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Integrated Sensing and Communications in Wireless Networks: A Key Technology Enabler for Offering New Services to Users

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A mia **mamma**,
A mio **papà**,
Ad **Erika**,
Ai miei **amici**,.
“Il successo non è definitivo, il fallimento non è mai fatale:
è il coraggio di continuare che conta.” - **Winston Churchill**

Abstract

This work provides a general view of Integrated Sensing And Communication (ISAC) systems, what are them and why this is a needed technology. The first section introduces the foundational concepts of modern communication systems, including an overview of ISAC's historical development. The following section deep dives into ISAC's architecture, analyzing strength points, weaknesses and open challenges. We dealt with particular attention with the bi-static offset problem. The document then explores various Joint Sensing and Communication (JSC) use cases, such as Human Activity Recognition (HAR) and security considerations, emphasizing the importance of data privacy implications. The third section examines the role of Machine Learning (ML) in ISAC, explaining data preparation, training, prediction, and specific roles that ML plays in enhancing ISAC capabilities ending with advanced techniques like federated learning. Finally, the document presents the SHARP algorithm, a real case algorithm developed in 2022 by a UNIPD's research team, explaining the dataset, the techniques employed in the design of the algorithm and the results. This comprehensive exploration underscores the critical role of ISAC in advancing modern communication systems and highlights future directions for research and application.

Contents

Listing of figures

Listing of acronyms

Symbols

4G fourth generation

5G fifth generation

A

AUC Area Under the Curve

C

CAS Communication-aided Sensing

CFO Carrier Frequency Offset

CFR Channel Frequency Response

CSI Channel State Information

D

DSP Digital Signal Processing

F

FL Federated Learning

G

GDPR General Data Protection Regulation

GHz Giga Hertz

GPSDO global GPS disciplined clock

H

HAR Human Activity Recognition

HCI Human Computer Interaction

I

IC Integrated Circuit

IoT Internet of Things

ISAC Integrated Sensing And Communication

J

JSC Joint Sensing and Communication

L

LO Local Oscillator

LOS Line of Sight

M

MIMO multi-input multi-output

MitM Man-in-the-Middle

ML Machine Learning

mmWave Millimeter Wave

N

NFC Near Field Communication

NNs Neural Networks

O

OFDM Orthogonal Frequency Division Multiplexing

P

PAN Personal Area Network

PIM Pulse Interval Modulation

PO Phase Offset

R

ROC Receiver Operating Characteristic

Rx Receiver

S

S&C Sensing and Communication

SAC Sensing-aided Communication

SHARP Sensing Human Activities through Wi-Fi Radio Propagation

T

TO Timing Offset

Tx Transmitter

1

Introduction to communications systems

The Internet is one of the most revolutionary things invented by the humankind in the last century and it is all based on communications systems and infrastructures. When dealing with the Internet we have to receive, send, manipulate and manage information. This could not be possible if the computers we have at home were not connected through communication systems. Communications systems are the fundamentals to guarantee the right convolution of signals and information. They are heavily spread around the world, covering the majority of the lands and of the seas as well. The communication can happen based on mainly two ways of sending signals: wired or wireless. When we have a wired communication we (usually) have a higher rate of information exchanged in terms of quantity, the main idea between the wired communication is that the wires cannot encounter obstacles or walls, just interference in some cases. The drawback of the wired connection is that we can not really understand anything from the connection itself and from the signals returning from it.

When we are taking into consideration a wireless connection it is just a different match. Without the wires taking the place of the conveyor of signals we have to use the air as our way of transmitting. The Wi-Fi technology (the most adopted in everyday use cases) uses radio waves in the range of 2.4 Giga Hertz (GHz)- 5 GHz. The wave propagates from the transmitter in the air in several different directions and not just in the direction of the receiver. The signal can encounter obstacles like doors, walls, long distances, closets and so on. When it comes to pure speed of transmission the wireless connections lose against their wired counterpart but in contrast, wireless transmissions can capture information about the space, the movements and other characteristics of where and how the receiver is placed, thanks to the calculations made by the machines using the data of the reflected waves. This very peculiar process is called "sensing" and is one of the two main technologies that we will discuss in this work.

1.1 Key Definitions

Modern communication technologies are based on a combination of various fields of engineering and sciences. In the following, we introduce some concepts that will be used in this thesis:

- Semiconductors and Integrated Circuit (IC): Those are at the base of every modern digital circuit and constitutes the base to create all the devices we see around the world;
- Digital Signal Processing (DSP): it is the way we can work with digital signals and perform activities on them, from cleaning a bad signal to extrapolate information from it;
- Wireless Communication Technologies: this category groups not only Wi-Fi but also all the others key technologies like bluetooth, cellular lines, Near Field Communication (NFC). When using wireless communication systems a new variety of operations and features may be implemented, using the radio signals as the veichle of information;
- Frequency and different portion of the radio spectrum: not only we can change the structure from wired to wireless but the technology has evolved to permit the use of the frequency spectrum as we want. Some higher frequency are better for certain operations than other lower frequency and viceversa. We note here just for the sake of curiosity two types: Millimeter Wave (mmWave), an high band frequency (roughly from 24GHz to 100GHz, and the sub-6GHz, which comprehend all the frequencies under the value of 6GHz;
- Machine Learning (ML) algorithms and the self-learning machines: there is an entire chapter dedicated to this technology but you will have for sure heard about this word-changing technology, often improperly named or misused;
- Channel State Information (CSI) is a metric in wireless communications that describes how a signal propagates through a channel as a function of frequency. The CSI provides information on how different frequencies of a signal are altered by the channel through which the signal travels. In practice, CSI represents the behavior of the channel over a range of frequencies and contains both the amplitude and phase of the signal for each specific frequency. This data is crucial for understanding and compensating for channel effects such as attenuation, reflection, diffraction, and interference, in order to optimize the quality and reliability of wireless communication. CSI will be our measuring tape to get information from the signal.

1.2 What is Sensing?

Sensing is the process of detecting and measuring physical properties or changes in the environment using various types of sensors. Sensing involves the use of devices called sensors to detect and measure physical phenomena such as temperature, light, pressure, sound, motion, and chemical composition. Sensors convert these physical properties into readable signals, typically electrical, which can then be processed and analyzed. There is a sensor for every type of physical event: for movement there are gyroscpes, or accelerometers, for pressure the are barometers, for sound there are microphones etc.

In this work, we will investigate how it is possible to integrate one or more sensing functions in an infrastructure that usually runs communications, so the sensor we need is something compatible with radio waves, something that can measure how the waves propagate and how it is returned from the environment. What is this sensor? There are several sensors employed in this mission but the most common are: Radars, Lidars, Opticals and Ultrasonic sensors. Some project ideas do not limit the use of other sensors in some objectionable way, we will focus on the main idea behind Integrated Sensing And Communication (ISAC) systems: use the already existing infrastructures (or near to that) and obtain an integration of sensing to get benefit from it.

So, sensing in the communication infrastructure means using the devices that permit the communications in a network to get some additional info while communicating at the same time. An example to clarify can be this: think of a car that already has sensors of proximity, e.g., a Tesla. Now this car can communicate with other devices like the telephone of the driver, or an internet provider to get access to the maps. How much benefit could we gain integrating the real time-proximity information in the communication channel and get other cars with the same sensors to get at an adequate distance and coordinate themselves? This is sensing and we will see in the next chapters how to get a perfect integration, which are the weaknesses of ISAC systems, how much effort we have to put to build an infrastructure and how to get the best from what we already have.

1.3 A brief history of ISAC

The first developments of ISAC, as we know it, can be traced back to the 1960s[1]. In the first systems, communication information was embedded into a group of radar pulses via Pulse Interval Modulation (PIM). The purpose at that time was implementing new communication functions into military radars, so a typical sensing-centring system, as we will approach later in Chapter 2. Early radars were mechanical and they were used to rotate their antennas to find enemies but this type of implementation faced a lot of problems and so phased-array radars were developed to circumvent those drawbacks. Phased-array systems generate spatial beams that can take directions electronically and in a long range. The first implementation was made in Germany, during WWII, named “Mammut”. Mammut was also the first multi-antenna system which, later in time, inspired the invention of multi-input multi-output (MIMO). MIMO was the technology that led to the modern era of communications (fourth generation (4G), fifth generation (5G), wireless networks etc). Research on radars and communications began to merge in the 90’s, during that period various ISAC schemes was proposed but the hardware and the infrastructures of that time weren’t solid enough to benefit entirely from that technology: the maintenance was to expensive. The general idea was to embed communication information into commonly employed radar waveforms. One technology that aided the development of ISAC is the Orthogonal Frequency Division Multiplexing (OFDM), in particular it can mitigate the impact of random communication data in a straight forward manner. Another important step in the development of ISAC is the

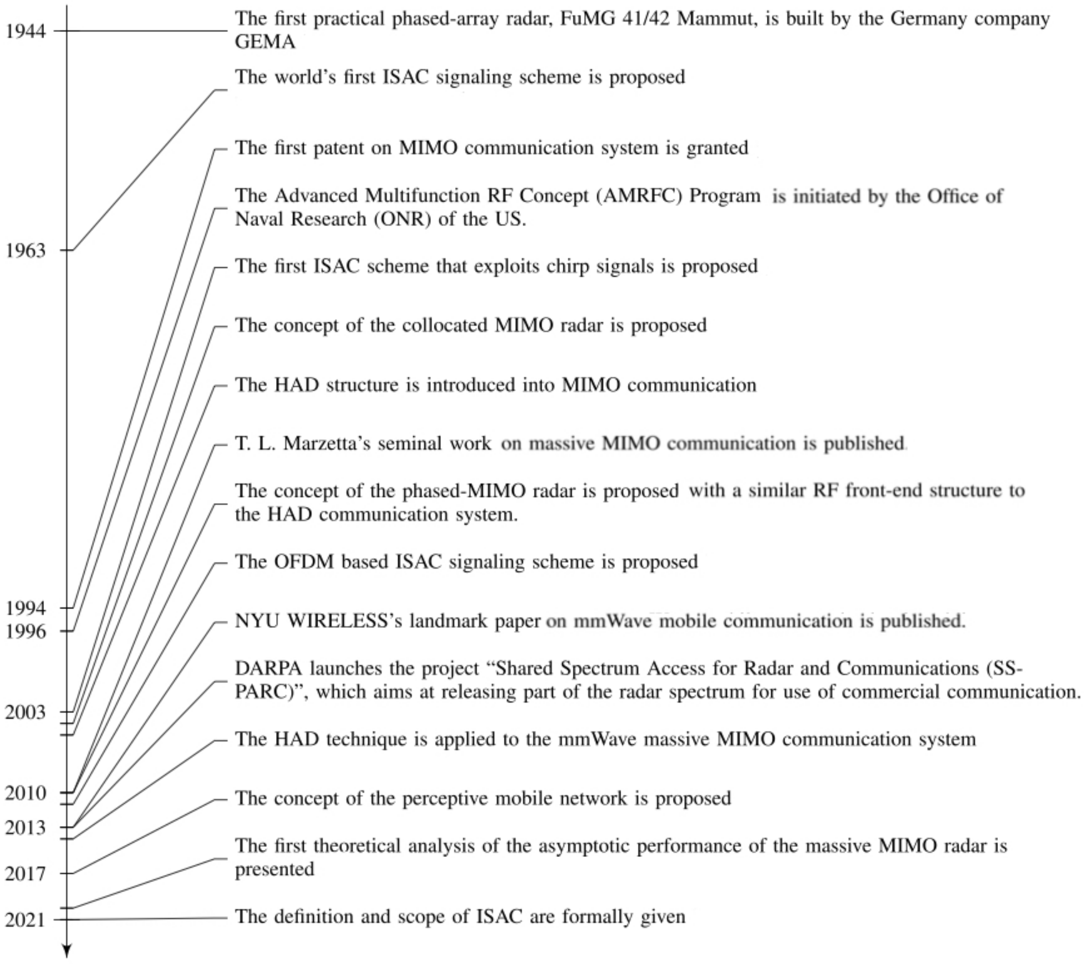


Figure 1.1: The fundamental steps in the ISAC history[1].

project founded in 2013 from the Defense Advanced Research Projects Agency: Shared Spectrum Access for Radar and Communications. It aimed to release part of the sub-6 GHz spectrum from the radar bands to use it with both radar and communication.

2

Integrated Sensing and Communication

Integrated Sensing and Communication is a design approach that combines the (radio) sensing and the communication techniques. The main idea behind ISAC is that the radio waves can serve the communication service and at the meantime the sensing service. The applications for this type of communication systems can vary and it can improve the efficiency, the latency as well as the security of certain environments. ISAC is not a new topic in the world of communications research but it has seen an exponential increment in interest since the last decade. The very first explanation for this is the implementation of new models of Wi-Fi and the faster hardware available at a reasonable price. A possible second reason could be the development of ML algorithms that can utilize the data collected from the sensors and return a reliable result.

2.1 Why do we need ISAC?

In a communication system we can also have separate Sensing and Communication (S&C): so why do we need ISAC? The integration is the key advantage, in this way we can have just one system that can do both sensing and communication and we can share the resources to improve the efficiency. Spectral efficiency is also a technical aspect that has improved through integrating S&C. Spectral efficiency refers to the ability to transmit or receive data in a specific frequency band efficiently. In other words, it measures how well a communication system utilizes the available radio spectrum to transmit information. Higher spectral efficiency means that more data can be transmitted in the same frequency band, or in the other hand, that less frequency band is needed to transmit the same amount of data. This concept is particularly crucial in wireless communications, where radio spectrum is a limited resource [2]. Not all the ISAC systems are equals, indeed the integration could happen at various levels of the system. When thinking about the advantages of an ISAC system we can divide them in two main points:

- Integration Gain: the reduction of the costs, time, and resources in general, deriving from the integration of the two functionalities in one single channel;
- Coordination Gain: sensing and communication can work together to build a single, more precise functionality. There are two cases: communication-aided sensing and sensing-aided communication. An example is using the sensing functionality to sense the room where the Wi-Fi signal is transmitted, to use the resources in the best way possible.

There are mainly three ways in which the integration could happen: Hardware Layer, Signaling Layer, Application Layer.

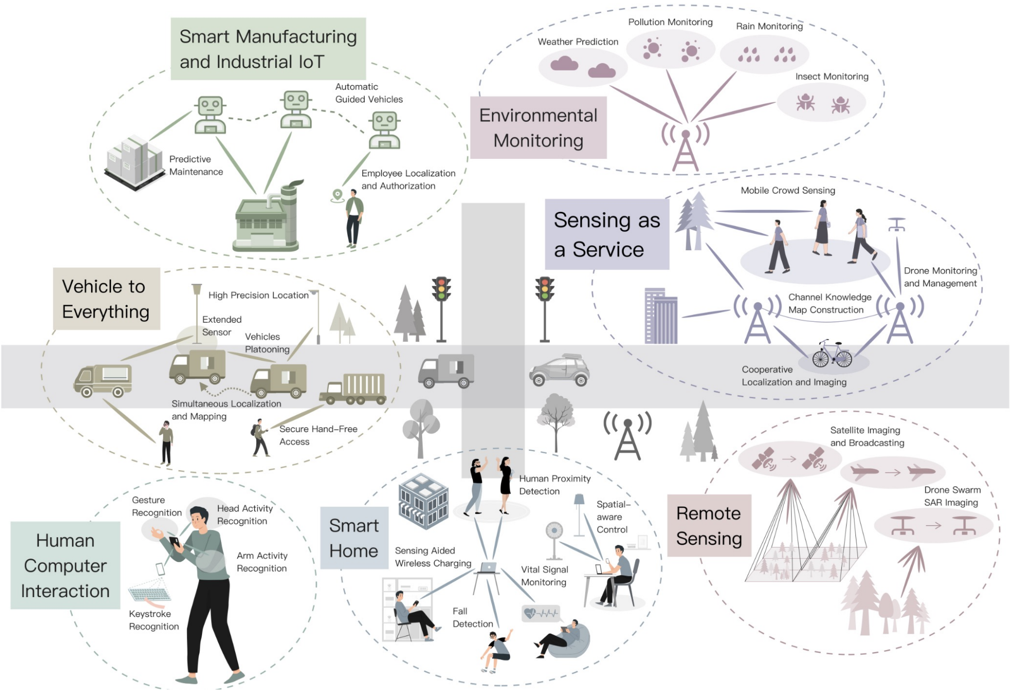


Figure 2.1: ISAC technology for future wireless networks [1]

2.1.1 Hardware Layer

A common strategy is to partition hardware resources, such as antenna arrays and radiofrequency chains, into distinct groups dedicated to specific functions. We can also have a different level of integration at the same layer: this depends on the tightlyness of the system. In the hardware layer a choice that can be made is about to whether use or not use a unified waveform. This choice depends on the specific requirements of the application, the level of integration desired, and the trade-offs between the simplicity of a unified approach and the customization offered by separate waveforms. It is always good to think about the system from the perspective of what it will have to do, how many funds it can absorb and how much customization we can put in it.

2.1.2 Signaling Layer

A fully unified waveform is a more favorable design, enhancing the efficient utilization of wireless resources and thereby improving integration gain. In summary, when S&C share spectrum, their communication characteristics align, and combining them into a unified waveform optimizes resource utilization and integration gain.

2.1.3 Application Layer

Integrating S&C functions at the application layer enables each function to leverage the output data of the other, gaining valuable insights for mutual support and collaboration. This means that communication is enhanced with sensing and vice versa. A typical example of integration in the Application layer is the Human Activity Recognition (HAR). In a modern Wi-Fi sensing model the raw CSI are transmitted to an additional signal processing unit for having better data quality, this process is called Data Augmentation. In the second place, the target signal is extracted from the complete data to remove redundant signals, and, at the end, a model-based or learning-based algorithm is used to analyze the augmented data to extrapolate information about the human movement or activity.

2.1.4 Waveform design

When engineering an ISAC system and so a single system with two different functionalities and two different metrics of accuracy, sensing and communication, implementing the trade-off between those two is inevitable. A good developed network, a strong infrastructure and robust channels are the key to build an ISAC system that allows not discarding as many properties of the dedicates S&C infrastructures. Sometimes, depending on the scope of the project, those systems are based on pre-existing channels and infrastructures, sometimes they are built from scratch to improve as much as possible the integration gain and the coordination gain (the benefits of having a S&C system integrated on a single infrastructure). Here i want to list the main waveform design that can be chosen when starting to build an ISAC system.

- Sensing-centric design: this system integrates communication messages into a classical sensing waveform, and has a high compatibility with radar systems. As cons this type of design has a low data rate.
- Communication-centric design: this system leverages the standardized communication waveform architectures and protocols to enable sensing functionality. It offers good compatibility with communications systems but it offers a poor sensing performance
- Joint design: the first two systems in this list represent an adjustment of existing architectures and they take advantage of the existing know-how to perform S&C integration. The best solution is instead to build up from scratch the entire ecosystem, take advantage of what is available and assemble every single part based on what the specific project really needs. This results in a case-by-case study of pros and cons but a joint design can have

really high level of both communication and sensing. The con is of course the studying and the engineering of dedicated waveform design. [3]

2.2 Challenges for ISAC

ISAC does not come without problems and open challenges, indeed one of the reasons of why it isn't so adopted up to now is because the research is developing remedies for those problems.

- The first and most important problem today when dealing with ISAC is Privacy and Security. We already know that this method implements sensing and communication in one single channel and, if from one side this is it's strength, from the other side this may be its weakness. Ensuring the leakage of data between the radar function (sensing) and the communication function is one of the hottest challenges in the research field. A possible solution to the security challenge is to apply cryptographic techniques at high layers of the network stack to encrypt the confidential data prior to transmission.

- When sharing a single channel for two different functions interference management becomes crucial. Specifically in the context of sensing-aided communication and communication-aided sensing, having interference and so a tampered signal may lead to exponential errors. Since one of the two functions depends on the other and vice versa if the signal is corrupted the results will be highly corrupted. Luckily this has been addressed by the increasing understanding and developing of the Deep Learning algorithms.

- The level of user acceptance and adoption of ISAC isn't as high as one might expect, given the potential benefits it offers. This is probably because it is a new and developing technology and its effectiveness in some fields has not been completely proven. This may result in a sub-problem: difficulty to interoperate between different systems as there is not been as of now a large adoption of ISAC systems.

- When utilizing a bistatic configuration, the transmitter and the receiver are located in two separate positions. Those two devices need to be as much synchronized as possible, but this is a challenge. If the synchronization is not precise, it is likely to generate offsets that will surely deteriorate the signal.

2.3 Bi-static offset

Bi-static configurations, in contrast with mono-static, are a promising way of setting up an ISAC system because they require close to zero changes in the actual infrastructure. Bi-static configurations are indeed very promising as they could integrate perfectly into communications systems. [4] The main drawback in bi-static configurations is clock asynchronism: the Transmitter (Tx) and the Receiver (Rx) are physically and spatially separated and their clocks from the Local Oscillator (LO) are not locked and asynchronous. Specifically, the basic clock is generated from the

LO, a fundamental component in radio devices used to generate a sinusoidal signal with a stable frequency. This signal is essential in various modulation and demodulation processes in radio Tx and Rx. When basic clocks of Tx and Rx are not locked in phase they are asynchronous and this introduces unwanted offsets in the received signals. Let's categorize the main types of offsets and see why this problem is hard to solve and is a challenge in the integration of sensing and communication (offsets exist also in those two separate worlds but while it is not a big deal in communications, when it comes to sensing offset is to be removed):

- Carrier Frequency Offset (CFO) is caused by the difference in clocks of the LO of the Tx and Rx. Two different oscillators cannot generate the same frequency and so the two carrier frequencies will also be different, leading to CFO. There are also other factors that cause this type of offset: changes in temperature in the environment, variations in voltage supply and ageing or degradation of the systems. A typical way to estimate CFO is by measuring two segments of repeated signals. We will soon see why estimating the offset is important and how to correct the problem using estimation.

- Timing Offset (TO) happens when there is no synchronized time reference in the system, between Tx and Rx. There is a precise way to transmit signals in communications systems and also a precise timing to do so but when the receiver and transmitter use their own LOs to generate this timing there could be an unknown shift in the time that the receiver sense than the actual time the signal was sent (transmission time). When the transmission is continuous there is no problem since the offset is always the same and we can address this problem quite easily, but it can become, in jargon, time-varying, when the transmission is discontinuous or when the synchronization point is changed.

- Phase Offset (PO) is more like a general type of interference and it can be caused by transmitting electronic devices, thermal noise and flicker noise.

2.3.1 Why is the offset problem a challenge to address (and why is it so difficult)?

In the communications field, the offset is already addressed using specific algorithms. In addition, the receiver determines the fine-timing and the remaining offset can be removed via channel equalization. In sensing, the offsets need to be treated properly. It is important to get an estimation of the propagation delays as precisely as possible. This is an open challenge but some ways to address the problems are already theorized and tested. A not-so-practical solution is to implement in the system a global GPS disciplined clock (GPSDO) which is a device that with an adequate level of accuracy can cost around 1000 dollars and it needs an open sky view to work properly (not to talk about the relatively large dimensions). In contrast with GPSDO there is a more practical technique called single-node sensing. This is a way to implement a sensing system that does not require additional and expensive devices and it is less complex as a solution in general.

2.3.2 Single-node approaches to addressing offset

When it comes to the methodologies applied to address the problem of offset using a single-node structure there are two principal branches: eliminating the factor at the base or estimating the size of the error and compensating with particular techniques. There is also a third one that mixes up the first two: the so-called hybrid method**??**. This technique utilizes the elimination in the fields that can benefit the most from it and where elimination cannot serve the cause the estimation and compensation method comes up. To conclude this paragraph, the bi-static asynchronism problem has yet to be fully addressed but the literature is widely open to research new technologies to solve it. Several algorithms of compensation have been implemented in systems to test the effectiveness and ones better than other showed real impact on the issue but have some critical aspects to be taken in consideration.

2.4 Some ISAC use cases

Now we are going to see more in detail some of the most known ISAC possible implementation [1].

1. Sensing as service: the recent deployment of dense cellular networks as part of 5G allows the current communications infrastructures to be reused for sensing with only small modifications in hardware, signaling strategy and communication standards. This means a rapid and inexpensive integration of communication and sensing into current Internet of Things (IoT) devices and cellular networks. We can get an idea of how this will lead to an ubiquity of ISAC;

2. Smart Home and In-Cabin services: recently, the ISAC-enabled IoT has shown great potential in daily activity recognition, health care, home security, driver attention and more. This is thanks to the almost zeroed cost in privacy since the sensing functionality does not require any real image or detailed description of the subjects in the environment;

3. Vehicle to everything (V2X): ISAC has been proven to be a better solution to existing ones when talking about the exchange of information and sensing between vehicles and vehicles or between vehicles and other receivers because of a reduction of delay and a reduction of the hardware employed in the construction of those systems;

4. Smart manufacturing and Industrial IoT: the presence of Wi-Fi in any industrial scenario such as construction, car manufacturing and similar opened a new efficient, powerful, and less expensive way of producing. Those scenarios often involve network nodes and robots that coordinate to complete particular difficult or delicate tasks. ISAC offers an unlimited set of advantages in this field, where in addition to ultra-fast and low-latency communications, the integration of sensing enables those robot-entities to coordinate themselves an navigate the workspace without incurring in obstacles or without dropping precious materials or tools;

5. Remote sensing and GeoScience: integrating sensing in communications means also having a description of the environment without worrying about day and night or weather conditions, this will lead ISAC technologies to an implementation in GeoScience mapping systems;

6. Environmental sensing: information like humidity and particle concentration can also be indicated from the propagation characteristics of transmitted signals;

7. Human Computer Interaction (HCI): in an increasingly connected world, HCI plays a crucial role in shaping user experience, especially when integrated with environments that incorporate advanced sensors and communication systems. Most of the operations that we do to interact with computers in general could be reinvented if thought in an ISAC environment. In a centimeter-precision sensing environment we could possibly use only gestures to interact with a computer ad typing in a virtual keyboard, eliminating wasted spaces.

2.5 A Sensing Application: Human Activity Recognition (HAR)

HAR is one of the more promising and successful field to take advantage of ISAC up to now. It represents a significant advancement in how we understand and interact with our environment, it involves the use of sensors and communication technologies to detect and interpret human movements and activities. In an ISAC framework, the integration of sensing and communication allows for real-time data collection and analysis, enabling systems to recognize activities such as walking, running, sitting, and more complex gestures with high accuracy. This integration improves the functionalities of smart devices and environments, leading to more responsive and adaptive systems. For instance, in smart homes, HAR can adjust lighting, heating, and security settings based on the occupants' activities, creating a more comfortable and secure living space. In the healthcare system there are a ton of ways HAR can improve the conditions of the workers or make easier many tasks. HAR can monitor patients' movements to detect falls or unusual patterns, providing responsively alerts to caregivers or medics. HAR will improve in the future, hand-in-hand with ISAC systems, providing wonderful new features in many different fields of application like fitness, workspace's safety, and personalized user-applications. It is noteworthy that HAR as others technologies is not a prerogative of the ISAC framework. As noted in [5], the recognition of the main human functionalities and activities is achievable also with small devices called wearables, belonging to the Personal Area Network (PAN) framework. HAR is also performed with video recognition through algorithms that search for a person in a live video from CCTV cameras or webcams. The thing that we should remember is that ISAC systems are the more promising in this way: they usually do not require additional hardware in the infrastructure, consume less power and could be performed all day long without requiring large amount of space for storing data.

Figure 2.2: Human Activity Recognition in an hospital chamber

2.6 Data Collection and Privacy-related topics

In the modern era the term “Privacy” is abused and it comes into place also when talking about something that has nothing to do with privacy or is privacy-related. Of course there is scepticism on the development of ISAC technologies because people have always been critical that a service can collect data and use them to specific purpose. In 2024 the entire world is data driven and of course those systems need to collect data in order to work properly. Lets see how ISAC systems collect data and how this data is stored. The first thing to be mentioned is that a sensing framework needs just a few types of data in order to perform the functions, which type depends on the infrastructure but usually it is radio signals and all that concerns the wave and its timings, sounds, length, and other technical details that we have covered in this chapter and will cover in Chapter 3. Is there a need to store the collected data in some type of storage to perform the Joint Sensing and Communication (JSC) functions? Theoretically no, if the infrastructure is strong enough (a thing that happens in most cases) all the calculations and predictions could be made on the fly. Of course data is important to make analysis and long term monitoring, not to talk that data is the fuel of all the algorithms that make the integration of sensing in the communication infrastructure possible. It is likely that a future, economic-based and not only research-based, system integrating sensing and communication will require to store some amount of data to work properly and to get more earnings. So how does this data get stored? We can imagine various scenarios: if the system is big enough and has a relevant importance in a business the data could be stored locally on disk drives; if we are considering a system that will serve some simple functions and family-sized the data are likely to be stored by the provider of the service, e.g., Vodafone or some others communication service providers. The main difference is that the owner of the service knows the destination of the collected data, this happens everyday with lots of others services. It is the provider's liability to assure that the stored data is secured and not targeted from cyber attacks, there are some security measures that can provide liability to the data storage:

- Authorization: a typical countermeasure to fraudulent attempts to steal data is authorization. It can happen in many ways like biometrics, codes, keys (typical authorization methods are OAuth, OpenID Connect and Kerberos);
- Cryptography: the data may be encrypted in several ways, an encrypted information without the decryption algorithm and the key is useless and will prevent attacks. To this purpose the blockchain's immutabilty and decentralization is great, we can ipotize a method to store data based on a blockchain requiring hashes, consensus algorithms and others tools that makes blockchain as secure as it is;
- Backup and Recovery: having a backup and be able to recover lost or stolen data is a great way to improve the user's trust in the system.

2.7 Security ISAC systems

Security is always an hot topic so we held it last to explore all the weakness of system of that importance and to understand whether it is possible to solve them or not. ISAC heavily relies on wireless sensing capabilities and distributed computing devices, increasing the risk of forged identities and data tampering. First of all let's try to understand how much information and sensitive data is transmitted through a communication and sensing integrated system. It is not only a matter of managing a communication channel, but also of managing all the sensing applications integrated in the system, thus having a double risk of attack, leakage of data, often sensitive. Just imagining an alarm system in a bank or in a house relying on a sensing application: not only a so called Man-in-the-Middle (MitM) could intercept the communication channel but also tampering the sensing application to enter the building without anyone knowing. Let’s now analyze all the classical types of attacks that could happen in a communication system[6]:

- Eavesdropping: the attacker can hear all the communications between the sensors or the devices in the network;
- Spoofing: the attacker can send confused signals to create noise and confusion in the system;
- MitM: attackers insert themselves within the communication to appear as operating nodes and manage incoming and outgoing data, creating a situation that allows them to steal data or manage the communication.

All this types of attacks constitutes an everyday challenge for cybersecurity agencies and are specific to communications systems: where there is an exchange of signals, there could be an interception of information and this have always been a problem to engineers that studied systems to prevent attacks. Blockchain addresses General Data Protection Regulation (GDPR) and other data rights regulations with a more automated approach. For perception data permission management, blockchain provides a traceable and accountable solution [7]. Limiting the aggregation of data preserves the leakage of the data itself and Federated Learning solve this as a charm. We will talk better and deeper later on about Federated Learning but for now lets say that is a ML technique of teaching a model that involves the decentralization of the dataset, aggregating only the final parameters and the resulting model from all the local instances of training.

3

Machine Learning algorithms in ISAC

Sensors and integration make possible having a big amount of data to share, to use, to augment and to sell. There is indeed a fruitful market based on the trading of data. In the world of ISAC, as well in others IT worlds those data are meaningless and useless without one very specific thing: an algorithm that can read, interpret, and use them to produce results and predictions based on some math formulas or experience. Those algorithms that can be trained with already owned data to predict future results based on what it has learned or seen in the past are called Machine Learning (ML) algorithms (in this section, since this isn't our first goal we will talk about ML algorithms and models like they're the same thing, but in a specific content they are not). This concept is abused nowadays and it could be losing some of its air of mystery, indeed an algorithm may possibly be just an algorithm, not a ML one. We can now divide the typical usage of data to create a model into three separated sections, but not far from each other.

3.1 Preparing and pre-processing data

Sensors and systems used for collecting data can obtain big amounts of data from different scenarios but those data usually are disordered and there could be missing rows, plus depending on what is the format of data, the algorithm chosen and many other thing, data needs a pre-process operation (making the data readable for the computer and the algorithm). This step of ordering and pre-processing data is the most important because it can determine the rate of success of the next two steps. Let's see which are usually the pre-processing phases in the machine learning workflow (sorted by order of proceedings):

- Data Cleaning: most of times data (especially data from radio signals) comes with noise, errors or inconsistencies. The data cleaning process consist in handling missing values, eliminating values out of range due to errors, correcting typos or human errors;

- Data Transformation: the model needs a certain type of data to be fed in the proper way and to learn the pattern that we want to register, so the data needs to be transformed using arrays, matrices, target features and so on;
- Data Reduction: It isn't always a good option to have a large amount of data, the size of the dataset needs to be coherent to the complexity of the model. It is possible to reduce the size of data, but paying attention to what we decide to eliminate, trying to not create imbalances or unintentional biases;
- Handling Imbalanced Data: one of the most common issue when collecting data to train a model is that the quantity of data we have at the end is imbalanced. It is not a problem of having too many or too little data but of having imbalanced quality and quantity of data amongst the categories of the data collected. An instance of this could be collecting a lot of data of a road when there is no traffic and having a little data of the same road when there is heavy traffic congestion. This could be solved in many ways: if the data needed is sufficient and more to the training we can think of reducing the imbalanced category of the collection to create equity inside the dataset. Another solution is the so called Synthetic data creation: training a simpler model with the data we have the less and creating a plausible synthetic dataset to balance the various categories;
- Data Augmentation: sometimes data just needs to be treated in a specific way e.g. some photos in a dataset are too big or too shiny, so we apply a data augmentation algorithm to obtain the desired output. This process is very specific and can vary from project to project.

3.2 Training (making the model learn)

We start this section by differentiating two main objectives that a developer could have when creating a ML algorithm: classification and regression. A classification model take an input and decide if it belongs to a category or another, a regression model takes some parameters and predict a correct value for that case. After the algorithm is defined and implemented it needs a vast amount of data to be trained: to predict, e.g., if a room is big or not, if a person is sleeping or not, first of all, the algorithm has to learn what is "big", what is "sleeping" and this can be achieved with the training.

We can represent in our minds the algorithm as a really complex mathematical function, made up of other sub-functions. When we "feed" the function with an independent variable (our data) it returns a value for the dependent variable (the result or the prediction), the relation of dependency is given by some parameters that can, and have to, change. This function needs to be adapted and shaped based on the purpose of the algorithm and nothing works as pretty as some, to say, real world data or simulated real world data. The training process itself is extremely resourceful and can be accomplished using computational power (mainly GPUs) but in a smaller scale it can be done in our home computers. The precision scale for the training is an aspect to take into consideration because can make the difference between a generalist and a very specialized algorithm, leading to miss-classifications or miss-predictions which in some very edge cases could also translate to a missed intervention for an elderly man who needed aid. To evaluate the precision of the trained algorithm it's common to use the accuracy or the precision metrics, depending on what type of result is needed,we will see it better in the next section. We have mainly two problems that we can run into when dealing with ML: overfitting and underfitting. What does this mean? Since the algorithm's first goal is predicting results it can predict in a very generic way because the parameters we used weren't precise and it didn't captured the real connections between data and results: this is called underfitting. To the other side we have overfitting: the parameters we used to train the algorithm were way to precise and the amount of data we had available couldn't make the algorithm recognize a pattern that can be used to predict well on new, unseen data.

3.3 Prediction of the result

Once the model is trained and the accuracy (or the metric used) is at the desired level the data collected is needed for an another purpose: ask the function what our information mean and interpret it to provide a solution to our previous answer: is the room empty or crowded, is the elderly man sleeping or he just doesn't move? Sometimes, depending on how we decided to pre-process our data, also the results may need to be interpreted: if our model has been trained to recognize photos of cats, dogs or other animals it will return a percentage of probability for those categories. It is not just a problem of interpreting the results of a prediction but also of understanding if those predictions are good enough and if we can do better and get back to the training phase, for doing this there is a pack of metrics that show us how good is in reality the model. There are some different metrics depending if our model is made for regression or classification. Let's see some of them for regression:

- Mean Absolute Error: the average magnitude of errors in a set of predictions, without considering their direction, i.e., whether the errors are positive or negative, and gives an intuitive sense of how far off predictions are from the true values on average;

- Mean Squared Error: it measures the average of the squared differences between the predicted values and the actual values. It quantifies the error in a model's predictions by giving more weight to larger errors, due to the squaring of the differences;

- Root Mean Squared Error: it is the square root of the Mean Square Error and gives an overall measure of the error magnitude, with higher sensitivity to large errors due to the squaring of differences before averaging.

And for classification:

- Accuracy: it is defined as the ratio of correctly predicted instances to the total number of instances in the dataset. Accuracy can be misleading in cases where the data is imbalanced, meaning that one class significantly weights more than the others;

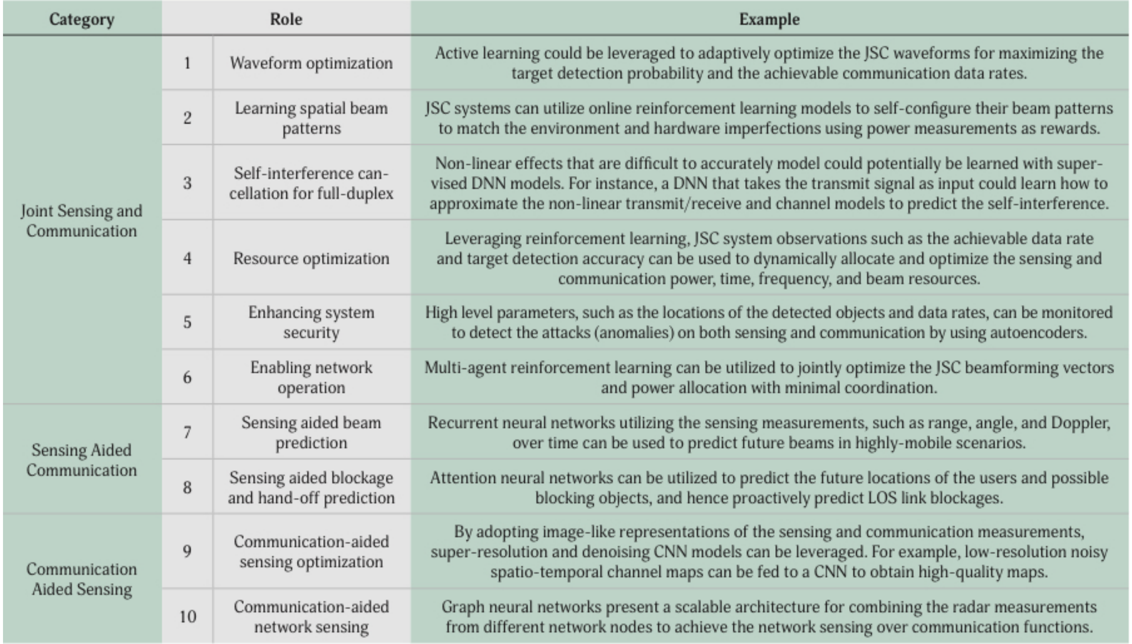
- Precision: metric used to assess the quality of a classification model, particularly in cases where the classes are imbalanced. It is defined as the ratio of true positive predictions (correctly predicted positive instances) to the total number of positive predictions made by the model (true positives plus false positives). High precision indicates that the model makes fewer false positive errors. Precision is especially important in situations where the cost of false positives is high;
- Recall: it is defined as the ratio of true positive predictions (correctly predicted positive instances) to the total number of actual positive instances in the dataset (true positives plus false negatives). Recall measures how well the model is at capturing all the true positives. High recall indicates that the model is good at detecting positive instances, but it may come at the cost of also capturing more false positives. It is particularly important in applications where missing a positive instance has serious consequences;
- F1-score: it is the harmonic mean of precision and recall, combining them into a single metric. The F1 score provides a balance between precision and recall, offering a more comprehensive view of the model's performance, making it useful when you need to consider both false positives and false negatives;
- Receiver Operating Characteristic (ROC) and Area Under the Curve (AUC) curves: two useful metrics used to compare different models graphically.

It will be a task of the developers to translate those results in a natural language sentence or number, easily accessible to all the users.

3.4 10 roles of ML in ISAC

We have seen what ML is and how it works, now we will analyze which are the major roles of ML in combo with ISAC and why those two technologies are destined tho grow together. Of course ML has many others application but the future of ISAC is clear: machine learning will help it to grow and to be adopted providing must-have functions. We will use the scheme provided in [8] to organise those 10 keys roles. Lets first divide the operation area of ISAC into three sub-areas as we have already seen in the previous Chapter 2:

- JSC: the two functionalities are utilized at the same time to accomplish two different tasks and there is no cooperation between the information and the radar function, the infrastructure is organized to take advantage of this technology to reduce costs and other practical consequences;
- Communication-aided Sensing (CAS) Radar function, sensing, using the communication function as a support to improve the sensing results themselves.
- Sensing-aided Communication (SAC) Communication function, sensing the environment to improve the resource allocation and the transmission of information.



Category	Role		Example
Joint Sensing and Communication	1	Waveform optimization	Active learning could be leveraged to adaptively optimize the JSC waveforms for maximizing the target detection probability and the achievable communication data rates.
	2	Learning spatial beam patterns	JSC systems can utilize online reinforcement learning models to self-configure their beam patterns to match the environment and hardware imperfections using power measurements as rewards.
	3	Self-interference cancellation for full-duplex	Non-linear effects that are difficult to accurately model could potentially be learned with supervised DNN models. For instance, a DNN that takes the transmit signal as input could learn how to approximate the non-linear transmit/receive and channel models to predict the self-interference.
	4	Resource optimization	Leveraging reinforcement learning, JSC system observations such as the achievable data rate and target detection accuracy can be used to dynamically allocate and optimize the sensing and communication power, time, frequency, and beam resources.
	5	Enhancing system security	High level parameters, such as the locations of the detected objects and data rates, can be monitored to detect the attacks (anomalies) on both sensing and communication by using autoencoders.
	6	Enabling network operation	Multi-agent reinforcement learning can be utilized to jointly optimize the JSC beamforming vectors and power allocation with minimal coordination.
Sensing Aided Communication	7	Sensing aided beam prediction	Recurrent neural networks utilizing the sensing measurements, such as range, angle, and Doppler, over time can be used to predict future beams in highly-mobile scenarios.
	8	Sensing aided blockage and hand-off prediction	Attention neural networks can be utilized to predict the future locations of the users and possible blocking objects, and hence proactively predict LOS link blockages.
Communication Aided Sensing	9	Communication-aided sensing optimization	By adopting image-like representations of the sensing and communication measurements, super-resolution and denoising CNN models can be leveraged. For example, low-resolution noisy spatio-temporal channel maps can be fed to a CNN to obtain high-quality maps.
	10	Communication-aided network sensing	Graph neural networks present a scalable architecture for combining the radar measurements from different network nodes to achieve the network sensing over communication functions.

Figure 3.1: A summary of the key roles of ML in ISAC systems

3.4.1 Joint Sensing and Communication

The main goal of JSC systems is to unify the needed for the two functions in a single infrastructure. The waveform should be carefully designed to ensure the communication and, of course, maintaining its characteristics (low latency, security, and high data rate), while being able to use the sensing functionality.

Role 1: JSC waveform design, ML has the potential to optimize the JSC waveform design through both model and data driven approaches. This task may be particular difficult because of the various S&C system requirements and also because the hardware is limited: designing a waveform adapted to all situations without hardware limitations and unlimited computational power would be easy, but it's not a real scenario. One probable direction is the design of hybrid conventional signal processing and machine learning solutions that learn how to solve complex JSC waveform design problems.

Role 2: Learning spatial beam patterns. Modern and future system's key characteristics is the presence of multiple antennas at the transmitter and receiver, it is essential to efficiently design a correct beamforming vector for those antennas. The beamforming needs change with what we want to prioritize: communication need to converge more power through the signal, radar needs wider beam width. This implies that there is a trade off when designing JSC beam patterns and a trade-off between sensing and communication functionalities. When dealing with hardware strict limitations this becomes particularly challenging. A ML solution in this sense would be online learning models that can self-learn site-specific spatial beam patterns, optimized specifically for the site geometry, hardware, and deployment scenario. In this way we have a trained model that can retrain itself day by day with new recorded data.

Role 3: Self-interference cancellation. The key for enabling ISAC is full-duplex, a technology that allows a system to transmit and receive signals. This requires handling the self-interference at the JSC transceiver and generally this is a big problem, high complexity and strict constraints. ML plays a major role in this sense because it can find the perfect correlation even in non-linear functions, usually Deep Neural Networks (NNs) are chose for this specific characteristic. ML models can also be designed to reduce the self-interference cancellation complexity.

Role 4: Resource optimization. We have already treated this topic in general in this work but it is advisable to focus a little more on what really means better allocate the resources available

3.4.2 Communication-aided Sensing

Role 5: Enhancing JSC system security. The main goal is to reduce the possibility of attacks and eavesdropping of the signal. First of all we need to recognize if there is or not an actual attacker and ML algorithms can easily perform this task. From the point of view of complexity in solid secure systems, ML helps finding a more relaxed constraint to optimize the security without an exponential growth of the complexity of the entire system.

Role 6: Enabling JSC network operation. We already saw that in those type of configuration as JSC systems the communication function and the sensing function happens on the same channel, and this opens to challenges. The channel will inevitably be congested of signals, and if not treated this may lead to interference and offsets. Noise and other types of disruptions of the signal will be present on a daily base and ML algorithms is the best countermeasure because it is possible to discern good from bad inputs and obtain a cleaned and disruption-free signal. Having an optimized signal opens to a wonderfully wide variety of operations because the device coordination is simpler and faster and the total complexity of the configuration drops.

3.4.3 Sensing-aided communication

Role 7: Sensing aided beam prediction. As wireless communication systems move to higher frequency bands (mmWave for instance), they benefit from larger available bandwidth but require large antenna arrays and narrow beams to maintain sufficient signal power. Aligning those beams require an elevated training and as the number of antennas rise the amount of expertise required raises exponentially. The alignment however depends heavily on the position of the antennas and the geometry of the environment around them. The powerful capabilities of neural networks in learning and approximating complex models could be effective for learning the mapping of radar detection data to beams.

Role 8: Sensing-aided blockage and hand-off prediction. In the high-frequency regime there is an high risk of penetration loss. To prevent this, mmWave and sub-teraheartz utilizes Line of Sight (LOS) links that in return are highly sensitive to blockage (power degradation or link disconnection). A typical solution for this is multiple connectivity, multiplying the links for the single user, preventing the loss of connection or disruption of the signal. However this technique degrades the signal and creates congestion in the system, dropping part of the overhaul performance. As for the other cases seen previously integrating sensing functions and ML in the process can higly improve the experience. It is possible to prevent link blockage using a well trained algorithm and potentially learn to predict if or not a LOS link blockage will happen in a proactive way.

Role 9: Communication-aided sensing optimization. Since the integration of sensing and communication operates on unified channels, communications signals and systems are not optimized for sensing function. ML has the potential to optimize the signal processing for the sensing objectives without changing hardware features. Then the side information about the communication environment, as said in the role 7 could be inserted in the training phase and utilized by the models to realize environment-aware sensing solutions: systems that can take advantage from the environmental situation and from the characteristics of it case by case.

Role 10: Communication-aided network sensing. The data-centric approach can allow to generalize better when building distributed JSC systems. This enables the scalability of the network while maintaining the complexity at a relative low level.

3.5 Federated Learning

We have already seen Federated Learning in the security section in chapter 2, but lets dive deeper in what Federated Learning (FL) is. From the theoretical point of view it is a decentralized approach to machine learning that enables multiple devices or servers to collaboratively train a shared model while keeping their data locally, but what does this means? Each participating device trains a model using its own local data and sends only the model updates, such as weights, to a central server. It addresses privacy and security concerns by ensuring that the raw data never leaves the devices where it was generated and this explains why it is a key technique in the development of ISAC systems: the collected data never leaves the device! This solves most of the eavesdropping/spoofing problems because there isn't a transmission of information. The server then aggregates these updates to form a global model, which is redistributed to all devices for further training. FL comply with data protection regulations like GDPR, a fundamental step to develop a prosper technology without encountering legal problems like rule-breaking functions. This approach also reduces the bandwidth needed for data transmission, as only model updates are communicated, not the raw data. FL is particularly useful when the data collected is confidential or where, because of the infrastructure, the transmission of blocks of raw data is impractical or impossible. Despite the evident pros just presented, FL also presents several challenges. Ensuring the robustness and security of the model updates is crucial, as malicious devices could potentially send corrupted updates to the central server (spoofing). This necessitates the implementation of secure aggregation techniques and anomaly detection methods to maintain the integrity of the learning process. The heterogeneity of data across different devices can cause difficulties in the management and pre-processing phase of the creation of the model. The computational and communication overhead on local devices can be significant, especially for complex models. Lastly, devices must have sufficient computational resources to handle local training, and efficient communication protocols must be taken into account to manage the frequent exchange of model updates. Synchronization across numerous devices also adds complexity to the general system, as devices may be offline or have intermittent connectivity, requiring robust strategies to handle asynchronous updates. Overall, Federated Learning represents a significant improvement towards more secure and privacy-preserving ML practices, addressing many of the concerns associated with traditional, centralized approaches. It is likely to become a fundamental component of future ML and JSC systems for all the reasons we have just explained, enabling more secure and efficient data utilization in the industry and research field.

4

SHARP

We have seen what ISAC is and why it is an important technology to develop in the near future,what ML is and how many ways there are to train a machine. We have all the tools to get a closer look of a real algorithm that has HAR functions. The algorithm in question is called "Sensing Human Activities through Wi-Fi Radio Propagation (SHARP)". The algorithm was created in 2022 and is explained in detail in [9]. Let's deep dive into the features and how it works.

4.1 Purpose and goals of SHARP

SHARP is a device-free HAR system that allows the classification of basic activities performed by humans or the detection of the presence of entities. The scope of the algorithm is to perform a classification task (human activity recognition) in an indoor environment and perform better at generalizing new cases than the present literature's algorithms. SHARP is an environment- and person-independent learning-based framework so it poses its roots in machine learning.

4.2 Dataset

We already know that in order to train a ML model the most important aspect is having a solid dataset. To analyze the effects of different room geometries and static obstacles the CSI samples were collected in three different environments: a bedroom, a living room, and a university laboratory. The data was obtained from three volunteers (P1,P2,P3) while they were walking, running, jumping in place, or sitting. CSI samples are computed during Wi-Fi communication knowing the starting conditions. The setup included two active terminals exchanging Wi-Fi traffic and one passive device in monitor mode, simulating a real-world scenario. The devices used were two Netgear X4S AC2600 routers as the Tx and Rx, transmitting 173 packets per second, with a

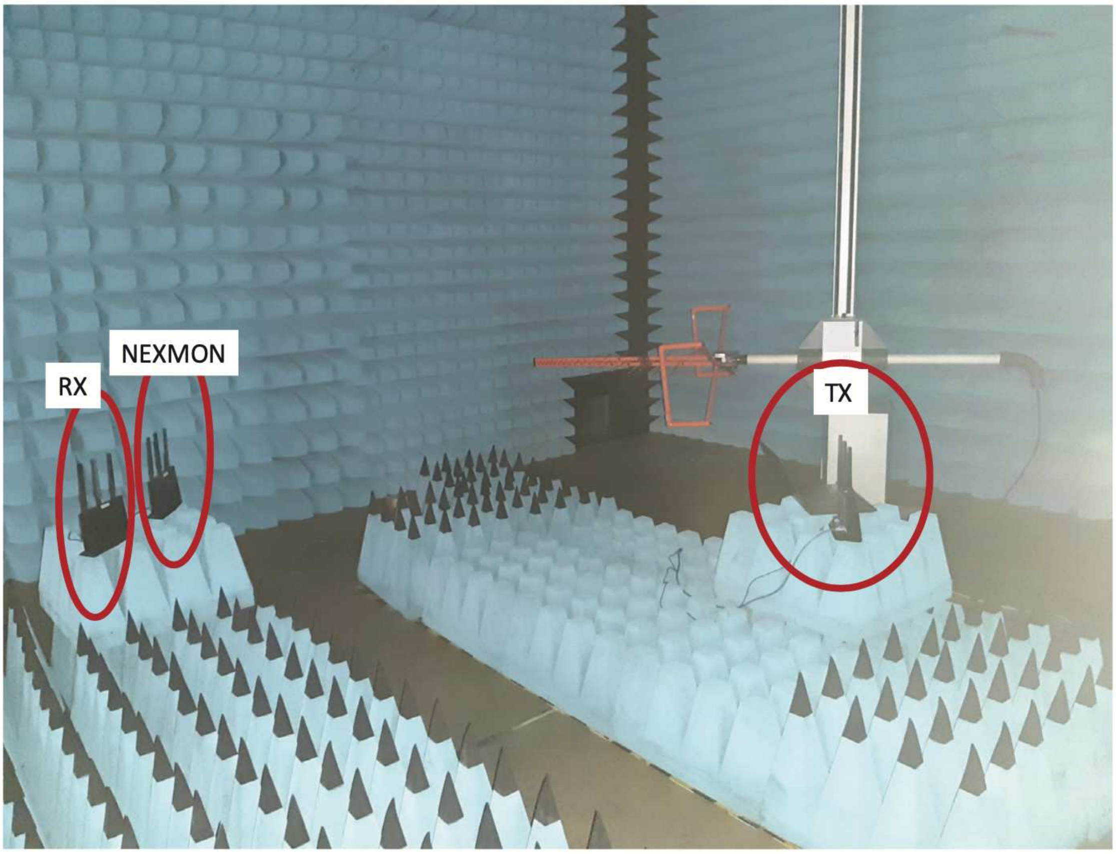


Figure 4.1: A semi-anecoica chamber used to collect data for the SHARP algorithm

new CSI sample every 6 milliseconds. This could simulate a real-life scenario where other devices are present in the network exchanging information. In the experiment the monitor router only provides sensing functionality, but the detection strategy will remain valid when communication and sensing functionalities are integrated into future ISAC devices. So how does the the data is organized in the SHARP dataset, and how much data is available to train the model? The dataset itself weights 6gbs and it is partitioned in 7 different sets(S1-S7), each corresponding to a different triplet of environment, day, and person. Each set includes 120 seconds of data per activity and 120 seconds of data with an empty room. Activities were continuously repeated during data acquisition. The campaigns took place from April 2020 to January 2022, resulting in almost 120 minutes of CSI data collected. The rooms were meticulously prepared to avoid interference or background rumors and collections were also conducted in a semi-anecoica chamber 4.1 fully covered by 40–50 cm long pyramidal radio-absorbing panels to test the best possible environment and the true capabilities of the algorithm.

4.3 Pre-processing steps

Some initial processing was performed to extract key features from the dataset. For each CSI sample, the Channel Frequency Response (CFR) values were divided by the average amplitude across the 242 monitored sub-channels to remove any unwanted amplifications. Then, the phase sanitization algorithm was applied. The CFR values were reconstructed on the three central sub-channels along with the other 242, resulting in a CFR complex-valued vector (amplitudes and phases) with 245 components. The Doppler vectors were calculated using 31 subsequent sanitized CFR samples. A threshold was then used to filter out noise with power below 12 dB. Finally, the Doppler trace, serving as the input feature for the HAR system, was created by stacking 340 consecutive Doppler vectors. These Doppler vectors were generated for each CSI acquisition using a sliding window, resulting in a complete Doppler trace that covered approximately 2 seconds of measurements.

- Normalization: Each CSI sample's CFR values are divided by the mean amplitude over the 242 sub-channels to remove unwanted amplifications;
- Phase Sanitization: application of a santization algorithm;
- Reconstruction: CFR values are reconstructed on three central sub-channels and the other 242, resulting in a CFR complex-valued vector of 245 components.

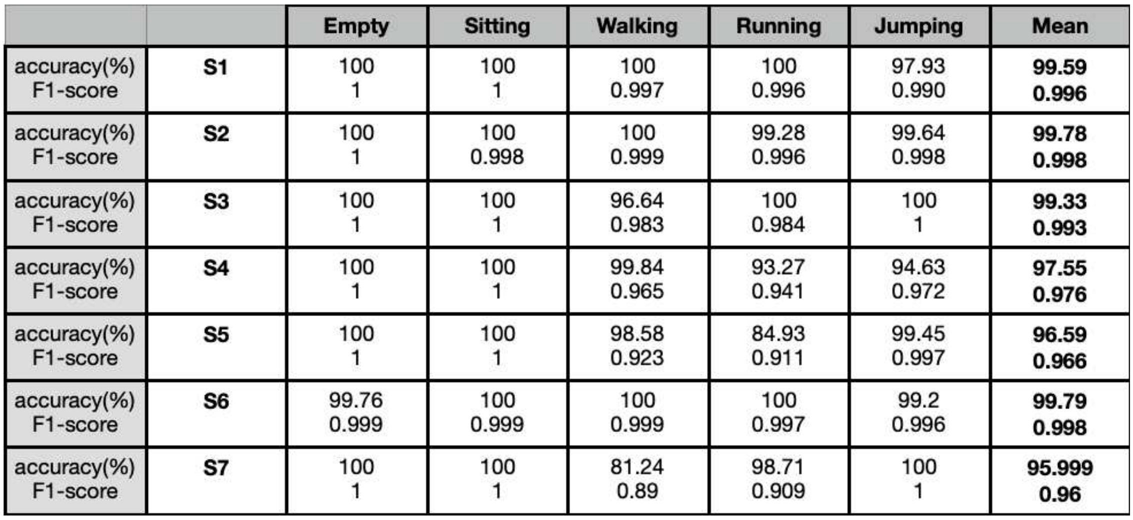
4.4 Model Architecture and Training

The model has to manage the data arriving from a commercial Wi-Fi access point and combine the information for the number of receiving antennas. The HAR algorithm consists of two steps:

- Computing the Doppler traces from the collected data at all the receiving antennas and use them to obtain activity estimates through a neural network based algorithm;
- The consequence of the first step is N (standing for the number of antennas) different results which are combined through a decision fusion method that leads to the final activity estimate.

The structure of the model itself is the following: three branches combining max-pooling and convolutional layers, pointing to a parameters number of 128,535. The output is flattened and sent to a 5 neuron output layer expressing the final result in percentages. A dropout technique is applied for regularization purposes randomly zeroing 20% of the elements in the flatted vector preceding the dense output layer.

The HAR learning algorithm has been trained by using the features extracted on set S1, 60% of the data makes up the training set, while the remaining 40% is evenly split between the validation and the test sets. All the other sets are considered only in the test phase. In figure 4.1 we can see all the results combined with the accuracy and F1 score, two metrics that we have seen previously. We notice that even if the model has been trained with S1, it generalize well also in other sets performing great results, always higher than 80% in accuracy. S6 and S7 are data collected in



		Empty	Sitting	Walking	Running	Jumping	Mean
accuracy(%) F1-score	**S1**	100 1	100 1	100 0.997	100 0.996	97.93 0.990	**99.59** **0.996**
accuracy(%) F1-score	**S2**	100 1	100 0.998	100 0.999	99.28 0.996	99.64 0.998	**99.78** **0.998**
accuracy(%) F1-score	**S3**	100 1	100 1	96.64 0.983	100 0.984	100 1	**99.33** **0.993**
accuracy(%) F1-score	**S4**	100 1	100 1	99.84 0.965	93.27 0.941	94.63 0.972	**97.55** **0.976**
accuracy(%) F1-score	**S5**	100 1	100 1	98.58 0.923	84.93 0.911	99.45 0.997	**96.59** **0.966**
accuracy(%) F1-score	**S6**	99.76 0.999	100 0.999	100 0.999	100 0.997	99.2 0.996	**99.79** **0.998**
accuracy(%) F1-score	**S7**	100 1	100 1	81.24 0.89	98.71 0.909	100 1	**95.999** **0.96**

Figure 4.2: Accuracy and F1-score of the SHARP algorithm between different datasets (S1-S7)

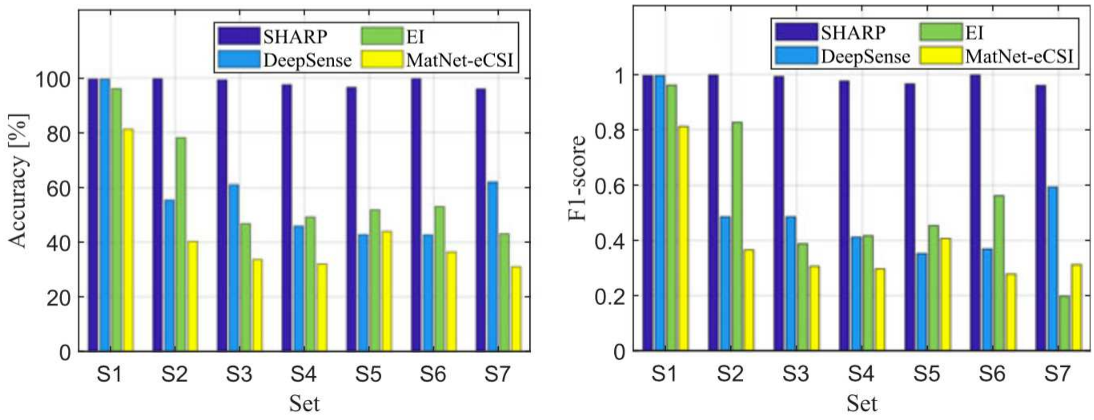


Figure 4.3: SHARP's Accuracy and F1-score in relation to other HAR algorithms in the literature

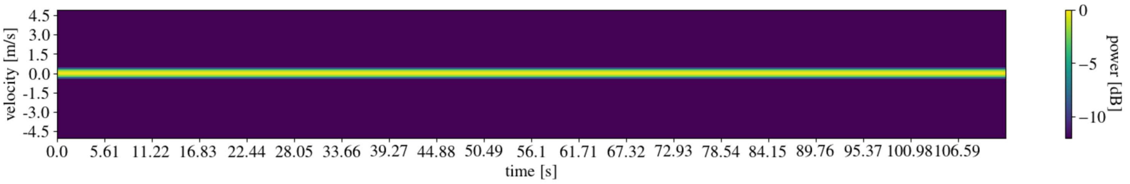


Figure 4.4: A plot of the Doppler spectrogram in an empty room

a vary different environment and those are the sets used to see how well the model performs at generalizing and we can see very high data in S6 and consistent data in S7 showing how good the algorithm really is, performing higher than all others peak models in the literature at the moment of writing. When dealing with new technologies and researcher's interests it is important to compare different works to see the vulnerabilities and strong points of each creation. So let's introduce 3 semi-equivalent works from other groups: DeepSense [10], EI [11], MatNet-eCSI[12], we can see them in comparison with SHARP in the figure 4.2. Taking it with all of the precautions of the case we can see an alignment in results where the environment is equivalent to the training set (S1) and an advantage in every situation where the environment has to be generalized (S2-S7). This shows once again a predisposition of the SHARP algorithm to adapt to unseen cases and the superiority to the current similar work, and makes it a good candidate to an adoption in some experimental cases in a everyday-use environment to conduce further investigations.

4.5 Human Activity Recognition performed by SHARP

From an outsider's point of view it is legit to wonder how the algorithm itself works and how can recognize just from radio waves if a man is present in a room and what he is doing. So it is now time to unveil the magic behind sensing and the SHARP algorithm and see some visual representations of the graphs that represent the input for the model and see which one is the output. We represent the velocity on the y-axis, the time passing in the x-axis and the color of the traced graph represents the power's intensity in dB (decibel), varying from yellow (high intensity) to deep purple (low intensity). For instance, we can see in Figure 4.4 the plot of the Doppler spectrogram when performing sensing in an empty room (from S1). We can see that the graph is very "quiet" and the algorithm don't have problems to perform the correct prediction of an empty space.

When dealing between the differences of a person walking, standing or running the things become a little bit more complex because we don't have anymore a quiet graph but we have indeed a confused graph with spikes and different patterns. Let's see as an example the graph of a sensed room with a person running inside. We notice at fig 4.5 that it is obvious that a person is inside and the room is not empty but at the same time it is really difficult to understand whether this subject is walking, running or idling. The magic happens when we compare this graph to an another graph representing a person walking. In figure 4.6 we can clearly see that there is a more ordered pattern representing a person walking.

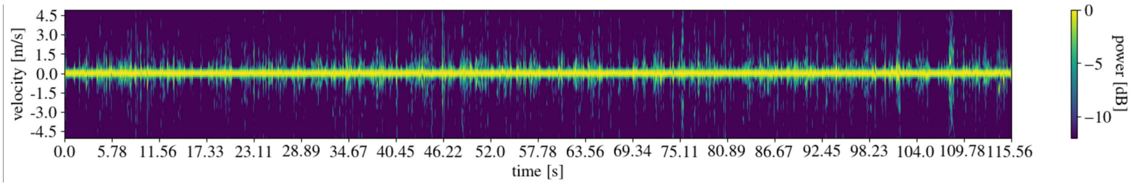


Figure 4.5: A plot of the Doppler spectrogram in a room with a man running inside

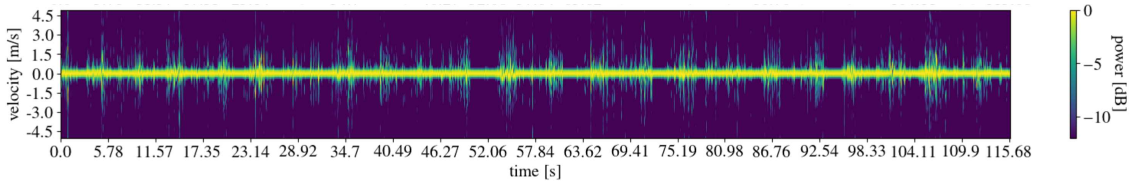


Figure 4.6: A plot of the Doppler spectrogram in a room with a person walking inside

This makes clear how does SHARP learn the patterns and how it can define just from a graph like these which one is the correct prediction and from this the system can apply all the consequences of the case, like perform an emergency call to the medics if the graph seems too quiet in a room in a nursing home.

5

Conclusion

To conclude this thesis let's analyze the status of ISAC works and what are critical aspects and future challenges. We have seen that integrating Sensing and Communication could lead to genuine advantages in the interested fields and open different scenarios, also previously unseen. We could say with moderate certainty that ISAC will be present in future generations of connections, not just because it will carry new applications in the communication systems, but also, as we have seen, could improve the existing infrastructure (communication-aided sensing and sensing-aided communications). To the current day, the works studying a perfect integration show that it is possible to put into place different ISAC systems already from the next 6th generation of cellular communication or from future Wi-Fi devices without the need of a drastic changes in the infrastructure. It is impossible to predict whether JSC systems will arrive sooner or later, because, as it is known, money and investments play an important if not crucial role in the developing of new emerging technologies as ISAC. It is noteworthy that things will evolve depending on the bubble created around the AI, Machine Learning and Deep Learning: if those studies will continue to create improved or simpler-to-use tools to aid researchers to develop systems to take advantage of ISAC systems, then the evolution in the integration will be faster than ever and certain. The SHARP framework serves as a practical implementation of these concepts, illustrating how careful data preparation, model architecture design, and training can lead to robust ISAC solutions. As the demand for more integrated and intelligent communication systems continues to rise, ISAC offers promising pathways for innovation and application. The future of ISAC carries immense potential, and continued exploration will be key to fully realizing its benefits, addressing known problems and expanding it's potential to reach the greater impact possible in the industry of communication.

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