2: Single-track chasis turning left around instant pole M.

- Level 1: quasi-omnidirectional, if the orientation of the vehicle can be adjusted independently of its position. All the deegrees of freedom are possible from a standstill, but may require a reconfiguration of the chasis beforehand. Having one or more steering angles connected and this momentarily restricted movement make a non-holonomic constraint.
- Level 2: fully omnidirectional. Every component in the velocity vector can be dictly influenced at any time from a standstill without reconfiguration of the chasis in each degree of freedom. This makes an overall holonomic kinematic system.

2.3 Typical chasis

In practice, the following are the most typical chasis in industrial trucks.

Single-track chasis. This is the most common kind of chasis, not only in industrial vehicle. As this is a widely used system, it is quite intuitive and familiar. It consists of a rigid wheel W_2 at one end and a steering wheel W_1 that steers around on the rolling direction of W_2. Each W can represent several wheels whose pole beams M can be equivalently transformed. The reference point will always be on the axis of W_2, but when there is no rotation, the point goes to infinity. All these make this kind of chasis in a line-movable, tuned vehicle with two degrees of freedom and two control variables. The steering angle α_1 represents the internal configuration and does not influence the speed whem stationary, but only the possible direction of the velocity vector $\overrightarrow{v}$ (non-holonomic constraint). The second control variable scales the vector and thus the speed of the movement.

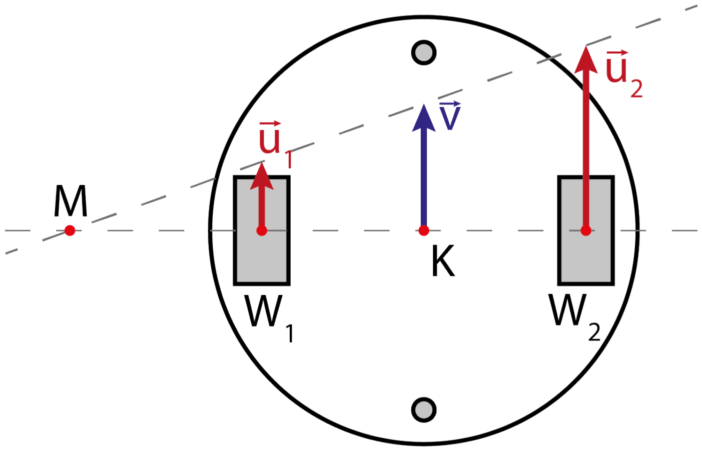


Figure 2.3: Differential kinematics chasis turning left around instant pole M.

Differential kinematics. In this chasis, two independently driven wheels share their axle. Additionally, it can be fitted with passive support wheels to avoid tipping over. Such chassis are also line-moving, but form a holonomic, nonoverdetermined system. Reference point K is simetrically located between both wheels, as it is shown in Figure 2.3. This makes floating angle β remain 0° all the time. The translation perpendicular to the wheels axle and rotation around the centre of this axle are movements that can be combined.

Driving-steering modules. This chasis requires that every wheel is individually steerable. The minimum amount of wheels would be three, but four are usually the preferred choice. The internal configuration of the chassis includes the steering angles of all actuated wheels (Figure 2.4). In order to execute a consistent movement, all wheel axles must intersect at a common instantaneous pole M. This responsibility lies with the vehicle control system, which usually tolerates minimal deviations that compensate for the wheels through lateral slip. Within this tolerance, the configuration results in a defined momentum pole and thus a certain type of movement (mode). The two coordinates of the moment pole correspond to two degrees of freedom, the last remaining degree of freedom is the speed with which the movement is executed in this mode. These vehicles can only drive off from a standstill in one mode without first adjusting the steering configuration. The AGV model where the communication system will be tested the first time (“Scooty”) is like this.

Mecanum wheels. Omnidirectional vehicles Mecanum consist of wheels that can move in any direction due to the attached rollers through all the circumference of them, as seen in Figure 2.5. These chasis are not overdetermined, as the wheels can react differently with their internal degrees of freedom. In addition, these landing gears are the only ones to offer a direct influence on all degrees of freedom of the position, as they only have holonomic constraints in total.

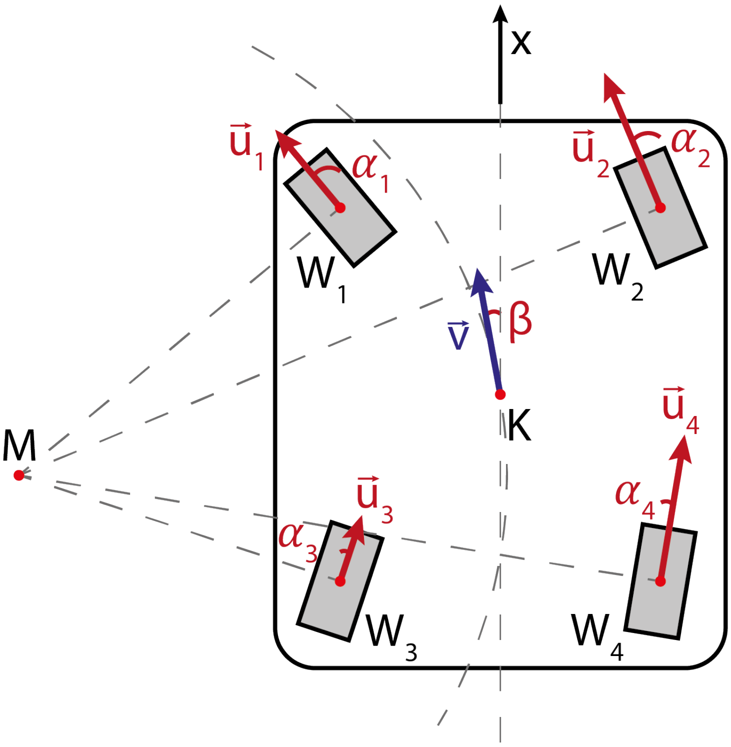
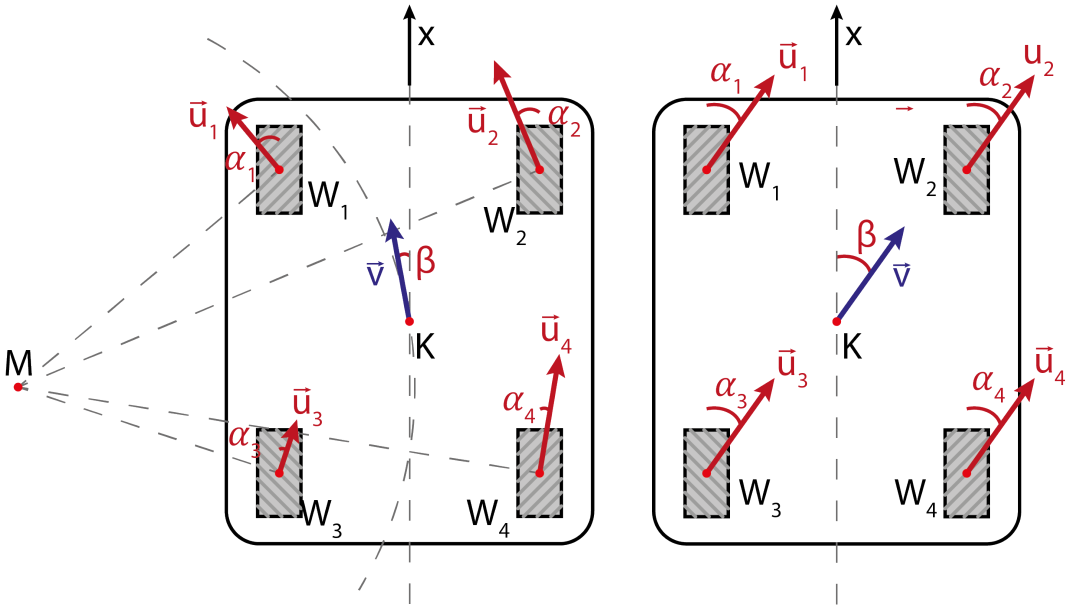


Figure 2.4: Driving-steering modules chasis turning left around instant pole M.

Figure 2.5: Mecanum wheel.



(a) Turning left around instant pole M.

(b) Doing a translation movement.

Figure 2.6: Mecanum chasis.

2.4 Velocities vector

Desired movement $\overrightarrow{u}_i$ can be derived for each wheel with the position vector $\overrightarrow{w}_i$ from the equivalent system of linked vectors $\overrightarrow{u}_i = \overrightarrow{v} + \overrightarrow{w}_i$. Direct control is, however, only possible under the assumption of fully holonomic constraints, as seen in **??**level 2, fully omnidirectional). This is clearly seen when the vehicle tries to start moving from a standstill, due to all the components of the velocity vector are zero and there is no information on the required movement mode. Then, all the quasi-omnidirectional chasis (level 1) need a period of time to reconfigure the steering angle, deviating from the desired velocity vector during this time.

Direct control through the velocity vector is widely used in driverless vehicles if their trajectories are specified by an external instance, but it is not possible to do a change in configuration when the vehicle is stationary. If the steering is to be controlled by an operator via the same interface, this leads to unexpected behaviour because the operator expects to be able to set the steering angle before driving off. Furthermore, this way of describing the degrees of freedom is also counterintuitive for the developer of an automatic software-based control system.

The three components of the velocities vector are always cordinated with each other, even if the desired movement corresponds to a line-moving vehicle and thus two control variables would be sufficient. On curved trajectories, the vehicle follows tangentially a circular trajectory with radius R, which sign is as it follows:

$$R = \frac{|\overrightarrow{v}|}{\omega} \begin{cases} > \ 0 & \text{Left turn} \\ \ 0 & \text{Pure rotation} \\ < \ 0 & \text{Right turn} \end{cases}$$

The ability of vehicles to align their orientation relative to the trajectory curve of their reference point is reflected in the variable direction of the vector $\overrightarrow{v}$, which defines again the **floating angle**:

$$\beta = \angle\overrightarrow{v} = \tan^{-1}\left(\frac{v_y}{v_x}\right)$$

The velocity vector distributes the information on movement mode and speed in such a way that no isolated nor intuitive meaning can be assigned to the components. Instead of this, the displacement can also be specified by giving the instantaneous pole position. The two coordinates of the polar beam vector $\overrightarrow{p}_K$ replace those of the velocity vector $\overrightarrow{v}$, and the angular velocity stays the same:

$$\begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} \Rightarrow \begin{bmatrix} p_{K,x} \\ p_{K,y} \\ \omega \end{bmatrix}$$

This leads to singularities in the case of pure translational movement as the angular velocity tends towards zero and the beams of the wheels are parallel and, therefore, the instant pole is at infinity and the angular velocity tends towards zero.

2.5 Parameters for intuitive control

Reference point K is chosen to make control intuitive and it depends on the type of vehicle. For the linear motion vehicles, it must be a potential instantaneous pole and be located on a symmetry plane of the vehicle. This makes possible a seamless transition between translation and pure rotation. For the area-moving vehicles, the choice is free because there is an equivalent motion vector for every point. Nevertheless, choosing a point on a simmetry plane would make it more intuitive. This point is normally constant relative to the vehicle, but it could move according to the situation.

In order to achieve a universally applicable interface, it is advisable to make the control variables largely independent of the vehicle geometry and its performance data. The parameters involved are standardised to vehicle-specific parameters so that an external specification requires as little knowledge as possible about the specific vehicle. One of these variables is **nominal velocity** v_n. The vehicle scalates it with a maximum velocity v_{max} to obtain an internal translation target value v_s:

$$v_s = v_n \cdot v_{max}$$

The maximum velocity is obtained from the respective wheel drives and danger considerations or braking distances.

As seen in Section 2.4, the curve radius R results from the ratio of rotation to linear speed and thus decisively defines the type of movement. Its reciprocal value represents the curvature $\kappa = 1/R$, which is zero for straight movements. As R diverge towards 0 in straight movements, κ diverges towards zero with pure rotation. Because of that, both R and κ are used depending on which is the predominant mode of movement. When there is predominant translation, the curvature is therefore used as a direct, intuitively tangible control variable. A predominant rotation, on the other hand, can be optimally described by the radius as an alternative control variable.

Table 2.1: Freedom of Omni-Curve Parameters depending on chassis type.

Kinematics	β	v_n	k_n
On rails	Constant	Free	Externally determined
Single-track	Constant	Free	Free
Differential	Constant	Free	Free
Driving-steering	Free	Free	Free
Mecanum	Free	Free	Free

In the interval $[-2, 2]$, nominal curvature κ_n is defined as a normalised control variable. Inside this interval, it results in curvature κ related to a specific curvature κ_g of the vehicle:

$$\kappa = \kappa_n \cdot \kappa_g \forall |\kappa_n| < 1$$

Then, if $|\kappa_n| \geq 1$, movement mode would be defined by radius instead, with a continuous transition at the limit radius $R_g = 1/\kappa_g$. Pure rotation around K ($R = 0$) at the end of this interval $\kappa_n = \pm 2$ leads to the second straight equation:

$$R = \frac{\pm 2 - \kappa_n}{\kappa_g} \forall |\kappa_n| \geq 1$$

These are described in **??**, where the normalised limiting curvature κ_g or the equivalent limiting radius R_g are plotted over the nominal curvature κ_n and show these curvature defined in sections. The solid lines correspond to the values taken to avoid divergence for the cases of predominant translation and predominant rotation. In contrast, the dashed lines correspond to the values of R and κ that have infinity in the unfavourable situations described above.

Values of R, κ_n and $\kappa > 0$ describe a turn to the left (clockwise), whereas the opposites describe a turn to the right (counterclockwise).

The floating angle β is only a degree of freedom in area-moving vehicles and would not in the rest if K is defined according to the way explained in this section. In Figure 2.2 and Figure 2.3, no β is show because it is always zero, while in Figure 2.4 and 2.6 it shows the direction of the tangent at K for the trajectory of the vehicle in the case of curved trajectories or the direction of the movement in translational trajectories. In movements to the left, β is positive, and negative to the right.

Depending on the type of chasis, the OCP defined as control variables can be free, constant or externally determined. 2.1 summarises this for the chassis types studied.

2.6 Ranges

It is important to know before designing a communication system the size of what is going to be sent. In the case of the OCP, they are three numbers and their ranges are:

- $\beta = [-\pi, \pi]$ (rad)

- $V_n = [0, 1]$

- $\kappa_n = [-2, 2]$

The required accuracy in the decimal part will be valid with four digits at the moment.

3 Communication technologies

There are many technologies that allow the exchange of information. The reason that no one clearly predominates over the others is that the choice of each depends on the characteristics of the system where it is to be implemented. The most common robot-to-robot communication technologies are presented below. The focus will be on characteristics such as:

- **Transmission speed**. Rate at which data can be transmitted over a communication channel. It is typically measured in bits per second (bps) or bytes per second (Bps).
- **Latency**. Delay between the time a signal is sent and the time it is received. It is typically measured in milliseconds (ms).
- **Range**. Maximum distance over which a communication signal can be transmitted and received reliably.
- **Power consumption**. Amount of electrical power required to operate the system. Lower power consumption is normally desirable, as it can extend the charge cylces, as well as the battery life in portable devices (like AGVs), and, of course, reduce overall energy costs.
- **Cost**, including hardware, software, maintenance, and other related expenses.
- **Robustness**. Combination of the various factors that affect the reliability and performance of a communication technology. It is closely related to characteristics such as transmission speed, range and latency, but it is defined differently depending on the application and environment. Other factors may affect the robustness: the quality of the components used, the design of communication protocol and the hability of the system to adapt to changing conditions.
- **Available hierarchies**, which can be centralized or distributed.

These technologies are divided into two groups: wired (mostly Ethernet) and wireless. As the aim is to have a mobile and flexible logistics system, wired technologies are not a practical option. Only wireless technologies will be considered.

In general, wireless technologies share certain problems, such as interference arising from many devices using the same frequencies or signal loss due to obstacles. Each type of technology is more or less affected by them and deals with these problems in a different way.

3.1 Wireless technologies

3.1.1 WiFi

This is one of the most important and widely used communication technologies in industries. Information in converted into radio signals and then is transmited from one device to another intended device. These devices use a set of standards and protocols known as the 802.11 family, which define the rules and specifications for how they communicate over WiFi, including the frequencies to be used, the maximum data transfer rates, and the security mechanisms to be employed.

Among all the standards that exist, the 802.11ac (2013) and the 802.11ax (2019) [SJT22] are the most modern and most widely used in industrial environments nowadays. They provide better connection quality and speed than previous versions, due to higher bandwidth and a better ability to handle multiple connected devices simultaneously, making them ideal for high device density environments. Overall, 802.11ax has better characteristics because it is most recent, but 802.11ac is more widely used and therefore, more tested and cheaper [NJW+15].

This technology is designed to transmit data over longer distances (in both standards, the range is up to 300 meters outdoors and 100 indoors, depending on the obstacles and interference sources) at higher data rates than other wireless technologies that are designed for short-range, low-power communication. That is why power consumption is higher. Newer standards are designed to be more power efficient. Both 802.11ac and 802.11ax use beamforming, which enables the wireless access point to direct the WiFi signal towards the device, reducing the amount of energy required to transmit the signal. Another way to save energy is power save mode, which consists in entering in a low-power state when there is no data to be transmitted or received.

The 802.11ac standard uses MIMO (Multiple Inputs, Multiple Outputs) technology to increase speed and range. It supports data rates of up to 1.3 Gbps on the 5GHz frequency band, and up to 450 Mbps on the 2.4GHz frequency band. Latency is relatively low, with typical delays ranging from 20 to 30 ms.

In the 802.11ax, beamforming uses a technique called “multi-user MIMO” (MU-MIMO) to enable the wireless access point to transmit multiple data streams to multiple devices simultaneously. This reduces the amount of energy required to transmit data and improves the overall efficiency of the network. This standard also includes more power saving features such as:

- Target Wake Time (TWT), which allows devices to schedule their wake-up times to reduce the amount of time they spend in active mode,
- Wake-on-Wireless LAN (WoWLAN), which enables devices to wake up from sleep mode in response to specific network traffic,
- Spatial Frequency Reuse (SFR), which enables the wireless access point to use the same frequency band for multiple devices without causing interference,
- 802.11ax power save (PS-Poll), which reduces power consumption during periods of low data activity.

Nevertheless, even with these features, it's likely that 802.11ax WiFi still has higher power consumption than other technologies, due to the higher data transfer rates and longer ranges of WiFi.

3.1.2 Zigbee

Zigbee is a wireless communication protocol that is designed to be low-power and low-data-rate using the IEEE 802.15.4 standard. Several versions of the Zigbee standard have been released since the first time in 2004. The latest is Zigbee 3.0 and when it was released (2015), it aimed to unify the previous versions of the standard into a single, interoperable standard for the Internet of Things (IoT). It includes support for a wide range of devices and applications, from smart homes to industrial automation [ASS+21].

The IEEE 802.15.4 standard specifies several frequency bands that can be used for communication. The most common frequency bands used for Zigbee communication are 2.4 GHz and 900 MHz, depending on the country. The 2.4 GHz band is used in most Zigbee devices, and it provides a good balance between range, data rate, and power consumption. The 900 MHz band is used in some industrial and commercial applications where longer range is required, but at the expense of lower data rates.

Zigbee supports mesh networking, which enables a large number of devices to communicate with each other. The mesh network allows for multi-hop communication, where data can be relayed from one device to another, increasing the range of communication.

The transmission speed of Zigbee ranges from 20-250 Kbps, with a latency of around 15 milliseconds. The range of Zigbee depends on several factors, including the frequency band used, the output power of the transmitters, and the presence of obstacles that can interfere with the signal. In general, Zigbee has a range of up to 100 meters in open air, but this can be reduced to a few meters in environments with high levels of interference.

It is designed to be low-power, with typical power consumption of around 30 mA during transmission and less than 1 mA during standby mode. Furthermore, its also have a low cost, making it an attractive option for IoT applications.

Mesh networking topology makes devices to communicate with each other directly or through other devices in the network, increasing the robustness of the network. Other features on the Zigbee devices that can improve reliability are:

- Retransmission: they can automatically retransmit messages that are not acknowledged by the recipient, increasing the chances that the message will be successfully delivered.
- Acknowledgment: they can request an acknowledgment from the recipient after sending a message, ensuring that the message has been received.
- Channel hopping: they can switch between different channels to avoid interference from other wireless devices operating in the same frequency band.
- Encryption: they can use encryption to secure communication between devices and prevent unauthorized access to the network.

3.1.3 Bluetooth

This technology uses short-range radio waves to establish wireless communication between devices. It emerged in the early 2000s, and has evolved over the years. Since the Bluetooth 4.x released in 2010, Bluetooth has improved speed, range and power consumption. It includes Bluetooth Low Energy (BLE) profiles for IoT (Internet of Things) devices and low energy peripherals.

Each version of Bluetooth is backwards compatible, meaning that newer devices can connect to older devices using earlier versions of Bluetooth, although they may not be able to take advantage of all the improvements in the newer versions. Bluetooth 4.x and later are excellent options for modern industrial communications due to their ability to offer long-range, low energy connections, allowing for reliable real-time data transmission. In addition, Bluetooth 4.x and later also have enhanced security features, making them suitable for use in critical industrial applications where security is a major concern.

In particular, Bluetooth 5.x [ZSBB21] has been designed to provide more robust and reliable connectivity, and may be particularly useful in industrial environments that require a high degree of reliability and resistance to interference. In addition, Bluetooth 5.x also supports the connection of multiple devices simultaneously, which can be useful for applications where a large number of connected devices are required on the same network. Because of these features, the fifth version will be the one to study in this work.

Its transmission speed is up to 2 Mbps and its latency is around 10 milliseconds. Bluetooth 5 includes Low Energy (LE) features that significantly reduce power consumption. For example, Bluetooth 5.x can operate for up to 10 years on a single coin cell battery, making it a very low-power option for industrial communication. The cost of Bluetooth 5 devices varies depending on the specific application and use case, but in general, Bluetooth 5 devices tend to be relatively low-cost compared to other wireless communication technologies like Wi-Fi and cellular communication.

3.1.4 LoRa

LoRa stands for Long Range and is a low-power, wide-area network (LPWAN) technology designed for Internet of Things (IoT) applications. It uses a chirp spread spectrum modulation scheme to achieve longer-range wireless communication with low power consumption. There are several versions, which have been developed over the years to meet different requirements of IoT applications. Some of them are: LoRaWAN, Lora Alliance, Lora Edge and Lora 2.4 GHz [CGM+18].

LoRaWAN would be the most suitable for industrial environments because it provides long-range communication and can operate in the unlicensed sub-gigahertz frequency bands (433 MHz, 868 MHz, and 915 MHz). It is to work in harsh environments and can penetrate walls and obstacles. It is also a low-power technology, which means that it can operate for long periods of time on battery power. In addition, it is scalable and can support a large number of devices, which is important for industrial applications where there may be many devices that need to communicate with each other and with a central system.

The transmission speed in LoraWAN is between 0.3 and 50 kbps, depending on factors such as the frequency band, modulation scheme, and spreading factor used. Its latency has a typical round-trip time of between 300 to 1000 ms, depending on factors such as the network configuration and packet size. The range can be from 2 to 15 km in urban areas and up to 30 km in rural areas, depending on factors such as the frequency band, antenna height, and terrain.

LoRaWAN end devices typically have a power consumption of between 1 to 10 mA during transmission, and between 10 to 100 μA during idle mode. In terms of cost, this devices can range from a few euros to several tens of euros, depending on factors such as the features and capabilities of the device. However, it is typically lower than other wireless technologies such as cellular or Wi-Fi.

LoRaWAN is designed to be backwards-compatible. Regarding robustness, LoRaWAN faces interferences, network congestion, battery life in its devices and environmental factors such as weather, terrain or obstacles. To mitigate these reliability issues, LoRaWAN networks can be designed and deployed using best practices and appropriate techniques, such as proper site selection, network planning, interference mitigation, and battery management.

3.1.5 Li-Fi

LiFi stands for Light Fidelity and uses visible light to transmit data instead of traditional radio waves used by other wireless communication technologies. A Li-Fi system consists of an LED light source that is modulated at a high frequency to carry the data, which is then received by a photodetector and converted back into an electrical signal. The latest version is LiFi 2.0 (2013), which uses LED light to transmit data.

Its transmission speed is very high, with theoretical maximum speeds of up to 224 Gbps. However, in practical implementations, they are likely to be lower. Latency in Lifi 2.0 is very low, as the signal travels at the speed of light. The latency is typically less than 1 millisecond (ms), which makes it suitable for real-time applications. The range of LiFi 2.0 is limited to the coverage area of the LED lights (a few meters). Nevertheless, it can be extended by using multiple transmitters and receivers, and by increasing the power of the LEDs [AST+21].

The power consumption of LiFi 2.0 is relatively low, as the LED lights used for data transmission also provide illumination. The power consumption depends on the number of LEDs used and the data transfer rate, but it is typically in the range of a few watts. Regarding the cost of LiFi 2.0 equipment, it is currently higher than that of other wireless communication technologies. The cost of a LiFi 2.0 transmitter and receiver can range from a few hundred euros to a few thousand euros, depending on the features and performance.

LiFi is not retro-compatible as the versions of LiFi use different part of the electromagnetic spectrum to transmit data. It is suposed to be interference-free as it operates on a different part of the electromagnetic spectrum than traditional wireless technologies such as WiFi and Bluetooth.

LiFi signals cannot penetrate through walls or other obstacles, which can be regarded as and advantage in terms of security as it is inherently more secure than Wi-Fi or other wireless signals that can be intercepted from a distance. However, it can regarded as a disadvantage as well, which causes loss of information when an obstacle appears. To enhance the distribution of light signals and improve coverage, optics such as lenses, diffusers, or reflectors can be used to control and direct the transmitted light.

3.1.6 4G

4G uses cellular networks to provide wireless communication between industrial devices. There are two main versions of 4G (Fourth Generation) communication technologies: LTE (Long-Term Evolution) and WiMAX (Worldwide Interoperability for Microwave Access), but LTE is the most commonly used version of 4G. It operates on various frequency bands depending on the region and country. The most commonly used frequency bands for LTE are: band 1 (2100 MHz), band 3 (1800 MHz), band 7 (2600 MHz), band 8 (900 MHz) and band 20 (800 MHz). Lower frequency bands such as Band 8 (900 MHz) and Band 20 (800 MHz) are more suitable for industrial environments because they can provide better coverage in large areas and penetrate obstacles such as walls and buildings more easily. These bands are also less prone to interference and can provide better signal strength in areas with weak signal. However, higher frequency bands such as Band 3 (1800 MHz) and Band 7 (2600 MHz) can provide higher data transfer rates and better capacity [KMB18].

4G LTE can provide high-speed data transfer rates, with theoretical maximums of up to 1 Gbps (Gigabit per second) in ideal conditions. However, in practical scenarios, the actual data transfer rates can vary depending on factors such as signal strength, network congestion, and the capabilities of the devices involved. Its latency is tipically low, with round-trip latency of around 30 to 50 milliseconds, although it can be as low as 10 milliseconds in some cases. The range can vary depending on the specific frequency band and the physical environment. In general, the range of 4G LTE can extend up to several kilometers in open areas with good signal strength, although it can be significantly lower in urban areas with dense buildings and other obstacles.

The power consumption of 4G LTE devices can vary depending on the specific device and usage scenario. In general, 4G LTE devices are designed to be power-efficient, with typical power consumption ranging from a few milliwatts to a few watts. Regarding costs, 4G LTE devices can range from a few hundred euros to several thousand euros, depending on the features and capabilities of the device. The cost of 4G LTE services can vary depending on the data usage and the specific service provider, but in general, it can range from a few euros per month to several hundred euros per month depending on the data plan and other factors.

This technology is backward-compatible. To avoid typical reliability problema, 4G LTE implements features such as Multiple Input Multiple Output (MIMO), Adaptive Modulation and Coding (AMC), Error Correction and Carrier Aggregation.

3.1.7 5G

5G (fifth generation) wireless technology is a high-speed cellular network that offers faster data transfer rates, lower latency, and greater connectivity than previous generations of cellular networks. 5G is designed to support a wide range of IoT devices, including AGVs, by providing reliable and high-bandwidth connectivity. There are mainly two types of 5G technology:

- Sub-6GHz 5G: This is the most common type of 5G technology, which operates on frequencies below 6 GHz. It offers faster speeds and lower latency than 4G LTE, but has limited capacity and coverage.
- mmWave 5G: This type of 5G technology operates on millimeter wave frequencies, which are much higher than sub-6GHz frequencies. It offers extremely fast speeds and low latency, but has very limited coverage and requires line-of-sight to work effectively.

Sub-6GHz 5G. It works by using radio waves that operate on frequencies below 6 GHz to transmit data between devices. The exact frequency bands used for sub-6GHz 5G can vary depending on the region and available spectrum. Its transmission speed is higher than 4G LTE, with theoretical peak speeds of up to 10 Gbps. This technology can offer low latency, with typical values in the range of 1-20 milliseconds with better coverage and range than mmWave 5G, with signals able to penetrate obstacles like walls and buildings. However, the range can still be limited in certain industrial environments, such as those with a lot of metal or interference.

Sub-6GHz 5G can be more power-efficient than mmWave 5G, as it requires less power to transmit signals at lower frequencies. The cost of deploying sub-6GHz 5G in industrial environments is generally expected to be less expensive than mmWave 5G due to its wider coverage and less complex infrastructure requirements.

mmWave 5G. It works by using high-frequency radio waves to transmit data between devices. These waves operate on frequencies above 24 GHz, typically in the range of 28-39 GHz.

This technology can offer extremely fast data rates, with theoretical peak speeds of up to 20 Gbps with very low latency, with typical values in the range of 1-10 milliseconds. Its range is one of the main challenges of mmWave 5G technology as it is its limited, which is typically measured in meters rather than kilometers. In industrial environments, the range of mmWave 5G may be limited by physical obstacles such as walls and machinery.

mmWave 5G technology can be power-hungry, especially when operating at high data rates. However, advances in energy-efficient chipsets and network architecture can help reduce power consumption. Its cost of deploying can be significant, as it requires specialized equipment and infrastructure. However, the cost may be justified by the potential benefits of faster data rates, lower latency, and improved operational efficiency.

Both technologies are backward-compatible with previous cellular technologies such as 4G LTE and 3G. To fix some of the problems in reliability, some aproaches have been made. One is to use advanced antenna technologies, such as beamforming, which can help to improve the signal strength and reduce interference. Another approach is to use advanced modulation and coding schemes, which can help to increase the data rate and improve the reliability of the wireless connection. Network operators can also deploy additional network infrastructure, such as small cells and repeaters, which can help to improve coverage and capacity in areas with poor signal strength [LMCP22].

3.1.8 Infrared

Infrared involves the use of infrared (IR) transceivers or sensors that can transmit and receive data signals via infrared light. These signals can be used to transmit data between different devices, such as AGVs or other robots.

Its transmission speed is low, being around 1-4 Kbps. This is much slower than other wireless technologies such as Wi-Fi or Bluetooth. However, the latency of IR communication is generally low, typically in the range of microseconds to milliseconds. The range of IR communication is limited and depends on factors such as the power of the transmitter, the sensitivity of the receiver, and any obstacles or interference in the environment. The range of IR is usually within a few meters and requires line-of-sight communication [KB97].

IR typically has low power consumption, it depends on factors such as the power of the transmitter and the sensitivity of the receiver. Regarding cost, IR technology is relatively inexpensive, with components such as transmitters and receivers costing only a few euros each.

As long as the devices have the same protocols and specifications, this technology should be backwards-compatible.

One of the main issues with this technology in terms of reliability is the need of a line-of-sight between devices to transmit information. This makes IR technology sensitive to obstacles but, if there are any, it is less likely that this technology is afectec by interferences. The reliability of IR can also be affected by the quality of the hardware used in the devices. Cheap or poorly designed IR components may be more prone to errors or interference, which can affect the reliability of the communication.

3.1.9 Laser

Laser typically involves the use of modulated laser beams to transmit data signals between devices. In this method, the laser is used to transmit the data in the form of light, which is then received by a sensor or photodiode at the receiving end. Laser communication technologies can be broadly categorized into two types: free-space laser communication and fiber optic communication (which is obviously not wireless and will not be considered) [**8121569**].

Free-space laser communication can be used for industrial communication by transmitting data between two points in space using a modulated laser beam. The laser beam is typically focused onto a receiver at the destination, which converts the modulated light signal back into an electrical signal for processing.

Free-space laser communication systems can achieve very high data rates, typically in the range of several gigabits per second (Gbps) to tens of Gbps or more. The latency is typically very low for free-space laser communication systems, on the order of microseconds (μs) to milliseconds (ms). The range of a free-space laser communication system depends on various factors, including atmospheric conditions, system design, and the power of the laser used. In ideal conditions, free-space laser communication can transmit data over distances of several kilometers or more, with some systems achieving ranges of tens of kilometers or more.

The power consumption of a free-space laser communication system depends on various factors, including the laser power, modulation scheme, and system design. Generally, free-space laser communication systems require less power than radio frequency (RF) communication systems, and can be designed to be energy-efficient. However, the power consumption can still be significant, particularly for systems that operate over long distances or require high laser powers.

In terms if cost of a free-space laser communication system can be more expensive than RF communication systems, particularly for long-range applications, because of the higher cost of laser components and the need for precision optics.

3.1.10 UWB

Ultra-Wideband (UWB) is a wireless communication technology that uses short-range, high-bandwidth radio signals to transmit data over a very wide frequency range. UWB operates at frequencies between 3.1 GHz and 10.6 GHz, which is a much wider bandwidth than other wireless technologies like Bluetooth or Wi-Fi. The main adventage this gives is that it makes possible to use a different frequency than most of the other wireless technologies, avoiding interferences. However, in Europe, the UWB frequencies are allocated in the range of 6 GHz to 8.5 GHz.

UWB works by transmitting short pulses of radio waves. These pulses are timed very precisely and are designed to spread out over a large range of frequencies, which allows UWB to transmit data at very high speeds over short distances. Because UWB signals are spread out over a wide frequency range, they are less susceptible to interference from other wireless signals and can penetrate walls and other obstacles more effectively, which is a plus point in terms of robustness.

Some of the most widely used UWB protocols and standards include:

- IEEE 802.15.4a, which defines the physical and MAC layer specifications for UWB communication in the 3.1-10.6 GHz frequency range. It supports data rates of up to 27 Mbps and includes features such as channelization, ranging, and localization.
- WiMedia Alliance: This industry consortium developed the Multiband OFDM (MB-OFDM) UWB standard, which operates in the 3.1-4.8 GHz frequency range and supports data rates of up to 480 Mbps. It includes support for wireless USB (WUSB) and wireless HDMI (WHDI) applications.
- Bluetooth Special Interest Group (SIG) has developed a UWB-based protocol called Bluetooth Low Energy (LE) Direction Finding, which allows Bluetooth devices to determine the direction and distance of other Bluetooth devices with high accuracy.
- Near Field Communication (NFC): a UWB-based protocol called NFC Tagged Object, which allows NFC-enabled devices to communicate with UWB-enabled tags and objects for use cases such as asset tracking and contactless payment.

Its transmission speed rates are up to several gigabits per second over short distances (up to 10 meters). In addition to this, UWB signals can penetrate obstacles such as walls and can provide accurate ranging and positioning information in indoor environments. However, the transmission rate decays rapidly as the source and receiver move further apart. For example, some UWB-based wireless USB (WUSB) solutions claim data rates of up to 480 Mbps at a range of 3 meters, while others can provide data rates of up to 1.5 Gbps at a range of 1 meter. Latency in UWB is typically in the range of microseconds to milliseconds.

Power consumption in UWB is low compared to other wireless technologies, such as Wi-Fi and Bluetooth. It typically consumes less than 1 watt of power, depending on the implementation and usage scenario. In terms of cost, UWB technology can be more expensive than other wireless technologies due to the complexity of the hardware and the specialized components required.

As mentioned above, the possibility of using frequencies over a wide range gives this technology the ability to avoid a lot of interference. Another potential problem is multipath fading, which occurs when the signal is reflected, scattered, or diffracted by objects in the environment, resulting in multiple copies of the signal arriving at the receiver with different phases and amplitudes. To address this, UWB uses time-domain transmission techniques that allow the receiver to resolve the different paths and combine them to improve signal quality.

3.2 Summary comparison

In Table 3.1, there is a summary of Section 3.1 to easily compare all the described technologies at a glance.

Power consumption is always related to the data rate and range. The amount of data is small for this application and so is the range needed. In order to extend battery cycles and battery lifes, technologies with medium or high power consumption should be discarded.

In Table 3.3, the different characteristics are weighted according to subjective criteria about how important is each of them for this project. This is a way of simplifying a complex decision by reducing everything to a number. For each characteristic, a number from 0 to five is given, where 0 is none, 1 is very bad and 5 is very good, always taking into account what “good” and “bad” is for this project.

Latency. As this is the most important characteristic, its weight is 30%. The highest score has been given to those below one second, and then the second highest to those between one and twenty seconds. LiFi, laser, infrared and UWB are the best in terms of latency, followed by Bluetooth, Zigbee, Wifi 6 and 5G.

Maximum transmission speed. The weight of this characteristic is not too high because the ammount of information derired to transmit is not very large. Some of the technologies that have low latency combine it with high transmission speeds, due to the high frequencies they use.

Maximum range. Range is not a critial issue as the AGVs are expected to be less than 3-2 meters apart. In some cases, a wider range would help avoiding loss of information when obstacles interfere and can be crossed. For example, LiFi has a good range for this application, but its signal cannot cross obstacles. However, this problem could be mitigated with optics and diffusers, which makes not having a bad score in robustness.

Robustness. As it was defined in Chapter 3, “robustness” is related to reliability to maintain communication and its performance. In the context of cooperative AGVs, “robustness” should be focused on latency first, then transmission speed and finally power consumption. Another important thing to look at is the communication protocols available in each technology as it deeply influences robustness. Each of them has its features to solve common or specific problems in wireless communication. To take that into account, Table 3.2 sums the main problems, some solutions and some features that improve robustness.

Backward-compatible. Different versions of the same technology can be put on the market and this can become a problem when it comes to upgrading or expanding the system in a network with older devices. The weight given is just 5 because this is an academic work with no wireless communication systems to which to adapt.

Power consumption.

Cost. Some the best options regarding the rest of characteristics must be rejected because of the high cost. If other options are available at a lower price, it is intended to test several technologies and to get a conventional and universal system is wanted, then cost should be low. This is why the weight of cost in the decision table is 10%. The best example is again LiFi, which emitters and receivers have a price of hundreads of euros. Having into account that several of these would be needed just to test, this technology should be discarded.

Table 3.1: Summary table with the main characteristics of the communication technologies considered.

Communication Technology	Latency [ms]	Maximum Transmission Speed	Maximum Range [m]	Backward-compatible	Power consumption	Cost
LiFi 2.0	<1	<<224 Gbps	Few meters*	No	Low	High
Laser	<1	10 Gbps	Tens of km	-	High	Very High
Infrared (CIR)	0.001-1	1-4 Kbps	Few meters*	No	Low	Very Low
Zigbee 3.0	15	250 Kbps	100 outdoors	Yes	Very Low	Low
Bluetooth 5	10	2 Mbps (@ 2.4GHz)	200 outdoors	Yes	Very Low	Low
WiFi 802.11ac	20-30	1.3 Gbps @ 5 GHz 450 Mbps @ 2.4 GHz	100 indoors 300 outdoors	No	Medium	Medium
WiFi 6 802.11ax	10-15	9.6 Gbps @ 5 GHz 600 Mbps @ 2.4 GHz	100 indoors 300 outdoors	No	Medium	Medium
LoRaWAN	300-1000	0.3 Kbps to 50 Kbps	$2\text{-}15 \cdot 10^{3}$ urban $2\text{-}30 \cdot 10^{3}$ rural	Yes	Very Low	Low
4G LTE	30-50	1 Gbps	Several km**	Yes	Medium	Medium
UWB	<1	480 Mbps @ 3 meters 1.5 Gbps @ 1 meter	10	No	Low	High
mmWave 5G	1-10	20 Gbps	1000	Yes	Medium	High
Sub-6GHz 5G	1-20	10 Gbps	Several km	Yes	Low	Medium

Appeal for this project. * It requires line-of-sight. ** In open areas, but highly reduced when there are obstacles.

Table 3.2: Reliability and robustness of the considered technologies.

Communication Technology	Reliability concerns	Robustness qualities
LiFi 2.0	Shadows from obstacles.	Interference-free, optics and diffusers.
Laser	Interference, inaccurate alignment.	Redundancy, error correction, encryption.
Infrared (CIR)	Obstacles, hardware quality.	-
Zigbee 3.0	Obstacles, radio interferences.	Mesh networking, retransmission and acknowledgment, channel hopping and encryption.
Bluetooth 5	Interference, signal attenuation, noise.	Adaptive Frecuency Hopping (AFH), Forward Error Connection (FEC), Secure Simple Pairing (SSP),Elliptic Curve Diffie-Hellman (ECDH).
WiFi 802.11ac WiFi 6 802.11ax	Interference, obstacles.	Dynamic Frecuency Selection (DFS) for interferences, Multiple Input, Multiple Output(MIMO) for signal strength and coverage.
LoRaWAN	Interference, network congestion.	-
4G LTE	Interference, network congestion, obstacles.	Multiple Input, Multiple Output (MIMO) for signal strength and coverage, Adaptative Modulation and Coding (AMC), Forward Error Correction (FEC) and retransmission to ensure data is transmitted and Carrier Aggregation to increase available bandwith.
UWB	Interferences, multipath fading	Wide frequency spectrum Time-domain transmission
mmWave 5G	Interference due to shorter range.	-
Sub-6GHz 5G	Interference due to lower frequencies.	Penetrates obstacles

Table 3.3: Decision table over communication technologies.

Communication Technology	Latency	Maximum Transmission Speed	Maximum Range	Robustness	Backward-compatible	Power consumption	Cost	Appeal for this project
Weighting	***30***	***5***	***5***	***25***	***5***	***20***	***10***	***100***
LiFi 2.0	5	5	4	4	0	4	2	79%
Laser	5	5	5	1	0	2	1	55%
Infrared (CIR)	5	1	3	4	0	4	5	**80%**
Zigbee 3.0	4	3	5	4	5	5	4	**85%**
Bluetooth 5	4	4	5	4	5	5	4	**86%**
WiFi 802.11ac	3	5	5	5	0	3	3	71%
WiFi 6 802.11ax	4	5	5	5	0	3	3	77%
LoRaWAN	1	2	5	2	5	5	4	56%
4G LTE	3	5	5	5	5	3	3	76%
UWB	5	5	3	5	0	4	2	**83%**
mmWave 5G	4	5	5	3	5	3	2	70%
Sub-6GHz 5G	4	5	5	4	5	2	3	73%

3.3 Two different approaches

The selected technologies will be **infrarred** and **Zigbee**. The reason for this is that, being a good candidate, each of them represents a different approach in communication. Zigbee and Bluetooth work in a mesh using radio signals, while infrared or laser use a "beamßpecifically directed to somewhere. They are very different, and in the process of developing them it may come clear which one is better.

4 Information flow inside the group

One of the aims of this concept is to be universal so that any vehicle can use it, regardless of its chasis type. However, and specially when trying to do cooperative transport, things like the height of the vehicle, its shape, its size or the way of loading and unloading can cause limitations on cooperativity. In the case of geometry, the shape or the height influence the way of measuring distances, as well as the configuration of possible formations. Tests should take this into account, as measuring distances is essential to ensure correct operation.

It is also important to note that with a centralised system there is the potential problem of overloading the network because of a large ammount of information on it. In addition, there can be interferences and noise when using the same frequency and the signals can be reflected and act as copies of the originals. However, all the vehicles should receive the information at almost the same time. The more decentralised the system gets, communication can become more sequential and increase the latency and thus cause positioning errors in vehicles. Tests with different degrees of decentralisation will be carried out at a later stage to find the balance between low network overload and low latency.

OCP parameters are sent to one or several vehicles. The rest of vehicles in the formation have to know somehow how to move. This can be done by sequencing secondary communications so that all of the vehicles know the OCP or just controlling the distance. In each of these two categories, there are also multiple options in terms of organisation. Furthermore, these categories can be combined. For each of the chosen technologies, the information flow will be different. However, there will also be common problems.

4.1 Common problems

4.1.1 Simultaneity in sending messages

There is a limitation in most conventional sensors as they cannot send and receive information at the same time on the same communication channel or frequency. This happens because they need all their power and resources to send the signal and makes it difficult to receive weak signals at the same time. This is known as “duplex” or “full-duplex”.

Some techniques to avoid this problem are:

- Frequency Division Duplex (FDD). The frequency spectrum is divided into separate channels for transmitting and receiving. Each channel operates at a different frequency, allowing devices to transmit and receive data simultaneously but on different frequencies.

- Time Division Duplex (TDD). The same frequency spectrum is shared for both transmitting and receiving, but the transmission and reception occur at different time intervals. Devices take turns transmitting and receiving data within predefined time slots. TDD allows for dynamic allocation of time slots based on the traffic demand and can be more flexible in managing uplink and downlink data transmission.
- Zigbee “CSMA-CA”. The Zigbee communication standard includes the CSMA-CA (Carrier Sense Multiple Access with Collision Avoidance) technique to prevent collisions between devices. Zigbee devices scan the channel, wait for random time periods, and avoid collisions to ensure efficient communication.

4.1.2 Directing communications

The way the destination address of a specific signal is determined can vary depending on the communication protocol and technology used:

- Infrared. The destination address is established through point-to-point communication. Each infrared transmitting device has a limited field of view and must be directly pointed at the receiver for the signal to be transmitted correctly. In this case, the destination address is physically determined by directing the infrared signal towards the receiving device.
- Zigbee. Devices communicate using network addresses and device addresses. Each Zigbee device has a unique network address and a device address within that network. When sending a Zigbee packet, the destination addresses are included in the packet header to identify the recipient device and its corresponding network.

4.2 Hierarchy

One or several AGVs receive the information from a coordinator. Once these AGVs know the OCP parameters, they communicate with the rest of the members of the group, stablishing a hierarchy:

- Level 1: the leaders or senders are the AGVs which receive the information directly from the controller.
- Level 2: the followers or repeaters, which are all the members of the group that have to repeat information to other member or members, excepting the leaders.
- Level 3: the ends of the formation or receivers. They do not have any members to transmit information to and they might not have to know the OCP in many cases. In the following figures, the red arrows represent essential OCP communication, while the orange arrows can be either OCP communication or simply distance control.

4.3 Lineal (IR-like)

For technologies such infrared, there is a strong dependence on the shape of the vehicle. Taking "Scooty" as example, this AGV has a shape similar to a rectangle in its ground plan. This means that a sensot attached to the sides of the robot could be able to communicate to the next 4 robots: one in front, one at the back, and two at the sides. It would be very difficult to achieve a communication to a robot located further than the immediate next ones or that is on its diagonal. This is also a problem when using distance sensors, regardless the communication system. Then, all the AGVs must be on a rectangular grid where all of them are aligned and there cannot be a missing AGV or communication would not go further.

Communication flow can go from the inner members of the group to the outer ones, or vice versa. The relative position that the AGVs have from point K is important as, depending on the parity of rows and columns, the selection of the leaders can change. This leads to the two different approaches that are described below. In every case, the OCP communication is represented by purple arrows and the orange ones represent distance control. This control can help fixing position or trajectory mistakes, but they can only be used when the AGVs are aligned. It is intended to minimise the number of sequential communications. to do that, repeaters should not communicate to another repeater, but another leader would be added instead.

From the inside to the outside of the group

Odd number of rows and columns. In Figure 4.1, the leader is positioned above the reference point K. The rest are followers or ends. If, as shown in Figure 4.2, the group goes bigger, the chosen leaders are in the surroundings of the leader in Figure 4.1, creating a pattern similar to a chessboard. The ends would remain for level 3 AGVs, which would only receive the parameters.

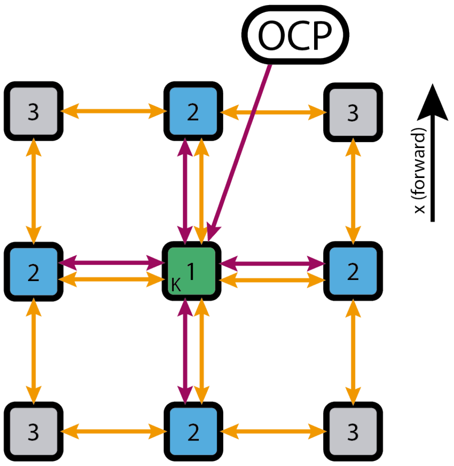


Figure 4.1: Communication scheme in a group with an odd number of rows and columns.

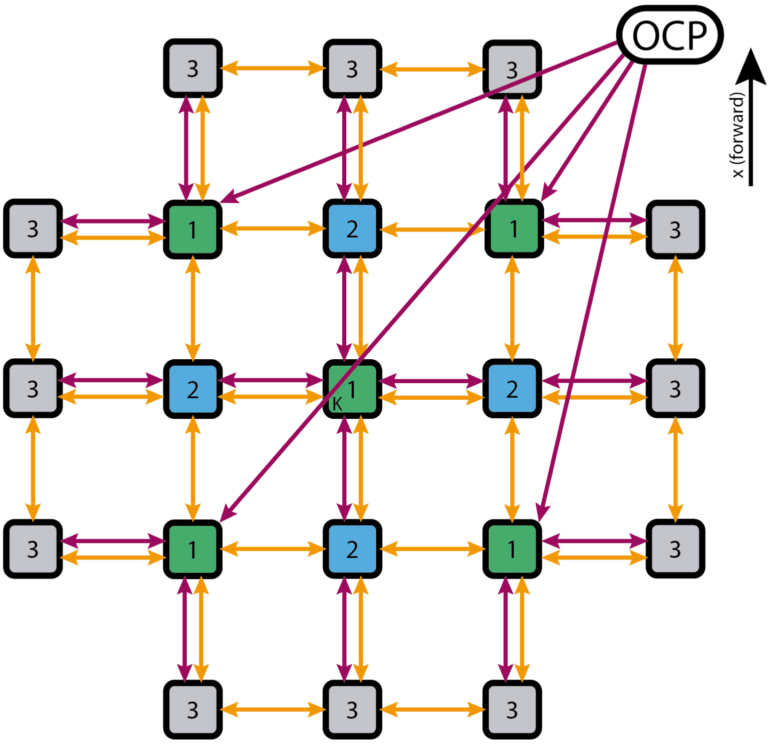


Figure 4.2: Communication scheme in a larger group with an even number of rows and columns.

Even number of rows and odd numer of columns and vice versa. In this case, the reference point K would not be above one of the AGVs, and the strategy to choose the leaders changes a bit. Figures 4.3 and 4.6 show the group divided in two, with a line passing through the reference point. This line creates two quadrants (I and II), in which each leader is the closer to K. If the group grows more, the same chessboard strategy can be followed in each quadrant, always trying to minimize the number of sequential communications.

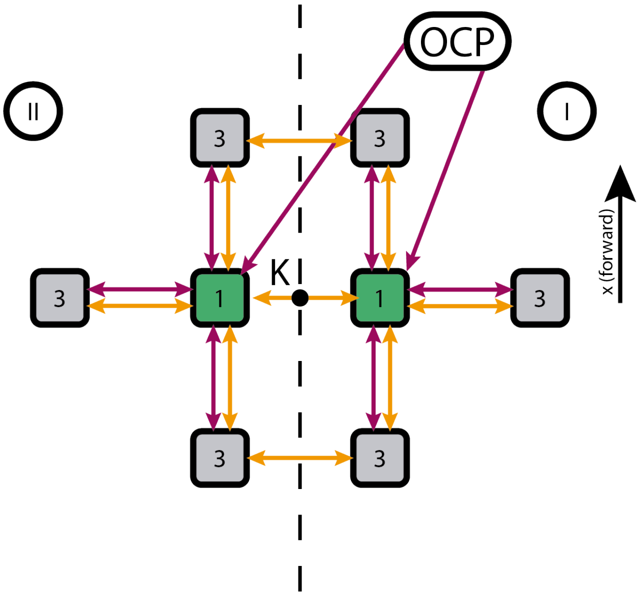


Figure 4.3: Communication scheme in a group with an odd number of rows and an even number of columns.

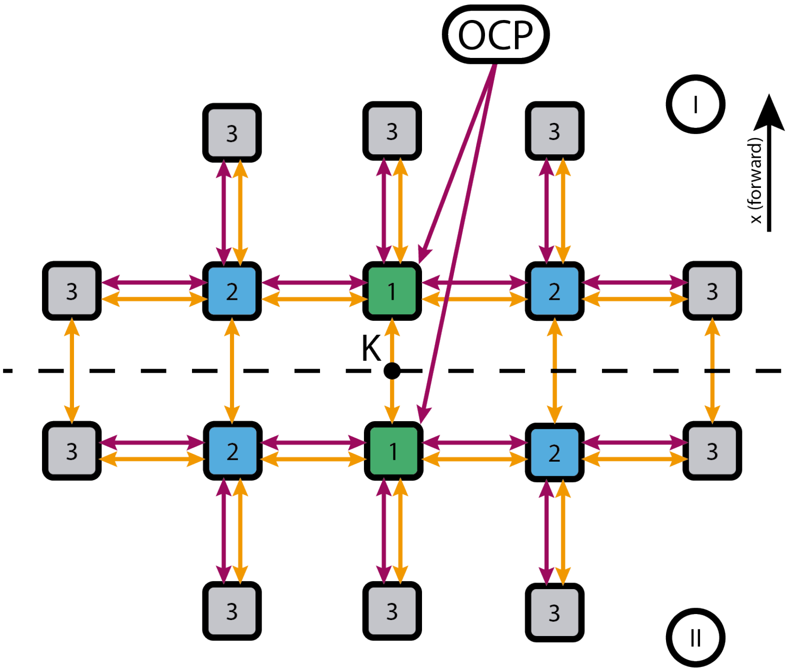


Figure 4.4: Communication scheme in a larger group with an odd number of rows and an even number of columns.

Even number of rows and columns. In a group where the number of rows and columns is even, the way to find leaders is doing as before but tracing two lines through K instead of one, resulting four quadrants (I, II, III, IV), as shown in Figure 4.5.

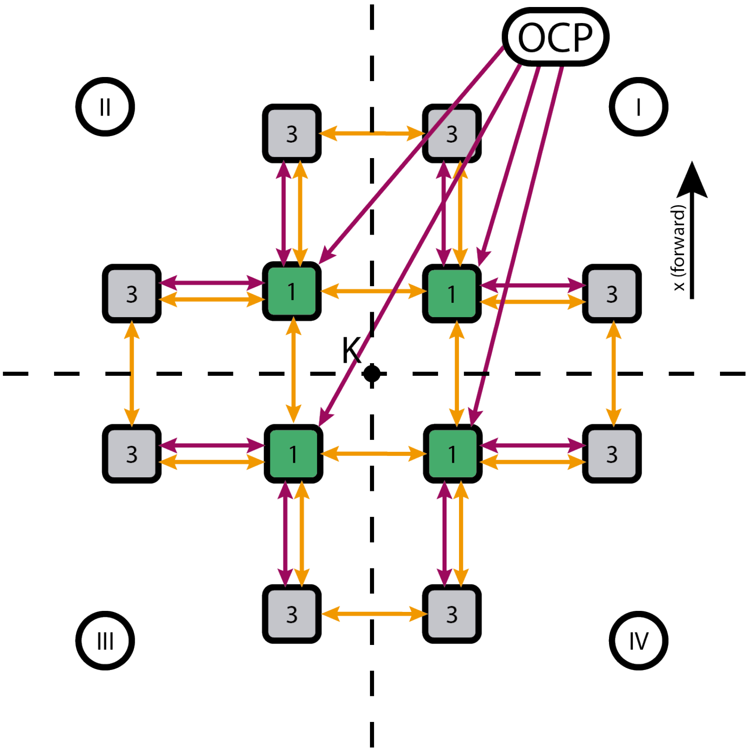


Figure 4.5: Communication scheme in a group with an even number of rows and columns.

From the outside to the inside of the group

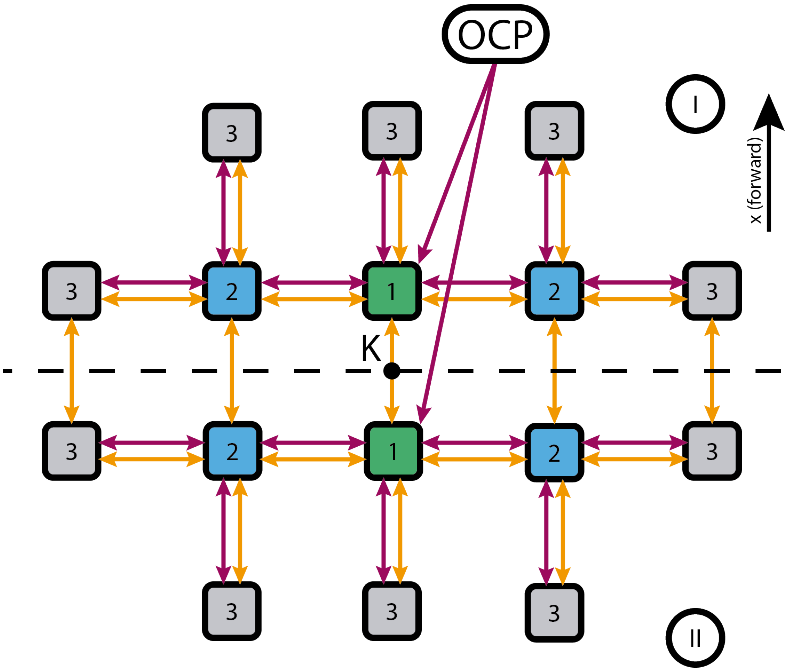


Figure 4.6: Communication scheme in a group like Figure 4.2 but communicating the OCP from the outside to the inside.

4.4 Mesh (Zigbee-like)

Using a mesh system gives much more freedom when designing group configurations. Shape, size and height of the vehicle does not matter. The only problem would be the need of using distance sensors to control the relative position in the group. The role of leader could be taken randomly by the first robots that pick a signal and then the information would be shared in the mesh, as shown in . In this case, not all the AGVs are aligned, and they stablish communication with the nearest (pink arrows) but they could also do it with further ones as long as the signal is capable of reaching. In the figure this is not shown to not fill it with arrows. All the members would act as repeaters (level 2) apart from the leaders, which receive from the coordinator.

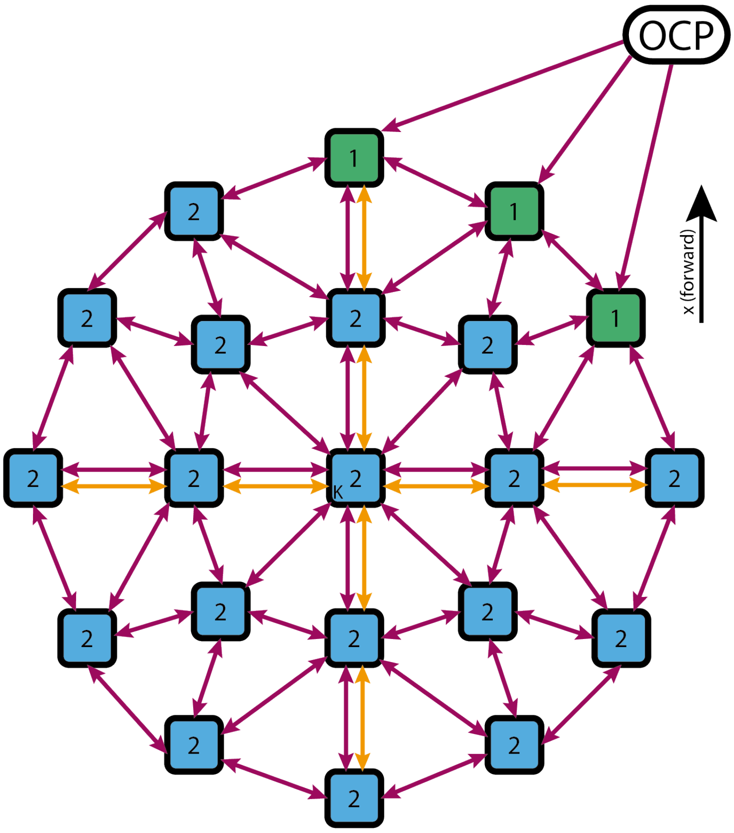


Figure 4.7: Communication scheme in a group creating a mesh.

Other more strange configurations can be achieved if the needs for transportation are different. For example, in Figure 4.8 is shown a group communicating in a mesh while they take a load. This load has an uneven weight distribution, and there is no need to use equispaced AGVs.

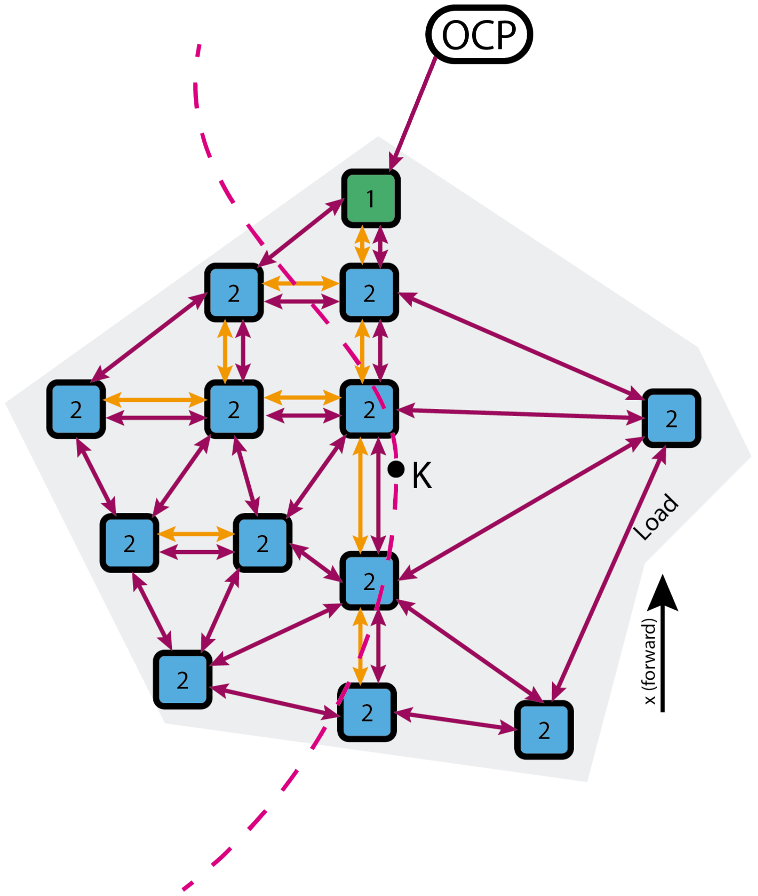


Figure 4.8: Communication scheme in a group with a non homogeneous load.

4.5 Substituting communication with distance control

In the cases where the level 3 AGVs are aligned with two or more AGVs, it could be possible to skip communicating OCP and, instead, just control the distance. This is a possibility because the relative position among the members of the group is always the same.

With regard to this control, if there are positional errors or deviations in the trajectory, it will be necessary to act to correct them. In fact, many of these deviations are unavoidable because the model does not take into account wheel slippage (in curves, for example). However, by the time action is taken, it may already be too late and the error may even have spread to other members of the group. The importance of this will be studied in the tests.

5 Components

In this chapter, the necessary components for each technology are presented. Minor components such as wires, resistances or breadboards are not mentioned.

5.1 Arduino Pro Mini Controller

The Arduino controller will be used in infrared technology as well as in Zigbee. The chosen model uses the ATMega328 chip.

Arduino Pro Mini 328 3.3V/8MHz. Datasheet of Arduino Pro Mini 3.3V.

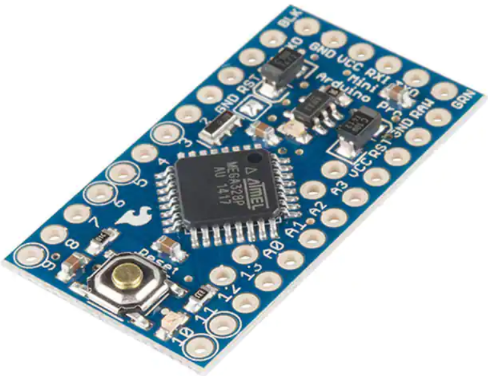


Figure 5.1: Arduino Pro Mini 3.3V.

5.2 FTDI

FTDI Adapter for Arduino Pro Mini is used to connect the Arduino board to a computer and then be able to upload the code to it. During tests, it is also used to supply power to the prototype.

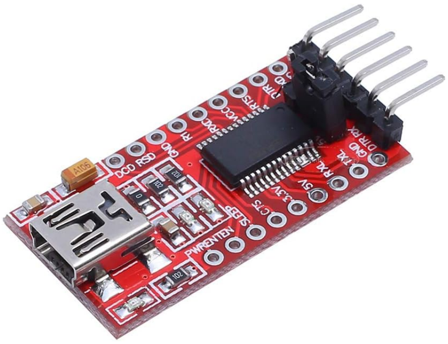


Figure 5.2: FTDI adapter for Arduino Pro Mini.

5.3 Infrared emitter

TSAL6200 Infrared emitter has been chosen due to its slightly wider viewing angle compared to similar emitters such as TSAL6100. More information can be found on its datasheet.

Figure 5.3: TSAL6200 Infrared emitter.

5.4 Infrared receiver

The TSOP4838 Infrared receiver has been chosen due to its compatibility with the TSAL6200 emitter. More information can be fount on its datasheet.

Figure 5.4: TSOP4838 Infrared receiver.

5.5 Zigbee module

For Zigbee, Digi XBee SX 868 RF Module is chosen. The main reason is that some of them are available and others are already working from another project and can be adjusted with minor changes for this project. There is more information about this modules in the datasheet of Digi XBee SX 868 RF-Modul.

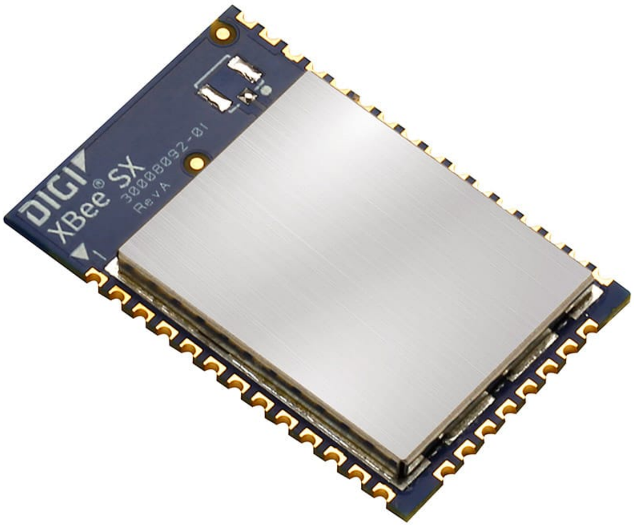


Figure 5.5: Digi XBee SX 868 RF-Modul.

6 Implementation

6.1 Infrared

Three devices are built to be tested afterwards (Figures 6.1 and 6.2). In this section it is described how these prototypes are built and programmed.

6.1.1 Connection of components

Receivers The TSOP4838 has three pin outputs, as described in its datasheet. 1 is the digital output, 2 is ground voltage and 3 is supply voltage. Its supply voltage range is 2 to 5.5 V, so it is supposed to work fine with this board when connected to V_{CC} on the board. Connecting one alone and testing the receiver using an example code and a remote controller, it is possible to see if it works, and it does.

Emitters For a simple circuit with an ordinary LED, the diode is connected to an output pin and to a ground pin. It also needs a resistance in series so that the maximum intensity value is not exceeded. For this regard, IR LED is basically a normal LED which light is not visible to human eye. According to the TSAL6200 datasheet, the typical voltage is 1.35V at test conditions.

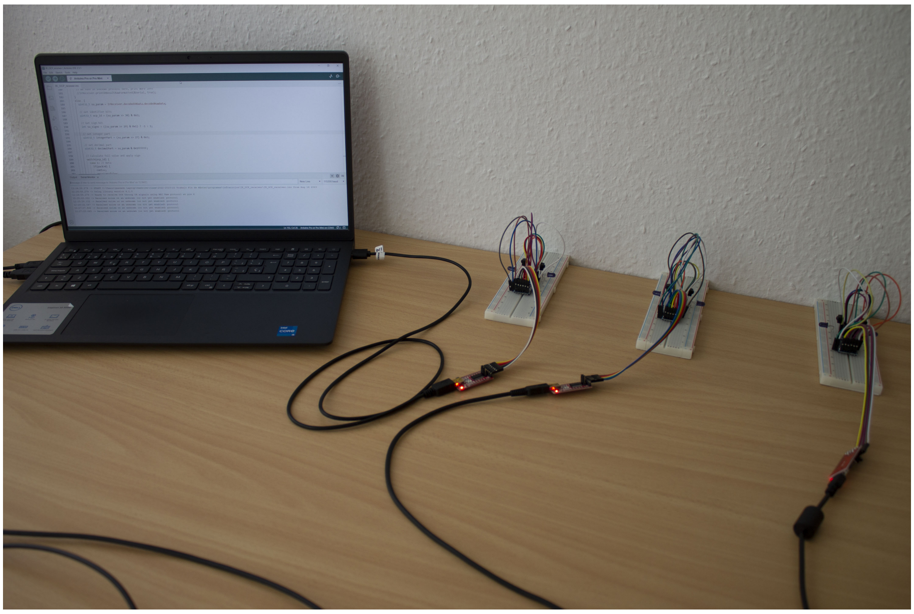


Figure 6.1: General overview of the three IR prototypes connected to a PC.

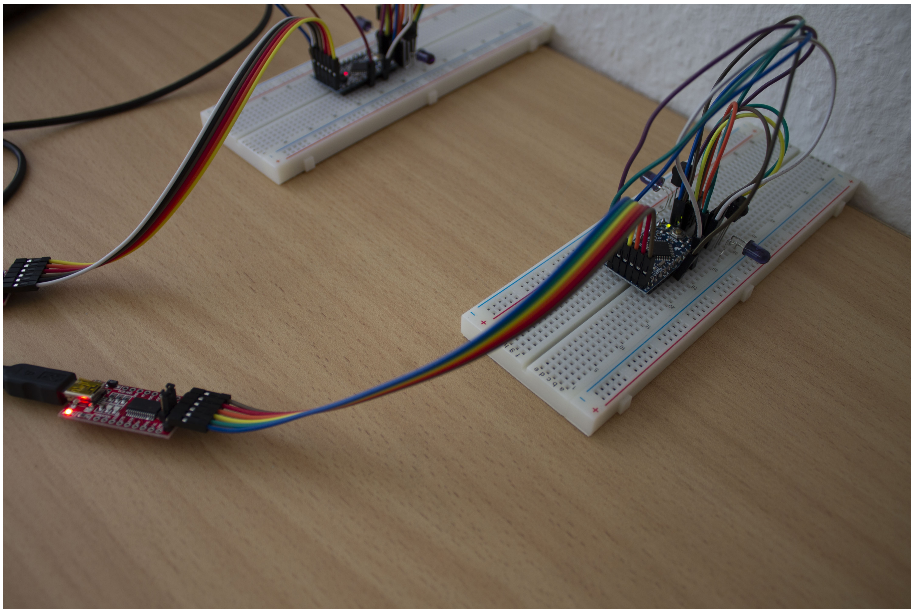


Figure 6.2: Closer look at one of the IR prototypes.

Even though the Arduino Pro Mini works at a supply voltage of 3.3 V, the voltage measured in a digital output pin when activated is 2.81 V. It is still higher than the IR emitter typical voltage, the resistance should be calculated according to this value:

$$R_{min} = \frac{V_{pin-gnd} - V_{TSAL6200}}{I_{max}} = \frac{(2.81-1.35)\ V}{0.1\ A} = 14.6\Omega \tag{6.1}$$

Then, it needs a resistance with a higher value than 14.6 ohms. When using a 22Ω resistance (the closest available), the measured value for the emitter is lower than 1.35 V: 1.223 V. Instead of using a resistance, as more than one emitter will be needed in the AGV, another solution is given. Two emitters in series would make a voltage drop close to the supply:

$$2 \cdot V_{LED} \approx V_{pin-gnd} \tag{6.2}$$

When measuring voltage in both emitters with this new configuration, they have a voltage drop of 1.156 V and 1.171 V. These values are considered to be close enough to the one measured with a resistance.

The transmitter is also sensitive to temperature, but the values of current and power dissipation are constant for the expected ranges of use (0 to almost 65).

To test if it is working, there is a “trick” to see if the IR LED is working. Uploading an Arduino code to the board that enables the pin output, it is possible to sée if it is working by pointing at it with a smartphone camera, as these cameras are sensitive to this kind of light.

Connection Connecting both emitters and receivers at the same breadboard, the resulting circuit is as shown in Figure 6.3.

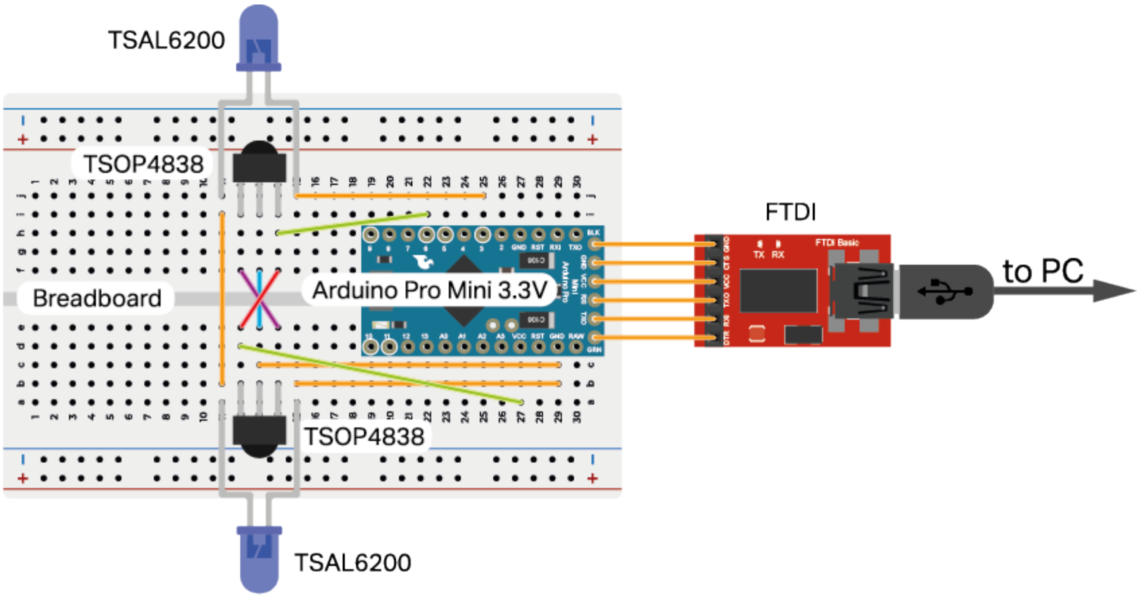


Figure 6.3: Connection diagram for the IR components.

The final prototypes are as seen in . They use the FTDI to connect to a PC for uploading the code and also to supply them with power during the tests.

6.1.2 Libraries and code

There is a library for Arduino called `IRremote.h`. It has a compilation of the most important protocols. These are developed by different manufacturers to use them on their devices to send commands, addresses and more, normally for remote controllers. Among all of these protocols, one was particularly interesting: NEC Raw protocol. Its arguments are two: one sends a 32 bit variable as unsigned integer for raw data and the other is an integer for number of repeats:

```
void  sendNECRaw (uint32_t aRawData, int_fast8_t aNumberOfRepeats=NO_REPEATS)
```

It is possible to use these 32 bits for data as desired, as long as the device receiving knows how to interpret the information. The proposal is as shown in Figure 6.4.

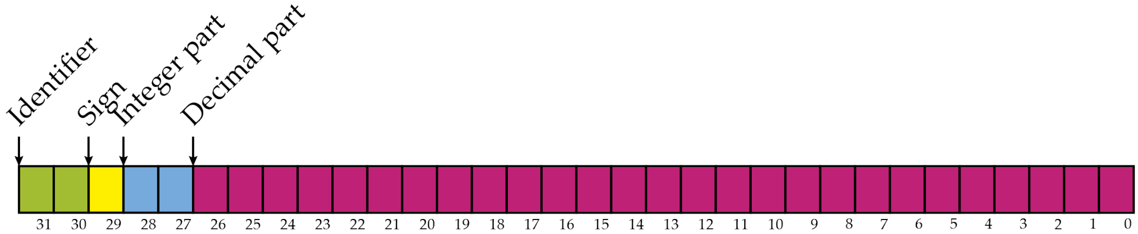


Figure 6.4: Distribution of bits of the raw data sent.

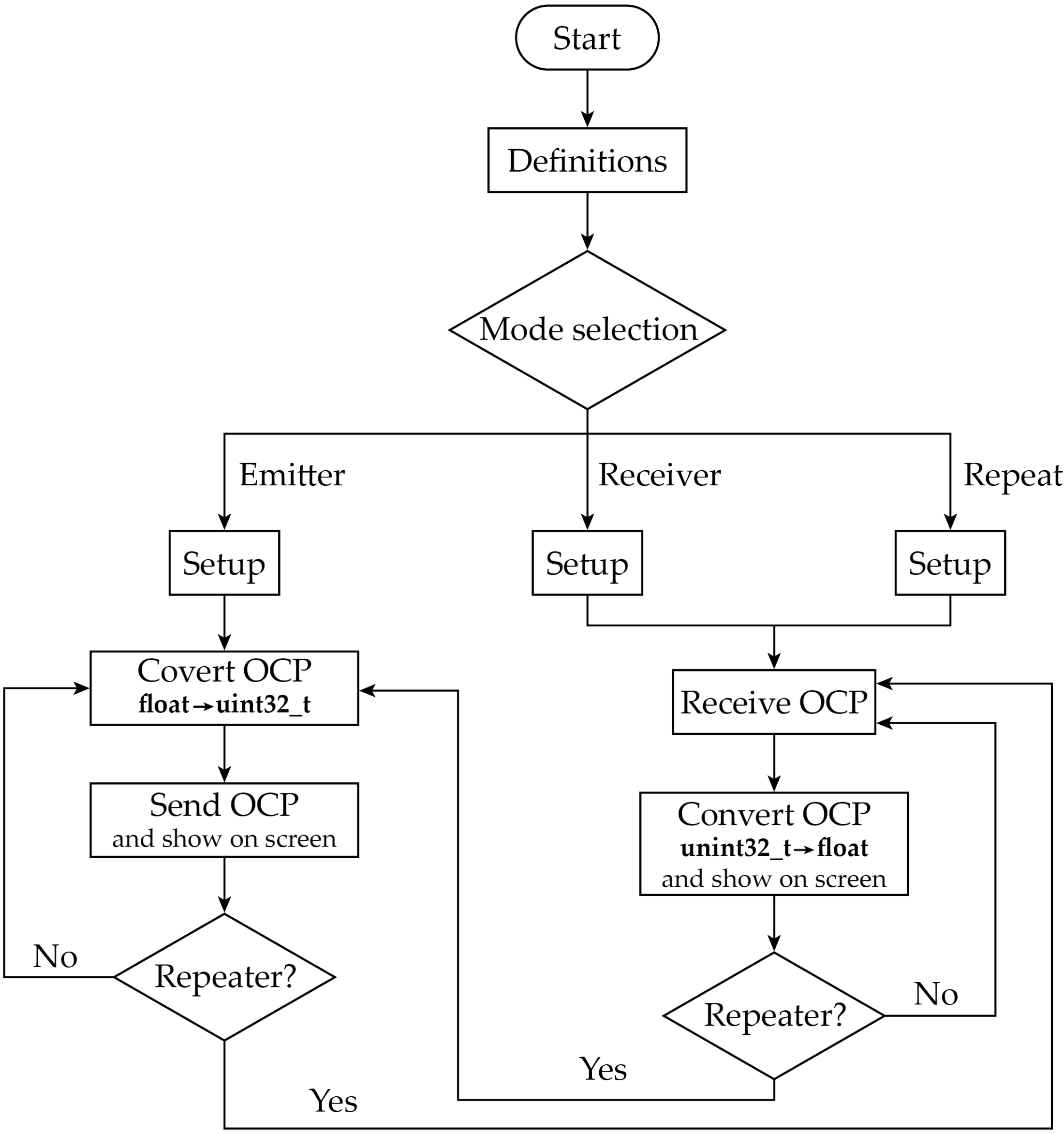


Figure 6.5: Flow chart for the infrared devices.

As shown in Figure 6.4, the two most significant bits are used to set an identifier, which with two bits can take four different values. Three are enough for the OCP, as there are only β, V_n and κ_n, that will take the values of 01, 10 and 11 respectively. The third most significant bit is used to know the sign. V_n can only be positive, but it is easier to use the same logic for every OCP. The next two are used for the integer part. The wider value range is $[-\pi, \pi]$, so the biggest integer is 3, which means that only two bits are needed. The remaining 27 bits are used for the decimal part of the number. For the tests, only 4 decimals will be used, and this number of bits is more than enough.

The code is available in the annex. It was developed using the the examples of sender and receiver available on the library. However, they suffered major changes and then they were mixed so that only one code is needed. The logic is as can be seen on Figure 6.5.

There are three available modes: sender, receiver and repeater. As the name suggests, the device acts as a sender, receiver or repeater (receaving and then sending) depending on the chosen mode. For sender, the device already knows the parameters, which are float type and have to be converted to unsigned integer of 32 bits. Then, the OCPs are sent and it starts again in an infinite loop. When receiving, the first thing it has to do is convert from unsigned integer of 32 bits to float using the inverse logic and then the parameters are shown on screen. When the repeater mode is active, it does both things secuentially. However, the way the prototypes are built do not allow to use this mode as it is likely to have interference due to the lack of the obstacle that the AGV would represent between two consecutive devices emitting.

6.1.3 Limitations

Neither this library nor later derived libraries allow assigning more than one output pin for transmitters or more than one input pin for receivers. This is normally not a problem, because this technology is mostly used in remote controllers. However, it is intended to send IR signals in more than one direction at the same time. Although it is the same information in all emitters, the voltage supplied by the board is not sufficient to supply more than two emitters or receivers in series.

6.1.4 Possible expansions

For the tests, a couple of emitters and receivers are enough. However, if more are needed, and in spite of having more pins available, they cannot be used the same way it was shown in Figure 6.3. In this case, a multiplexer would be needed. Then, with the output pin, the signal is sent, while with other two pins it is decided which is the emitter that sends each time. As the multiplexers are really fast, this would make a great difference in terms of latency.

6.2 Zigbee

Four Digi XBee SX 868 RF boards are used. A general view of all the components used can be seen in Figure 6.7. One is used on the coordinator device (Figure 6.6) and the rest on the modules (6.8). All of them are taken from a previous project and already have the connections between the Arduino and Zigbee, as well as the power supply and the antenna on the modules.

The code for the coordinator is written in Python, while the modules use Arduino. All the files are available in the annex. The modules code sets a configuration and then sends or receive, following a similar logic as the IR code. To change the values that each module has, it is necessary to connect the module to the computer and upload an updated code using a USB (Figure 6.9). The coordinator logic flow is as shown in Figure 6.10.

Figure 6.6: Zigbee coordinator device.

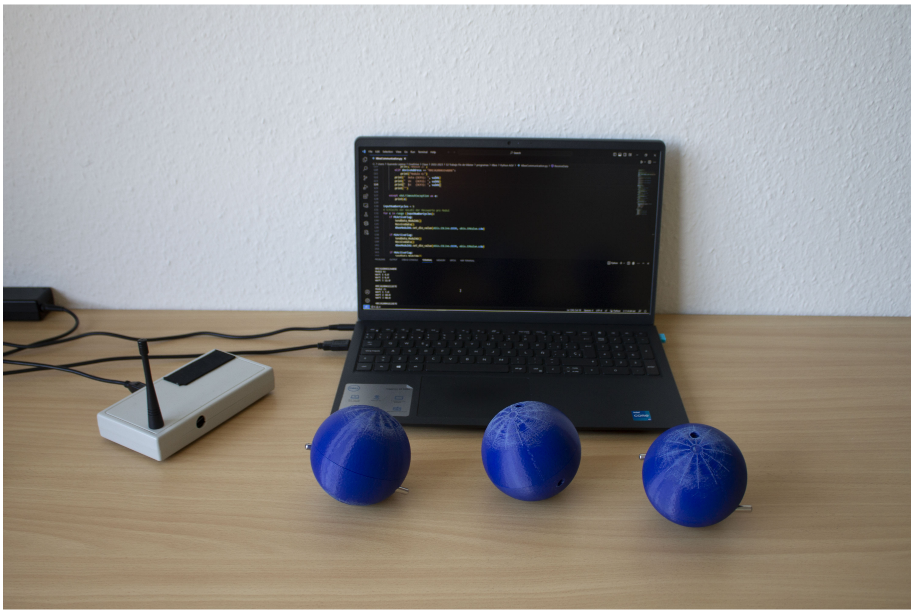


Figure 6.7: General view of all the devices, being the coordinator connecteed to a PC.

Figure 6.8: Three modules used for the tests.

Figure 6.9: Zigbee module connected to PC.

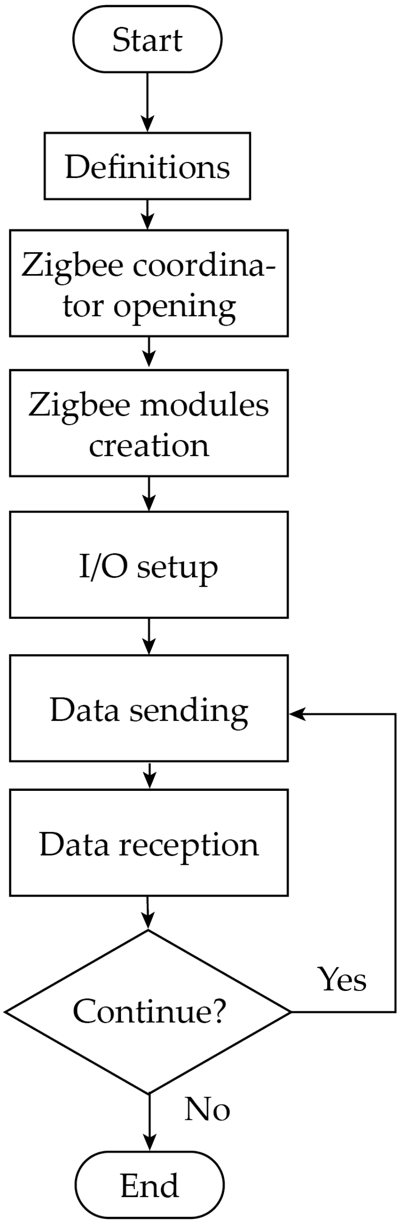


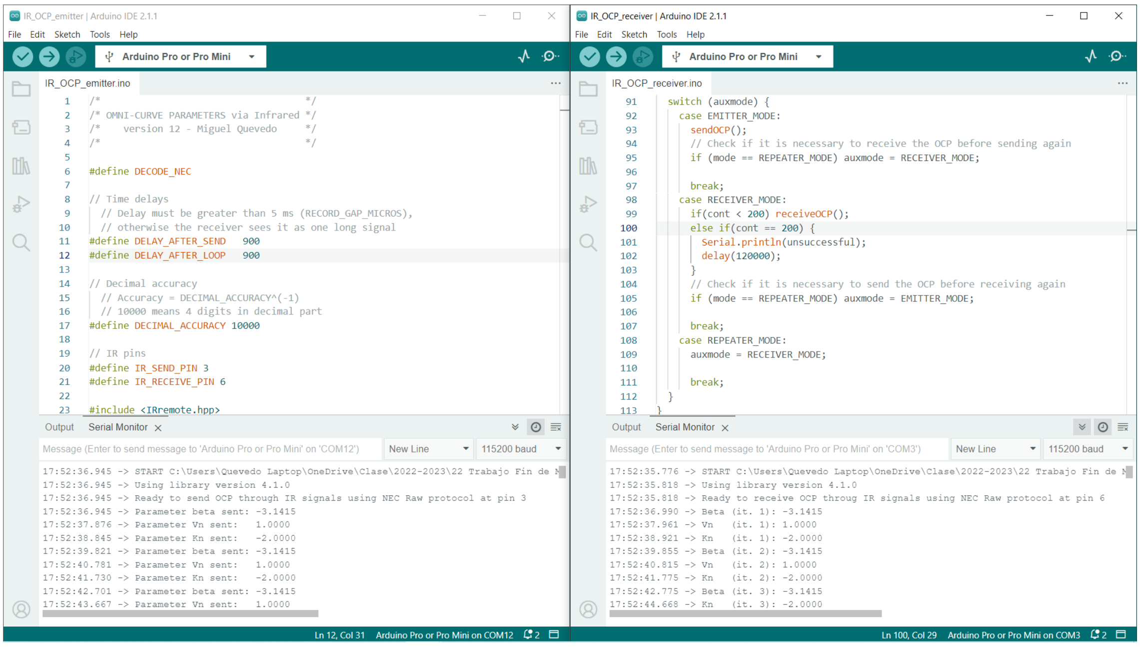
Figure 6.10: Flow chart for the zigbee coordinator code.

7 Testing and results

In this chapter, infrared and Zigbee are tested. It is intended to check the technologies capabilities shown in Chapter 3.

7.1 Infrared

To write, build and upload the code to the boards, as well as showing the results on screen, Arduino IDE 2.1.1 has been used. This code is the same for emitter, receiver and repeater. Before uploading the code to the board, the working mode is selected. However, in a possible future enhancement, the mode could be given as an initialization signal to avoid having to upload the code every time a change of function is required.



```
/*                                 */
/* OMNI-CURVE PARAMETERS via Infrared */
/*    version 12 - Miguel Quevedo     */
/*                                 */

#define DECODE_NEC

// Time delays
  // Delay must be greater than 5 ms (RECORD_GAP_MICROS),
  // otherwise the receiver sees it as one long signal
#define DELAY_AFTER_SEND   900
#define DELAY_AFTER_LOOP   900

// Decimal accuracy
  // Accuracy = DECIMAL_ACCURACY^(-1)
  // 10000 means 4 digits in decimal part
#define DECIMAL_ACCURACY 10000

// IR pins
#define IR_SEND_PIN 3
#define IR_RECEIVE_PIN 6

#include <IRremote.hpp>
```

```
17:52:36.945 -> START C:\Users\Quevedo Laptop\OneDrive\Clase\2022-2023\22 Trabajo Fin de
17:52:36.945 -> Using library version 4.1.0
17:52:36.945 -> Ready to send OCP through IR signals using NEC Raw protocol at pin 3
17:52:36.945 -> Parameter beta sent: -3.1415
17:52:37.876 -> Parameter Vn sent:   1.0000
17:52:38.845 -> Parameter Kn sent:   -2.0000
17:52:39.821 -> Parameter beta sent: -3.1415
17:52:40.781 -> Parameter Vn sent:   1.0000
17:52:41.730 -> Parameter Kn sent:   -2.0000
17:52:42.701 -> Parameter beta sent: -3.1415
17:52:43.667 -> Parameter Vn sent:   1.0000
```

```
  switch (auxmode) {
    case EMITTER_MODE:
      sendOCP();
      // Check if it is necessary to receive the OCP before sending again
      if (mode == REPEATER_MODE) auxmode = RECEIVER_MODE;

      break;
    case RECEIVER_MODE:
      if(cont < 200) receiveOCP();
      else if(cont == 200) {
        Serial.println(unsuccessful);
        delay(120000);
      }
      // Check if it is necessary to send the OCP before receiving again
      if (mode == REPEATER_MODE) auxmode = EMITTER_MODE;

      break;
    case REPEATER_MODE:
      auxmode = RECEIVER_MODE;

      break;
  }
}
```

```
17:52:35.776 -> START C:\Users\Quevedo Laptop\OneDrive\Clase\2022-2023\22 Trabajo Fin de
17:52:35.818 -> Using library version 4.1.0
17:52:35.818 -> Ready to receive OCP throug IR signals using NEC Raw protocol at pin 6
17:52:36.990 -> Beta (it. 1): -3.1415
17:52:37.961 -> Vn   (it. 1): 1.0000
17:52:38.921 -> Kn   (it. 1): -2.0000
17:52:39.855 -> Beta (it. 2): -3.1415
17:52:40.815 -> Vn   (it. 2): 1.0000
17:52:41.775 -> Kn   (it. 2): -2.0000
17:52:42.775 -> Beta (it. 3): -3.1415
17:52:44.668 -> Kn   (it. 3): -2.0000
```

Figure 7.1: Example interface and output given by the emitter and the receiver.

7.1.1 Success at receiving

At first, it is observed how sensitive this technology is to obstacles. It does not lose the signal completely, but enough consider it noise, and therefore, fail at communicating that packet.

Table 7.1: Unsuccessful communications in 200 packets.

Distance [cm]	**Angle [deg]**	**Repetitions**	**Delay after sending [ms]**								
			2000	**900**	**750**	**500**	**100**	**50**	**25**	**10**	**5**
40	0	0	104	109	88	102	113	99	88	-	-

It does not seem to exist a clear relation between the delay between messages and success at receiving. In any case, the number of wrong received groups of OCP is quite high. A group is considered to be wrong received when at least one of the OCP is missing, either because a signal has been interpreted as noise or because it has simply not been detected and has been skipped.

7.1.2 Repetitions

In NEC protocol there is an option to repeat the signal when sending without making major changes in the code for receiver or emitter. Doing this takes a bit more time, but can help ensure message reception. Same delays test is run adding repetitions, as it is shown in Table 7.2.

Table 7.2: Unsuccessful communications in 200 packets adding repetitions.

Distance [cm]	**Angle [deg]**	**Repetitions**	**Delay after sending [ms]**								
			2000	**900**	**750**	**500**	**100**	**50**	**25**	**10**	**5**
40	0	0	104	109	88	102	113	99	88	-	-
40	0	1	77	83	94	86	92	90	80	85*	88*
40	0	2	91	89	82	84	90	112	71	85	95*
40	0	3	116	99	92	96	101	96	76	91	82*

Table 7.3: Percentage of successful communications in 200 packets.

Distance [cm]	**Angle [deg]**	**Repetitions**	**Delay after sending [ms]**								
			2000	**900**	**750**	**500**	**100**	**50**	**25**	**10**	**5**
40	0	0	48,0	45,5	56,0	49,0	43,5	50,5	56,0	-	-
40	0	1	61,5	58,5	53,0	57,0	54,0	55,0	60,0	57,5	56,0
40	0	2	54,5	55,5	59,0	58,0	55,0	44,0	64,5	57,5	52,5
40	0	3	42,0	50,5	54,0	52,0	49,5	52,0	62,0	54,5	59,0

According to Table 7.3, the option that ensures most successful communications is with a 25 ms delay between messages and a number of repetitions in each message of 2. However, transmission time is also a big concern that has to be taken into account.

7.1.3 Latency and transmission speed

The time used in each test to received the 200 packets is different. This is due to the implemented delay but also due to the number of transmissions received as noise that have to be repeated in order to achieve the expected number of OCP packets. Using the previous results, the average time to successfully receive a message is calculated according to:

$$(7.1)\quad \bar{t} = \frac{total\ time\ communicating}{number\ of\ successful\ communications}$$

And the average time for each test is shown in Table 7.4:

Table 7.4: Average time in seconds to receive a full OCP packets.

Distance [cm]	**Angle [deg]**	**Repetitions**	**Delay after sending [ms]**								
			2000	**900**	**750**	**500**	**100**	**50**	**25**	**10**	**5**
40	0	0	132,82	67,47	44,82	35,52	11,49	6,93	4,64	-	-
40	0	1	109,52	55,04	50,84	35,18	13,52	9,91	7,59	7,30	7,77
40	0	2	129,45	63,60	54,15	39,32	19,27	21,60	12,33	13,05	14,67
40	0	3	174,53	80,00	63,90	50,96	27,48	24,81	18,38	20,28	18,99

It can be seen that in general the time values decrease as the delay decreases and increase with the number of repetitions. This is not exactly the case with delays of 10 and 5 ms, which, due to a multitude of messages interpreted as noise, make communication very inefficient.

The maximum transmission speed (TS_{max}) achieved is the inverse of the value corresponding to a delay of 25 ms and no repetitions. If, on average, it takes 4.64 seconds to send a complete packet, the speed would be:

$$(7.2)\quad TS_{max} = \frac{1\ packet}{4.64\ s} = 0.216\ packets/s = 12.93\ packets/min$$

This is far from expected and desired. The fastest after this (disregarding the 5 and 10 ms delay ones) would be 50 ms delay without repetitions and then 25 ms with one repetition. This will be the preferred configuration for the next tests.

7.1.4 Distance and angle

From the random distance of 40 cm and the zero degree angle, it was concluded that 25 ms delay between messages and no repetition would be used in further tests. Now, other distances and angles, are tested in these conditions. The results are shown in Table 7.5:

Table 7.5: Successful packets as function of other distances and angles.

Delay [ms]	**Repetitions**	**Angle [deg]**	**Distance between emitter and receiver [cm]**						
			20	**40**	**50**	**60**	**70**	**80**	**100**
25	0	0	122 (61%)	112 (56%)	0 (0%)				
25	1	0	118 (59%)	120 (60%)	21 (10,5%)	0 (0%)			
25	2	0		88 (44%)	0 (0%)				
25	0	5	117 (58,5%)						
25	1	5		8 (4%)	0 (0%)				
50	0	0			0 (0%)				
50	1	0			31 (15,5%)				

It was intended to use the best conditions found on previous tests to try different distances, starting from 20 cm. It was similar until 50 cm distance was tested. No packets would reach the receiver, which only received noise. Later, another attempt was made adding one repetition to each message, with which it was possible to receive some packets, although very few (10.5%). With two repetitions, the results were even worse, so it was decided to try with a delay of 50 ms. This only worked when using one repetition, and only 15.5% of the packets could arrive well and taking huge times to reach the number of 200 packets.

Then, to test the angle deviation, using 25 ms delay and none and one repetition, it was clear that the only results similar to not having deviation were when the emitter and receiver were really close.

The rest of distances were not tested because it seemed clear that they would not work.

7.1.5 Robustness

Defined as a *combination of the various factors that affect the reliability and performance of a communication technology*, this case is clearly not robust. It is expected that some packets come with errors but not at the scale that resulted from the tests. It is not reliable. And, in addition to all, the system very slow and with a short range.

7.1.6 Other considerations

Individual message transmission. When a successfully received message is regarded individually, it is noticeable that the time needed is really short. This time includes the whole processing of one parameter from a the way it is received to its final representation. As it is not always the same time, some samples are taken and the average time is calculated (Table 7.6).

Table 7.6: Time that takes for one individual message to be shown on screen.

Repetitions	**Shown on screen [s]**		**Dif. [ms]**	**Average**
	Sent	**Received**		
0	51,633	51,710	77	**68,3125**
0	40,835	40,869	34	
0	1,93	1,967	37	
0	25,168	25,242	74	
1	6,521	6,613	92	
1	54,787	54,869	82	
1	45,999	46,089	90	
1	47,806	47,879	73	
2	7,618	7,675	57	
2	0,832	0,906	74	
2	24,817	24,857	40	
2	47,561	47,659	98	
3	15,377	15,424	47	
3	10,657	10,758	101	
3	5,884	5,968	84	
3	28,557	28,590	33	

Power supply. What spoils the expected good features of IR is the large number of unsuccessful receptions, which are repeated at the cost of too much time, as well as the short range. The signals are very sensitive to obstacles, electric noise when the wires are moved and angle deviations. If this problem could be solved, this technology could still be considered as an alternative for communicating OCPs. The reasons behind the numerous unsuccessful receptions can be varied. Interference is discarded because the tests were conducted in an environment free of this kind of signals. However, one reason that may explain these results would be an insufficient voltage at the emitters. The voltage provided is within the working range of these emitters, but their performance may be influenced to some extent by a low value. To solve this, they could be powered by an external supply at a higher voltage, and controlled from the Arduino board pins via a transistor.

Limited group configuration. In addition to all the problems outlined so far, the IR technology already had a disadvantage in its conception. Due to the strong directionality of the emitters, it is not only sensitive to deviations, but needs a transmitter-receiver pair on each side of the AGV to cover both axes of the plane. This would make communication possible with adjacent AGVs on the sides, rear and front, but not with AGVs arranged on their diagonal, nor with other AGVs further away or behind one another.

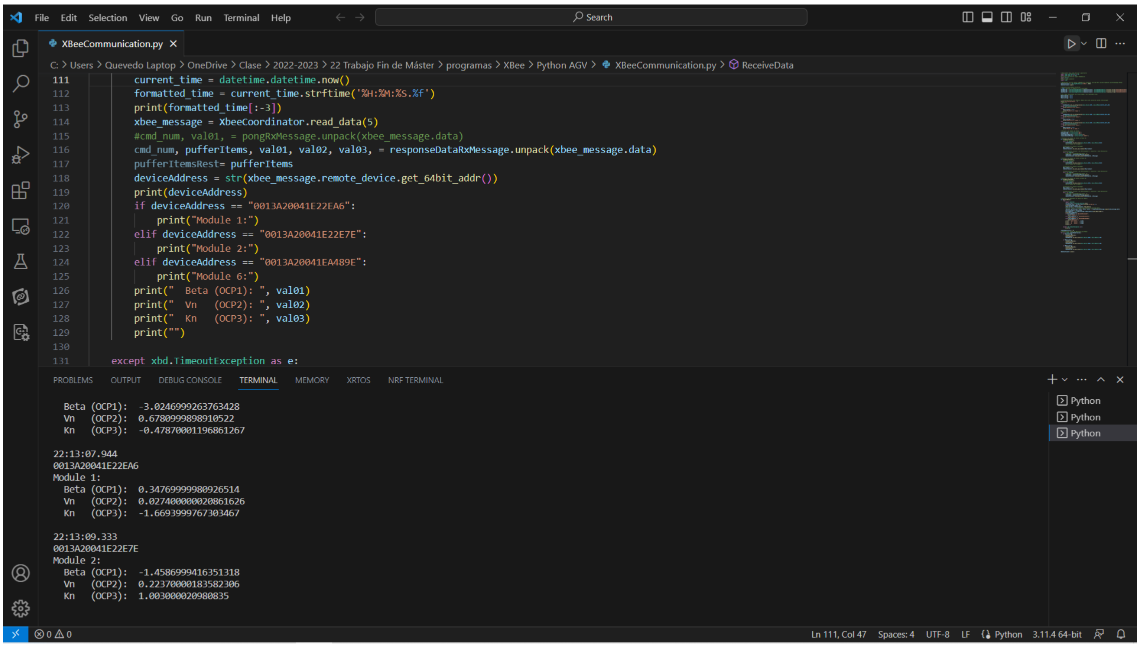
7.2 Zigbee

Tests for Zigbee are done for the expected conditions that the AGVs would have in terms of distance. This means that the maximum distance could be, for example, 1.5 m and the minimum 40 cm. The angle is not regarded in this technology test because it works with radio waves instead of light beams. On one side, the Python code of the coordinator gives an output of the packets received from the modules. On the other, using a the Zigbee software XCTU, a radio range test can be done. Even tough the conditions are the same, this programs cannot be used at the same time, so tests will take place twice.

The tests consist in changing distance among the modules from 40 cm to more that 1.5 m and see how it affects to the output from the coordinator and the radio range test. The distance from the coordinator to the nearest module will always be two meters. The modules are disposed in the shape of an equilateral triangle in all the test except the last, in which they are disposed in a line to see what happens if one module is more than six meters away from the coordinator.

7.2.1 Latency and transmission speed

Neither latency nor transmission speed can be properly measured the way the code is done. However, the output from the coordinator (Figure 7.2) shows a new received packet from the same module at a rate of approximately 1.2 seconds, which is also much shorter than infrared.



```
        current_time = datetime.datetime.now()
        formatted_time = current_time.strftime('%H:%M:%S.%f')
        print(formatted_time[:-3])
        xbee_message = XbeeCoordinator.read_data(5)
        #cmd_num, val01, = pongRxMessage.unpack(xbee_message.data)
        cmd_num, pufferItems, val01, val02, val03, = responseDataRxMessage.unpack(xbee_message.data)
        pufferItemsRest= pufferItems
        deviceAddress = str(xbee_message.remote_device.get_64bit_addr())
        print(deviceAddress)
        if deviceAddress == "0013A20041E22EA6":
            print("Module 1:")
        elif deviceAddress == "0013A20041E22E7E":
            print("Module 2:")
        elif deviceAddress == "0013A20041EA489E":
            print("Module 6:")
        print("  Beta (OCP1): ", val01)
        print("  Vn   (OCP2): ", val02)
        print("  Kn   (OCP3): ", val03)
        print("")

    except xbd.TimeoutException as e:
```

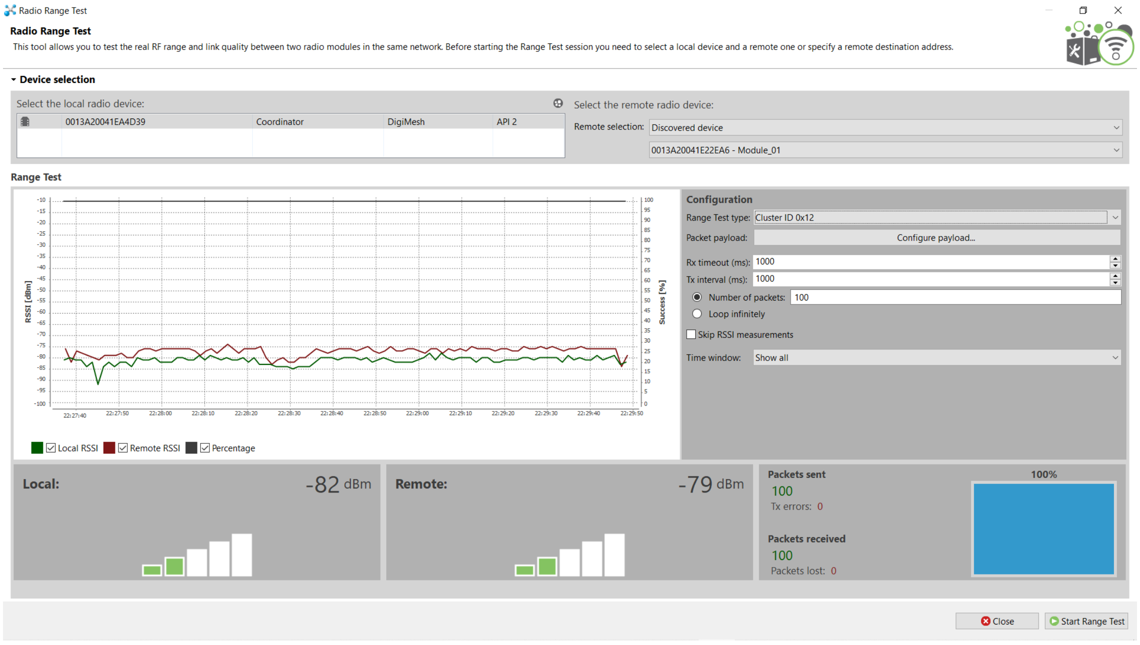
```
  Beta (OCP1):  -3.0246999263763428
  Vn   (OCP2):  0.6780999898910522
  Kn   (OCP3):  -0.47870001196861267

22:13:07.944
0013A20041E22EA6
Module 1:
  Beta (OCP1):  0.34769999980926514
  Vn   (OCP2):  0.027400000020861626
  Kn   (OCP3):  -1.6693999767303467

22:13:09.333
0013A20041E22E7E
Module 2:
  Beta (OCP1):  -1.4586999416351318
  Vn   (OCP2):  0.22370000183582306
  Kn   (OCP3):  1.003000020980835
```

Figure 7.2: Example output given by the central module.

7.2.2 Range and success at communicating

Radio range tests are carried out with the XCTU program. It measures the power relation in decibels per one milliwatt (dBm). This dimensional measure gives an idea of how strong the transmission is, so the higher is the value, the stronger is the signal. It can be converted to watts doing:

$$P = 1\ mW \cdot 10^{\frac{x}{10}}\ [mW] \qquad (7.3)$$



Radio Range Test

Radio Range Test

This tool allows you to test the real RF range and link quality between two radio modules in the same network. Before starting the Range Test session you need to select a local device and a remote one or specify a remote destination address.

Device selection

Select the local radio device:

0013A20041EA4D39	Coordinator	DigiMesh	API 2

Select the remote radio device:

Remote selection: Discovered device

0013A20041E22EA6 - Module_01

Range Test

Configuration

Range Test type: Cluster ID 0x12

Packet payload: Configure payload...

Rx timeout (ms): 1000

Tx interval (ms): 1000

● Number of packets: 100

○ Loop infinitely

☐ Skip RSSI measurements

Time window: Show all

Local: -82 dBm

Remote: -79 dBm

Packets sent 100

Tx errors: 0

Packets received 100

Packets lost: 0

100%

Figure 7.3: Example output from the radio range test window in XCTU.

Figure 7.3 shows an example output of the radio range test console. It measures the power relation between coordinator and module one. The results for all distances are shown in **??**:

Table 7.7: Results of radio range tests.

Distance [cm]	Radio range [dBm]		Packets	
	Local	Remote	Sent	Received
40	-82	-79	100%	100%
60	-79	-76	100%	100%
80	-80	-76	100%	100%
100	-82	-78	100%	100%
150	-82	-75	100%	100%

No packets were lost in any of the tests, which is already a great advantage compared to infrared. Maybe this changes at bigger distances, but for the range wanted for AGV group conditions that is perfect. For the rest of modules, another diagram gives the information in a more visual way. This information is shown below.

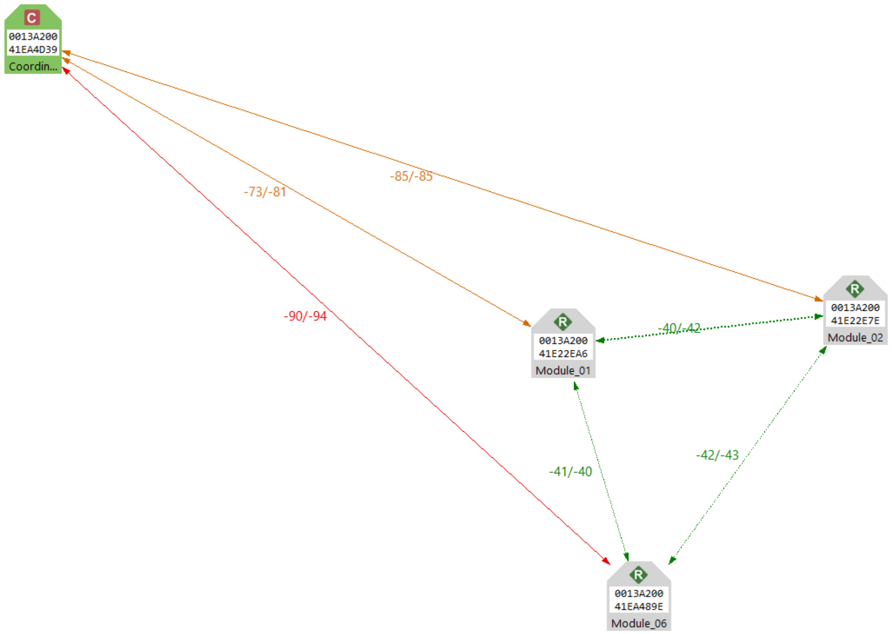


Figure 7.4: 40 cm between modules.

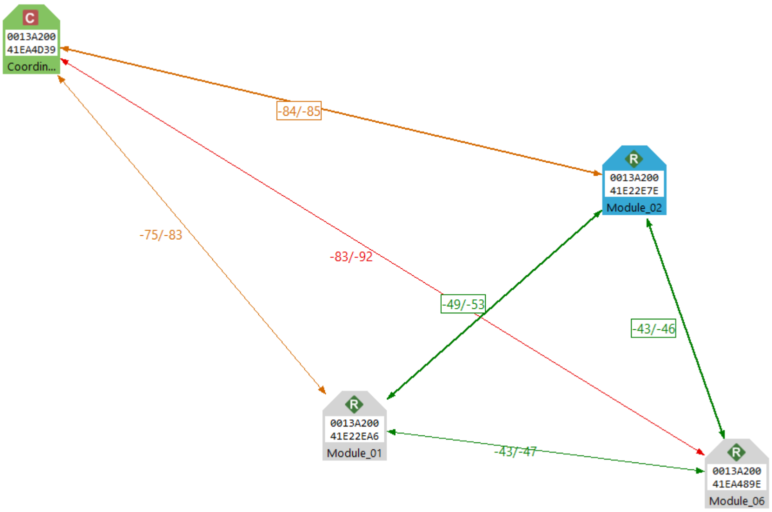


Figure 7.5: 60 cm between modules.

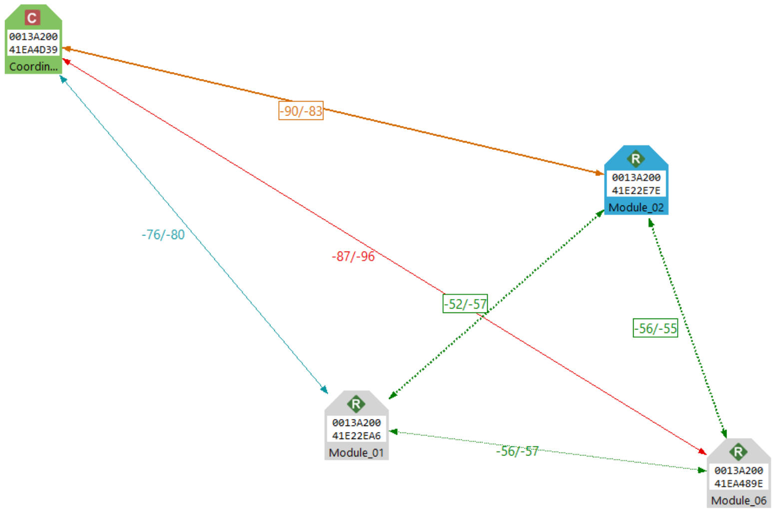


Figure 7.6: 80 cm between modules.

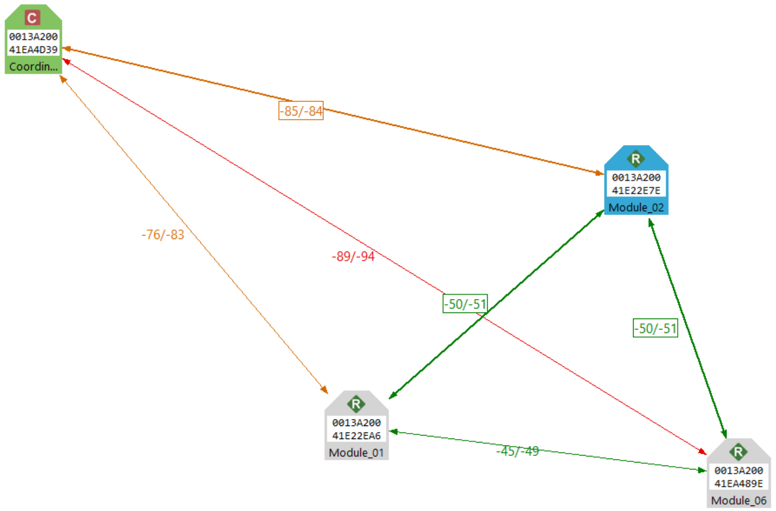


Figure 7.7: 100 cm between modules.

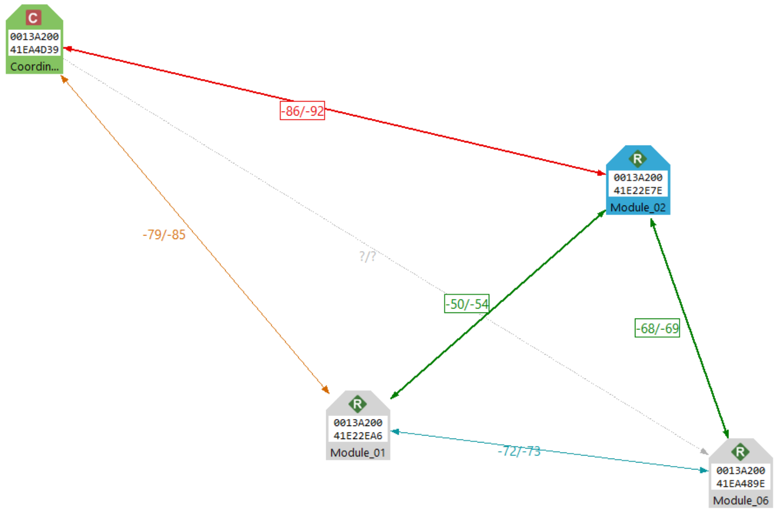


Figure 7.8: 150 cm between modules.

Table 7.8: Range test for 40 cm between the modules.

Distance: 40 cm				
	Coordinator	**Module 1**	**Module 2**	**Module 6**
Coordinator	-	-73	-85	-90
Module 1	-81	-	-40	-41
Module 2	-85	-42	-	-42
Module 6	-94	-40	-43	-

Table 7.9: Range test for 60 cm between the modules.

Distance: 60 cm				
	Coordinator	**Module 1**	**Module 2**	**Module 6**
Coordinator	-	-84	-75	-83
Module 1	-85	-	-49	-43
Module 2	-83	-53	-	-43
Module 6	-92	-47	-46	-

Table 7.10: Range test for 80 cm between the modules.

Distance: 80 cm				
	Coordinator	**Module 1**	**Module 2**	**Module 6**
Coordinator	-	-76	-90	-87
Module 1	-80	-	-52	-56
Module 2	-83	-57	-	-56
Module 6	-96	-57	-55	-

Table 7.11: Range test for 100 cm between the modules.

Distance: 100 cm				
	Coordinator	**Module 1**	**Module 2**	**Module 6**
Coordinator	-	-76	-85	-89
Module 1	-83	-	-50	-45
Module 2	-84	-51	-	-50
Module 6	-94	-49	-51	-

Table 7.12: Range test for 150 cm between the modules.

Distance: 150 cm				
	Coordinator	**Module 1**	**Module 2**	**Module 6**
Coordinator	-	-79	-86	?
Module 1	-85	-	-50	-72
Module 2	-92	-54	-	-68
Module 6	?	-73	-69	-

Results summary From Figures 7.4 to 7.8 and Tables 7.8 to 7.12 it can be seen that as the distance grows, the power decreases. In the range of distances used, the values stay in the normal for a wireless network. The only situation when the coordinator do not keep direct communication with a module in the last test, but it keeps communicating with the rest of the mesh.

7.2.3 Robustness

The fact that no packets are lost and that it is really fast communicating, makes Zigbee a very robust option to implement the OCP communication. Furthermore, it allows to take more freedom in creating group configurations and using AGVs with different shapes, heights and sizes.

8 Conclusion and Outlook

After studying and comparing several technologies, the chosen ones represent different approaches or systems in communication. This is interesting, because each of them requires different things, and also give different advantages and disadvantages. However, although these conclussions are specific to these technologies, some might be valid for other ones that use a similar concept. For example, IR and laser have a high dependence on the orientation of their sensors, and the concept of mesh is similar in Zigbee and Bluetooth 5.

Looking at de results of the tests, it seems clear that Zigbee and its mesh concept is far better than IR to communicate the OCPs. In spite of all the problems regarding robustness on the IR prototypes (poor rate of reception, short range and slowness in general), lineal communication cannot compete against mesh systems. Even though these IR problems were solved, the mesh concept looks ideal for a group of AGVs.

Outlook

Next thing to do following this work would be to implement Zigbee in the AGVs and test their performance. Another interesting next step could be to deepen on the mesh technologies and compare Zigbee and Bluetooth 5, and also test the concepts for information flow and discover which is the best option for each case.

Bibliography

[ASS+21] P. D. P. Adi, V. Sihombing, V. M. M. Siregar, G. J. Yanris, F. A. Sianturi, W. Purba, S. P. Tamba, J. Simatupang, R. Arifuddin, Subairi, D. A. Prasetya. “A Performance Evaluation of ZigBee Mesh Communication on the Internet of Things (IoT)”. In: *2021 3rd East Indonesia Conference on Computer and Information Technology (EIConCIT)*. 2021, pp. 7–13. DOI: `10.1109/EIConCIT50028.2021.9431875` (cit. on p. 25).

[AST+21] M. A. Arfaoui, M. D. Soltani, I. Tavakkolnia, A. Ghrayeb, C. M. Assi, M. Safari, H. Haas. “Measurements-Based Channel Models for Indoor LiFi Systems”. In: *IEEE Transactions on Wireless Communications* 20.2 (2021), pp. 827–842. DOI: `10.1109/TWC.2020.3028456` (cit. on p. 27).

[BC22] C. Brenner, A. Colomb. “Anwendung der Omni-Kurven-Parameter zur Bestimmung der Aktor-Stellgrößen und universellen Bewertung der Bewegungsmöglichkeiten unterschiedlicher Fahrwerke”. In: *18. Tagungsband der Wissenschaftlichen Gesellschaft für Technische Logistik (WGTL)*. Vol. 18. Logistics Journal: Proceedings. Wissenschaftliche Gesellschaft für Technische Logistik (WGTL). Sept. 2022. DOI: `10.2195/lj_proc_brenner_de_202211_01`. URL: `https://nbn-resolving.org/urn:nbn:de:0009-14-55825` (cit. on p. 11).

[CB20] *Konzept zur intuitiven Steuerung omnidirektionaler Flurförderzeuge mit beliebiger Radkonfiguration*. Logistics Journal: Proceedings. Wissenschaftliche Gesellschaft für Technische Logistik (WGTL). 2020. ISBN: 978-3-00-066746-6. DOI: `10.2195/lj_Proc_colomb_de_202012_01` (cit. on p. 11).

[CGM+18] D. Croce, M. Gucciardo, S. Mangione, G. Santaromita, I. Tinnirello. “Impact of LoRa Imperfect Orthogonality: Analysis of Link-Level Performance”. In: *IEEE Communications Letters* 22.4 (2018), pp. 796–799. DOI: `10.1109/LCOMM.2018.2797057` (cit. on p. 26).

[FWH+22] X. Fu, D. Wang, J. Hu, J. Wei, C.-B. Yan. “Leader-Follower Based Two-AGV Cooperative Transportation System in 5G Environment”. In: *2022 IEEE 18th International Conference on Automation Science and Engineering (CASE)*. 2022, pp. 67–72. DOI: `10.1109/CASE49997.2022.9926664` (cit. on p. 11).

[HL19] F. Huzaefa, Y.-C. Liu. “Centralized Control Architecture for Cooperative Object Transportation using Multiple Omnidirectional AGVs”. In: *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2019, pp. 6526–6532. DOI: `10.1109/IROS40897.2019.8968499` (cit. on p. 11).

[KB97] J. Kahn, J. Barry. “Wireless infrared communications”. In: *Proceedings of the IEEE* 85.2 (1997), pp. 265–298. DOI: `10.1109/5.554222` (cit. on p. 30).

[KMB18] F. Krasniqi, A. Maraj, E. Blaka. “Performance analysis of mobile 4G/LTE networks”. In: *2018 South-Eastern European Design Automation, Computer Engineering, Computer Networks and Society Media Conference (SEEDA$_C$ECNSM)*. 2018, pp. 1–5. DOI: `10.23919/SEEDA-CECNSM.2018.8544937` (cit. on p. 28).

[LMCP22] R. G. Lazar, A. V. Militaru, C. F. Caruntu, C. Patachia–Sultanoiu. “Performance analysis of 5G communication based on distance evaluation using the SIM8200EA-M2 module”. In: *2022 26th International Conference on System Theory, Control and Computing (ICSTCC)*. 2022, pp. 37–42. DOI: `10.1109/ICSTCC55426.2022.9931884` (cit. on p. 30).

[NJW+15] S. Narayan, C. Jayawardena, J. Wang, W. Ma, G. Geetu. “Performance test of IEEE 802.11ac wireless devices”. In: *2015 International Conference on Computer Communication and Informatics (ICCCI)*. 2015, pp. 1–6. DOI: `10.1109/ICCCI.2015.7218076` (cit. on p. 24).

[RLS20] C. Rizzo, A. Lagraña, D. Serrano. “GEOMOVE: Detached AGVs for Cooperative Transportation of Large and Heavy Loads in the Aeronautic Industry”. In: *2020 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC)*. 2020, pp. 126–133. DOI: `10.1109/ICARSC49921.2020.9096078` (cit. on p. 11).

[SG04] B. Stouten, A. de Graaf. “Cooperative transportation of a large object - development of an industrial application”. In: *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA ’04. 2004*. Vol. 3. 2004, 2450–2455 Vol.3. DOI: `10.1109/ROBOT.2004.1307428` (cit. on p. 11).

[SJT22] M.-T. Suer, P. Jose, H. Tchouankem. “Experimental Evaluation of IEEE 802.11ax - Low Latency and High Reliability with Wi-Fi 6?” In: *GLOBECOM 2022 - 2022 IEEE Global Communications Conference*. 2022, pp. 377–382. DOI: `10.1109/GLOBECOM48099.2022.10001475` (cit. on p. 24).

[ZSBB21] V. A. Zyulin, A. N. Semenova, A. K. Brazhnikova, D. A. Burilov. “Features of Building MESH Networks Based on Bluetooth Low Energy 5.1 Technology”. In: *2021 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (ElConRus)*. 2021, pp. 81–84. DOI: `10.1109/ElConRus51938.2021.9396530` (cit. on p. 26).

All links were last followed on August 22, 2023.

Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

place, date, signature