Université de Lille
Faculté des Sciences et Technologies

State of the art of the communications protocols used in Swarm Robotics and Swarm robotics Blockchain control

Ilias EL ABBASSI

Master Informatique
Master in Computer Science

Département d'Informatique
Faculté des Sciences et Technologies

July, 2023

This report partially satisfies the requirements defined for the Project/Internship course, in the 3rd year, of the Master in Computer Science.

Candidate: Ilias EL ABBASSI, No. 42026415,
ilias.elabbassi.etu@univ-lille.fr

Scientific Guidance: Gerald DHERBOMEZ,
gerald.dherbomez@univ-lille.fr

Département d'Informatique
Faculté des Sciences et Technologies
Campus Cité Scientifique, Bât. M3 extension, 59655 Villeneuve-d'Ascq

July, 2023

Abstract

This research paper is in reality a state of the art, about the communications protocols used in the field of Swarm Robotics.

Swarm robotics is an area of research that investigates the collective behavior of large groups of robots, inspired by the behavior of social insects such as ants and bees. One of the key challenges in swarm robotics is developing communication protocols that enable the robots to coordinate their actions effectively and reliably.

This state of the art offer a global view of the communication protocols used today. We will discuss about centralized and decentralized protocols used in swarm robotics.

But again, we are going to focus part of the state of the art on the use of Blockchain in Swarm Robotics, ie what Blockchain can bring to Swarm Robotics in term of communication and control ?

Furthermore one of the problems is that Swarm Robots are prone to environmental constraints, those constraints are sometimes a barrier to the use of some other communication protocols.

Keywords: Robotics, Swarm Robotics, multi-robot systems, protocols, communication, blockchain, WiFi, Bluetooth, overview, centralized, decentralized

Résumé

Ce papier de recherche est en réalité un état de l'art, sur les protocoles de communication utilisés dans le domaine des Swarm Robotics (Essaim de robots).

La robotique en essaim est un domaine de recherche qui étudie le comportement collectif de grands groupes de robots, inspiré du comportement d'insectes sociaux tels que les fourmis et les abeilles. L'un des principaux défis de la robotique en essaim est de développer des protocoles de communication permettant aux robots de coordonner leurs actions de manière efficace et fiable.

Cet état de l'art offre une vision globale des protocoles de communication utilisés aujourd'hui. Nous discuterons des protocoles centralisés et décentralisés utilisés dans la robotique en essaim.

Mais encore, nous allons focaliser une partie de l'état de l'art à l'utilisation de la Blockchain chez les Essaims de Robots, c'est-à-dire comment la Blockhain peut apporter aux Essaims de robots en termes de communication et de contrôle ?

De plus l'un des problèmes est que les Essaims de Robots sont sujets aux contraintes environnementales, ces contraintes sont parfois un obstacle à l'utilisation de certains protocoles de communication.

Mots-clés: Robotique, Essaim de robot, system multi-agent, protocoles, communication, blockchain, WiFi, Bluetooth, états de l'art, centralisé, décentralisé

Contents

List of Figures

List of Tables

Listings

Glossary

base

The stable platform to which an industrial robotic arm is attached.

ISM radio bands

The ISM radio bands are portions of the radio spectrum reserved internationally for industrial, scientific, and medical (ISM) purposes. [18]

Low Earth Orbit

An orbit around Earth with a period of 128 minutes or less. At approximately 73 km to 3000 km altitude from Earth.

mechatronics

Mechatronics engineering, is an interdisciplinary branch of engineering that focuses on the integration of mechanical, electrical and electronic engineering systems.

robot end effector

A peripheral device that attaches to a robot's wrist, allowing the robot to interact with its task.

Chapter 1

Swarm Robotics

First and foremost, we will discuss about our main topics which are robotic and its branch Swarm Robotics. To understand the latest we also need to have a bit of understanding of its root; Robotics. We will first discuss about what really is robotics for today and its history. We will discuss about the technologies that derive from it. Like multi robot system in particular. We will review the difference that discriminates Swarm Robots to Multi robot systems.

In the second part we will list few criteria that designate Swarm Robotics.

1.1 Robots and Robotics ?

Robotics and Robots are two specific words, I want to disambiguate this first. Robots are machines that are capable of doing tasks, such as physical tasks like assembly task or manufacturing, but it can also do cognitive tasks like decision making. Whereas in the other hand, Robotics is the field of study that creates those robots. It includes many other fields of study, like mathematics, electronics, computer science, Mechatronics and more.

Robots or automatons were always a fascinating part of human history. We can find traces of this aspect of the human in many parts of the world and in different decades and centuries. Engineers from around the world have tried to create self-operating machines, even from older civilizations like Ancient Greece, Ptolemaic Egypt, ancient China etc. We have literature trace of animal reassembling automaton, like the artificial birds of Mozi and Lu Ban , or even a washstand automaton by Philo of Byzantium. [19]

In the early beginnings of robotics, we can notice some works, like the machines from 13th century Muslim Scientist Ismail Al-Jazari. He builds many machines driven by hydropower like a peacock and automated gates and doors. But also a humanoid waitress, that could serve water and tea. And many more machines. Other engineers like the wildly know Leonardo Da Vinci sketched a humanoid robot, that could move its arms, head and jaw. [19]

Figure 1.1: In this picture we can see the model of Leonardo's robot with inner workings. Possibly constructed by Leonardo Da Vinci around 1495.

Modern robotics started in the mid twenty centuries, with a notable work from the neurophysiologist,e cybernetician and robotician William Grey Walter. They were the first robots in history that were programmed to "think" the way biological brains do and meant to have free will. [20]

We can also point the telemanipulator or Remote manipulator created in 1942, which was able to solve the problems cause by manipulating and handling radioactive materials. Notably, in the context of that time, with the Manhattan project, to build a nuclear bomb.

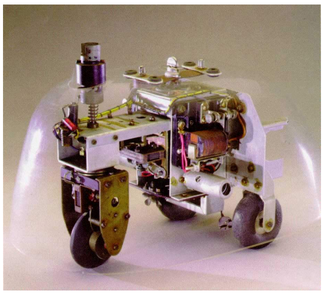

Figure 1.2: Here you can see a prototype of the tortoise robot why Grey Walter

Figure 1.3: Manipulator arms inside the Hot Bay of the Engine Maintenance Assembly and Disassembly Facility, in Area 25 of the Nevada Test Site. [1]

Different types of robots

There exist a lot of different robots, here we will list just a few to know the main ones :

- Stationary Robots : referring to robots where the Base doesn't change its position over time. They generally manipulate their environment by controlling the position and orientation of an Robot end effector. Like robot arms, Cartesian robots and more.

- Wheeled Robots : in opposition to the stationary robots, Wheeled robots change their position over time, mostly driven by motors.

- Legged Robots : as Wheeled robots, legged ones are also able to change their position but this the ability to move their legs. It is much more complex to implement than driving wheels, especially on uneven environment.

- Flying Robots : they are robots that can float and in the air using their wings, airplane or bird/insect shaped balloon propellers.

- Multi robot system : Formally, it's a collection of two or more autonomous mobile robots working together to achieve a certain goal.

- Swarm Robots : they are a sub-genre of Multi robot system. they are mostly multiple simple robots, that share a common goal.They work by collaborating to achieve this goal. Mostly inspired by mimicking insects like bees and ants.

- Micro/Nano Robots : generally spoken about robot used in micrometer or nanometer scaled environment, that can operate in those environments.

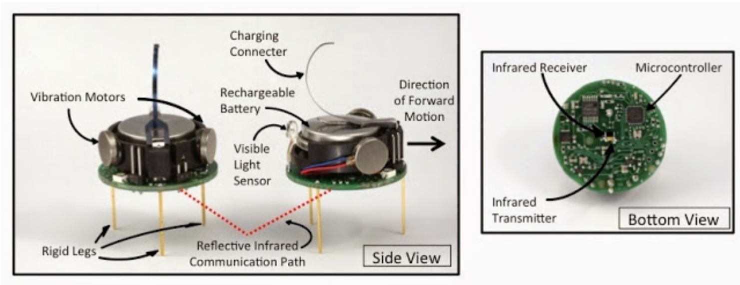

Figure 1.4: One of the simplest robot used in swarm robotics : Kilobot [2]

1.2 What is Swarm Robotics ?

Swarm robotics is a sub field of robotics, it aims to design and program a group of simple and autonomous robots, to work together in a coordinated way to achieve a common goal. We achieve this by using algorithms and communications protocols, which allow the robots to exchange information and collaborate.

It's a technology that mimics the behavior of social insects such as ants and bees. Those insects work in large groups to accomplish complex common tasks such as nest-building, foraging etc. The robots inside a swarm are usually small, simple and inexpensive, which allows the formation of large swarms, that can also be divided by groups. They are most of the times equipped with sensors, to communicate with its environment, such as cameras and proximity sensors to be aware of their surroundings. But they may also be equipped with actuators such as wheels or manipulators, to interact with their environment.

The key point and advantage of swarm robotics, is that it allows the achievement of complex tasks that would be too difficult or impossible for a single robot to accomplish. For instance, swarm robots can be used for searching people on rescue operations, but also to explore unknown environments. In order to achieve the common goal, we use various control algorithms, that varies a lot depending on the task complexity. One approach is to use a decentralized control system, in which each robot inside the swarm operates independently but communicates with its neighbors to achieve the goal.

Swarm robotics have a number of potential applications in various fields, including agriculture, manufacturing, and medicine. For instance, swarm robots could be used to pollinate crops, assemble products in a factory, or perform minimally invasive surgeries. However, the field is still relatively new, and there are many challenges that must be addressed, such as developing effective communication protocols and ensuring the robustness and scalability of the system.

Taxonomy on Multi Robot Systems (MRS)

Multi Robot System as said in the previous parts, is a sub-field of robotics. A multi robot system, is a set of robots, working as a team, they may be heterogeneous or homogeneous, in the sense that a team of robot can have different design and specificity. MRS are described with few characteristics [21] :

- Cooperation : defined as joint operation or action amongst a group of individuals [21]
- Awareness : defined as the knowledge of the existence of other individuals in a system [21].
- Communication : defined as the act of relaying information from one individual, either directly or indirectly, to another individual [21].
- Coordination : defined as cooperation in which the actions of the group are performed as a reaction to the previous actions of the group. Coordination can be either centralized or decentralized. [21]

Difference between swarm robots and multi robot system

In this part we will discriminate MRS with Swarm Robots. They differ in a few key points, their sizes, their level of coordination and communication and their autonomy.

MRS are typically involved on a smaller size of robots, they work most of the times in a structured environment with a centralized control system. They are designed to accomplish specific tasks, and each robot of the system has most of the times its own roles, which specialize it.

On the other hand, swarm robotics are involved with a much larger size of robots, working in unstructured environments with a decentralized control system. Robots inside the swarm are homogeneous, and most of the time simple. They work all work together to accomplish a global goal.

Another key difference is the level of coordination and communication between the robots. As said above MRS robots communicate and are controlled in a centralized manner, since they need to work in coordination, to achieve their task. Whereas in swarms, robots need to communicate with each others but most of the times only locally, in a decentralized manner, with robot making their own decisions based on local information.

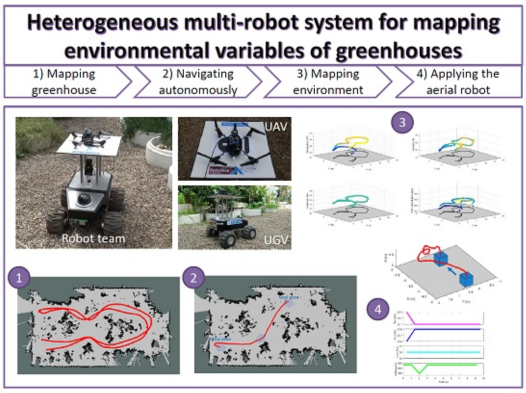

Figure 1.5: Heterogeneous Multi-Robot System for Mapping Environmental Variables of Greenhouses [3]

Figure 1.6: A Swarm of open-source Jasmine micro-robots recharging themselves

One more difference is the level of autonomy of the robots. In MRS, robots like said above may be highly specialized and require significant programming and control. Whereas in swarm robotics, robots are often designed to be more autonomous, making decisions based on local information and the overall task emerging from the local interactions.

Overall, multi-robot systems and swarm robotics represent different approaches to designing and controlling groups of robots. While both can be used to accomplish complex tasks, the choice of approach will depend on the specific application and requirements of the system.

Qualification criteria for designating swarm robots

Here is a definition from Erol Sahin [22] : "Swarm robotics is the study of how a large number of relatively simple physically embodied agents can be designed such that a desired collective behaviour emerges from the local interactions among agents and between the agents and the environment.".

This definition also comes with a set of criteria to qualify Swarm Robotics [23]:

- Robots of the swarm must be autonomous robots, able to sense and actuate in a real environment.
- The number of robots in the swarm must be large, or at least the control rules allow it.
- Robots must be homogeneous. There can exist different types of robots in the swarm, but these groups must not be too many.
- Robots must be incapable or inefficient respect to the main task they have to solve, this is, they need to collaborate in order to succeed or to improve the performance.
- Robots have only local communication and sensing capabilities. It ensures the coordination is distributed, so scalability becomes one of the properties of the system.

Difference table

	communication	size	homogeneity	complexity
Multi Robot System	Mosty centralized	A few robot	Each robot have specific design depending on its purpose and goal inside the system	Each robot is designed to accomplish a really specific task, so they all need to be programmed differently
Swarm Robots	Mostly decentralized with some case of centralization	From 2 to indefinitely	Each robot in the swarm is identical, it may exist a sub-set in the swarm that differ a bit but should not be much.	Each robot in the swarm is doing simple task for the common goal

Chapter 2

Communication protocols in Swarm Robotics

Swarm robotics, is an exciting field which cross robotics and collective intelligence, which holds tremendous potential for achieving complex tasks through the coordination of large numbers of autonomous robots. One of the key aspect that enables effective collaboration inside a swarm of robot is efficient and reliable communication. In this chapter, we dive into the state of the art of communication protocols used in swarm robotics, exploring the various techniques and protocols that facilitate seamless information exchange among those robots.

Effective communication protocols are essential for enabling robots to exchange information, share situational awareness, and coordinate their actions within a swarm. Those protocols define the rules and mechanisms for data transmission and reception, allowing robots to work together and accomplish tasks that would be challenging or impossible for a single robot to achieve.

In this chapter we will explore a range of communication protocols that have been developed and applied in swarm robotics. We will examine both existing and emerging protocols, along with their strengths, weaknesses, and real-world use cases. In the first part we will list, examine and breakdowns how different protocols used for swarm robotics are. Those protocols include WIFI, Bluetooth, Zigbee, Lora and more. Then we will discuss about different technologies to implement swarm robot's communications. And finally, we will examine the problematic swarm robots can encounter while communicating in a different environment, especially underwater.

2.1 Communication protocol ?

2.1.1 What is a communication protocol ?

A communication protocol is a system of rules that allows two or more entities of a communications system to transmit information via any variation of a physical quantity. The protocol defines the rules, syntax, semantics, and synchronization of communication and possible error recovery methods. Protocols may be implemented by hardware, software, or a combination.

Communicating systems use well-defined formats for exchanging various messages. Each message has an exact meaning intended to elicit a response from a range of possible responses pre-determined for that particular situation.The specified behavior is typically independent of how it is to be implemented. Communication protocols have to be agreed upon by the parties involved. To reach an agreement, a protocol may be developed into a technical standard.

Communication system defines a few aspects, such as the message format, addressing, routing and also the error control mechanism...

Here are simple definition of few aspects :

- Message format : defining the received/transmitted message packet format
- Addressing and routing : Define how an entity (robot in our case) is identified within a network. And define how datas are routed from the source to the destination.
- Error control : define error detection methods, to detect error and conflicts during data transmission and reception.

2.2 Wireless Networks and Wireless sensor Networks

Wireless networks are one of the core technology for Swarm Robotics. It enables the swarm to communicate with all of the robots seamlessly. But Wireless networks are also a big field, and it can be hard to choose one protocol over another. So in this overview we will list a few of the most used protocols in today's technology. We will present them in terms of their functioning, flaws, strength, scalability and more.

Wireless networks include all networking systems, that doesn't rely on wired communicating, like wireless local area networks (WLAN), satellite communication networks, cell phone networks, microwave networks, radio and spread spectrum technologies, free-space optical communication and also wireless sensor networks; in which we will talk a bit further later.

Has specified before, wireless networks are computer networks that use wireless data communication between other nodes in the network. Wireless network implementation takes place in the physical layer of the OSI Model network structure.

2.2.1 The OSI model network structure

To further understand wireless networks, we will need to review our OSI (Open system Interconnection) Model structure. The OSI model was and still is a stepping stone for today's networking architecture, it provides seven layers to abstract different steps for heterogeneous communications. In the paper "Research based on the OSI model" [4] they cite that the OSI model biggest strength comes from its Independence between its layer, each layer can be implemented differently as long as up to provide the same services and the interface does not change the adjacent layers on it [4].

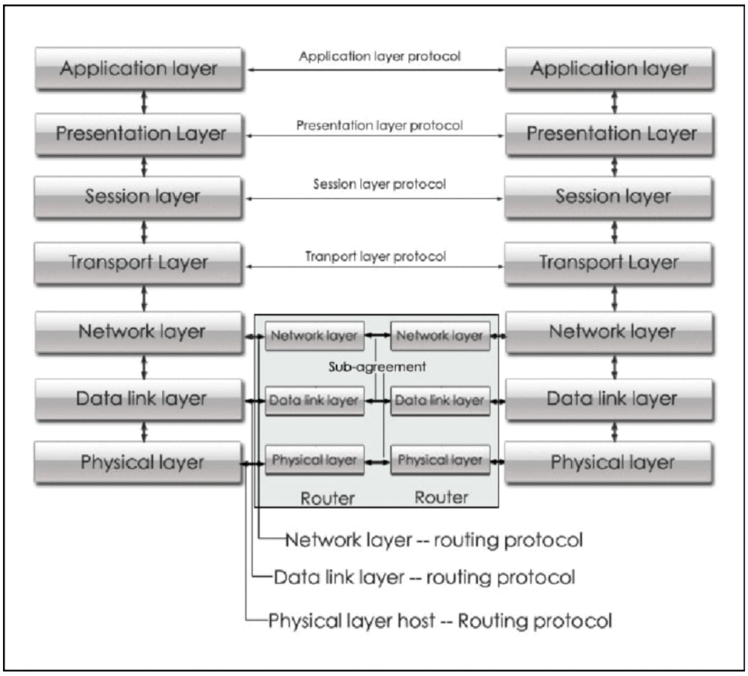

Figure 2.1: OSI seven layer model structure [4]

The seven layers are :

- **Physical Layer** : This is the lowest layer of the model where the actual physical transmission of data is done over the network. It works with cables, wires, radio waves etc. We can cite for instance, Ethernet by wired LAN, WiFi by wireless LAN, Fiber optic cables etc.

- **Data Link Layer** : This layer is responsible for the transmission of data between two instances of the network. It converts bits from the physical layer to organized and meaningful data chunks called frames. But it also handles error detection and correction. Ethernet protocol (IEEE 802.3) for instance, but also Bluetooth.

- **Network Layer** : This layer does the routing and data forwarding. It determines the best travel path for data from source to destination. Internet Protocol (IP) counts in this layer.

- **Transport Layer** : This Layer ensures reliable and error-free delivery of data between nodes. It breaks down large chunks of data into smaller segments, handles the sequencing, and also provides error detection and recovery mechanisms.

- **Session Layer** : it establishes, manages, and terminates communication sessions between devices. It allows two devices to start and maintain a connection, ensuring that data flows smoothly between them.

- **Presentation Layer** : it is responsible for the formatting and conversion of data into a format that the receiving device can understand. It deals with tasks such as data encryption, compression, and data representation, ensuring that data is presented in a meaningful way. You can cite for instance, Hypertext Markup Language (HTML), Secure Sockets Layer (SSL) etc.

- **Application Layer** : This is the last layer of the model, it is where users interact with the network. For instance, we can list File Transfer Protocol (FTP), Domain Name System (DNS) etc.

Most communication protocols that we will explain further in the overview, mainly describe a new functioning in the physical layer and data link layer.

2.2.2 Types of Wireless networks

I would also like, most of the main wireless networks that exist. Those wireless networks take part in the Layer 1 of the OSI Model, the Physical layer. They establish the transmission of data from end-to-end nodes.

Types of wireless networks :

- **personal area network (PAN)** : network that works within the range of the user, approximately 10 meter radius around the user. ISM radio bands and infrared is often used within this distance. For instance, we can list Bluetooth and irDA.

- **local area network (LAN)** : network that works within the range of local entity such as a residence, school, university, office building etc. Wifi and Ethernet are the most used technologies in LAN network.

- **metropolitan area network (MAN)** : network that interconnects computers within the range of a geographic location of the size of a metropolitan area.

- **wide area network (WAN)** : Whereas MAN wide area networks work within the spectrum of a large geographic area.

- **Cellular network** : the network is distributed over land areas called cells, each served by at least one fixed-location transceiver. These base stations provide the cell with the network coverage which can be used for transmission of voice, data, and other types of content.

- **Space network (SN)** : this is a program run by the National Aeronautics and Space Administration (NASA), that enables spacecraft communication with Earth. Most spacecraft here operates in Low Earth Orbit at approximately 73 kilometer to 3000 kilometers of altitude.

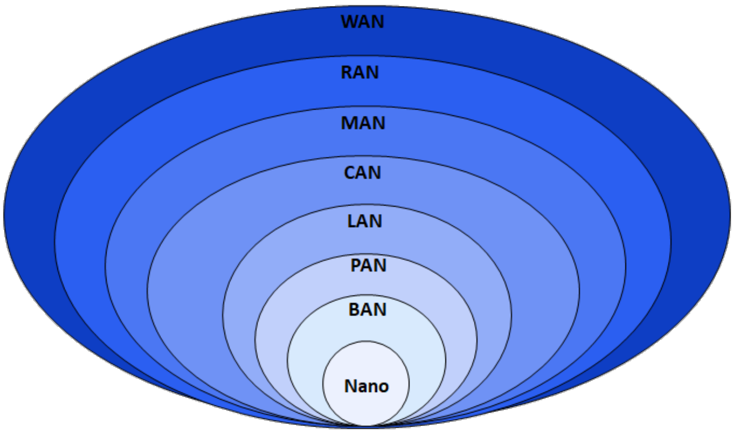

Figure 2.2: Data Networks classification by spatial scope

2.2.3 Wireless sensors network (WSN)

Wireless sensor networks, are used in swarm robotics to enhance the system of the robots. Each node of the swarm is equipped with sensors that can sense, collect, process and transmit data wirelessly.WSNs usually works like a ad-hoc network, without centralized routing, each node can transmit and receive its own data.

WSNs usually monitor physical condition, like temperature, sound, pressure, water level, humidity etc.

2.3 Review off different communication protocols used in Swarm Robots

2.3.1 Bluethooth

Bluetooth is a widely used technology in a lot of devices, it works within the personal area network (PAN). Bluetooth technology uses the 2.4 GHz ISM spectrum band, 2400 to 2483 MHz. It employs the Ultra high frequency (UHF) radio waves in the ISM radio Band.

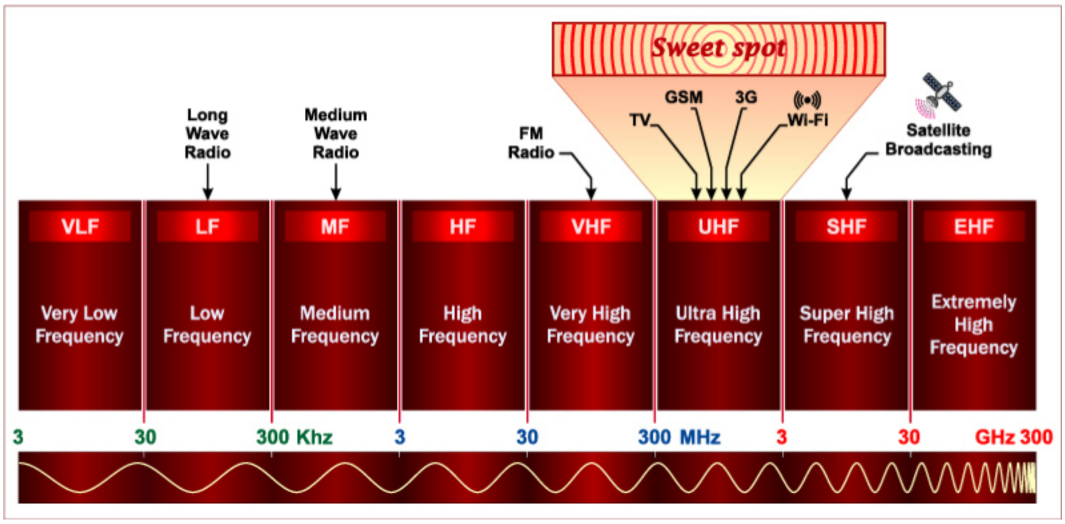

Figure 2.3: ISM Band

The ISM radio band is a portion of the radio spectrum (ranging from 3Hz to 3THz), used for industrial, scientific and medical purpose. Note that ISM stands for the three fields listed.

Bluetooth interface works on a antenna power of 0dBm (1mW) and can be extended up to 20dBm (100mW) worldwide. This interface complies with ISM band rules up to 20dBm in America, Japan, and most European countries [24]. Those values are the gain of the transmitted data, it describes how well the input power converts into radio waves. The lower this value, the less the radio wave will carry its information further.

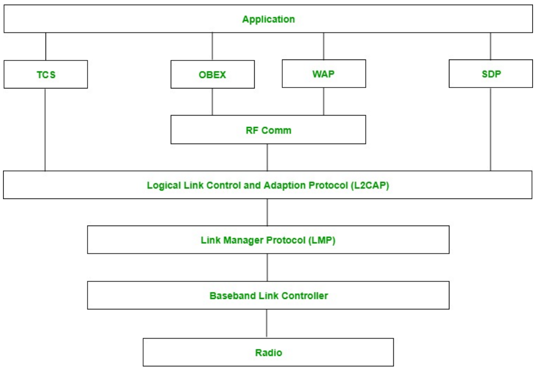

Figure 2.4: bluetooth stack schema by raman from GeeksForGeeks

Frequency hopping

Bluetooth uses a technique called frequency-hopping spread spectrum (FHSS) to carry its data over the 2.4-2.46GHz frequency range. The data signal is transmitted on different frequency channels in a pseudo-random sequence. The signal hops between channels hundreds of times per second, and each hop lasts only a fraction of a second. This helps to reduce interference from other devices that may be using the same frequency channel and improves the reliability and security of wireless communication through Bluetooth. [5] The hopping frequency is mostly set to 1600 times a second approximately.

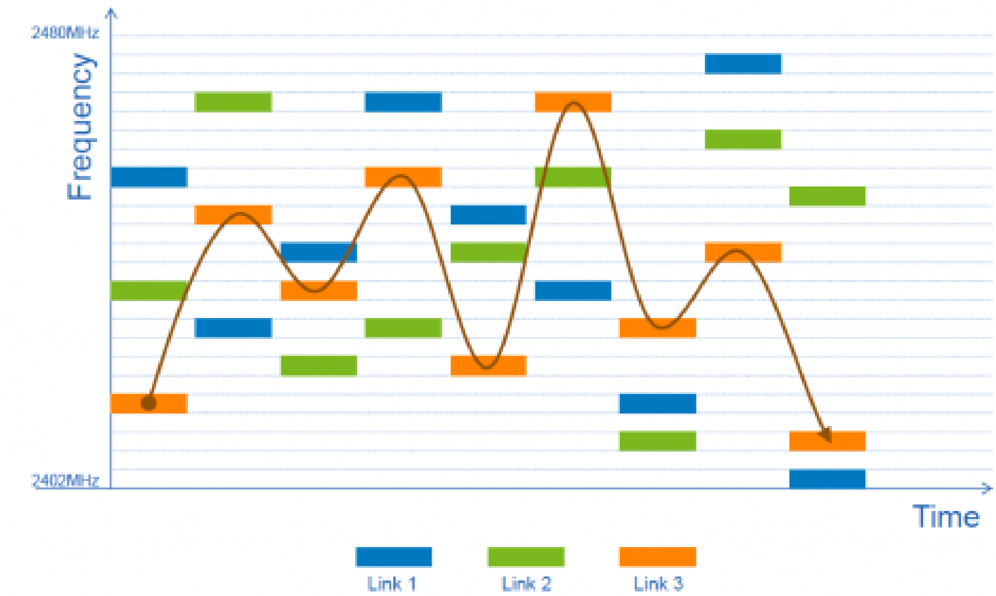

Figure 2.5: Example of Bluetooth frequency usage for multiple signals [5]

In Bluetooth the hopping is done trough 79 channels typically. Bluetooth devices also use a primary-secondary architecture, where the primary device controls the hopping sequence and timing. This helps to ensure that all devices are synchronized and that they are hopping on the same frequency channels [5].

Piconet and scatternet

Bluetooth uses a a piconet,this is a network that works like an ad hoc network. Here, we use the term master and slave to describe the type of nodes inside the piconet. A master will have one or multiple slaves in the network.
Master devices scan for other devices, and initiate a connection. Usually, the master is the smartphone/tablet/PC.
Slave devices advertise and wait for connections. The nodes occupy the same physical channel, they are synchronized to a common clock and hopping sequence.

The piconet network can connect up to only 7 active slave nodes, but also up to 255 inactive nodes that can be brought back to life by the master. This limitation is due to the frequency hopping. Each connection in a piconet is assigned a specific hopping pattern, so as the number of active connections increases, the available frequency slots become more limited, leading to reduced network efficiency and increased potential for collisions and interference. To attenuate this Bluetooth technology has set a standard rule of active slave node in a piconet.

But we can connect other piconet together thanks to a higher level protocol, called scatternet. This can help increase the number of simultaneous active devices, see the figure below.

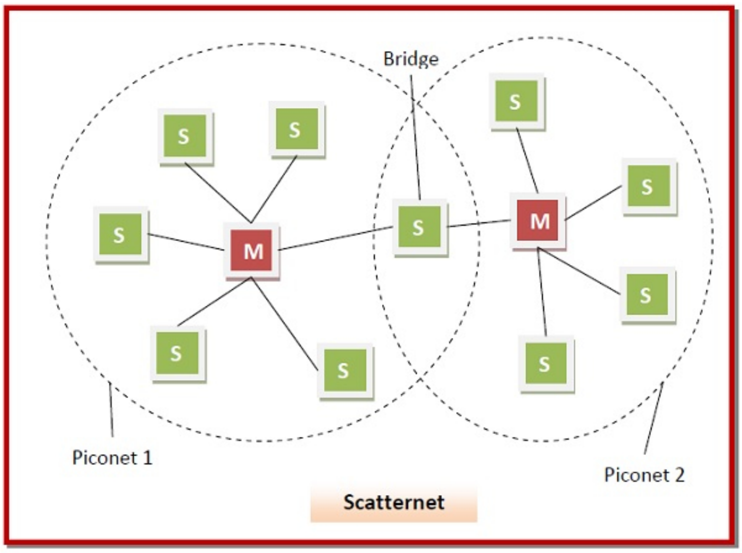

Figure 2.6: scatternet

We can notice that we now have a new type of node. The bridge node, it can be either a master or slave node in the piconet,this node will act as a slave in the other piconet and will link together the two networks.

Should I use Blueetooth in Swarm robotics ?

Now that we have a few explanations of the different mechanics used in Bluetooth, we can make certain statement to argument the use of Bluetooth in swarm robotics. One of the strongest aspect of Bluetooth is its power consumption which is fairly low. This is a strong point for swarm robotics and any other technology. But this point gets easily shadowed by the fact that we can only connect only up to seven slaves at the same time. And setting up a scatternet can be quite a hassle. Also, the distance of communication is quite low, so it limits the swarm possibilities to only within a restrained perimeter. Also, depending on the swarm environment, interference can occur, since Bluetooth operates in the 2.4GHz frequency band. This range is shared by various wireless technologies such as WiFi, microwaves and cordless phones. So the presence of some may introduce interference, and potentially impacting the swarm communication.

Weak aspect for swarm robotics	**Strong aspect for swarm robotics**
Limited bandwidth	Low power consumption
Limited number of connections	short-range communication
Interference concerns	Simultaneous Communication
Easy implementation	Multi-hop communication complexity

2.3.2 zigbee

Zigbee is a standard based wireless protocol, aimed to create a small personal area network by using low power digital radio. This technology is mainly used in home automation device, wireless sensor network and IoT overall. Due to its low complexity and energy consumption. Like Bluetooth Zigbee protocol is mostly set in the 2.4 GHz range in the ISM band, like most wireless protocols. But some device also use 784 MHz in China, 868 to 868.6 MHz in Europe and 902 to 928 MHz in the US and Australia. But most device use the 2.4 Ghz range. Depending of the frequency range in the ISM data transmission rate can vary from 20 kbit/s to 250 kbit/s.

IEEE 802.15.4

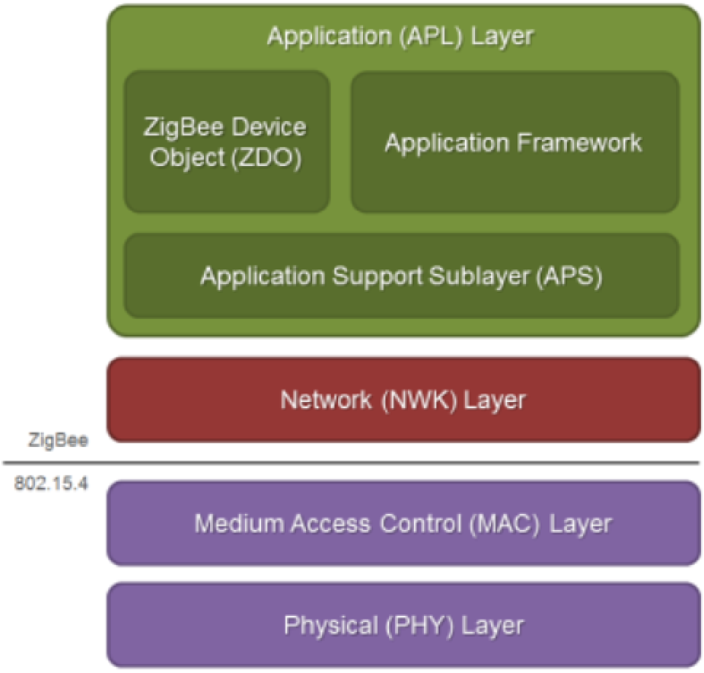

Figure 2.7: zigbee protocol stack [6]

The physical layer and MAC layer are specified by the IEEE 802.15.4 (Institute of Electrical and Electronics Engineers).

Physical layer : like said above Zigbee operates in 2.4 GHz frequency band throughout the world with up to sixteen channels. There are two other frequency bands where the 802.15.4 can be used. They are the 868 to 868.6 MHz band and the 902 to 928 MHz frequency band in North America. These bands have one and 30 channels respectively. [25] The physical layer is based on direct sequence spread spectrum (DSSS).

MAC Layer : the Medium Access Control layer enables the transmission of the MAC frames through the physical channel [25]. It provides few services like beacon management, channel access, frame validation, Acknowledgment etc.

network nodes

It exists three types of nodes within the Zigbee network, the coordinator, router and the end device. Each node type have has a specific role within the network.The coordinator and router can be called Full Function Device (FFD) while the end dive are also called the Reduced Function Device (RFD).

The coordinator, is the central device inside the network, it is responsible for network initialisation and management. It assigns addresses to all the device within the network and manage them. It maintains the network security by managing security keys, managing resources and network configuration.

The Router serves as an intermediate device within the network, they participate in the routing of data packets between nodes in the network. They help to extend the network's coverage by relaying messages between devices. They also maintain routing tables.

End device, those nodes are usually sensors or actuators that gather data information or perform specific tasks. They can only communicate directly to the coordinator or neighboring routers.

network topology

Network topology plays a crucial role in the design and functionality of communication networks. It takes into consideration the arrangement and interconnection of elements such as links and nodes within a network. In the Zigbee protocols we can count three different types of network topology: the start topology, tree topology and mesh topology. Each of these topologies influences how messages are routed and which devices are connected to one another.

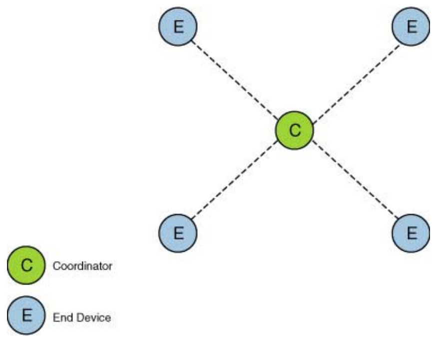

Figure 2.8: Zigbee star topology [7]

Star topology : This is the simplest and basic topology within the Zigbee technology. On the network, all communications between devices pass by the coordinator node. Even if this topology is simple of utilisation, the fact that all communications reside on the coordinator, if a failure occurs on this node then the whole network will fail at communicating.

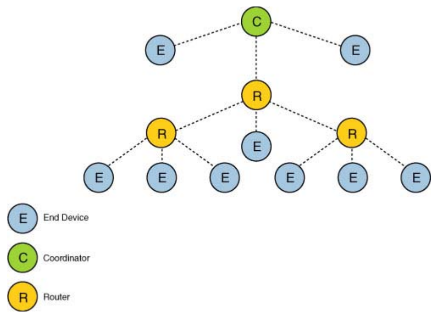

Figure 2.9: Zigbee tree topology [7]

Tree topology : This topology is based on the star topology but here we added a new type of node the Router node. Each router node serve has a parent node to the end device. This format of network helps increasing the network coverage, allowing devices that are distant from the coordinator to connect and communicate effectively.

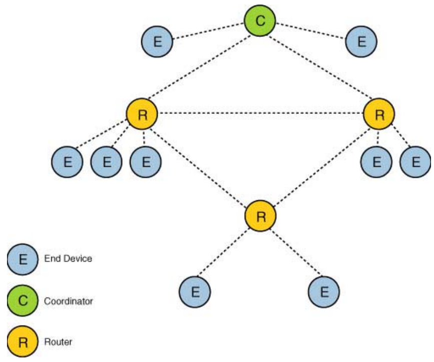

Figure 2.10: Zigbee mesh topology [7]

Mesh topology : Similar to a tree topology, a mesh topology has a coordinator, a number of routers and end devices. However, the main point of distinction is the availability of numerous potential message delivery channels. The mesh network's web-like topology is made possible by the ability of every device to communicate with every other device. Because more devices can be added to improve the coverage area, this flexibility enables a greater network range. Additionally, the afflicted node can dynamically discover an alternative path to reach its target if a transmission path fails or is blocked, removing dead zones from the network. The Zigbee network's dependability and sturdiness are improved by its self-healing capabilities. Additionally, because any device can connect to any destination device within the network, the mesh topology makes the process of adding or deleting devices from the network simpler.

specificity of zigbee

Zigbee protocols implement a **self-organizing** method, this means that each device within the networks can autonomously discover and join an active Zigbee network. When a device wants to join an active network it will pass in network discovery mode, and it will join a nearby network which match its criteria, like network id or security credentials. This makes the networks scalability really good. But we also have **dynamic routing**, to establish efficient communication paths between devices inside the network. IT allows devices to dynamically select the best routes to send the data packets based on the network topology.

Should I use Zigbee in Swarm robotics ?

Zigbee protocols can be used in swarm robotics, but only by bypassing the common topology. For each robot to communicate freely inside the network and without interference and failure within the swarm, we will need to set each robot as a router/coordinator node in the networks [26]. Still Zigbee is a really good protocol for swarm robotic, thanks to its low power consumption and it is fairly low cost as a technology. As said above Zigbee is a self-organizing network and it use dynamic routing method for wireless communication between devices. Those aspect give Zigbee a good advantage for a possible implementation in swarm robotics.

2.3.3 Lora and LoRaWAN (Long Range Wide Area Network)

LoRa is a popular and preferred physical layer technology for IoT embedded systems because of its long range and high capacity of nodes within the network, it also has a long battery life and it is bi-directional, secured and efficient [10]. LoRa use radio communication to transmit data, based on spread spectrum modulation techniques. It encodes information on radio waves using chirp pulses. LoRa is set to be a low power wide area network.

Low-power wide-area network (LPWAN or LPWA network) is a type of wireless telecommunication wide area network designed to allow long-range communication at a low bit rate between device, such as sensors for instance.

LoRa is ideal for applications that transmit small chunks of data with low bit rates. Data can be transmitted at a longer range compared to technologies like WiFi, Bluetooth or ZigBee. These features make LoRa well suited for sensors and actuators that operate in low power mode. A single LoRa gateway can cover hundred-kilometer square of area. [10]

LoRa can be operated on the license free sub-gigahertz bands, for example, 915 MHz, 868 MHz, and 433 MHz. It can also be operated at 2.4 GHz to achieve higher data rates compared to sub-gigahertz bands, at the cost of range.

Both Lora end nodes and gateways are transceivers, this means that they both transmit and receive signals in the same device. Communication is bi-directional.

Chirp spread spectrum

Chirp spread spectrum (CSS) is a spread spectrum technique that uses wideband linear frequency modulated chirp pulses to encode information. A chirp is a sinusoidal signal whose frequency increases or decreases over time. This technique is being used in military and space communication due to its robust nature and long-range capacity. [10]

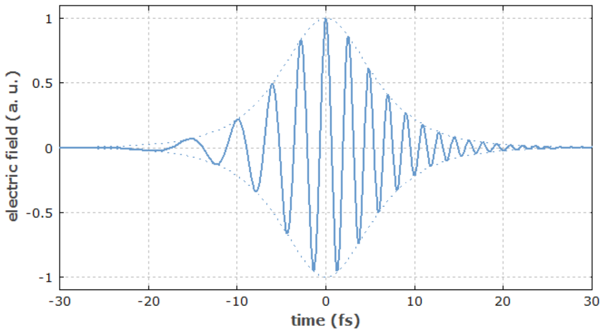

Figure 2.11: Chirped pulse, where the frequency grows with time [8]

A chirp signal, is also often called a sweep signal, due to the fact that its frequency increase or decrease with time, which crease a sweep tone. We call those sweeps up-chirp and down-chirp.

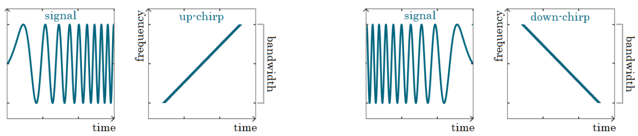

Figure 2.12: up and down chirp with its corresponding signal [9]

Those chirps signals are then used as carrier signals on which a message is encoded on.

LoRaWan

Even though LoRa covered the physical part, there still gaps in the upper layers. So LoRaWan was created to make up for that. It is a cloud based medium access protocol (MAC) layer protocol, but it acts mainly as a network layer protocol for managing communication between low power WAN gateways and end-node devices as a routing protocol.

LoRaWAN is based on star topology. The LoRa network consist of four basic elements [10] the LoRa node or End Points, the Gateway, the Network Server and application Server.

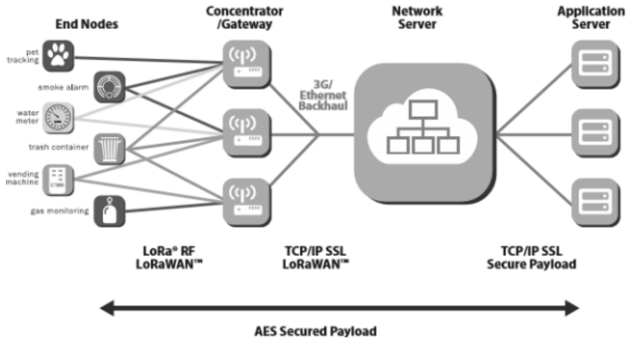

Figure 2.13: LoRaWAN network architecture [10]

The end points or LoRa nodes are mainly sensors or application. [10] The gateway comprises the net element of the LoRa network. The data transmitted by the LoRa end points are sent to all the gateways and each gateway which receives a signal need to transmit it to a cloud based network server via cellular, Ethernet, satellite, or Wi-Fi. [10] The network server has all the intelligence. The data received from different gateways is filtered, security checks. [10]

Within the different LoRa device, we can discriminate three basic classes according to their battery lifetime and downlink communication latency. They are called class A, B and C. [10]

- **Class A device**, Bi-Directional End Devices, those devices are the lowest powered device, These devices have one uplink transmission slot and two downlink receive slots.[10]

- **Class B device**, Bi-directional end-devices with scheduled receive slots, there are more receive slots than class A which opens at scheduled times. The gateway sent scheduled beacon to the end device for the end device to open their additional receive slot at periodic times. [10]

- **Class C device**, Bi-directional end-devices with maximal receive slots ,these devices open their receive slots all the time. The receive slot is closed only when the end device is transmitting. Since the class C end devices have their receive slot open all the time they consume more power than the other two classes. But these classes provide lowest latency for communication. [10]

LoRa and LoRaWAN for swarm robotics ?

LoRa is an excellent physical layer in my opinion for swarm robotics if the swarm is spread over big distances. With LoRa we can directly transmit information from device to device within the swarm. And Thanks to LoRaWAN we will be able to monitor all the data from the robot in a distant server. We can even reconfigure each loRa device to be a different class depending on the need of the swarm.

2.3.4 MQTT (Message Queuing Telemetry Transport)

MQTT (Message Queuing Telemetry Transport) is a messaging protocol for restricted low-bandwidth networks and extremely high-latency IoT devices. It is designed for connections to remote locations that have devices with resource constraints or limited network bandwidth. MQTT run over a transport protocol that provides bi-directional connections like TCP/IP.

There are two types of device in MQTT. Brokers and clients. A broker is a server that receives all messages from the clients and then routes the messages to the appropriate destination. It maintains a record of the subscribers and ensures that each subscriber receives the message once, regardless of the number of subscribers or their locations. A clients can be any device it should just be able to run an MQTT library and have access to a TCP/IP connection.

Publisher Subscriber pattern

MQTT work with the public and subscriber pattern. This is done via a central server, the broker, that manage all the routing for the message forwarding and publishing. A publisher role is to publish data to a topic. When he does ask the broker to keep a queue of data that he is sending. While a subscriber, "subscribe" to a publisher topic. For that the subscriber device needs to ask the broker to forward him the specified topic data to him when there is. The publisher and subscriber have no idea of each other, the only pass by the broker, even though there is still some case where this can happen, it is not the case here. This decoupling allows for flexible and dynamic communication patterns, as publishers and subscribers can change without affecting the overall system.

Topics

Topics is what describes the type of message that the queue store. It is structured by a series of forward slashes (/). Each forward slash represents a category or subcategory. For instance, if a publisher wants to publish odometry value he can create a topic <odom/value> and push its odometry in it. Furthermore, we can create multiple topics inside a device, for instance we could also give the x position of the odemtry like so <odom/x>.

The broker will now expose those new topics on the demands of the subscriber. They will just need to ask for an existing topic. For instance, if I want the x

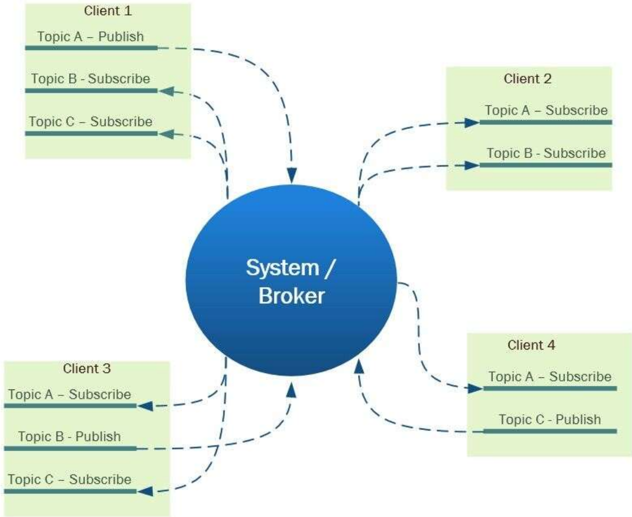

Figure 2.14: publisher subscriber schema [11]

odometry value, I will subscribe to <odom/x>. I will now be able to receive this specific value from the publisher. Furthermore, there exist, two wildcard characters + and #, this permit the device to subscribe to multiple device at once, for instance if I want all odemtry data I can subscribe to the <odemtry/#>.

Should I use MQTT for Swarm Robotic ?

MQTT is a really good option for your swarm if the connectivity constraint is not too high. As long as we can keep a TCP/IP connection, with WiFi, 4G or even 5G. It is really easy of installation on most board, there exists a framework for practically any board language. It can be implemented on a lot of board like ESP, arduino, raspberry pi etc.

The simplicity of the publisher subscriber makes it also really easy to use. Which makes it a good fit for Proof of Work.

2.4 Protocols used depending of the Swarm Robots environment

The field of swarm robotics has observed significant advancements in recent years. A Robot in a swarm can operate in various different environments, ranging from indoor spaces to outdoor, from aerial to underwater, and each of these environments represents unique challenges and requirements. To effectively communicate and coordinate within these environments, swarm robotics rely on the utilization of specific communication protocols. This chapter digs into the exploration of protocols used in swarm robotics, within those different environments.

Understanding the swarm environment, impact communication protocols is essential for designing robust and efficient swarm robotic systems. Different environments impose various constraints, such as signal range, interference, mobility, and resource availability, which directly influence the choice of communication protocols.

This chapter will aim to provide a comprehensive analysis of the protocols used in swarm robotics, considering the environment as a critical factor in the protocol selection process. It will explore grounded, underwater and aerial environments, and dig into the protocols best suited for each scenario.

2.4.1 Grounded

Grounded environment is the most versatile in term of communication protocols we can use in swarm robotics, within the grounded environment we can use most of the wireless protocols listed above. Which are mainly based on radio waves, like Bluetooth, Zigbee, WiFi or even LoRa.

There exist a lot of different environmental constraints, in swarm robotics communication protocols, we will list a few of them with a bit of explanation :

- **signal interference**, this refers to the disruption, degradation, or distortion of a signal that may be caused by the presence of unwanted external signals or factors in the communication channel. It can occur when signals from different sources interfere with each other; usually when they are in the same frequency range; leading to a decrease in the quality and reliability of the intended signal. Like said before interference can arise from various sources, including other wireless devices operating in the same frequency range, environmental factors, electrical noise, or physical obstacles.
- **signal attenuation**, this refers to the loss of signal strength in the network connection. It can occur due to a variety of factors. It may cause signals to become distorted or indiscernible. An example of this is the WiFi signal and strength getting noticeably weaker the further that your device is from the router.
- **Non-Line-Of-Sight (NLOS)**, this refers to the radio propagation that occurs outside of the line-of-sight between a transmitter and receiver. It refers of a non direct transmission with obstacle like ground, building, trees, and more. Some of these obstacles reflects the frequency, but other absorb or disturb the signal.

Those three criteria will not only be important for grounded swarm robots but also for any other environment. The goal here is to minimize their effect in the swarm robot system.

rural

The rural environment, is an open area where is not that much building or home. The population density is really low. There are mostly agricultural area, with practically almost direct line-of-sight between transmitter and receiver.

In those types of environment, any communication protocols can be applied without much constraints. Whether it is low range or long range. The attenuation of signals is not pronounced.

urban

The urban environment, is the opposite of the rural environment, with a lot of buildings and homes. Also the population density is really high. There is practically almost no direct line-of-sight between transmitter and receiver. Those constraints make perturbation and attenuation of signal higher.

In this type of environment, any low range communication protocols can be applied without much constraints. But with long range communication protocols, we may have a bit of perturbation.

2.4.2 Underwater

Underwater environment is quite a tough environment to work in. Working within those environments is totally different compared to grounded robots. With the Underwater environment everything should be adapted, whereas it is hardware, software, navigation etc. Communication, is one of the big challenges in those environments. Since most communications and controls of robots in the surface and in the air , are not adequate for underwater robotics.

The discrimination of the communications used underwater are mainly based on reception meter, noise and transmission rate. Some protocols listed are WiFi, Bluetooth, IR, acoustic wave methods, light-based transmitter or even electrocommunication.

Underwater robots always struggled to compete with its aerial and grounded counterpart. This is mainly due to the problems with communication underwater, the hazardous environment, the cost and difficulties with construction of underwater robots. [27]

One of the biggest challenges that are associated with underwater robotics is the lack of effective communication methods that are available. Normally the use of high-frequency radio, Bluetooth, IR and radar could be used to communicate amongst agents. However, high attenuation due to water interferes with the aforementioned methods. Wi-Fi's 2.4 GHz transmission rate, which is commonly used in most of today's home Wi-Fi routers, is highly absorbed in water. This is why microwaves use 2.45 GHz. This energy transfer severely reduces the range that the Wi-Fi signal can travel underwater [27]

acoustic wave methods

Underwater acoustics or hydroacoustics refer to the study of the propagation of sound in water and the interaction of the mechanical waves that constitute sound in the water. Standard frequencies associated with underwater acoustics are between 10 Hz and 1 MHz. Since the propagation of sound in the ocean at frequencies lower than 10 Hz is usually not possible without penetrating deep into the seabed, whereas frequencies above 1 MHz are rarely used because they are absorbed very quickly. [28]

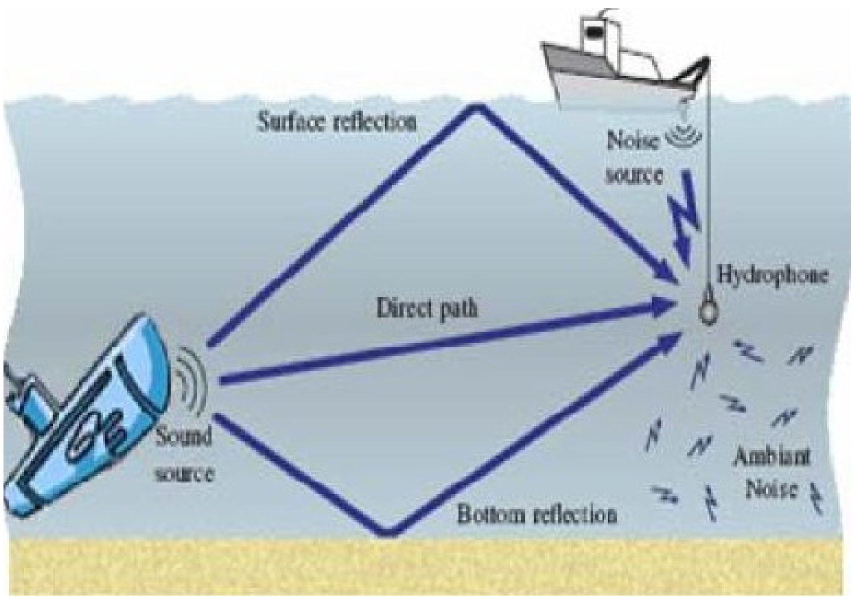

Figure 2.15: Example of multi-path propagation

Acoustic wave communication is a popular method for underwater communication, it is usually used by ships to communicate or it is even used to map the seafloor.

One of the main benefits of acoustic waves is its ability to travel long distances without significant attenuation. However, acoustic waves still have a downside, as they can refract on hard surfaces, causing them to bounce around and increase the amount of noise in the transmission. [27] Acoustic communication can also only transmit at a BAUD rate of up to 10kbps. This means that only a small amount of data can be sent at a time. This Can be acceptable if the swarm size is relatively small, but scalability wise this can lead to problems within the communication. As said in the underwater swarm robot paper, "Both factors make acoustic communication an unsuitable choice for swarm robotics, especially for swarm with more than a few agents." [27]. Also underwater communication faces others problems like multi-path propagation, this is a phenomenon where signals reach the receiver antenna by two or more path. But in my opinion acoustic waves may be a good choice when its constraints are not a problem in our swarm system.

There are several ways of employing such communications, but the most common is by using hydrophones, receiving acoustic wave communication. Modulation methods for acoustic waves are mostly the same as the radio waves method, like Frequency-shift keying (FSK), Phase-shift keying (PSK), Frequency-hopping etc.

light based transmitter

Light based communication is also considered within the underwater environment, Blue LED and Blue laser are already used.

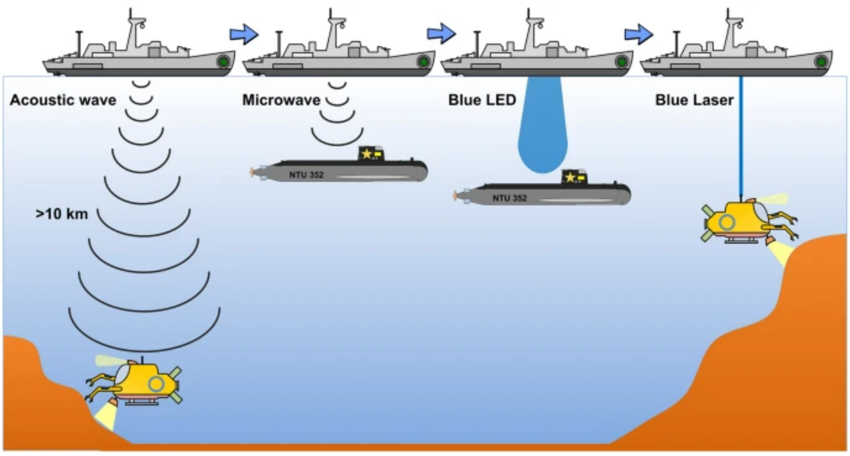

Figure 2.16: Schematic of underwater communication system [12]

450nm Blue lasers achieved 4.8 Gbps data rate transmission underwater over a range of 5.4 meters. But one problem with light based communication is that they only work in a strictly line-of-sight environment. This significantly reduces the range of communication, and those methods are also affected by the clarity of the water. [27]

electrocommunication

Another approach for underwater communication is mimicking the method used by weak electric fish. They use a certain form of elctrommunication. This methods has been experienced and searchers have noticed that electrommunication doesn't not fault within different conditions like still water, flowing water or water littered with obstacles has no effect on the performance of electrocommunication [27]. But like said the underwater swarm robot communication paper, "electrocommunication has also its limitations regarding its short range and its potential to fail in certain situations when the receiver is parallel to the isopotentioal line of the electric field." [27]

method combination

A new method that has been proposed for underwater swarm networks is to use hybrid optical and acoustic communication, so that high data rates can still be achieved and the swarm can still communicate when the members of the swarm move out of range of the optical communication. While the researchers focused on the power consumption of the network, the benefits of a multi-method communication system can be used to help alleviate some of the shortcomings of both communication methods. In the case of the hybrid optical and acoustic methods, the swarm gains long range communication when needed, and short range, high data rate when the agents are closer to one another. The acoustic communication also acts as a redundancy if the water is highly turbid.

Li-Fi

Li-Fi represents an advanced communication system that utilizes the visible light, ultraviolet, and infrared spectrum's to transmit data at remarkable speeds. Currently, the transmission of data through visible light is exclusively achievable through LED lamps.

From an end-user perspective, Li-Fi technology shares similarities with Wi-Fi. However, the key technical distinction lies in the transmission method. While Wi-Fi relies on radio frequency to transmit data by inducing voltage in an antenna, Li-Fi employs the modulation of light intensity for data transmission. This unique approach allows Li-Fi to operate effectively in environments that are sensitive to electromagnetic interference.

2.5 Technologies to implement Swarm robots

In this part we will discuss a bit about how we can develop and implement swarm robot systems. With a focus on the Robot Operating System (ROS)

2.5.1 The use of Robot Operating System (ROS) and ROS2 for Swarm Robots

ROS is an open-source, meta-operating system for your robot. It provides the services you would expect from an operating system, including hardware abstraction, low-level device control, implementation of commonly-used functionality, message-passing between processes, and package management. It also provides tools and libraries for obtaining, building, writing, and running code across multiple computers. ROS is similar in some respects to 'robot frameworks,' such as Player, YARP, Orocos, CARMEN and Microsoft Robotics Studio. [13]

The ROS runtime "graph" is a peer-to-peer network of processes (potentially distributed across machines) that are loosely coupled using the ROS communication infrastructure. ROS implements several different styles of communication, including synchronous RPC-style communication over services, asynchronous streaming of data over topics, and storage of data on a Parameter Server. These are explained in greater detail in our Conceptual Overview. [13]

ROS is not a realtime framework, though it is possible to integrate ROS with realtime code. The Willow Garage PR2 robot uses a system called pr2_etherCAT, which transports ROS messages in and out of a realtime process. ROS also has seamless integration with the Orocos Real-time Toolkit. [13]

ROS

We already talked about the publisher and subscriber pattern, which consist of a publishing message on topics and subscribing to this topic to receive its data.

Nodes are individual processes that perform specific computations in a modular manner. They can control various aspects of a robot's functionality, such as sensors, actuators, localization, or planning. The Master acts as a central registry, allowing nodes to find each other, exchange messages, and invoke services.

The Parameter Server provides a centralized location for storing and accessing data by key-value pairs. It enables nodes to share and retrieve parameters, configuration settings, or other relevant information.

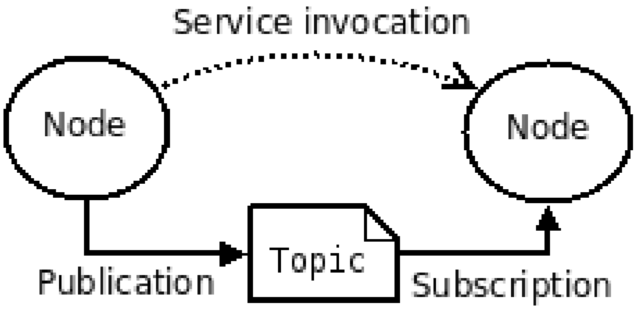

Figure 2.17: ROS Basic subscriber and publisher[13]

Messages are the means of communication between nodes. They are structured data units that carry specific information. Messages can be simple, consisting of basic data types, or complex, including nested structures and arrays.

Topics facilitate the publish/subscribe communication model in which messages are distributed among nodes. A node can publish a message on a specific topic, and other nodes interested in that type of data can subscribe to the topic to receive the messages. Topics enable decoupled communication, allowing nodes to operate independently without direct awareness of each other.

Services provide a request/reply communication model for more interactive exchanges. A node can offer a service, specifying a request and a corresponding reply message structure. Other nodes can then send requests to the service and receive replies. Services are suitable for scenarios where a direct response is required.

Bags are a mechanism for storing and replaying ROS message data. They are useful for recording sensor data or other types of information for offline analysis, testing, or development of algorithms.

The ROS Computation Graph architecture facilitates a decoupled and flexible system. Nodes communicate directly with each other, and the Master provides name registration and lookup services. The use of names allows nodes to dynamically connect and interact, providing scalability and adaptability to changing network topologies.

The ROS Computation Graph operates in a peer-to-peer manner, where the Master serves as a name service, enabling nodes to find and connect to each other. TCPROS, a TCP/IP-based protocol, is commonly used for communication between nodes.

The decoupled nature of ROS allows for easy reconfiguration and addition of new components. Nodes can be started, stopped, or restarted in any order without causing errors. The ability to remap names at runtime provides flexibility in building and modifying complex robotic systems.

ROS 2 and its difference with ROS

ROS 2 is the new version of ROS, nowadays every robotics project tends to its use. As ROS and ROS2 are still very similar, they are still few subtility in its functioning, we will list a few here :

- While ROS is based on TCP/IP and relies on a centralized ROS Master node to facilitate communication between nodes. ROS 2 uses a Data Distribution Service (DDS), which is an industry-standard protocol it also provides a flexible and efficient communication mechanism. With publish subscribe and request response communication patterns.
- ROS lacks intrinsic support for real-time and safety-critical systems. Whereas ROS 2 introduces features like Quality of Service (QoS) settings, this enables developers to build applications that require real-time guarantees and to meet safety standards.
- ROS was designed for single-machine or small robotic systems. So it can face challenges in terms of scalability and performance when dealing with large scale systems. While ROS2 focuses on improving scalability and performance. [29]

packages

ROS and ROS 2 is an open source framework, this allowed the community to improve the framework and implement tines of libraries and packages. To be reused by the community. This helps developers get started fast and to not re implement redundant tasks. Like Lidar scanning, odometry, kinematics, sensors data reading etc.

It exists few packages to implement swarm robotics here is a few, ROS2SWARM for ROS 2 and micros_swarm_framework for ROS.

The micros_swarm_framework package

Micros_swarm_framework Package makes coding for swarm robotics much easier by providing a swarm-level abstraction, as well as tools for swarm management, various communication mechanisms and so on. It also provides essential data structures, such as Neighbor, Swarm, and Virtual Stigmergy, to the user.

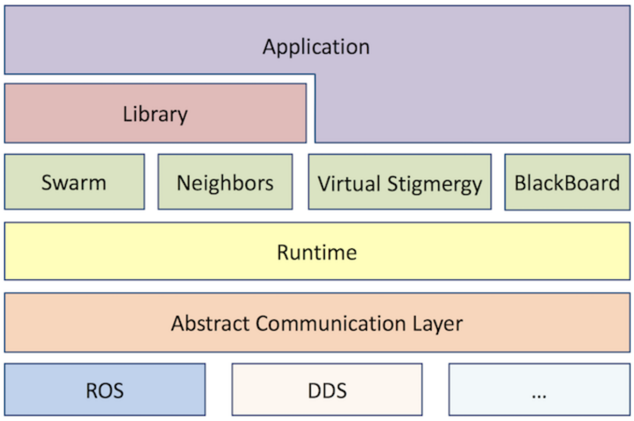

Figure 2.18: micros_swarm_framework package

In order to make it modular and extensible, the package developers chose to decompose the framework into a layered structure. The Communication Interface layer is to implement an abstraction of the underlying communication mechanisms, and provides a set of unified interface to layer above. At the core of the framework is a runtime platform, based on which APIs, including abstract data structures, such as Swarm, Neighbor, and Virtual Stigmergy, are provided to the user.

The ROS2SWARM architecture package

ROS2SWARM offers a comprehensive library of pre-defined behavioral primitives designed specifically for swarm robotics applications. These primitives can be easily extended and customized to suit the unique requirements of different swarm scenarios. Emphasizing the fundamental principle of distributed control in robot swarms, the package enables each robot to execute swarm behaviors independently and autonomously.

To facilitate certain behaviors that require data sharing among robots, ROS2SWARM1 utilizes global namespace ROS 2 topics. This allows swarm members to communicate and exchange information, with the prerequisite that all robots in the swarm must be connected to the same network.

2.5.2 Microsoft Robotics Studio for Swarm robots

Microsoft Robotics Developer Studio (MRDS) is a discontinued Windows-based environment for robot control and simulation that was aimed at academic, hobbyist, and commercial developers and handled a wide variety of robot hardware. It requires a Microsoft Windows 7 operating system or later.

Microsoft Robotics Studio was cut off in September 2021, it is no longer actively maintained or supported by Microsoft.The last stable release was in 2012, and since then, Microsoft has shifted its focus to other robotics-related projects and platforms.

However, it's worth noting that some individuals or organizations may still use MRDS for legacy projects or for experimentation purposes. But in terms of widespread industry adoption and active development, other robotics frameworks and platforms such as ROS and ROS 2 have gained more popularity.

2.5.3 other alternatives

Orcos

Orocos is an advanced software tool for controlling machines and robots, it is designed to be portable and it is written in C++ Over time, Orocos has evolved into a comprehensive project that includes middleware and development tools for robotics software. The two main components of the project are the Real-Time Toolchain (RTT) and the Orocos Component Library (OCL).

RTT provides a framework for creating real-time components in C++. It enables developers to write code that can respond and interact in real-time. And OCL consists of essential components needed to initiate an application and dynamically interact with it during runtime.

To enhance the functionality of Orocos, additional libraries have been developed. These include the Kinematics and Dynamics Library (KDL), which allows for modeling and computation of kinematic chains, and the Bayesian Filtering Library (BFL), which facilitates inference and estimation algorithms based on Bayes' rule.

Another valuable component is the Reduced Finite State Machine (rFSM), it provides a compact and powerful implementation of statecharts using the Lua programming language. Additionally, the Instantaneous Task Specification using Constraints (iTaSC) framework enables the generation of robot motions by specifying constraints between different parts of the robot and its environment. [30]

CARMEN

CARMEN, the Carnegie Mellon Robot Navigation Toolkit! CARMEN is an open-source software collection that empowers you with comprehensive tools for controlling mobile robots. It is designed to be modular and it offers a wide range of essential navigation functionalities.

Thanks to it you can easily handle various aspects of robot control, such as base and sensor control, logging important data, obstacle avoidance to ensure a smooth path, accurate localization for precise positioning, efficient path planning, and reliable mapping capabilities. [31]

Chapter 3

Blockchain and Swarm Robotics

I wanted to get some time to talk about how blockchain could increase the efficiency and reliability of a swarm robotic system. Blockchain technology has gained a lot of interest in the last decade, thanks to it's versatile use cases. Industries such as Insurance, Education, Private transport and Ride sharing, government and public benefits, retail, real estate etc. Have started implementing blockchain to reduce costs, to increase transparency and to build trust [14]. Swarm robotics were not spared by researchers that tries to find use cases of this technology within Swarm Robotics technology.

Blockchain is a rapidly developing technology that first emerged in the context of Bitcoin. Blockchain demonstrates the potential of combining peer-to-peer networks and cryptographic algorithms to enable a group of participants to reach a consensus on a specific matter and record that consensus without relying on a central authority.

Integrating blockchain with other distributed systems, like Swarm Robot system may offer a promising opportunity to enhance its security, autonomy and flexibility. By leveraging the capabilities of blockchain technology, swarm robotics can benefit from enhanced trust, transparency, and decentralized coordination, leading to more efficient and robust collective behavior.

3.1 Brief introduction to Blockchain

Blockchain technology is normally associated with cryptocurrencies such as Bitcoin. It is a database of record of transactions which is distributed, and which is validated and maintained by a network of computers around the world. Instead of a single central authority such as a bank, the records are supervised by a large community and no individual person has control over it and no one can go back and change or erase a transaction history. Its stored information cannot be manipulated due to blockchain's built in distributed nature of structure and confirmed guarantees by the peers.

Blockchain allows anyone on the network to access everyone else's entries which makes it impossible for one central entity to gain control of the network. Whenever someone performs a transaction, it goes to the network and computer algorithms determine the authenticity of the transaction. Once the transaction is verified, this new transaction is linked with the previous transaction forming a chain of transactions. This chain is called the Blockchain.

Blockchain Architecture

The underlying technology concept in Blockchain is the use of decentralized database. Each database inside the Blockchain network exist in multiple computers and each of those copies are identical. Where most organizations maintains their data in a centralised database, which make it vulnerable to falsification, Blockchain solves this problem thanks to its decentralised structure. Blockchain can be considered as a peer to peer network that runs on top of the internet.

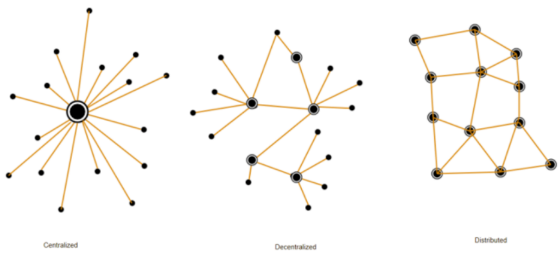

Figure 3.1: different network types [14]

Blockchain architecture can be divided in three layers listed here from top to bottom. The application layer, decentralized ledger layer and the Peer-to-Peer Network layer.

Application layer contains the application software of the Blockchain. For instance, the Bitcoin wallet software creates and stores private and public keys enabling users to keep control over the unspent bitcoins. Application layer provides a

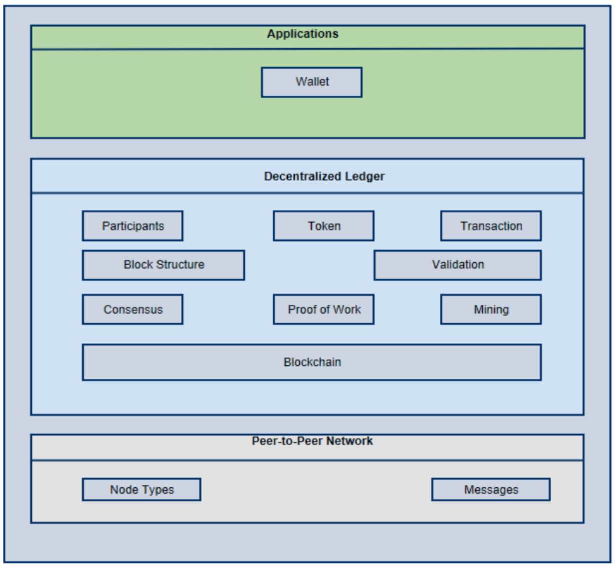

Figure 3.2: Blockchain layer architecture [14]

human readable interface where users can keep track of their transactions. [14]

Decentralized Ledger is the middle layer in a blockchain architecture that confirms a consistent and temper-proof global ledger. In this layer, transactions can be grouped into blocks which are cryptographically linked to one another. [14]

The bottom layer in the Blockchain architecture is the Peer-to-Peer Network where Node types play different roles and various messages are exchanged to main the Decentralized Ledger.

Chain structure

The chain structure is initiated with a genesis block, a block with no predecessors followed by data blocks. Any data block in a chain will have header and body sections in it. Each data block will have an index number, block creation timestamp, hash of the previous block, a proof, and a list of transactions. And an interlinked chain of blocks will be created by adding the hash of the previous block into the new block. This interlinked structure makes the data structure immutable. [15]

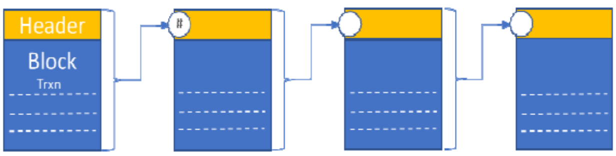

Figure 3.3: Blockchain data model [15]

Consensus

Consensus algorithm is at the core of Blockchain, it is a process that helps achieve unanimity between all the peers and untrusted parties in the network. It helps to reach a common agreement about the present state of the distributed ledger. This agreement is achieved to select one or more nodes that are responsible for validating and recording the transactions, generating the data blocks, and broadcast the newly generated blocks to the Blockchain network. So the efficiency of the consensus algorithm impacts directly the security and performance of the entire Blockchain. The Most common consensus algorithms used are Proof of Work (PoW) , Proof of Stake (PoS) , Delegated Proof of Stake (DPoS) and Practical Byzantine Fault Tolerance (PBFT). There are also about 30 new consensus algorithms derived based on these 4 algorithms like Ripple Protocol Consensus Algorithm (RPCA), Proof of Authority (PoA), Tendermint, Stellar, Proof of Bandwidth (PoB), Proof of Reliability (PoR), Proof of Luck (PoL), and many more.[15]

The selection of a consensus algorithm is purely based on the node computational power, since each algorithm aims to solve complex mathematical puzzle,

3.2 How Blockchain could be useful for swarm robots ?

security

One of the main obstacles to the large-scale deployment of swarm robots is security. Previous research has highlighted the necessity of developing systems in which swarm agents can detect and trust each others. This is important, since it has been demonstrated that the inclusion of swarm agents that are "faulty" or have malicious intents could be a big potential risk for the swarm's goals as well as a big security breach. [16] Security is also about providing core services such as data confidentiality, data integrity, entity authentication, and data origin authentication. But security was for a long time overlooked in research, since it was considered complex due to the complexity and heterogeneity of swarm robotics system. So Technology such as blockchain can provide not only a reliable peer-to-peer communication channel to the swarm's agents, but are also a way to overcome potential threats, vulnerabilities, and attacks. [16]

In the Blockchain encryption scheme, public key and digital signature cryptography are utilized to facilitate secure transactions and to verify the identity of each agent within a network. Each agent is assigned a pair of keys: a public key and a private key. The public key serves as accessible information, it is publicly available within the network, and can be linked to a unique account number. On the other hand, the private key is treated as confidential information, it is never revealed to an external agent. The private key is exclusively used to validate the agent's identity and authorize its operations. By employing these cryptographic techniques, the Blockchain system ensures secure communication and authentication within the network. [16]

In swarm robotics, public key cryptography plays a crucial role in enabling secure communication among robots. By using public key cryptography, robots can share their public keys with other the robots in the network to enable encrypted communication. This means that any robot can send information to specific robot addresses, knowing that only the intended recipient with the corresponding private key can decrypt and read the message. Even if a robot's public key is intercepted, it poses no risk since it cannot be used to decrypt the messages. Moreover, this cryptographic mechanism ensures that third-party robots sharing the same communication channel cannot decrypt the information, maintaining the privacy and security of the communication within the swarm. [16]

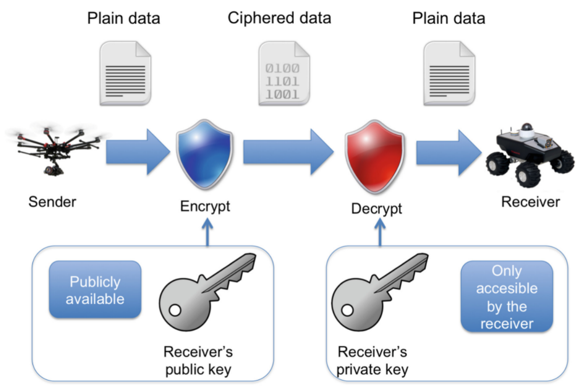

Figure 3.4: Public key cryptography allows robots to be sure that the content of a message can only be read by the owner of the corresponding sending address. [16]

In addition to public key cryptography, digital signature cryptography plays a vital role in swarm robotics. With digital signatures, robots can use their private key to encrypt messages, and other robots can decrypt them using the sender's public key. While the message contents are not kept secret since any robot can access the sender's public key, the use of the sender's private key to encrypt the message provides undeniable proof of the message's authorship. This cryptographic technique ensures that the message could not have been sent by anyone else, establishing trust and verifying the authenticity of the sender. [16]

Distributed Decision Making

Distributed decision-making algorithms have found wide application in various robotic tasks, such as dynamic task allocation, collective map building, and obstacle avoidance. However, effectively deploying large numbers of agents with distributed decision-making capabilities remains a challenge. This challenge involves important trade-offs, such as balancing speed and accuracy in collective decision-making processes. Finding autonomous and flexible solutions for robot decision making in distributed systems is crucial to address the evolving industry challenges. In this context, Blockchain technology stands out as a promising tool for ensuring consensus among participants in decentralized networks. Blockchain enables the creation of distributed voting systems, enabling robot swarms to reach agreements and establish a shared view of the world. This technology holds great potential in addressing the complex decision-making requirements of modern robotic systems.

Blockchain technology can enhance the decision-making process in robotic swarms. When an agent faces a decision that requires consensus, it can initiate a special transaction, creating unique addresses for each available option. Once included in a block, this information becomes public, enabling other swarm members to vote by transferring tokens to the address representing their chosen option. Using mechanisms like majority rule, agreements can be swiftly and securely reached. All agents would be able to monitor the address balances involved in the voting process, ensuring transparency and facilitating auditing.

The first figure (ab) represents one of the agent recognizing an object of interest during its mission. In order to reach an agreement, the swarm robot executes two transactions, One for the different ambiguity in the recognizing process. This results in the creation of two special addresses representing the possible options and then it registers them in the Blockchain. In the second figure (b) The rest of the swarm gathers around the object to obtain different perspectives. Each swarm agent issues a new transaction to the account matching their classification algorithm. In the third figure (c) When the voting process ends, the entire swarm reaches an agreement about the object based on the voting results.

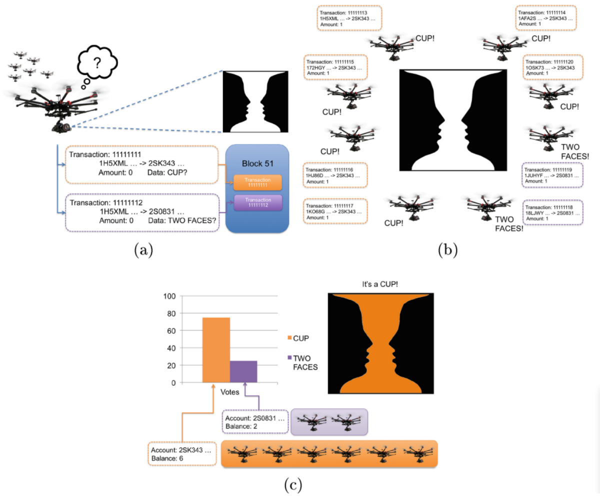

Figure 3.5: process of distributed making showed in the "The Blockchain: A New Framework for Robotic Swarm Systems" paper [16]

path planning

Given the definition defined in the "Blockchain-based Multi-Robot Path Planning "[17] paper "Path planning for robots is the process of calculating a route that a robot takes traversing from point A to point B without interfering with other objects along the way. Multirobot path planning is when this task is being undertaken collaboratively by a robot team." [17]

In this same paper, they implemented and benchmarked a decentralized path planning solution for swarm robots. By using the Hyperledger Fabric [32] blockchain platform, that provides tools to build professional blockchain architecture. Hyperledger adopts an alternative to the commonly know proof-of-work consensus, called the ordering service which is a computational and power-efficient consensus mechanism . [17] Hyperledger is also a smart-contract-based Blockchain platform. Smart contracts ;also called chaincode in the context of Hyperledger fabric; are executable scripts that are stored on the Blockchain and accordingly executed by all the peers on the network in the attempt of fulfilling the terms of the contract.

In this decentralized approach to swarms robot path planning. Each agent independently calculates its own path, following a prioritized sequence determined by the Probabilistic Road Map (PRM) algorithm ; a motion planning algorithm in robotics, which solves the problem of determining a path between a starting configuration of the robot and a goal configuration while avoiding collisions. All robots are provided with the same workspace specifications and the information about stationary obstacles. The PRM path planning mechanism consists of two primary stages:

(a) constructing the roadmap and (b) finding the optimal paths for each robot.

The roadmap construction process involves generating a collection of nodes within the open areas of the workspace. These nodes are then connected with nearby nodes, creating a network of edges. To ensure the integrity of the roadmap, each generated node is checked for overlap with stationary obstacles. Similarly, the edges are examined for any intersections with paths of other collaborating robots. If a node is found to be overlapping with an obstacle or an edge intersects with other edges or obstacles, they are promptly removed from the roadmap to maintain its accuracy and validity.

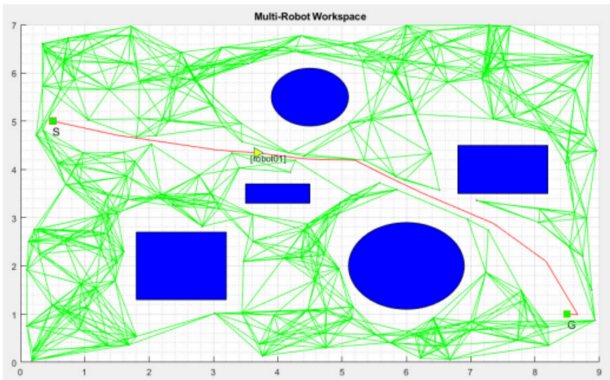

Figure 3.6: Probabilistic roadmap for the second robot. The edges (green links) do not collide with the previous path (red line) or with the static obstacles (blue circles and rectangles). [17]

After the roadmap construction stage, a collision-free arrangement of interconnected nodes is obtained. These nodes are carefully positioned to avoid collisions with static obstacles and other paths, ensuring a safe and clear passage for the robots. Consequently, any continuous trajectory traced along the constructed edges, starting from a designated start point (S) and reaching a desired goal point (G), represents a successful path for the robot to follow.

Here is how the hyperledger was configured. "Multiple Robot client applications are implemented using the Java Software Development Kit (SDK) for Hyperledger Fabric and logically connected with one peer node (peer0.org1.dcu.ie). The peer node hosts the multi-robot chaincode and its own replica of the ledger. The ordering server node (orderer.dcu.ie) is responsible for encoding blocks and committing them on the." [17]

The Certificate Authority (CA) is responsible for issuing digital certificates that serve as the digital identities for participants within the Fabric network. They used the SOLO ordering consensus algorithm, which is a centralized ordering service. It

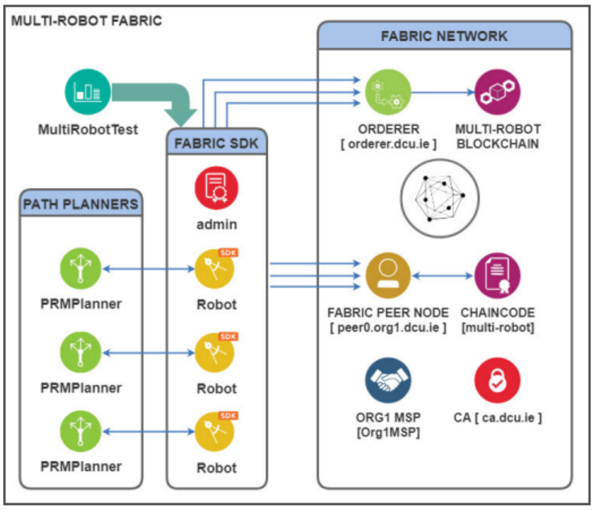

Figure 3.7: Hyperledger Fabric network configuration. Multiple robot application built using Fabric SDK running on a multi-robot chaincode. [17]

was configured to ensure commitment of single transactions into individual blocks to maintain the real-time delivery of transactions into the ledger.[17]

The chaincode implements different methods, that can be evoked by each robot client platform by sending a transaction. The three main methods listed in the paper are getWorkspace, setMyPath and getAllPaths.

additional information

One advantage of storing all agreements and transactions in the Blockchain is that new agent joining the swarm can easily integrate the swarm without the need for extensive learning and training. These new robots can quickly synchronize with the existing swarm by downloading the ledger, which contains a comprehensive record of all past agreements and accumulated knowledge stored in the Blockchain. This eliminates the time and effort required for individual learning and allows new robots to benefit from the collective wisdom of the swarm.

Chapter 4

Conclusion

This state of the art main purpose was to propose a gate for new comers in Swarm robotics. It was aimed to be not too technical, to gain an overview of what are the current challenges in terms of communications protocols. And also gain an overview of what can be achieved in term of swarm agent communication and control with an also rising technology that is Blockchain. We have described a few protocols from low range one like Zigbee or Bluetooth to long range one like LoRa/LoRaWan and even MQTT that rely on underlying physical layer like WiFi.

One aspect talked about swarm robot communication was the constraints set by different environment. Especially for underwater environment, that can be quite challenging to communicate into, since it is completely different to work with than with grounded robots. We have seen methods like acoustic wave, Li-Fi, and even light based methods, to overcome the constraints that underwater environment sets. Method combination was also mentioned, by merging different methods to overcome the different weakness of each method.

In another hand to also get an overview of Swarm Robots implementation we have discussed about different kind of technologies used in the industry to build industrial and hobbyist swarm robots. One of the main technology used nowadays is obviously ROS and ROS 2, those frameworks offer a large set of already build package create by its big community. It almost exists one package for every aspect of building a robot. That makes the process of having a simulated prototype really easy.

To Conclude the state of the art, we discussed about how a rising technology that is gaining popularity like Blockchain can improve the swarm robotics field. By combining the two technologies, we have stated that few use cases of blockchain like security, path planning and decision making.

4.1 Perspectives

Make recommendations for future work on your thesis or dissertation topic.

References

[1] online contributors, “Remote manipulator — Wikipedia, the free encyclopedia,” 2023. [Online; accessed 24-April-2023]. [Cited on pages ix and 3]

[2] M. Rubenstein, C. Ahler, N. Hoff, A. Cabrera, and R. Nagpal, “Kilobot: A low cost robot with scalable operations designed for collective behaviors,” *Robotics and Autonomous Systems*, vol. 62, no. 7, pp. 966–975, 2014. Reconfigurable Modular Robotics. [Cited on pages ix and 4]

[3] J. J. Roldán, P. Garcia-Aunon, M. Garzón, J. De León, J. Del Cerro, and A. Barrientos, “Heterogeneous multi-robot system for mapping environmental variables of greenhouses,” *Sensors*, vol. 16, no. 7, 2016. [Cited on pages ix and 6]

[4] Y. Li, D. Li, W. Cui, and R. Zhang, “Research based on osi model,” in *2011 IEEE 3rd International Conference on Communication Software and Networks*, pp. 554–557, 2011. [Cited on pages ix and 11]

[5] “Hedy lamarr and frequency hopping technology.” [Cited on pages ix, 15, and 16]

[6] “Zigbee stack layers.” [Cited on pages ix and 18]

[7] “Exploring zigbee network topology: Unveiling the three types for robust communication.” [Cited on pages ix, 19, and 20]

[8] D. R. Paschotta, “chirp,” [Cited on pages ix and 22]

[9] T. Tulka, “Lora spreading factor explained,” [Cited on pages ix and 22]

[10] S. Devalal and A. Karthikeyan, “Lora technology - an overview,” in *2018 Second International Conference on Electronics, Communication and Aerospace Technology (ICECA)*, pp. 284–290, 2018. [Cited on pages ix, 21, 22, and 23]

[11] S. Munnings, “Getting started with publish-subscribe messaging systems.” [Cited on pages ix and 25]

[12] T.-C. Wu, Y.-C. Chi, H.-Y. Wang, C.-T. Tsai, and G.-R. Lin, “Blue laser diode enables underwater communication at 12.4 gbps,” *Scientific Reports*, vol. 7, p. 40480, 01 2017. [Cited on pages ix and 29]

[13] “Ros wiki.” [Cited on pages ix, 31, and 32]

[14] s. Sarmah, "Understanding blockchain technology," vol. 8, pp. 23–29, 08 2018. [Cited on pages ix, 37, 38, and 39]

[15] S. Ranganathan, M. Mariappan, and K. M. PG, "Design methodology for using blockchain in swarm robotics," in *2021 IEEE 19th Student Conference on Research and Development (SCOReD)*, pp. 76–81, 2021. [Cited on pages ix, 39, and 40]

[16] E. Castelló Ferrer, "The blockchain: A new framework for robotic swarm systems," in *Proceedings of the Future Technologies Conference (FTC) 2018* (K. Arai, R. Bhatia, and S. Kapoor, eds.), (Cham), pp. 1037–1058, Springer International Publishing, 2019. [Cited on pages x, 40, 41, 42, and 43]

[17] A. Mokhtar, N. Murphy, and J. Bruton, "Blockchain-based multi-robot path planning," in *2019 IEEE 5th World Forum on Internet of Things (WF-IoT)*, pp. 584–589, 2019. [Cited on pages x, 43, 44, and 45]

[18] online contributors, "Ism radio band — Wikipedia, the free encyclopedia," 2023. [Online; accessed 8-June-2023]. [Cited on page xv]

[19] online contributors, "Robot — Wikipedia, the free encyclopedia," 2023. [Online; accessed 24-April-2023]. [Cited on page 2]

[20] online contributors, "Elmer and elsie (robots) — Wikipedia, the free encyclopedia," 2021. [Online; accessed 24-April-2023]. [Cited on page 2]

[21] S. Verret and D. Suffield, "Current state of the art in multirobot systems," 2005. [Cited on page 5]

[22] E. Şahin, "Swarm robotics: From sources of inspiration to domains of application," in *Swarm Robotics* (E. Şahin and W. M. Spears, eds.), (Berlin, Heidelberg), pp. 10–20, Springer Berlin Heidelberg, 2005. [Cited on page 6]

[23] I. Navarro and F. Matía, "An introduction to swarm robotics," *ISRN Robotics*, vol. 2013, 01 2013. [Cited on page 7]

[24] M. Verma, S. Singh, and B. Kaur, "An overview of bluetooth technology and its communication applications," *International Journal of Current Engineering and Technology*, vol. 5, pp. 1588–1592, 05 2015. [Cited on page 14]

[25] B. Mihajlov and M. Bogdanoski, "Overview and analysis of the performances of zigbee-based wireless sensor networks," *International Journal of Computer Applications*, vol. 29, no. 12, pp. 28–35, 2011. [Cited on page 18]

[26] B. Zhang and S. Gao, "The study of zigbee technology's application in swarm robotics system," in *2011 2nd International Conference on Artificial Intelligence, Management Science and Electronic Commerce (AIMSEC)*, pp. 1763–1766, 2011. [Cited on page 21]

[27] J. Connor, B. Champion, and M. A. Joordens, "Current algorithms, communication methods and designs for underwater swarm robotics: A review," *IEEE Sensors Journal*, vol. 21, no. 1, pp. 153–169, 2021. [Cited on pages 28, 29, and 30]

[28] online contributors, "Underwater acoustics — Wikipedia, the free encyclopedia," 2023. [Online; accessed 20-June-2023]. [Cited on page 28]

[29] T. K. Kaiser, M. J. Begemann, T. Plattenteich, L. Schilling, G. Schildbach, and H. Hamann, "Ros2swarm - a ros 2 package for swarm robot behaviors," in *2022 International Conference on Robotics and Automation (ICRA)*, pp. 6875–6881, 2022. [Cited on page 33]

[30] "Orcos documentation." [Cited on page 35]

[31] "carmen documentation." [Cited on page 36]

[32] "hyperledger fabric foundation." [Cited on page 43]

Appendix A

Fiche nº1

A.1 Description of the article

Title of the article : An Introduction to Swarm Robotics

Link of the article : `https://downloads.hindawi.com/archive/2013/608164.pdf`

List of the authors : Iñaki Navarro and Fernando Matía

Affiliation of the authors :

Name of conference / journal : Hindawi Publishing Corporation ISRN Robotics

Classification of the conference / journal : VIA SJR H-INDEX 17 classification Q2

Number of citations of the article (which source?) : 227 citations (source google scholar)

A.2 Summary of the article

This article introduces us to the topic of swarm robotics trough different angle. The origin and inspiration that allowed the creation of swam robotics. It also briefly describes what swarm robotics are about, and how to discriminate it from multi-robot type systems, thanks to five criteria. This paper also provides us with the taxonomies of swarm robots, which is derived from multi-robotic systems. To complement on swarm robotics they have implemented basic behaviours and tasks in swarm robotics. Those experiments were made inside a simulation. To list a few of these experiments they have implemented, dispersion, pattern formation, task allocation and more algorithms. To end the article they have pointed out few real world applications for swarm robotics.

Problematic The problem was to give and overview of the domain of swarm robotics, by pointing out the definition of swarm robotics, how to discriminate swarm robotics from its counterpart multi-robotic systems.

Possible leads (pointed out by the authors) No leads pointed out by the authors

Research question No research questions. But only an overview of swarm robotics and the difference with multi-robots systems. We can still talk about how to simulate swarm robots and the different solutions proposed.

Approach adopted The authors have proposed a list of the different platforms used in the most relevant swarm-robotics experiments found in the literature at that time.

Implementation of the approach They have listed a few Robotic platforms where you can allocate robots on demands. Each platform are categories by their swarm size, the robot type, the computing abilities, communication protocol and more. Those most of the times are labs that put into disposition for the researcher who has no access to direct swarm robotics systems. They also listed software simulation, like the Player/stage/gazebo simulators which can run swarm sizes up to at least 100,000 simple robots. But also Webots, Microsoft Robotics Studio and more.

Results The paper gave us a nice overview of swarm robotics, for a better understanding of the domain. By giving us clear definition and criteria, we are now able to identify swarm robots from other multi-robot systems. Also by giving us all the basic task of swarm robots and how to approach them, we now can have a good foundation to understand algorithms and implementation of swarm robotics method we may find in others research paper or articles.

Appendix B

Fiche nº2

B.1 Description of the article

Title of the article : Current Algorithms, Communication Methods and Designs for Underwater Swarm Robotics: A Review

Link of the article : `https://ieeexplore.ieee.org/abstract/document/9153840`

List of the authors : Jack Connor, Benjamin Champion, and Matthew A. Joordens

Affiliation of the authors :

Name of conference / journal : IEEE SENSORS JOURNAL

Classification of the conference / journal : VIA SJR H-INDEX 132 classification Q1

Number of citations of the article (which source?) : 73 citations (source google scholar)

B.2 Summary of the article

This article introduces us to the topic of underwater swarm robots. It provides us with an overview of the art of underwater swarm robotics, and it's problematic. The topics tackled here are how robots can move in an underwater environment. To this problematic the article shows us two methods, using propeller based robots or Bio-inspired Robots.

They give us an overview of sensors used to perceive and communicate with the world around a swarm of robots. They list the sensors with their benefits, flows and limitations within an underwater environment.

The main topics for our state of the art, is the communication protocols approached in this article. Here the authors analysed the state of the art in underwater communication. And provide us with an overview of why certain protocols are not adequate underwater. And why other types of communications are better. The discrimination of the communications used underwater are mainly based on reception meter, noise and transmission rate. Some protocols listed are WiFi, Bluetooth, IR, acoustic wave methods, light-based transmitter or even electrocommunication.

Another part of the article is the Control of a swarm of robots, using centralized control or decentralized control. The paper also gives us with a description of swarm algorithms, that are a form of intelligence that is based on the behaviours that are found in nature. To conclude, it also provides us with few underwater swarm robotics applications.

Problematic The main problem of this paper is to give an understanding of the problematic encountered in underwater environments. Most of the communications and controls of robots in the surface and in the air, are not always adequate for underwater robotics. So this paper tackles the problem of underwater communication and control for swarm robotics and tries to give us other suitable solutions.

Possible leads (pointed out by the authors)

Research question How can we communicate and controls robots and especially here swarm robots in an underwater environment?

Approach adopted Here the authors approached the problem, by listing a few of the state of the art in swarm robotics communication protocols. Each technology listed where discriminated by giving an overview of why it's a good solution or not to our problem of underwater communication.

Implementation of the approach

Results For the communication part, for our state of the art, the paper proposed to use light based communication protocols and acoustic waves to communicate. But also to fusion the two methods, to compensate the flows of each method.

Appendix C

Fiche nº3

C.1 Description of the article

Title of the article : The blockchain: a new framework for robotic swarm systems

Link of the article : `https://link.springer.com/chapter/10.1007/978-3-030-02683-7_77`

List of the authors : Eduardo Castelló Ferrer

Affiliation of the authors :

Name of conference / journal : Part of the Advances in Intelligent Systems and Computing book series (AISC,volume 881)

Classification of the conference / journal : VIA SJR H-INDEX 28 classificatin Q4

Number of citations of the article (which source?) : 4 citations (source google scholar)

C.2 Summary of the article

This article focuses on the benefits of implementing core Blockchain principles into swarm robots. It provides us with few techniques used in Blockchain to palliate some swarm robotics problematic like security, behaviour control and decision making.

The paper also gave us a brief introduction to the Blockchain technology, even if it's not detailed. It helps the reader to dive into the article without prior knowledge of the topic.

One of the aspect talked on the paper, is security. They proposed a well known and simple trick used in most of the communication protocols and especially in Blockchain. Which is the use of complementary private and public key. Due to the core functionality of this keys, one robot agent can communicate with other agent securely without worrying about leaking his message. The messaged transmitted is encrypted with the public key of the receiver, so only the receiver can read the content of the message, thanks to its private key. So if a third-party have access to the encrypted file, he will not be able to read its content. Furthermore, a message can be signed by the sender private key. The fact that the message was encrypted with the sender's private key proves that the message could not be sent by anyone else.

Other topics discussed in this paper are in distributed decision making. Blockchain here helps the swarm robots merge toward a common outcome. For instance, thanks to Blockchain we can create a distributed voting system, that will help the swarm reach the same outcome.

This paper also tackles behaviour differentiation. Here they proposed to combine classical swarm robotics control techniques and Blockchain to tackle problems beyond security and distributed decision making issues. They stated that we could use sidechains; a technology that enables us to link several Blockchain in a hierarchical manner; that will allow swarm robot agents to act differently according to the particular Blockchain used.

The last part that interest us for our state of the art, is the limitations and problems at that time, of implementing Blockchain for swarm robotics. Few of these limitations are latency, throughput and bandwidth .

Problematic The problem was to explain how Blockchain technology can provide innovative solutions for swarm robotics.

Possible leads (pointed out by the authors) The author points out that the Blockchain technology could be the key to progress in swarm robotics. And that it could lead to new technical approaches.

Research question How can Blockchain technology can be implemented in the field of swarm robotics?

Approach adopted The author gave us a brief introduction to Blockchain and then tried to explain how the technologies used inside the Blockchain can be adapted to swarm robotics. There was not experienced in this paper, it was mainly theoretical.

Implementation of the approach

Results Here the Blockchain technology gave us a sneak peak at how a group of agent can reach an agreement without the need of a controlling authority.

Appendix D

Fiche nº4

D.1 Description of the article

Title of the article : A Blockchain-Controlled Physical Robot Swarm Communicating via an Ad-Hoc Network

Link of the article : `https://link.springer.com/chapter/10.1007/978-3-030-60376-2_1`

List of the authors : Alexandre Pacheco , Volker Strobel and Marco Dorigo

Affiliation of the authors :

Name of conference / journal : International Conference on Swarm Intelligence, Part of the Lecture Notes in Computer Science book series (LNTCS,volume 12421)

Classification of the conference / journal :

Number of citations of the article (which source?) : 8 citations (source google scholar)

D.2 Summary of the article

This paper presents us the application of the Blockchain technology to swarm robotics. By providing us a successful implementation of a Blockchain-Controlled robot swarm. Where many simulations were already done in the past. Nobody actually made a physical proof of feasibility in real life.

Their implementation is ruled by a smart contract on the Ethereum blockchain. Alson they established an Ad-hoc Mesh Network using the B.A.T.M.A.N routing protocol, thanks to that the robot can exploit the WiFi module of the Pi-puck without compromising the decentralization of the robot swarm.

Problematic Since the presentation of Blockchain controlled swarm robots, many people have simulated the feasibility of swarm robots and Blockchain, despite this no one really created a real world simulation. The problem of this paper was to palliate the last statement.

Possible leads (pointed out by the authors) One important question is when we want to implement this method to real robot, we need to know if we have the computations and communications required to run this implementation. Also, since this paper was to show the feasibility of this method in real life, the implementation may not be the most efficient, so working on this is a leading point for the future.

Research question Can we control swarm robots thanks to the Blockchain technology, and how to compensate security issues thanks to this technology ?

Approach adopted They have created experiences, with a swarm of Pi-puck robots. Were the goal was to determinate the fraction of white tiles in a checkerboard environment. They tested their implementation of Blockchain-controller swarm robots, by increasing the number of Byzantine robots inside the swarm, that distribute false information. And also by increasing the swarm size and decreasing it.

Implementation of the approach Each Pi-puck robots are controlled thanks to parallel routines that execute at different frequency.

The consensus algorithm used is proof-of-authority. Proof-of-authority requires a majority of preselected nodes to agree on the state of the Blockchain.

The smart contract used is implemented so the robots can store their local estimates on the Blockchain.

An Ad-hoc network based on the B.A.T.M.A.N protocol was implemented to, palliate the use of a single WiFi router.

Results Thanks to the Blockchain protocols, and its different technologies, like public-key/private-key pair technology, swarm contracts, consensus protocols etc. The searcher was able to protect a swarm of robots from a Sybil attack, and they reduced the influence of Byzantines robots.

Appendix E

Fiche nº5

E.1 Description of the article

Title of the article : Robot Swarm Communication Networks: Architectures, Protocols, and Applications

Link of the article : `https://ieeexplore.ieee.org/abstract/document/4684993`

List of the authors : Ming Li, Kejie Lu, HuaZhu, Min Chen, ShiwenMao, B. Prabhakaran

Affiliation of the authors :

Name of conference / journal : 2008 Third International Conference on Communications and Networking in China

Classification of the conference / journal :

Number of citations of the article (which source?) : 72 citations (source google scholar)

E.2 Summary of the article

In this paper the research team proposed a new architecture to communicate called "robot swarm communication networks". The robots are clustered into one or multiples teams of swarm robots. In this architecture each swarm can be monitored and controlled by a central server. Also within each swarm a self-organizing ad-hoc network is formed. So all the robots are connected together.

Problematic

Possible leads (pointed out by the authors) The authors lead us to the following problems: How to design and develop a secure real-time software system such that administrators and mobile users can monitor, coordinate and control robot swarms remotely?

Research question

Approach adopted

Implementation of the approach

Results

Appendix F

Titre de l'annexe

F.1 Section

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

F.2 Une autre section de l'annexe F

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.