Software-Defined Radio for Spectral Analysis and Integrated Sensing and Communications

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Abstract

Nowadays, in the actual context where wireless communications systems are becoming always more crucial, enabling heterogeneous services and massive device connections, different criticalities must be taken into consideration. In particular, spectrum congestion has become a critical issue that must be challenged; for this reason, spectrum analysis and Integrated Sensing and Communication (ISAC) can be optimal solutions to sense the radio spectrum and monitor its status or to save resources by integrating two different technology without any interference. In this background, the use of reconfigurable and software-based RF technology like Software-Defined Radio (SDR) can be an interesting proposal to overcome these well-known issues and support the solutions under investigation.

This thesis is divided into three parts: in the first part, the theoretical background is presented along with a general overview of the technological aspects and the critical issues involved. In the second part of the thesis, the most relevant publications produced or submitted within this Ph.D. program are appended. Finally, in the third part conclusions and future directions are drawn.

Firstly, the spectral analysis is presented with a description of the possibilities enabled by SDR technology and the different heterogeneous services that can be executed to support modern mobile communication technologies. Two SDR systems are described, the first one is capable of acquiring a certain frequency band to successively post-process it for unknown signals detection and recognition, while the second is able to actively support modern communication systems through different services, in particular, monitoring in real time the frequency band of interest, executing signal detection and localization algorithms by means of distributed SDR system.

Subsequently, the advantages of ISAC approach are presented, with a particular interest in radar and communication integration. The attention

will be on Synthetic Aperture Radar (SAR) systems and the possibility to integrate different functionalities thanks to SDR paradigm. In particular, two main functions will be presented; the integration of a transparent communication link, able to combine identification and localization processes in classic SAR systems without any interference in the normal imaging process. The second one will regard the capacity to reflect the SAR signal similarly to a classic Corner Reflector (CR), using all the advantages and flexibility of SDR technology.

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List of Publications

J: Journal publication; **C:** Conference publication.

Appended Papers:

J1 A. Piccioni, R. Alesii, F. Santucci and F. Graziosi, "SDR-Based Integrated Sensing and Communication Framework for Satellite SAR Systems," UNDER SUBMISSION TO *MDPI Sensors*.

C1 A. Piccioni, Á. L. Z. Sosa, R. Alesii and F. Graziosi, "SDR-Based Distributed System for Mobile Communication Network Monitoring and Support," SUBMITTED TO *2023 IEEE Global Communications Conference (GLOBECOM) - Workshop on FutureG Experimental Test Platforms for Advanced Systems Implementation and Research*.

C2 A. Piccioni, R. Alesii, F. Santucci and F. Graziosi, "SDR-Based Ground Target for Identification and Tracking through Satellite SAR Systems," *2021 IEEE Aerospace Conference (50100)*, Virtual Conference, Mar. 2021, pp. 1-10, doi: 10.1109/AERO50100.2021.9438499.

C3 A. Piccioni, R. Alesii, F. Santucci and F. Graziosi, "Software-defined Corner Reflector for Satellite SAR Systems," *2022 IEEE Aerospace Conference (AERO)*, Big Sky MT, US, Mar. 2022, pp. 1-7, doi: 10.1109/AERO53065.2022.9843608.

C3 A. Piccioni, R. Alesii, F. Santucci and F. Graziosi, "SDR SAR Target: Corner Reflector and Communication," *2022 3rd URSI Atlantic and Asia Pacific Radio Science Meeting (AT-AP-RASC)*, Gran Canaria, ES, May-Jun. 2022, pp. 1-4, doi: 10.23919/AT-AP-RASC547-37.2022.9814344.

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Part I

Thesis Background

Chapter 1

Introduction

With the modern evolution of wireless communications systems, nowadays the idea of mobile networks is dramatically changing; different from previous mobile systems, 5G is and will be the cornerstone of this change thanks to the possibilities enabled by this modern technology. Many services that in the past required ad hoc development now have moved to the wireless and mobile approach, thanks to the versatility of modern 5G and future mobile generations, which will enable the dynamic resources allocation, that allows the execution of a large amount of heterogeneous services. Referring to the International Telecommunication Union (ITU) recommendations [3], these services can be classified into three main categories as in Fig. 1.1:

- **enhanced Mobile Broadband (eMBB)**: the purpose of this group of services is to give access to the internet with higher performance compared to the previous technologies, focusing on high-capacity connectivity. The evolution of video broadcasting belongs to this category, where high-quality solutions like Ultra High Definition (UHD) or future 8K video streaming require a high data rate to share a quality of video that is becoming a standard requirement. Relative to video streaming, other eMBB services are *work in the cloud*, extremely increased during and after the Covid-19 pandemic, and *play in the cloud*, where the network allows players to enjoy videogames without the necessity to be equipped with high-performance PCs or consoles. These are just a few of the modern services that will be enabled by 5G and future mobile networks.
- **ultra Reliable and Low Latency Communications (uRLLC)**: modern mobile systems can support services that require higher performance compared to the previous technologies, not only in terms of data rate. uRLLC collects all the services that require high reliability with very low latency; it represents

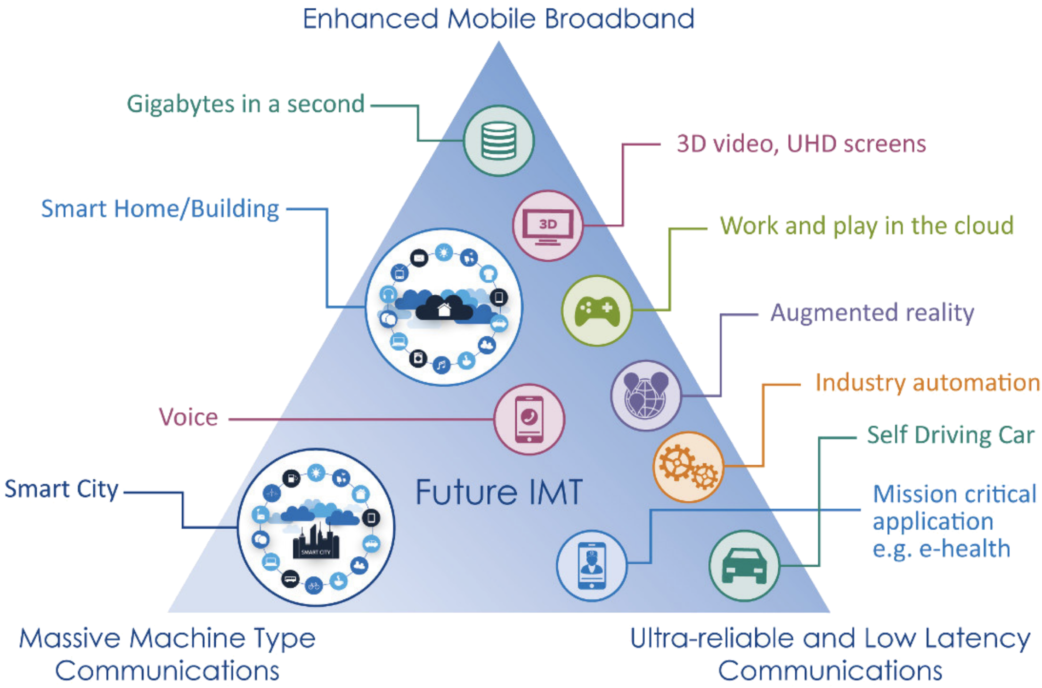

Figure 1.1: 5G service classification. Source: [3].

the smart grid control of applications and technologies that are becoming established in the industrial and research community. These mission and safety critical services range in diversified fields: Industry 4.0, where the technology progresses are oriented to industrial automation and remote operations (e.g. control, assistance, monitoring); autonomous driving and autonomous vehicles, where the main purposes due to automation revolve around higher safety in traffic circulation, reduced pollution and time and consumption safety; e-health, where advanced techniques like telesurgery, teleconsulting and Internet of Medical Things will expand the operative range of classic health system.

- **massive Machine Type Communications (mMTC)**: the natural consequence of the Internet of Things (IoT) turns around the necessity to connect more and more devices; therefore, mMTC services involve high-density connectivity scenarios. This need started from several fields, in particular from smart home applications where the automation and remote control of sensors is increasing the number of devices connected to the network. The further evolution is the smart cities scenario, where each smart home must be connected together with an infrastructure to monitor and control the entire city itself.

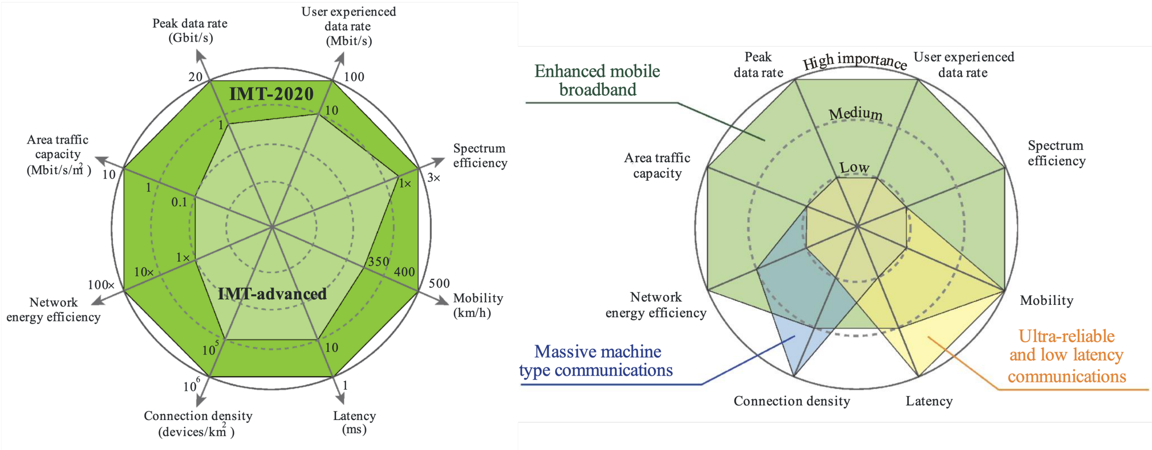

Figure 1.2: 5G specifications compared with 4G on the left, with a distinction between each service category on the right. Source: [3].

Industry 4.0, together with uRLLC services, requires a high-density scenario of connected devices for automation purposes and monitoring.

Among all the innovations carried out by 5G technology, the facilitation of heterogeneous services depending on the specific requirements has brought the new definition of service-enabler for 5G mobile network and future mobile communication systems, thanks to the multitude of services that can be processed.

The set of rules and requirements for 5G have been standardized by ITU Radiocommunication Sector (ITU-R) under the name of International Mobile Telecommunications 2020 (IMT-2020 Standard). Following the ITU-R recommendations shown in Fig. 1.2, where is a comparison between 5G and LTE (IMT-advanced) requirements, the minimum target performance that must be guaranteed by 5G are:

- higher area traffic capacity, capable to support up to $10Mbps$ per square meter;
- maximum peak data rate over $10Gbps$;
- user experienced data rate increased up to $100Mbps$;
- higher spectrum and network energy efficiency;
- higher mobility capacity up to $500km/h$;
- very low latency compared to 4G systems, with a minimum of $1ms$ for uRLLC services;
- high connection density capability, guaranteeing up to 1 million devices per square km.

All the innovations and advantages carried out by 5G network and 6G in the future present serious side effects that must be taken into account. Referring to mMTC scenarios, nowadays the growth of wireless technology and the necessity of connectivity have become a reality in everyday scenarios. In this case, the side effects correspond to an impressive increase of the number of devices per user and density of devices connected to the network, with IoT approach that is turning into massive IoT scenarios [4], while in future systems these numbers are expected to increase exponentially up to tens of billions of connected devices in the world.

Referring to a generic smart home scenario, as an example, in the last decade the number of connected devices per home has increased from a few devices to tens. Besides smart home scenarios, another cause of this growth is often related to wireless sensor networks, whose usage has gone up in the last few years for diversified practical cases. An example is represented by sensor network for mission critical services, like structural health monitoring [5] or early warning [6] systems, where sensor nodes are connected to the 5G network to monitor the health state of buildings and prevent disasters or are able to propagate a warning during and after critical events like earthquakes. Another usage of sensor networks is for cultural heritage services like sound spatialization applications [7].

The increase of connected devices represents a side effect in the modern mobile systems evolution, whose outcomes can be noticed in different layers of the ISO/OSI model architecture. Referring to the Physical layer, the main issues are related to the use of spectral resources, which will be investigated in the following.

The modern technology development of massive IoT and mMTC services has brought side effects that must be taken into consideration. The main criticality of massive IoT progression regards spectrum management, which is a resource that has saturation issues for decades due to the wireless technology evolution [8]. Despite the spectrum regulation made by governments of each country, spectrum usage has increased exponentially, as shown in Fig. 1.3; the increase of wireless technologies and also the increase of users connected via radio to those systems lead to a congestion of the spectrum. As a matter of fact, this issue starts from the discovery of radio communications up to modern times due to several reasons, like the born of new radio technologies or performance enhancement, which is a natural consequence of technology progression. In this direction, referring in general to wireless communication technologies, a first improvement in the bit rate capacity was due to bandwidth enlargement. In addition, the capacity to connect multiple users to a certain wireless communication system has brought spectrum saturation even in terms of power,

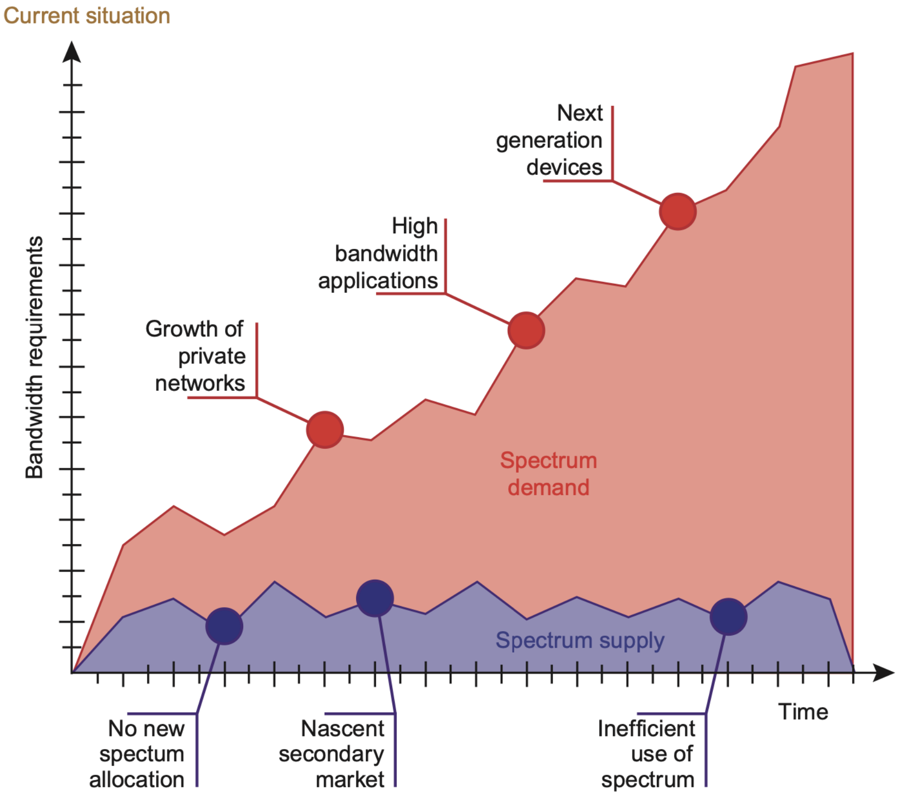

Figure 1.3: Projection of spectrum demand compared with the supply estimations. Source: [8].

whose consequence is the performance reduction due to interference. Another example is radar technology, where higher bandwidth ensures better performance and resolution for target detection. These are just instances of how the spectrum is affected by the evolution of telecommunication systems and their improvements [9–11].

Another consequence of spectrum congestion is Radio Frequency Interference (RFI), a well-known issue that can have different causes. In general, RFI are frequent in highly-dense environments, where the multiplicity of transmitting devices in a certain area causes performance degradation and service outages [12, 13]. Other causes of RFI can be placed in security contexts, where RFI sources are used for radio jamming attacks for service disruption [14, 15].

The critical issues previously described are some collateral effects of the evolution of modern mobile communication systems and wireless technology in general. These are just some of the issues related to technological progress, and represent an indication of the relevance of assistance techniques while supporting this advancement. For this purpose, this activity has been focused on two main solutions for the aforementioned criticalities related to the physical layer: Spectrum Analysis and Integrated

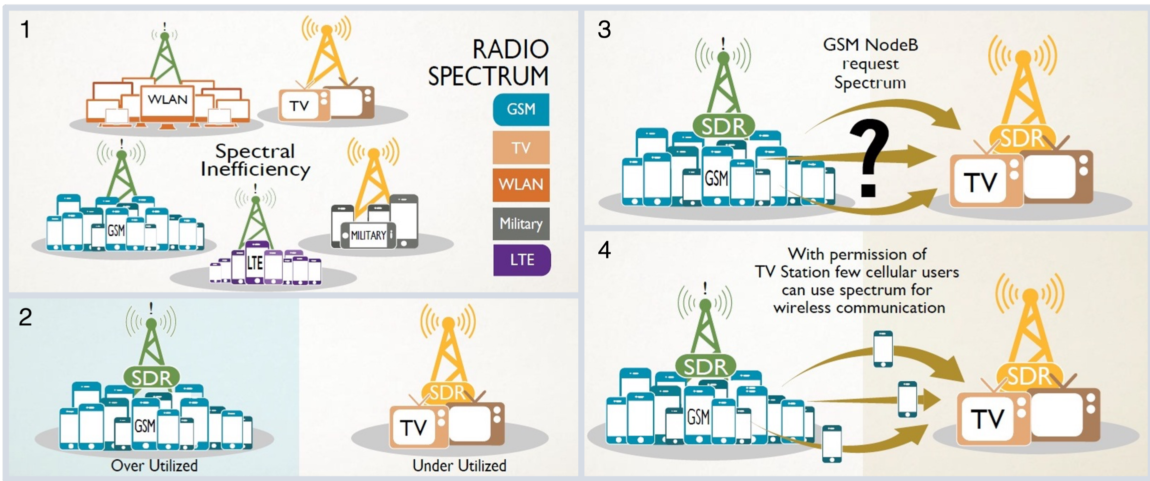

Figure 1.4: Example of cognitive radio application. Source: Wipro.

Sensing and Communication (ISAC). In this work, both solutions have been described in the next sections and investigated in the next chapter.

1.1 Spectral Analysis

In the aforementioned context of spectrum congestion it is clear how spectral analysis is becoming a necessity to improve the overall efficiency of spectrum usage. Spectral analysis is a general definition that collects different kinds of techniques to analyze the spectrum for different purposes, e.g. detect RFI and illegal signals or transmissions, monitor the spectrum status in terms of power, detect some inactivity or optimize the spectrum usage to allow the connection of additive users, just to name a few. Different proposals have been published in the research community for this purpose, and one of the most interesting solutions is the so-called cognitive radio. Also known under the definition of Dynamic Spectrum Access (DSA) or Dynamic Spectrum Management (DSM), cognitive radio is a term coined by Joseph Mitola III in 1999 [16]. Under this definition, he conceives that modern radio communication systems should be cognitive of the spectrum status to optimize the resources for every user connected. Moreover, he strongly relies on the flexibility of software radios technology, so that a communication system can be more intelligent and able to be reconfigured in real time. The natural evolution is represented by radio platforms that are able to "sense" the spectrum and adapt the communication parameters based on the necessity; in Fig. 1.4 is reported a practical example about CR. Nowadays, cognitive radio represents a research branch of radio systems with a high appeal due to the possibilities offered. The process of making more intelligent the communication systems, allowing them to understand the operative status to improve the performance, is in line with the purposes of smart and automatic systems toward the modern communication technologies are directed.

Generally speaking, cognitive radio collects a set of functions required to make a radio device smart and cognitive of the radio spectrum in use. In literature different functionalities have been defined for cognitive radio applications; according to [17], a classification can be made in 4 different functions:

- **Spectrum sensing**: through the sensing operation is possible to detect when the spectrum is unused (i.e. spectrum holes) so that is possible to allocate those resources to secondary users as soon as the primary is in an idle state. Spectrum sensing techniques are still under investigation by the research community, and different sub-classifications have been defined [18–20]. One of the most common classifications divides spectrum sensing techniques into three different approaches, as reported in Fig. 1.5: *interference based*, with the classification in primary and secondary users supported by interference analysis and mitigation, *cooperative* where the spectrum sensing is fulfilled through multiple devices that operates together, and *non-cooperative* where a single cognitive radio device acts independently to sense the spectrum. In this case, different techniques have been proposed for spectrum activity detection of a primary user, as reported in [21], like matched filter, energy detection or cyclostationary feature-based detection.

- **Spectrum management**: it concerns the analysis of the spectrum status and the decision of the best spectrum resources to allocate for a secondary user

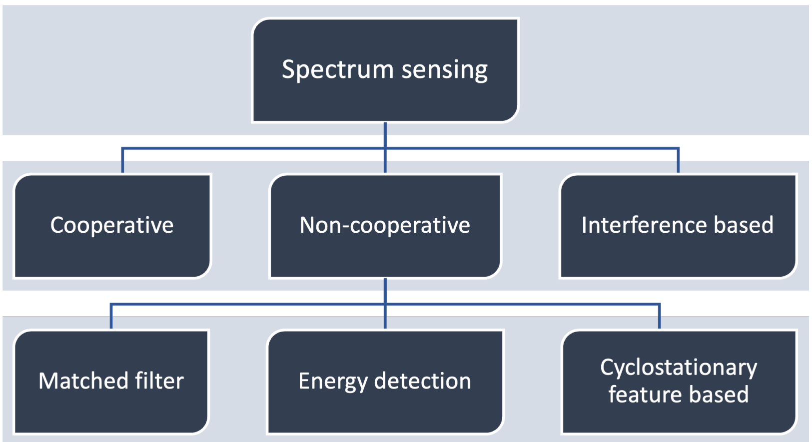

Figure 1.5: Common classification of spectrum sharing techniques. Source: [21].

without generating additive interference to the primary.

- **Spectrum mobility**: after the resources allocation for a secondary user, its communications must be kept without interruptions even when the primary user requires the same spectral resources; therefore, a seamless transition to different spectral resources is required for the secondary user.
- **Spectrum sharing**: different secondary users can access the same spectrum holes, hence, the cognitive radio system must be able to share the spectral resources between several users without interference.

1.1.1 Software-Defined Radio

Today, cognitive radio refers to activities that are mainly focused on resource allocation for additive users, whereas spectral analysis represents just a segment of the entire process. As introduced earlier, software radio receivers play an important role in cognitive radio technology. While the first research activities of software receivers started during the 1970s [23], it was with Joseph Mitola III, as introduced before, that software radios were presented for the first time. In this first approach based on cognitive radio, the software radios were just a real time reconfigurable devices capable to execute different functionalities, i.e. the fundamental functions of cognitive radio. This first idea of software radios was the milestone of the modern of Software-Defined

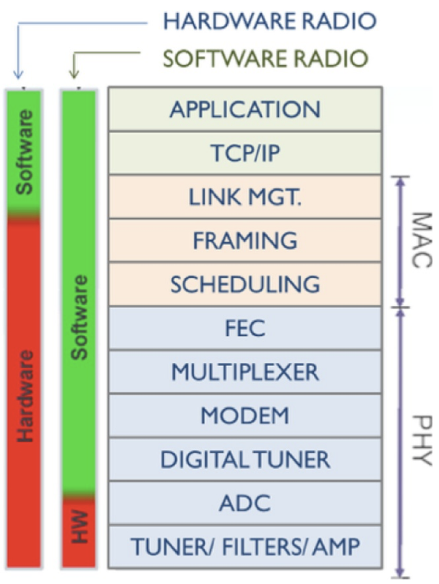

Figure 1.6: Hardware-software division of RF functionalities in SDR and traditional radio platforms. Source: [22].

Radio (SDR). Generally speaking, SDRs are devices where ad hoc functional blocks are replaced by programmable hardware platforms, e.g. Field Programmable Gate Array (FPGA), that execute the same functionalities and more by means of software programming [22]. Except for the component related to the software programming, the only hardware components in SDR devices are the transmitter and receiver analog front-ends, based on all the analog elements like filters, amplifiers and mixers, and the blocks responsible for the Digital-to-Analog Conversion (DAC) in the transmitter and the Analog-to-Digital Conversion (ADC) in the receiver; in Fig. 1.6 is represented a comparison between SDR device and the equivalent ad hoc platform in PHY and MAC ISO/OSI layers. The main difference with classic radio platforms is in the signal processing: SDR devices offer digital signal processing, enabling the flexibility to switch between different digital processing while classic devices require ad hoc development; the main trade-off is on the performance since the software-based development is certainly slower than the hardware, but the use of application-specific integrated circuits or FPGAs allows different design methodologies with different performance, depending on the necessity. In general, SDR platforms are composed by two elements, as presented in Fig. 1.7: the *motherboard*, responsible for the ADC/DAC conversion, the processing of digital samples from/to the RF front-end and the interconnection with

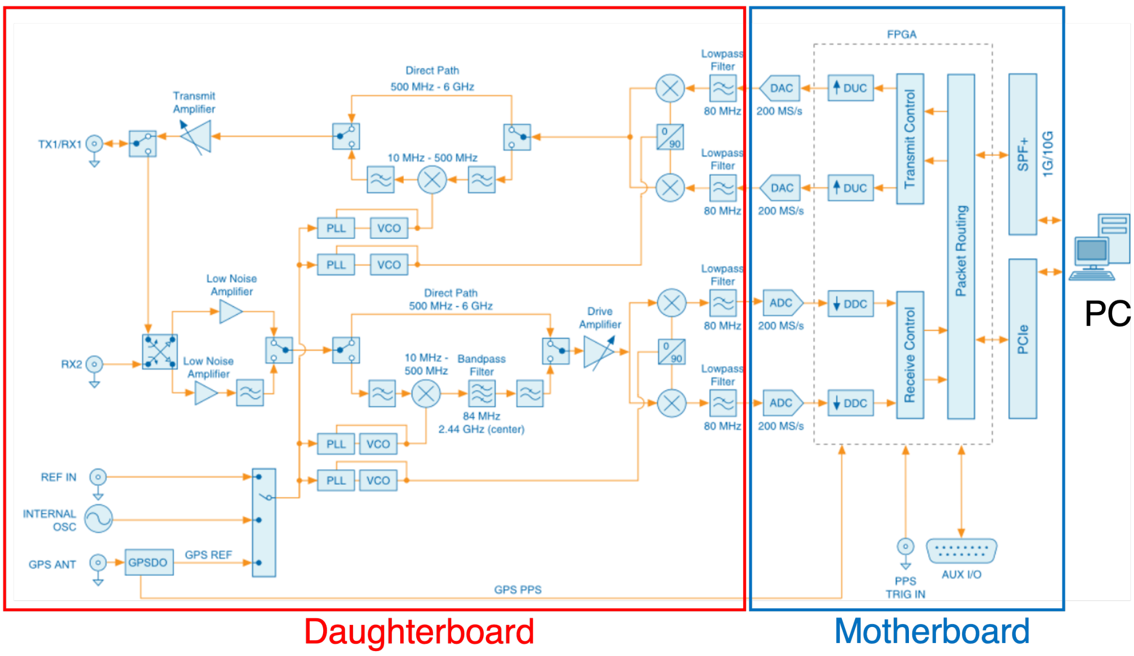

Figure 1.7: NI Universal Software Radio Peripherals (USRP) 2954R schematic with the distinction between motherboard and daughterboard. Source: National Instruments.

the software side, and the *daughterboard*, that contains the adjustable RF front-end. In general, more expensive SDR platforms are equipped with more than one daughterboard, enabling Multiple-Input Multiple-Output (MIMO) applications through one SDR device.

Nowadays SDR development has earned the interest of the research community. In particular, in the last decades, SDR has become not only an RF platform capable to be reconfigured in real time but a paradigm that is able to redefine modern communication systems. This is due to the variety of advantages offered by SDR, like the reduced development costs with a single platform or the replacement of ad hoc systems with SDR devices controlled by software, which are easy to handle for updates compared with classic devices where physical replacements are required. Moreover, SDR devices offer the versatility to implement every specific task through a single device, the interoperability to develop *multi-standard* and *multi-technology* systems able to operate simultaneously [24, 25].

1.2 Integrated Sensing and Communication

In addition to communication, sensing represents a major branch of telecommunication. In general, sensing and communication technologies are developed independently, through different hardware and physical resources; as introduced before, the criticalities involved in modern systems forced to develop a joint approach whose interest is becoming always more important, especially for future mobile communication systems like 6G. Indeed, the possibility to extract information from the surrounding environment, physical or virtual, allows a set of new actions to automatize and improve the overall performance of the communication system. ISAC represents a novel paradigm to deal with these well-known issues, embracing the concepts of resource-saving, hardware consumption reduction and spectral efficiency increase, just to list some advantages of this novel approach [26] [27] [1].

This dual strategy has been carried out due to the variety of applications that can benefit from it; for example, in autonomous vehicles scenario are required high-resolution sensing techniques to detect objects and obstacles together with low-latency communication to prevent traffic congestion and avoid critical accidents due to unexpected events. Another case is based on local communication networks, e.g. Wi-Fi, where energy-saving strategies lead to sensing techniques integration for location awareness, activity detection and recognition, or indoor localization; instead, in flight control scenarios sensing techniques are merged with pilots' communications. These

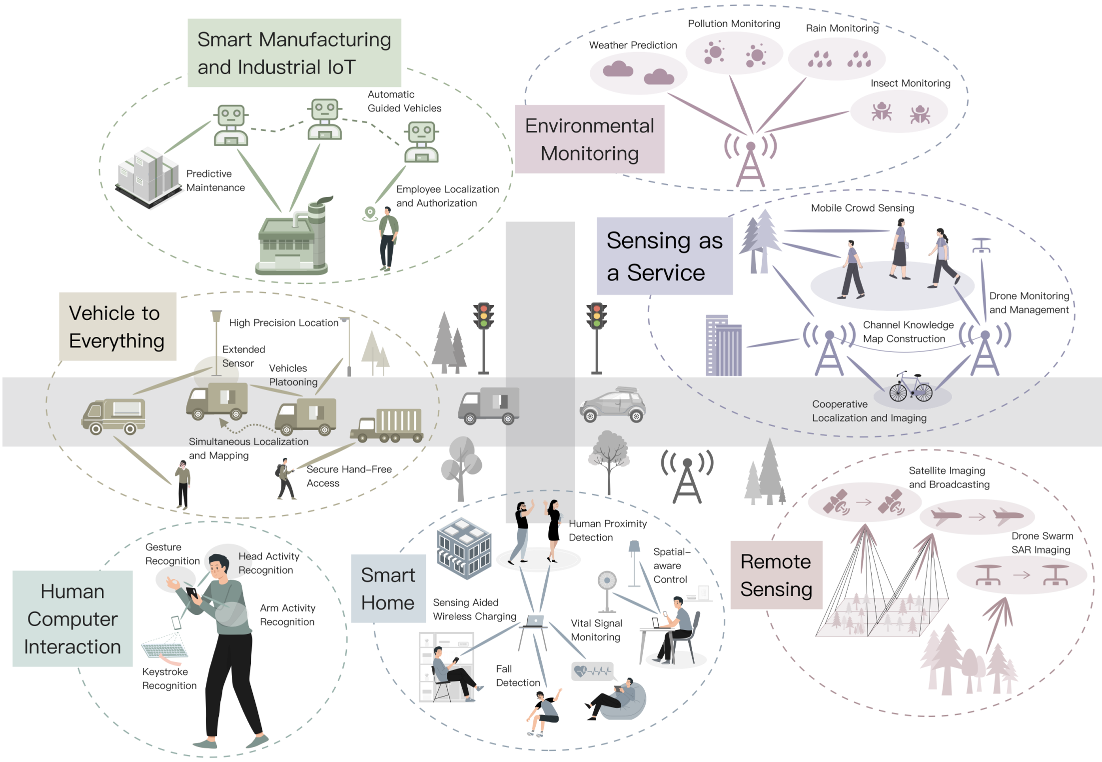

Figure 1.8: Representation of ISAC utility in heterogeneous context. Source [1].

and other scenarios are well reported in [27] with the description of joint design techniques made at different levels of integration. In Fig. 1.8 are explained some examples about the utility of ISAC in everyday scenarios. In this background, the rising interests of the research and industrial areas in ISAC applications are justified by the advantages of this dual approach, which is constantly increasing the level of merger between sensing and communication.

Nowadays, the ISAC approach has been well investigated by the research community and is still under investigation thanks to the many possibilities offered. For this reason, it is becoming an approach significantly important for future communication systems like 6G since ISAC will have an important role in the development of further mobile systems [28]. Following the last ITU-R report toward 2030 and beyond [2] both technology will have a mutual benefit from ISAC development. In [2] is reported a first type of sensing and communication classification that has been made depending on the level of integration, based on three different levels:

- **Coexistence**, where sensing and communication are two distinct technologies with physically separated hardware, with the possibility to share the same spectral resources supported by interference mitigation techniques.

- **Cooperation**, with physically separated hardware where some information between the two technologies are shared to reduce the cross interference or even to improve the performance of both services.
- **Co-Design**, where both technologies are designed with a single system that relies on information sharing and, in particular, on a shared framework for waveform design; this level of integration will be the core of ISAC concept.

Moreover, referring to [2], different stages are classified for ISAC development; firstly, sensing and communication should simply share resources like hardware or spectrum in co-design integration, with the implementation as a single system capable to act simultaneously in both ways. Then, in further development both services should work together to enhance the overall performance. In the end, the future view of ISAC development will regard a coordinated system able to combine both technologies even with other innovations like Artificial Intelligence (AI), multi-node cooperation sensing, etc.

1.2.1 Radar & Communication

Among all sensing techniques, radar represents one of the most used and studied for a long time. It represents one of the first sensing techniques that was attempted to integrate with communication services. The first activities in radar and communication integration date back to early 1960s [29], while a first practical system was proposed in late 1970s with a Ku band subsystem capable to act as radar or two-way communication system in the NASA Space Shuttle program [30]. In recent years, the aforementioned issues related to both technologies forced to invest resources in sensing and communication integration, leading the way to ISAC applications. The first actions made in this direction by a nation can be traced back to USA Defense Advanced Research Projects Agency with the Shared Spectrum Access for Radar and Communications (SSPARC) program [31].

Today, the joint approach between communication and sensing has been well investigated by the research community and is still under analysis. It must be noticed that this joint approach has been defined in literature under several names, each one with a different purpose and level of combination between the two technologies [32]. A first classification has been defined under the name of communication and radar spectrum sharing (CRSS) [33]; in this case, the sharing between the two technologies is classified depending on the type of integration: the radar-communication coexistence (RCC) and the dual-function (or dual-functional) radar-communication (DFRC). The importance of CRSS classification is attributed to the distinction between coexistence and joint development between the two technologies.

In RCC applications, the joint approach is focused on the physical coexistence between the two services, which are capable to operate relying on interference mitigation techniques in shared or disjointed hardware without losses in terms of performance; for this reason, the development of a joint system is based on the coexistence of both technologies in the same resource (frequencies, hardware, RF elements, etc.) through cross-technology effects mitigation [33] [34]. A common approach of RCC is the opportunistic spectrum access, where radar is considered the primary service, while communication is the secondary that senses and operates similarly to cognitive radio applications. The classification in primary and secondary services has a key role in this type of application [35] [36]; in general this approach is defined as non-cooperative. On the contrary, DFRC applications are defined as partially-cooperative/cooperative, with the distinction between primary and secondary service still valid. In DFRC applications, as suggested by the name, the joint system can operate both services simultaneously, with the cooperation extended to single or multiple transceivers [33] [36] and even to sidelobes management [37] or waveform design [38]; the cooperation provides the sharing of physical resources like antennas, analog front-ends, waveforms, etc. In [39] are considered four different DFRC strategies in the context of autonomous vehicles: separate coordinated signals, communication-based waveform, radar-based waveform and dedicated joint waveform. Indeed, DFRC applications are usually denoted as communication-centric DFRC, where communication is the primary service that is used to sense the environment [40], or radar-centric DFRC where the purpose is to integrate information in radar waveforms [41].

Besides CRSS classification, other names are used in literature to identify the joint approach between sensing and communication. Another definition has been made in [42] under the name of radar-communications or RadCom, where the authors refer to a single hardware platform for radar and communications functions through a single waveform in automotive and V2V scenario, taking advantage of single carrier spread spectrum and OFDM multiple carrier approaches; this cooperative approach based on OFDM has been recalled by [43] to reduce the waveform peak-to-average power ratio in the RadCom system. Other common definitions for cooperative communication and sensing are joint communication and radar (JCR) [32] [44] and joint radar and communication (JRC) [45] [46], which basically imply the same concept distinguishing between, respectively, communication-centric and radar-centric design.

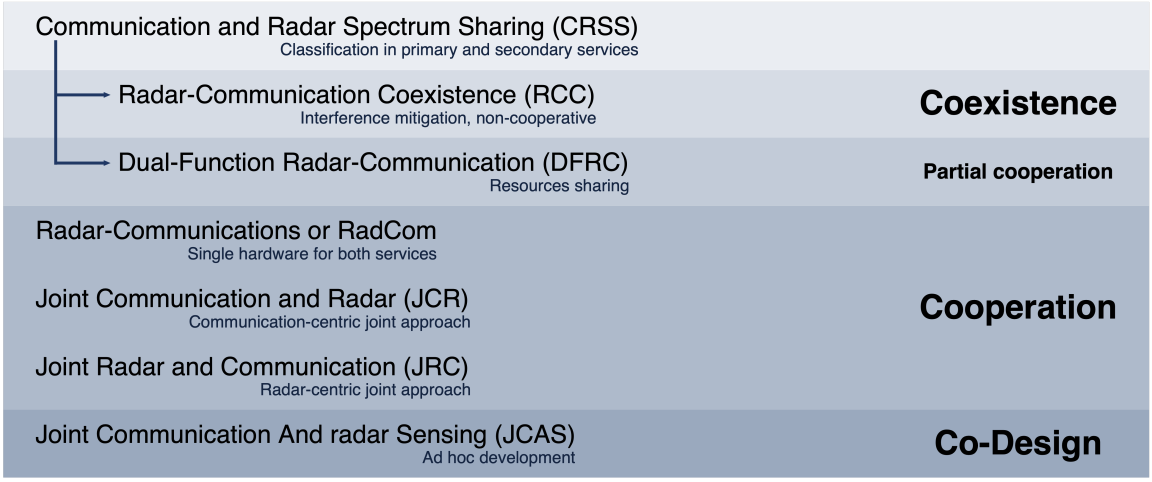

Figure 1.9: Comparison between all known definitions for radar and communication integration, classified in coexistence, cooperation and co-design.

Another term often used in literature is joint communication and radar (or radio) sensing (JCAS), also known as joint sensing and communication (JSAC) [47]. Similarly to what happens with JRC and JCR definitions, the JCAS acronym is used in two opposite ways; occasionally, it specifies the same kind of integration described in DFRC [32] [48], hence in the background of communication and sensing coexistence, but in general it refers to a deeper level of integration between them, classified as co-design [49] [50] in the same way of ISAC definition. In this approach, the classification of primary and secondary services falls apart in favor of a joint ad hoc system design capable to execute both services in a single or distributed device. All these definitions have been collected in Fig. 1.9, with a characterization following the ITU classification for joint sensing and communication [2].

1.2.2 Synthetic Aperture Radar Overview & Communication

Different radar-based technologies have been developed in the last decades for different aims. One of the most famous for remote sensing purposes is Synthetic Aperture Radar (SAR), which allows the analysis of the earth's surface for several disciplines with different purposes, from civilian and scientific fields like geophysics, geology, oceanography, and meteorology, just to name a few, up to military (e.g. intelligence, enemy detection and recognition, security), humanitarian, economic and commercial applications. SAR enables the acquisition of high resolution images that are independent of daylight and weather, taking advantage of a very large synthetic antenna aperture carried by the movement of the radar system [51]. Generally speaking, SAR systems can be developed in several scenarios depending on the type of application and its constraints and requirements. Spaceborne SAR represents the most common scenario due to the high coverage area and high revisit frequency, despite the complexity of satellite approach. Several satellite orbits are considered, like Earth Orbit (LEO) as for ESA Sentinel-1 [52] or the Italian COSMO-SkyMed [53] constellations, Medium Earth Orbit (MEO) as in [54], or Geosynchronous Earth Orbit (GEO) as planned for GeoSTARe [55]. Another scenario is represented by airborne SAR systems, based on airplanes or unmanned aerial vehicles, where the reduced coverage area due to the lower altitude, differently from the spaceborne approach, is compensated by lower complexity and higher resolution (i.e. in the order of meters). Planar or ground SAR systems are used for local testing of simplified environments with very high resolution (i.e. centimeters or less), as in [56] where a planar SAR has been developed for proof of concept purposes or in [57] where an automotive SAR system has been conceived and validated.

Different SAR acquisition techniques have been proposed to improve critical aspects like image resolution, swath (i.e., ground SAR coverage perpendicular to the flight direction) and coverage area. Compared to stripmap mode [51], ScanSAR, spotlight and TOPSAR can be optimal solutions. While stripmap makes use of fixed antenna and fixed beam, scanSAR takes advantage of multiple sub-swath to increase the overall coverage area with the drawback of reduced spatial resolution [58]. Differently, spotlight method exploit beam steering techniques to reach the high spatial resolution illuminating a certain area for a longer time compared to the other acquisition methods, with the disadvantage of discontinuous image acquisitions, as reported in [59]; in general, spotlight is used for high-resolution images of smaller and remote areas, i.e., islands or small groups of islands. TOPSAR method can be considered

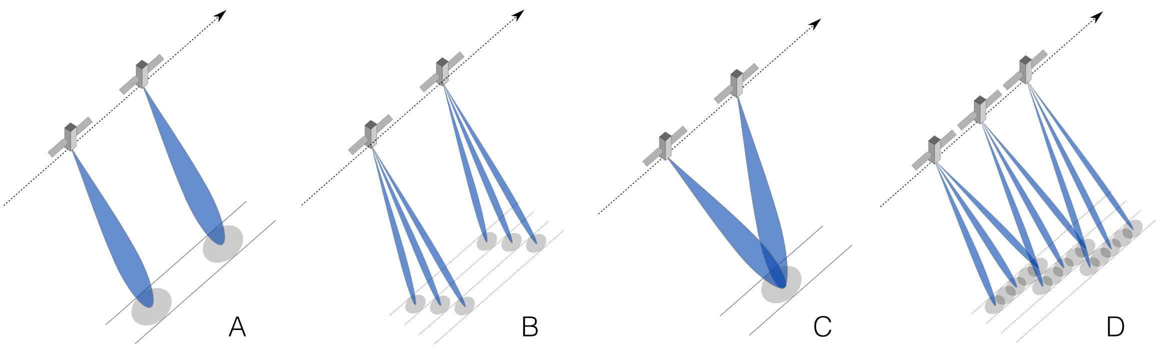

Figure 1.10: Simplified representation of stripmap (**A**), scanSAR (**B**), spotlight (**C**), and TOPSAR (**D**) acquisition techniques.

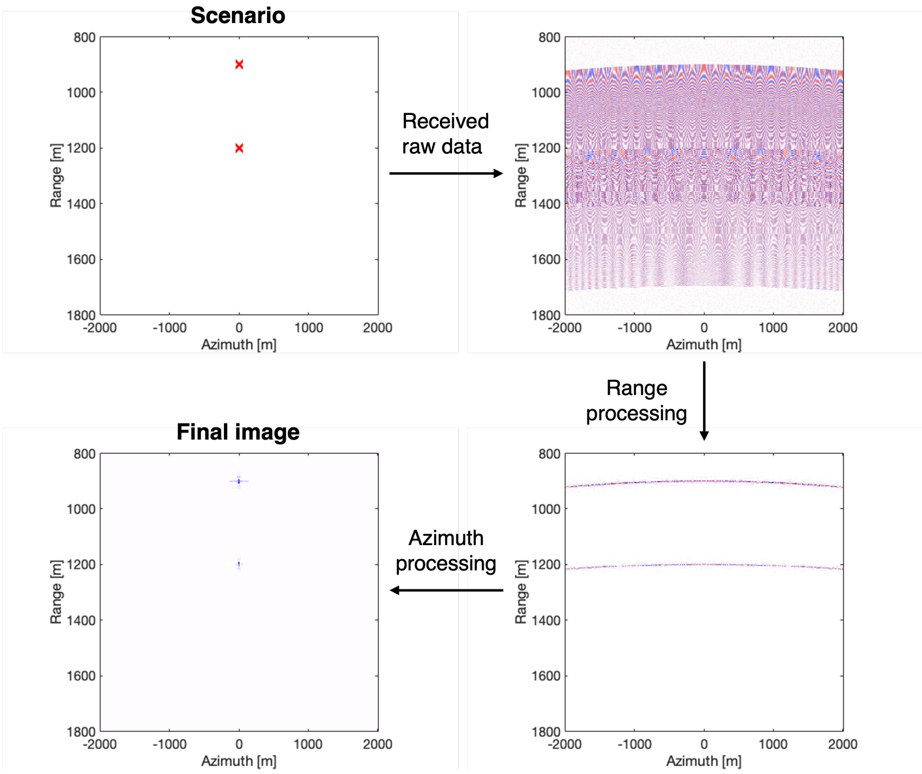

Figure 1.11: Simulation of SAR image processing workflow with a simulated scenario.

a meeting point between wide swath and high spatial resolution; like scanSAR, it performs sub-swaths with the addition of beam steering in flight direction through burst-based acquisitions [60]. In Fig. 1.10 both acquisition methods are displayed through a simplified representation.

Similarly to radar, SAR Working principles are based on the transmission of a frequency modulated signal called chirp with a certain Pulse Repetition Interval (PRI); after the chirp transmission, the SAR listen to collect the replicas backscattered by the targets and the environment, using a low duty cycle (i.e., in general near the 10%). Then, after the acquisition of a certain area, the SAR transfers the raw data to a ground center to process the data and obtain the final image, transforming the backscattered replicas of each PRI to an image of the illuminated area through different processing algorithms. The common points of each algorithm are the range processing and the azimuth processing [51, 61]. Both can be considered as a double matched filter in range and azimuth directions, firstly using the range reference function to perform the pulse compression and then through the azimuth reference function; the entire processing is summarized in Fig. 1.11.

SAR systems, in particular for spaceborne scenarios, are frequently supported by ground target devices; calibration represents a set of tasks that a generic SAR system needs to execute to correct functional parameters, like power emission, gains, frequency, etc. In general, SAR systems can execute two different calibration tasks, the internal calibration that is able to execute by itself, and the external calibration [62]. Ground targets are exploited for external calibration tasks to support the SAR imaging process; in particular, in these phases are executed processes like geometric calibration, used to map the geometric position of the ground target to the final image acquired by the SAR system, or the radiometric calibration for the evaluation of the measurements with respect to known target replicas. Besides calibration tasks, ground target like Corner Reflector (CR) represents an essential element for remote sensing geopositioning, where they can be used as a reference to monitor particular phenomenon of objects or areas [63]. CRs are devices located in areas without natural reflectors, where the supporting tasks are fulfilled through SAR signals backscattering with high radar cross-section (RCS), hence making it response visible in the final SAR image so that its known position can be used to map the final image with respect the geographic coordinate system.

CRs are classified into two main categories; passive CRs are size dependent and cheap since they are developed with big metal plates with sides in the order of meters, depending on the design choices, so that they can operate in certain frequency bands with certain gains. Several shapes have been studied and the most used are triangular, rectangular, and circular, as described in [64]; the choice between the shapes is based on RCS constraints, which is a key factor in their design. The great advantage of passive CR is the absence of a power supply, which allows the positioning of these devices everywhere independently of weather conditions, as well as the high RCS and high analog gain. Due to the metal material, the main drawback is its size and weight which increase the complexity to locate this device in remote areas. Differently from passives, active CRs are powered with a power supply, battery or solar panels; they do not simply backscatter the SAR signals but execute amplification and filtering before transmitting the signal back to SAR. In general, an active CR achieves better performance through the high gain alongside the smaller and compact size; the main disadvantage is the power source that limits the possibility to install it in every environment [65]. In Fig. 1.12 are reported both CR categories in a simplified image.

Different from radar approach, the integration of communication tasks in SAR systems in ISAC contexts is in a very early stage. Due to the complexity of SAR technology and its major dissemination in spaceborne approaches, both literature

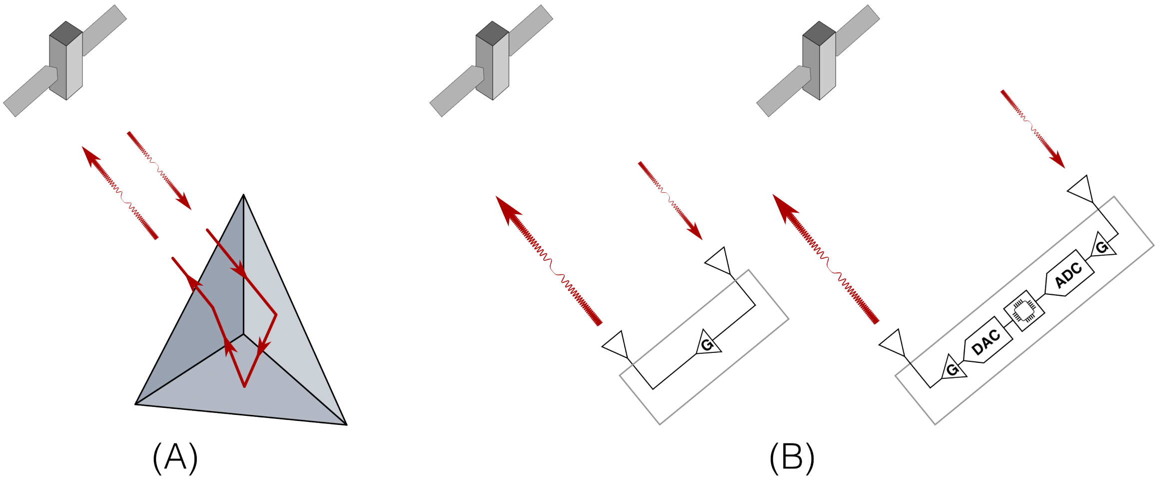

Figure 1.12: Simplified representation of passive (A) and active (B) CRs.

and industrial domains do not offer a strong knowledge about ISAC in SAR, despite the possibilities enabled by this dual approach. In particular, referring to the military field, many benefits could be enabled by SAR and communication systems, saving resources to transmit information about enemies while monitoring the movements of the allied forces. In civilian domain, an interesting solution can be pollution analysis through ground devices placed in a certain location while analysing the overall environment through SAR images. These are just few examples of the possibilities enabled by the dual SAR and communication approach. Among all the research activities presented in the literature, few interesting works are related to the joint SAR communication approach, as [66] where an airborne MIMO SAR system has been proposed through orthogonal multimodal waveforms and space-time coding (STC) techniques for communication, and [67], where continuous phase-modulated codes are used to transmit information while acquiring images through SAR technology. In [68] where a novel time-frequency spectrum shaping (TFSS) architecture for bistatic SAR systems is presented. Due to the nature of SAR technology, communication embedding techniques is one of the most interesting solution for communication integration in SAR systems.

Orthogonal Frequency Division-Multiplexing (OFDM) represents another opportunity for the joint approach between communication and radar/SAR; OFDM has become a key technique for modern wireless communication technologies, and it has been demonstrated that can be an optimal solution even for sensing techniques, in particular SAR [69–71]. Another interesting approach takes advantage of watermarking technique for the development of a dual-function SAR and communication framework taking advantage of information embedding [72]. In [73] is presented a cellular-aided

SAR system that exploits existing mobile communication base stations to enable a bistatic SAR imaging process through a UAV SAR receiver, inverting the usual SAR communication joint approach: while usually the communication is embedded in SAR technology, due to the SAR systems' features, in this case the aim is to exploit existing communication signals for SAR imaging purposes. It must be underlined that, despite the novelty of the dual approach between SAR and communication, all the presented works are related to novel approaches that rely on SAR systems developed ad hoc or particular modified versions. In this sense, in literature there are very few works that refer to consolidated SAR systems; this approach can be an interesting solution to exploit previous SAR technologies already on-air, especially without modification considering the high complexity of this task.

Referring in general to SAR ground targets contributions, they can be used to integrate communication processes in the contexts of ISAC applications; an example is reported in the next chapters of this dissertation, where it demonstrated how an SDR ground target can be used to integrate a code modulation-based communication link in a generic satellite SAR system [74, 75]. This type of application validates the possibility to integrate communication services in SAR technology, as in [56] where is presented an uplink channel integrated into a planar SAR system, with the communication service implemented through backscattering modulation with spreading techniques code-based as deployed, for instance, in UWB RFID systems.

All the presented definitions for radar (and SAR) and communication joint approach can be compared with the ITU-R classification for ISAC levels of integration; in Fig. 1.9 each definition have been classified based on coexistence, cooperation and co-design levels of integration. Due to the necessity of flexible and dynamic platforms for the integration of sensing and communication services, SDR technology can be an interesting solution to support this innovative solution; for this reason, the SDR approach has been accurately investigated in this dissertation.

Chapter 2

Thesis contribution

Referring to the context defined in chapter 1, this thesis investigates two possible solutions for the aforementioned issues related to wireless communications. In particular, the attention was on the development via SDR technology, taking advantage of the flexibility and the capacity of these software-based RF devices. Two different activities have been carried out, spectral analysis and ISAC.

For what concern the first one, this thesis is focused on the development of a spectral analysis application able to monitor the spectrum, detect the RFI sources and localize them through multiple acquisitions. In this sense, a first activity, which has not been published yet but has been planned to do in further activities, has been performed with the research project *EM_MONITORING_CCR* between the University of L'Aquila and the Gran Sasso National Laboratory (LNGS) of the National Institute for Nuclear Physics (INFN). The LNGS scenario is one of a kind since is placed inside the Gran Sasso mountain of the Italian Appennini mountain chain, where advanced nuclear physics and astronomical experiments are conducted with the protection of the mountain from external interference. For this reason, the purpose of the research project is the analysis of the unintentional RFI that can be emitted by the of experiments.

In this spectral analysis activity, the RF spectrum from 10MHz to 6GHz has been acquired and post-processed through the SDR device NI USRP 2954R with a 100MSps sample rate for each acquisition; in order to localize the RFI sources, the above-mentioned spectrum has been acquired in three different locations, generating a huge amount of digital signal samples to process (almost 3TB, corresponding to at least two hours of continuous signal acquisition and recording at 100MSps). In the first part of this activity, each acquisition for each location has been framed in time to evaluate the Power Spectrum (PS) of each frame; then, each PS has been processed

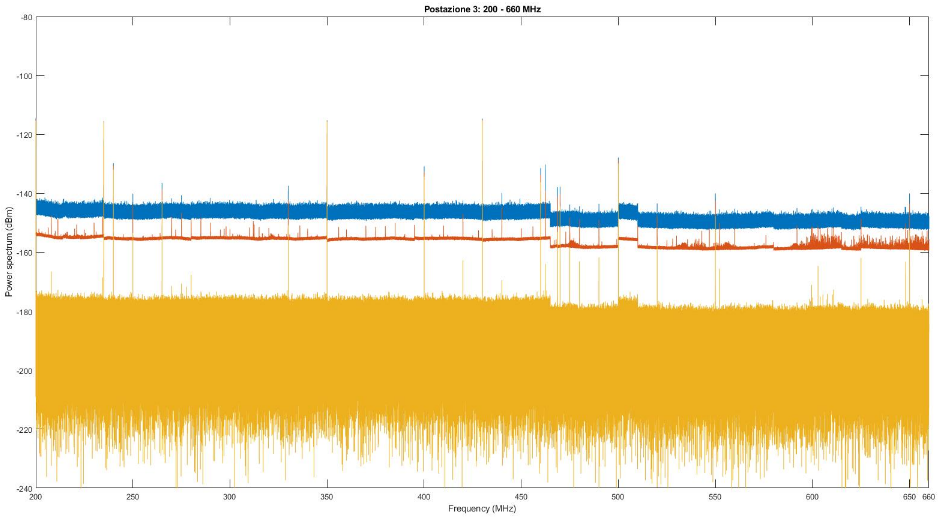

Figure 2.1: Maximum (blue), average (red) and minimum (orange) PSs acquired in the spectrum 200-660MHz.

to evaluate the maximum, average and minimum PS of each acquisition. This first approach gives the opportunity to evaluate what signals are present in those 100MHz (derived from the 100MSps sample rate of each acquisition); with the minimum PS is possible to detect the signals that are always present in the entire acquisition. Instead, with the maximum PS all the signals can be detected, including the sporadic ones that are not present in the minimum PS; finally, the average PS is an indication of how much a signal is present in all of the sub-frames: if closer to the minimum PS could be a sporadic signal, while if closer to the maximum it could have occurred frequently, as long as the amplitude of that signal has not a higher variability. It must be underlined that this is an experimental approach to have a first overview of the acquired spectrum.

Due to the early stage of this research activity based on spectral monitoring in particular locations, for now the entire maximum, average and minimum PS have been collected for each position, with a brief preview reported in Fig. 2.1. The further activities of this project will include the recognition of known signals, i.e. mobile communications signals or Wi-Fi signals, the extraction of unknown signals processed through a model, to obtain information like periodicity, continuity, etc., and the execution of specific signal recognition processing to collect some features about these unknown signals.

A second activity carried out for spectral analysis purposes has been the implementation of a distributed system based on SDR technology to execute different

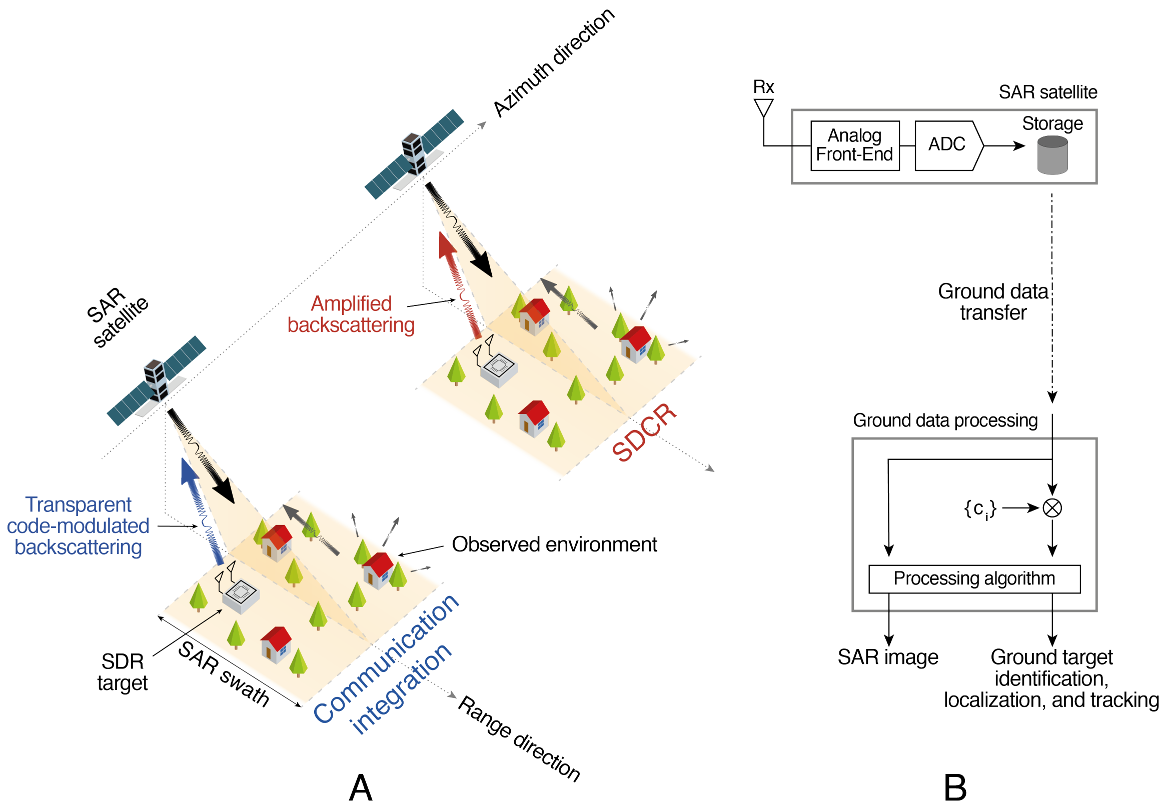

Figure 2.2: Unified scenario with the two functionalities executed by the SDR-based ground target (**A**) and the further processing for communication extraction, target localization and tracking (**B**).

services depending on the necessity, to support modern mobile communication systems and other wireless communication technologies in default and critical scenarios. In this sense, a default scenario for the above-mentioned system includes spectrum monitoring in real time with the elaboration of maximum, average and minimum PS mentioned before the execution of signal detection and localization algorithms in real time.

Referring to ISAC activities, the attention has been focused on the integration of communication technology in sensing techniques based on radar, in particular on SAR technology. In this direction, this work has been focused on the integration of a communication link through a ground target based on SDR technology, implementing code modulation techniques to the SAR backscattered replicas that must be transparent, meaning that it must not interfere with the classic SAR imaging process in the same way of steganography applications. Moreover, the classic airborne or spaceborne SAR system must not have any modification for the integration of this communication link. Relying on the code-based communication embedding technique, this operation will allow the identification of the ground target as a first communication stage, the target localization through SAR image processing of the demodulated data and the tracking with multiple localization images.

To integrate this ISAC functionality into the SDR device, an intermediate step has been implemented. Considering the necessity of SAR ground targets for calibration and other high-level objectives, like CRs, this intermediate step involved the definition of the so-called Software-Defined Corner Reflector (SDCR), which can be considered a first development of the SDR paradigm in ISAC context and will be part of the future advancement of this work. The aim of SDCR functionality is to backscatter the SAR signal without communication embedding techniques to highlight the area in which the SDR target is located; together with the transparent communication link integration, SDCR can be jointly developed for an SDR-based ground target that is able to execute both functionalities and switch between them dynamically, as reported in Fig. 2.2.

Both functionalities have been tested in a simulated environment to evaluate their effectiveness in SAR systems, referring to the satellite approach without losses in generality. Then, the next step has regarded the testing of the proposed approach in a controlled and static environment through cables, then the final step in this dissertation has been focused on a test in real environment. Due to the impossibility of operate and emit signals at licensed frequency bands (i.e., ESA Sentinel-1 missione at 5.405GHz carrier frequency), the proposed SDR device has been validated in an emulated scenario using real data available from the reference satellite, ESA Sentinel-1A (S1A) in stripmap acquisition mode, due to the well-known complexities of TOPSAR mode processing for image formation. The emulation is justified by the limited areas covered by S1A in stripmap mode. This approach has been useful to validate the entire framework without the necessity of emitting signals in licensed bands.

Tab. 2.1 summarizes the activities taken into consideration in the works appended to this thesis.

2.1 Publications appended to the thesis

The chapters presented in the second part are based on the following publications or submitted manuscripts. Below, one briefly presents the main contributions of each chapter (publication or manuscript)[1].

[1] **J:**Journal,**C:**Conference.

Table 2.1: SDR functionalities described in this thesis. The checkmarks are used to indicate which functionality is described in the corresponding paper.

	Spectral analysis	ISAC	
C1	✓		PS analysis
C2		✓	Communication link
C3		✓	SDCR
J1 & C4		✓	Communication link & SDCR

J1 A. Piccioni, R. Alesii, F. Santucci and F. Graziosi, "SDR-Based Integrated Sensing and Communication Framework for Satellite SAR Systems," UNDER SUBMISSION TO *MDPI Sensors*.

In this work is presented a novel ISAC framework for satellite SAR systems that enable the integration of two functionalities using the advantages of SDR technology: the so-called SDCR to support SAR system for calibration and high-level application tasks, and the integration of communication through code-based modulation in the context of communication embedding, without interfering in classic SAR imaging process. The proposed ISAC framework has been fully detailed and validated through an emulation test, due to the impossibility to emit signals in licensed frequency bands; using real SAR satellite data acquired and freely available from ESA Sentinel-1 SAR mission, the emulation has been tested integrating a local replica of the SAR chirp into the real raw data acquired in stripmap mode.

Author's contribution: The author contributed to the idea formulation, developed a prototype of the proposed SDR target, performed the emulation to generate the results and wrote the manuscript.

C1 A.Piccioni, A.L.Z.Sosa, R.Alesii, F.Graziosi, "SDR-Based Distributed System for Mobile Communication Network Monitoring and Support," SUBMITTED TO *2023 IEEE Global Communications Conference (GLOBECOM) - Workshop on FutureG Experimental Test Platforms for Advanced Systems Implementation and Research.*

In this work is presented a novel distributed system capable to support modern mobile communication networks through the advantages and the flexibility of SDR technology. In the idea behind this work, the proposed system can execute different services depending on the requirements, which can be classified as default services like power emissions analysis and spectrum monitoring, or critical services in uncommon scenarios where all the fundamental services cannot be guaranteed. A prototype of the proposed systems has been developed through the SDR platform NI USRP 2954R; the prototype, in the first stage of this research activity, is capable to monitor the spectrum through spectral analysis, signal detection and localization techniques. The prototype has been tested in a limited environment through an interfering source to evaluate the validity of the system rather than verify the performance of each technique since they depend on the adopted parameters and the environment itself.

Author's contribution: The author contributed to the idea formulation, developed a prototype of the proposed SDR-based system and tested it, performed the analysis of the results and wrote the manuscript.

C2 A. Piccioni, R. Alesii, F. Santucci and F. Graziosi, "SDR-Based Ground Target for Identification and Tracking through Satellite SAR Systems", in Proc. of *2021 IEEE Aerospace Conference*, Virtual Conference, Mar. 2021.

In this activity is presented a novel approach to integrate a communication link in remote sensing technology, which can be seen as a precursor approach for ISAC applications. The proposal investigates the literature on the joint approach between radar and communication, characterizing the different definitions between the two technologies. Besides, this work has proposed an SDR-based ground target that is able to integrate a transparent communication link through a code modulation technique without interference in the classic spaceborne SAR imaging process. Assuming no modifications in the imaging process, the code is applied to the raw data enabling different services: the code identification in the raw data represents a first communication step, while the application of classic imaging processing allows the localization of the target, highlighting its contribution while reducing the one of the environment, and tracking through multiple images. This analysis is supported by simulations to test the effectiveness of the communication link and its transparency, with all the advantages and disadvantages involved.

Author's contribution: The author contributed to the idea formulation, performed the simulation with the analysis of the results and wrote the manuscript.

C3 A. Piccioni, R. Alesii, F. Santucci and F. Graziosi, "Software-defined Corner Reflector for Satellite SAR Systems", in Proc. of *2022 IEEE Aerospace Conference*, Big Sky MT, US, Mar. 2022.

This work presents a novel development of targets for the support of satellite SAR systems. Starting from the benefits of active and passive CRs is possible to take advantage of SDR technology to present a novel reflector called SDCR, integrating the flexibility of SDR to work with different SAR systems that operate ad different bands; moreover, is possible to integrate additive processing thanks to the reconfigurable nature of SDR. After a complete description of the proposed target, three prototypes have been developed based on two different SDR platforms, the ADALM pluto and the platform NI USRP 2954R, to compare the different nature of these SDR devices. Finally, the prototypes have been tested in a controlled environment to validate the proposal.

Author's contribution: The author contributed to the idea formulation, developed a prototype of the proposed SDR-based system and tested it, performed the analysis of the results and wrote the manuscript.

C4 A. Piccioni, R. Alesii, F. Santucci and F. Graziosi, "SDR SAR Target: Corner Reflector and Communication", in Proc. of *URSI AT-AP RASC 2022*, Gran Canaria, SP, May. 2022.

This activity presents a novel target for SAR systems based on SDR technology; The flexibility and the reconfigurable nature of SDR technology lead to the integration of a communication link in sensing technology, as part of ISAC application, together with the possibility to support SAR systems acting as SDCR. In this work, the SDR proposal has been validated with a real test in a controlled environment for both functionalities, while the effectiveness of the communication link integrated by the novel target has been tested through a simulation of its behavior.

Author's contribution: The author contributed to the idea formulation, developed a prototype of the proposed SDR-based system and tested it, performed the simulation with the analysis of the results and wrote the manuscript.

Part II

Appended Papers

Journal J1

SDR-Based Integrated Sensing and Communication Framework for Satellite SAR Systems

Alex Piccioni, Roberto Alesii, Fortunato Santucci and Fabio Graziosi

Under submission to
MDPI Sensors

Abstract

Nowadays the modern progress in wireless communications technologies are forcing the integration of services of a different nature, in particular regarding sensing and communication. In this direction, Integrated Sensing and Communications (ISAC) is becoming a promising research activity, and a flexible and versatile technology like Software-Defined Radio (SDR) can be an interesting solution for this purpose. In this work, a modern ISAC framework is proposed based on SDR technology in Synthetic Aperture Radar (SAR) context, taking advantage of SDR to execute two different functionalities for ISAC and SAR support. This novel approach will be fully described and investigated, supported by a testing operation through an emulation step, using real raw data available from on-air satellite SAR systems.

J1.1 Introduction

Today the evolution of communications technologies is constantly focused on the wireless approach; modern mobile systems can reach high performance with dynamic resource allocation, becoming an enabler for a plethora of heterogeneous services that can be executed by modern communications systems like 5G, B5G, and 6G. On the other hand, sensing techniques are becoming popular due to the possibility to extract information about a certain place or the phenomena that occur in a certain area. In this sense, remote sensing has been consolidated as one of the most promising that is studied by the research and industrial community for a variety of fields, like geology, meteorology, and geophysics disciplines, or military, humanitarian, and commercial applications.

Both communication and sensing are affected by well-known issues of high capacity demand, which have an impact on resource management for both services. Referring to the physical layer, interference and spectrum congestion represent critical factors for performance improvements of both services. Besides, automation and smart approaches are capturing the attention of modern communication systems for environmental sensing services like location awareness, movement detection, etc., enabling them to be cognitive of the surrounding area for the dynamic optimization of communications performance. Usually, communication and sensing are developed independently through disjointed hardware for ad hoc systems and different spectral resources. Nevertheless, the modern approaches are oriented toward hardware usage reduction and spectral efficiency increase; these motivations encouraged the integration of both services, enabling a joint approach between sensing and communication [26, 27]. For this reason, Integrated Sensing and Communication (ISAC) has become an interesting solution investigated by the academic and industrial community; the importance of ISAC will increase even further in the next years, since it will be a key factor in next-generation mobile networks like 6G [2, 28] where concepts like location awareness and movement recognition will help to increase the network capacity. In particular, following the International Telecommunication Union (ITU) report toward 2030 [2], communication systems can support sensing services at radio level through the concept of "network as a sensor"; vice versa, communication can benefit from sensing techniques for more accurate beamforming, interference management, just to name few examples. The capacity of ISAC will enable new services that can be merged into mobile networks, like high-accuracy positioning, localization, tracking, imaging, etc. In this background, the advantages provided by ISAC result in a rising interest from research and industrial communities, leading to an increasing level of merger between communication and sensing services. Additionally, Radar and Synthetic Aperture Radar (SAR) represent one of the major fields in which ISAC concepts are exploited, and the research community is strongly focused on this integration as detailed in the next section.

In this context, Software-Defined Radio (SDR) can be an intersection between the necessity of flexibility to execute different tasks depending on the application and the high RF performance required for both communication and sensing services. Generally speaking, in SDR devices ad hoc functional blocks are replaced by programmable hardware platforms, e.g. Field Programmable Gate Array (FPGA), that execute the same and more functionalities through software programming [22]. Compared to the classic radio systems, the only hardware elements that remain are transmitter and receiver analog front-ends (i.e., filters, amplifiers, mixers, etc.) and the blocks responsible for the analog-digital conversion (ADC and DAC). Today, SDR has earned the interest of the research community becoming not only an RF platform reconfigurable in real time, but a paradigm that enables redefining modern communication systems. This is happening thanks to the advantages offered by SDR, like the reduced development costs through a single platform, or the replacement of ad hoc systems with software-based devices that are easy to handle for updates; moreover, SDR also offers the versatility to implement every task through a single device and the interoperability to develop *multi-standard* and *multi-technology* systems able to operate simultaneously [24, 25].

SDR can be an interesting solution to support the integration of sensing and communications technologies. As a matter of fact, SDR advantages can support this integration at several levels, from the simple integration of one technology to the other one to the ad hoc co-design of systems able to perform both technologies in symbiosis. Therefore, in this work is presented a novel SDR-based target used to broaden out ISAC framework in the context of SAR systems, referring to the satellite scenario without losing generality, alongside with the supporting task action as a reflector; the proposed target can operate in two ways, representing the key feature to integrate a code-based communication link that is transparent to the final SAR image of the environment, without forcing modification in SAR systems already on-air, or acting as a reflector to increase the Radar Cross-Section (RCS) of a certain area. The rest of the paper is organized as follows: in section J1.2 is described the state of the art of ISAC, with an accurate literature overview on radar and SAR communication integration; section J1.3 presents a general description of SAR technology and its features that relevant for this work. In section J1.4 the above-mentioned ISAC framework is fully described, investigating the peculiarities and the critical issues involved with the presentation of both functionalities performed by the SDR-based target, while in section J1.5 the proposed framework is emulated using real SAR data distributed by the European Space Agency (ESA) Sentinel-1 mission, which has been taken as a reference platform for this activity. Finally, in section J1.6 are reported some conclusive remarks about the activity and the results.

J1.2 ISAC: State of the Art and Radar-Communication

Nowadays ISAC represents a paradigm that includes a large amount of possible techniques and applications for the integration between communication and sensing services, from mobile networks and Vehicle-To-Everything (V2E) to local communication systems, from radar-based remote sensing applications to indoor localization and activity recognition [1, 27]. Recalling the ITU-R report [2], a first type of sensing and communication classification is defined depending on three levels of integration: **coexistence**, where sensing and communication are two distinct technologies with physically separated hardware that share the same spectral resources through interference mitigation techniques, **cooperation**, with physically separated hardware and the exchange of some information between the two services to reduce the cross interference or even to improve the performance, and **co-design**, where both technologies are designed with a single system that relies on information sharing and shared framework for waveform design, and this level of integration will be the core of ISAC paradigm. Moreover, different stages are classified for ISAC development; firstly, sensing and communication should simply share resources (i.e., hardware or spectrum) in co-design, with a single system implementation that is capable to act simultaneously in both ways. Then, in further development both services should work together to enhance the overall performance; in the end, the future view of ISAC will regard a coordinated system able to combine both technologies even with other innovations like machine learning and artificial intelligence, multi-node cooperation sensing, etc.

A variety of practical scenarios can benefit from ISAC paradigm; for instance, in flight control scenarios the pilots' communications are integrated with aircraft detection techniques. Another example is the autonomous vehicles and Vehicles-to-Everything (V2X), where sensing techniques for object and pedestrians detection will be integrated into low latency communications to avoid traffic congestion and critical events [76]. Other scenarios are based on local networks such as Wi-Fi in smart home contexts, where energy-saving strategies enable the integration of indoor localization and activity detection services [77]. An emerging approach regards the integration of sensing techniques in cellular networks in a context defined as "sensing as a service", where the base stations are used to sense the environment to extract information like the speed and the position of multiple targets in urban scenarios with cars and pedestrians [78]. Remote sensing and geoscience represent another field where ISAC is emerging as a solution to integrate communication services through signal embedding, enabling interesting solutions with low-speed communications for a variety of purposes; an example is reported in [74, 75] with the integration of a code communication link in SAR systems.

Referring to all the sensing applications related to radar technology, ISAC is often used to describe this integration from a generic point of view, while different names have been defined in literature for the joint approach between radar and communication. The investigation for radar and communication integration started decades ago [29], while a first practical system was proposed in late 1970s by the NASA Space Shuttle program [30]. Recently, the first actions made in this direction by a nation can be traced back to USA Defense Advanced Research Projects Agency with the Shared Spectrum Access for Radar and Communications (SSPARC) program [31]. Today, the joint approach between communication and radar sensing has been well investigated by the research community and is still under analysis, with several definitions in literature, each one with different purposes and levels of combination [32]. A first classification has been defined under the name of Communication and Radar Spectrum Sharing (CRSS) [33]; in this case, the sharing is classified on the type of integration: the Radar-Communication Coexistence (RCC) and the Dual-Function (or Dual-Functional) Radar-Communication (DFRC).

In RCC applications, the joint approach is focused on the physical coexistence between the two services, which are capable to operate relying on interference mitigation techniques in shared or disjointed hardware without losses in terms of performance; therefore, the development of a joint system is based on the coexistence in the same resource (i.e., frequencies, hardware, RF elements, etc.) through cross-technology effects mitigation [33, 34]. A common approach of RCC is opportunistic spectrum access, where radar is the primary service, and communication is the second one that senses and operates similarly to cognitive radio applications; in general this approach is defined as non-cooperative. On the contrary, DFRC applications

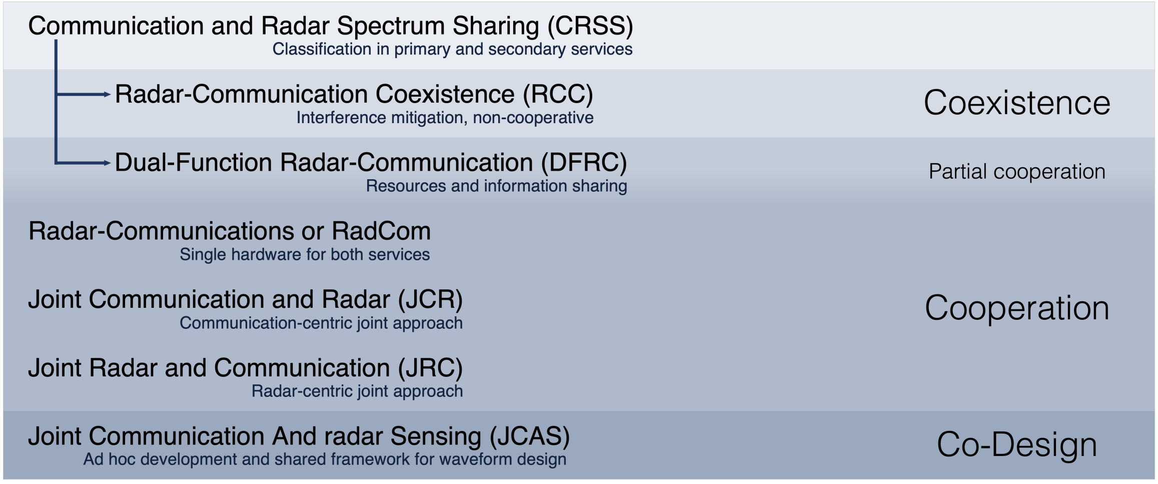

Figure J1.1: Summary of known radar & communication definitions compared with ITU-R classification [2].

are defined as partially-cooperative/cooperative, with the distinction between primary and secondary service still valid. In DFRC the joint system can operate both services simultaneously, with the cooperation that is extended to single or multiple transceivers [33, 36] and even to sidelobes management [37] or waveform design [38]; the cooperation provides the sharing of physical resources like antennas, analog front-ends, waveforms, etc. In [39] are considered four different DFRC strategies in the context of autonomous vehicles: separate coordinated signals, communication-based waveform, radar-based waveform and dedicated joint waveform. Indeed, DFRC applications are usually denoted as communication-centric DFRC, where communication is the primary service that is used to sense the environment [40], or radar-centric DFRC where the purpose is to integrate information in radar waveforms [41].

Besides CRSS, other names are used in literature to identify the sensing and communication joint approach. Another definition has been made in [42] under the name of radar-communications or RadCom, where the authors refer to a single hardware platform for both services through a single waveform in automotive and V2V scenarios, taking advantage of single carrier spread spectrum and OFDM multiple carrier approaches; this cooperative approach based on OFDM has been recalled by [43] to reduce the waveform peak-to-average power ratio in the RadCom system. Other common definitions for cooperative communication and sensing are Joint Communication and Radar (JCR) [32, 44] and Joint Radar and Communication (JRC) [45, 46], which imply the same concept distinguishing between, respectively, communication-centric and radar-centric design. Another term often used in literature is Joint Communication And radar (or radio) Sensing (JCAS), also known as Joint Sensing And Communication (JSAC) [47]. Similarly to JRC and JCR definitions, the JCAS acronym is used in two opposite ways; occasionally, it specifies the same kind of integration described in DFRC [32,48], so in the background of communication and sensing coexistence, but in general it refers to a deeper level of integration between them, classified as co-design [49,50] in the same way of ISAC definition. In this approach, the classification of primary and secondary services falls apart in favor of a joint ad hoc system design capable to execute both services in a single or distributed device. All the definitions presented above for the joint approach between radar and communication exploit different levels of integration; referring to the classification listed in [2] about communication and sensing in general, in Fig. J1.1 these definitions are summarized and referenced to the general concepts coexistence, cooperation, and co-design.

Different from general radar systems, the integration between SAR and communication is at an early stage; this is probably due to the specific remote sensing purposes of SAR techniques compared to the variety of application fields of radar technology. One of the most common approaches regards the communication embedding in SAR waveforms, as described in [56] where a backscattering communication framework is proposed for target localization and uplink communication. Other relevant works for SAR and communication integration have been proposed in [66], where the authors proposed a MIMO SAR system with different orthogonal multimodal waveforms designed to integrate a communication link during imaging processes, and [69], where continuous phase-modulated codes are used to transmit information while acquiring images through SAR technology. In [68] is presented a novel approach for information embedding in SAR using time-frequency spectrum shaping to integrate the communication while keeping high performance for the imaging process. Orthogonal Frequency Division-Multiplexing (OFDM) represents an interesting solution for the joint approach between communication and radar/SAR; OFDM has become a key technique for modern wireless communication technologies, and it has been demonstrated that can be an interesting solution even for sensing techniques like SAR imaging [66,69–71]. Another innovative approach takes advantage of watermarking technique to develop a framework for dual-function SAR and communication through information embedding in SAR imaging systems [72]. In [73] is presented a novel cellular-aided SAR system that takes advantage of existing mobile communication base stations to enable a bistatic SAR imaging process through UAV SAR receiver, reversing the usual SAR communication joint approach: while in general the communication is embedded in SAR technology, due to the features of SAR systems, in this case the purpose is to exploit existing communication signals for SAR imaging purposes. It must be underlined that, despite the novelty of the dual approach between SAR and communication, all the presented works are related to novel approaches that rely on SAR systems developed ad hoc or particular modified versions. In this sense, in literature there are very few works that refer to consolidated SAR systems; this approach can be an interesting solution to exploit previous SAR technologies already on-air, especially without modification considering the high-complexity of this task.

J1.3 Synthetic Aperture Radar Overview

Different radar-based technologies have been developed in the last decades for different aims; one of the most famous remote sensing applications is SAR. This particular type of radar technique allows the acquisition of daylight and weather independent images of a certain area with high-resolution (i.e., in the order of meters), taking advantage of a very large synthetic antenna aperture obtained through the movement of the radar system [51]. Generally speaking, SAR systems can be developed in several scenarios depending on the type of application. Spaceborne SAR systems are the most common implementation due to the high coverage area and high revisit frequency, despite the complexity of satellite approach. Different satellite orbits are considered for satellite SAR systems, like Low Earth Orbit (LEO) as for ESA Sentinel-1 [52] or the Italian COSMO-SkyMed [53] constellations, Medium Earth Orbit (MEO) as in [54], or Geosynchronous Earth Orbit (GEO) as planned for GeoSTARe [55]; for satellite SAR constellations, the orbit represents a trade-off between coverage area, image resolution and revisit frequency. Another approach is represented by airborne SAR systems based on airplanes or UAVs (e.g., drones or aircraft without human pilot), with a reduced coverage area due to the lower altitude, differently from the spaceborne implementation, which is balanced by lower complexity and higher resolution. Airborne SAR systems are employed mainly for the analysis and monitoring of specific areas [79] with ad hoc development. In the same way, planar or ground SAR systems are used for local analysis and testing of simplified environments with very high resolution (i.e. centimeters or less), as in [56] where a planar SAR has been developed for proof of concept purposes or in [57] where an automotive SAR system has been conceived and validated.

Different SAR acquisition techniques have been proposed to improve critical aspects like image resolution, swath (i.e., ground SAR coverage perpendicular to the flight direction), and coverage area. Compared to stripmap mode [51], ScanSAR, spotlight, and TOPSAR can be optimal solutions. While stripmap makes use of fixed

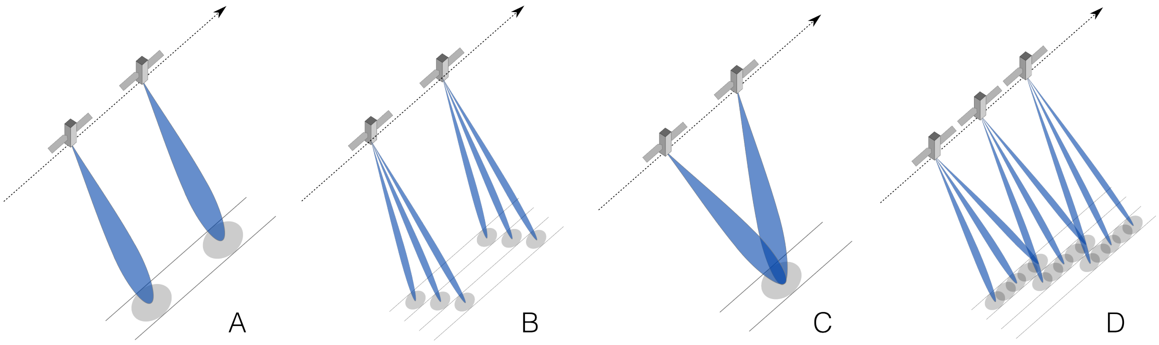

Figure J1.2: Simplified representation of stripmap (**A**), scanSAR (**B**), spotlight (**C**), and TOPSAR (**D**) acquisition techniques.

antennas and fixed beams, scanSAR takes advantage of multiple sub-swath to increase the overall coverage area with the drawback of reduced spatial resolution [58]. Differently, spotlight method exploits beam steering techniques to reach a high spatial resolution illuminating a certain area for a longer time compared to the other acquisition methods, with the disadvantage of discontinuous image acquisitions, as reported in [59]; in general, spotlight is used for high-resolution images of smaller and remote areas, i.e., islands or small groups of islands. TOPSAR method can be considered a meeting point between wide swath and high spatial resolution; like scanSAR, it performs sub-swaths with the addition of beam steering in flight direction through burst-based acquisitions [60]. In Fig. J1.2 both acquisition methods are displayed through a simplified representation.

SAR working principles are based on the transmission of a frequency-modulated signal called chirp with a certain Pulse Repetition Interval (PRI); after the chirp transmission, the SAR listens to collect the replicas backscattered by the targets and the environment, using a low duty cycle (i.e., in general near the 10%). Then, after acquiring a certain area, the SAR transfers the raw data matrix (one dimension corresponds to multiple PRI in the range direction, while the other to the azimuth direction) to a ground station for the image processing, transforming the backscattered replicas of each PRI to an image of the illuminated area. Different algorithms have been proposed in literature to process the raw data into the final images; the common points between the multitude of processing algorithms are the range processing and the azimuth processing [51, 61]. Basically, both processing can be considered as a double matched filter in both directions, firstly using the range reference function to perform the pulse compression and then using the azimuth reference function to obtain the final image; the entire processing is briefly summarized in Fig. J1.3.

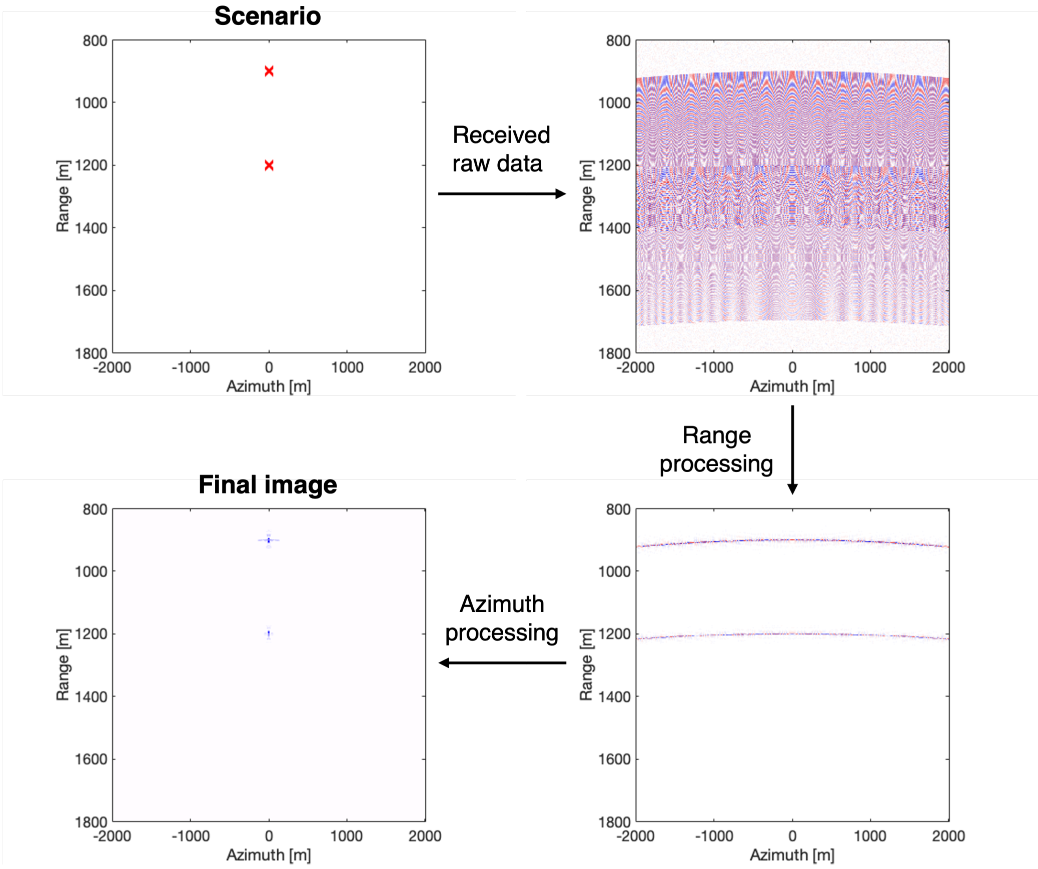

Figure J1.3: Simulation of SAR image processing workflow in a stripmap scenario.

In general, SAR systems are supported by ground targets, particularly in spaceborne scenarios; ground targets can support SAR technology in many ways, and calibration represents one of the most common tasks used to correct functional parameters like emitted power, RF gains, frequency correction, etc. Usually, two main calibration tasks are accomplished by SAR systems, the internal calibration executed by itself, and the external calibration through the support of ground targets [62]; internal calibration tasks are performed by SAR systems to correct RF components (i.e., gain and phase). In external calibration operations are executed several processes, among which geometric calibration to map the final image pixels into a certain location, the radiometric calibration to evaluate the measurements captured by SAR with the reference target replicas, or other types of calibration like antenna and polarimetric calibrations. To fulfill external calibration processes, the assistance of ground targets is fundamental. Besides calibration tasks, ground targets can support SAR systems for high-level operations like remote sensing geopositioning, for instance to monitor a particular phenomenon or objects in a certain environment [63]. A particular target used for this purpose in satellite SAR systems is the Corner Reflector (CR), a device that is typically located in areas without natural reflectors; CRs can backscatter satellite SAR signals with higher RCS compared to the surrounding environment, highlighting in the final SAR image its response and the area in which is located, so that its response can be used for external calibration support or its known position can be used to map the final image into the adopted geographic coordinate system. CRs are classified into two main categories:

- **Passive CRs**: they are powerless targets based on metal plates, whose shape, size, and analog gain depend on the required RCS and the SAR operative frequency; in general, a passive CR is a 3-faces cube where the faces shape can be quadratic, triangular, circular, etc. The absence of power supplies allows to place passive CRs in every environment independently of weather conditions, with the drawbacks of low performance and high sizes and weight that increase the complexity to locate them in remote areas [64, 80].
- **Active CRs**: This category of CR exploits power supply to achieve better performance and additive processing (e.g., amplification, filtering, etc.) alongside the smaller and compact size; compared to the previous, active CRs can reach high RCS with the power source, but limiting the possibility to install it in every environment [65].

Recently, taking advantage of SDR technology, a novel category of CRs has been presented, the so-called **Software-Defined Corner Reflector** (SDCR). The usage of SDR technology to perform CR functionality enables the same assets of classic CRs, especially the advantages of active CRs, jointly with the benefits of SDR implementation. In particular, with SDCRs is possible to backscatter SAR signals outperforming classic CRs with additive tasks performed in the digital domain, such as filtering, amplification, etc.; in this way, is possible to integrate a wide range of digital functions that could not be performed by classic CRs. Indeed digitalization, which is a key feature of SDR technology, enables plenty of possibilities like automatic controlled gain for adaptive signal reception and transmission, interference mitigation techniques, real-time signal processing for additional tasks, and satellite signal monitoring (in terms of power, Doppler shift, etc.), just to name a few. Besides, SDR integrates features like the flexibility of a wide frequency range, depending on the SDR platform adopted, allowing the use of SDCR with a large set of SAR technologies and satellite constellations, with the possibility to dynamically change the RCS based on

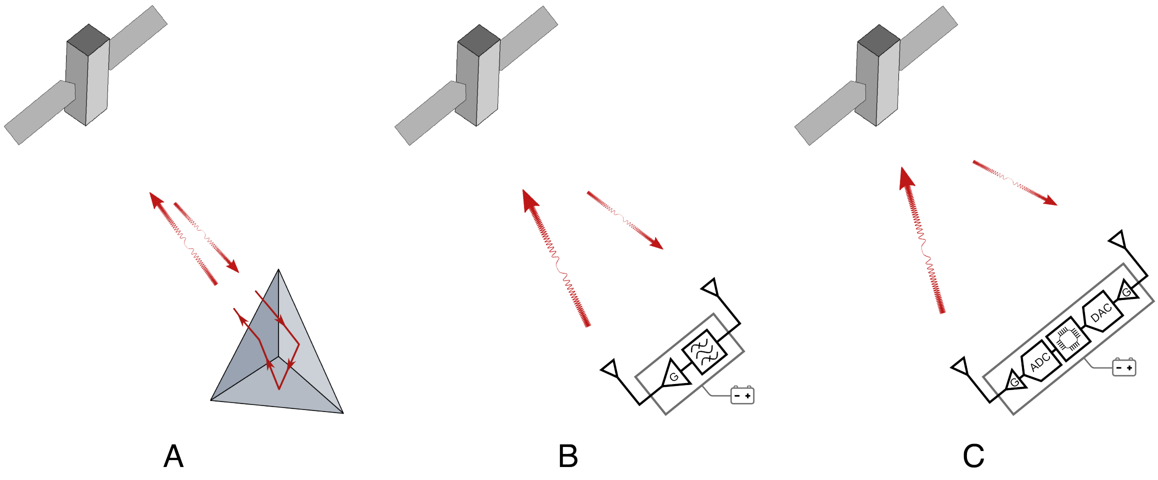

Figure J1.4: Representation of passive CR (**A**), active CR (**B**), and SDCR (**C**).

the necessity. Two main drawbacks are present in SDCR functionality; the first is the requirement of a power source like active CRs, but it must be noticed that SDR power consumption is limited and depend on the SDR platform. The second drawback is due to the digitalization process involved with SDR technology; this aspect will be detailed in the next section. Further information about SDCR can be found in [75, 81], where this novel CR category is introduced and fully investigated with the analysis of advantages and drawbacks referring to two different commercial SDR platforms. Both classic CRs and SDCR are represented and compared in Fig. J1.4.

J1.4 ISAC Framework Implementation

As mentioned before, the aim of this work is to present and describe a novel target capable to operate in ISAC contexts, enabling the integration of communication services in technologies that are not designed for this purpose like SAR and radar in general, while supporting the classic sensing processes. Relying on SDR technology, the proposed target is able to switch between two functionalities for two separate tasks; moreover, SDR flexibility allows to switch dynamically between them based on the task required in a certain area at a specific time. Different from all the published works that are available in literature, the aim of this ISAC framework is to support SAR imaging process and integrate communication service while avoiding modification in consolidated systems, in particular considering the well-known difficulties related to systems already on-air, e.g. satellites. Besides, the objective is to support satellite systems already on-air even for high-level techniques, not only for SAR calibration steps, while standing out in the area in which the SDR target is placed.

Moreover, a further purpose of this activity is to draw the attention to SDR technology not only as a component useful for testbed development, as in [82,83] where SDR platforms are used as transceivers for testing operations, but also as enabler of new tasks and functions that can be performed through a dynamic and flexible platform. In this section, firstly the target functionalities will be presented and described, then the SDR target development will be shown in detail referring to the ESA Sentinel-1 SAR satellite constellation, which has been considered the reference architecture for this activity.

J1.4.1 SDR Functionalities

The first functionality of the proposed SDR target allows the integration of a code-based communication link that is transparent with respect to the usual SAR imaging process; the use of code modulation techniques, similar to CDMA and DSSS, facilitates the communication link during the imaging process. The transparency guarantees in the final image a low contribution of the target compared to the surrounding environment, so that its contribution can be neglected. The aim of this strategy, which can be considered a communication embedding approach, is to hide the presence of the proposed target in the final SAR image in the same way as steganography techniques; the consequence is that the SDR target contribution is not visible in the image but can be detected in the raw data containing the replicas received by the SAR. This communication service can be considered a hybrid approach that falls under both definitions of communication embedding, since technically the purpose is to embed a communication link in a signal transmitted by a different technology, and steganography, because from SAR's final image point of view the SAR target is hided while communicating. Then, once the raw data containing the replicas backscattered by the environment plus the SDR target are sent to a ground data processing center, the code modulation can be exploited to obtain several interesting results except for the classic SAR image of the environment:

- **Communication link extraction** through code matching, from a simple identification task (which is a basic form of communication) to more complex information exchange with higher data rates [74];
- **Target localization**, which can be obtained through the classic imaging process of the demodulated raw data; similarly to DSSS approach, the code will reduce the contribution of the replicas due to the environment while highlighting the target one. The outcome will be a second image that can be mapped

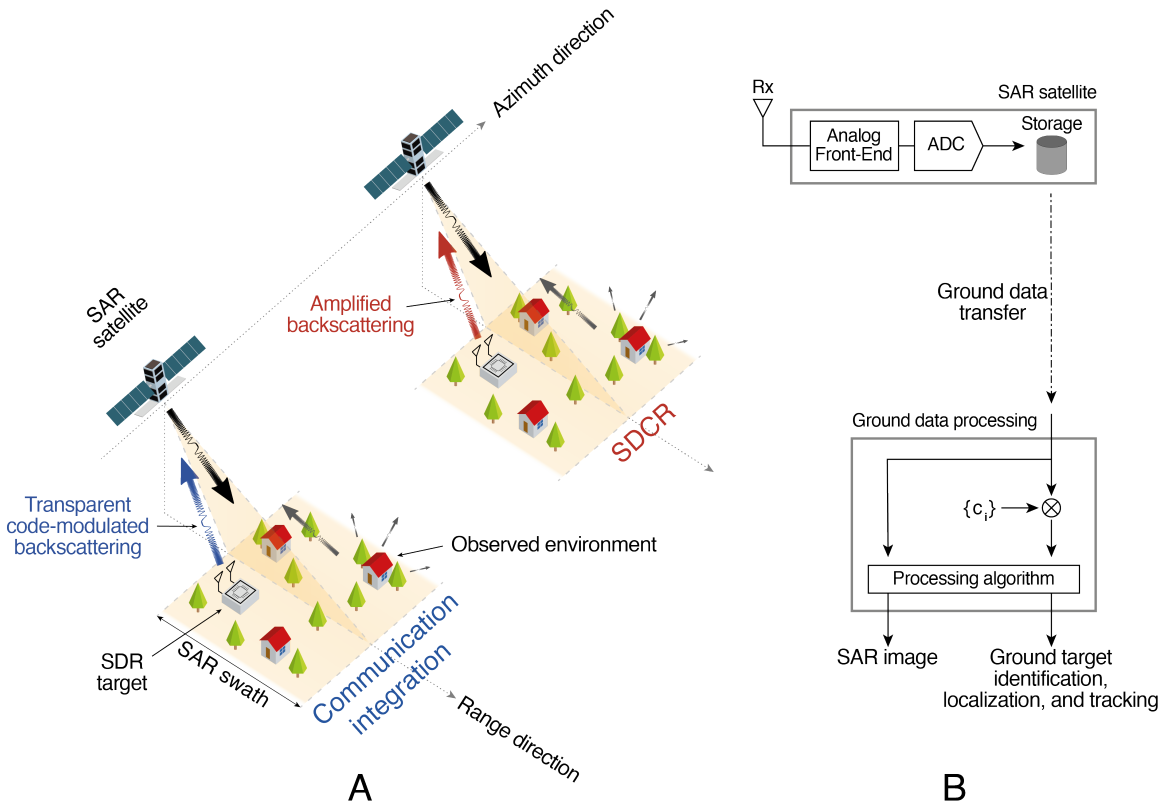

Figure J1.5: Schematic representation of the proposed SDR-based ground target with the communication integration task in blue and the SDCR functionality in red (**A**) and a generic satellite SAR operative behavior with the subsequent communication extraction, target localization, and tracking (**B**).

into geographical coordinates, just like the classic SAR final image, where the target position will be illuminated enabling target localization;

- **Target tracking**, which is a direct consequence of multiple target localization images that allow monitoring the trajectory of the SDR target or, vice versa, to monitor the satellite SAR trajectory if it changes.

The second functionality presented in this work is the so-called SDCR, whose relay action has been previously described with all the advantages and possibilities offered; through SDCR, the proposed SDR target can be an interesting and flexible solution to support SAR satellites in calibration tasks or high-level tasks like geopositioning, environmental analysis, etc. It must be highlighted that for operation in SAR support scenario (i.e., calibration), the information about the SAR satellite must be known a priori, which is possible only with free access platforms like ESA Sentinel-1 but not with private SAR systems; another factor that must be considered is that the uncertainty about calibration target's response must be very accurate to avoid errors in the satellite SAR system. For this reason, low-performance SDR targets with fluctuations or not-perfect filtering in the received and transmitted chains could not be indicated for this purpose. The main difference with respect to the communication integration task is that in SDCR functionality the aim is to reflect the SAR signals illuminating the surrounding environment in the final image, while in the first functionality the objective of the proposed SDR target is to backscatter the SAR signals and conceal its response in the final image. Then, the raw data containing the replicas backscattered by the illuminated area plus the SDCR are transferred to the ground and processed as usual. Both functionalities are summarized in Fig. J1.5 together with a schematic representation of the SAR satellite and further processing to obtain the final SAR image, the communication extraction, and the localization and tracking images.

Two main drawbacks must be considered in the proposed framework; the first is the additive delay introduced by the SDR technology, as anticipated in the previous section, which depends at least on the time needed by receiver and transmitter analog front-ends plus the time required for the digital and analog conversion, i.e. Analog-to-Digital Converter (ADC) and Digital-to-Analog Converter (DAC). Every additive processing integrated through the SDR platform can be performed in the hardware domain (i.e., FPGA), where the discrete number of clock cycles required for a specific task will make the additive FPGA latency deterministic. In the software domain the performance are different, since the timing involved are on a completely different scale compared to the hardware domain: the latency introduced by software processing could be neglected, but the main delay is due to the interconnection between the software and the hardware, increasing the overall delay. In this framework, the outcome of the SDR delay corresponds to a shifted peak in the pulse compression, which has an impact on the final image moving the SDR target response in the range direction with respect to the real target position. Therefore, depending on the reference SAR system, low delays can correspond to an unshifted response in the final image due to the SAR ground resolution, in case the shift is lower than the SAR resolution, but higher delays can correspond to a higher shift with false positioning of the SAR target in the final and localization image. The use of high-performance SDR targets together with an hardware-oriented SDR design can be a good solution to overcome this issue.

The second drawback is related only to the communication integration functionality, in particular to the design choices of the code adopted for the communication embedding. Assuming that the code is based on two symbols, $[+1, -1]$ the first assumption required regards the balanced properties to guarantee the transparency of the code with respect to the final image: if the code is not locally balanced, hence its sum is not equal to 0, the communication link will interfere in the final image and the SDR target contribution will be visible. Another aspect that must be considered is the type of the code: to guarantee the transparency is required a code sequence with high correlation, like for instance the Gold or Kasami sequences.

J1.4.2 Target Development

To operate both functionalities with high performance, several requirements must be fulfilled and different design methodologies can be adopted for this purpose depending on the selected satellite SAR systems; for this activity, the choice of the reference SAR system has fallen to the ESA Sentinel-1 satellite system for several reasons, in particular for the different type of SAR data distributed on the ESA platform. ESA Sentinel-1 is the first of five missions launched by ESA, composed of two polar-orbiting C-band SAR satellites operating day and night with 12 days repeat cycle per each satellite, with a 180° orbital phasing so that both satellites can have a joint repeat cycle of 6 days. Other interesting information about Sentinel-1 mission are: 693km altitude, image resolution in the order of meters, four different acquisition modes among which stripmap and wide-swath, up to 400km of swath width depending on the acquisition mode; Interferometric Wide (IW) swath is the main operational mode which covers a large part of the globe, implemented through TOPSAR acquisition mode with three sub-swaths for an overall swath width of 250km. More information about ESA Sentinel-1 mission are provided in [84]. At the writing step of this paper, only the Sentinel-1A (S1A) is operative, since Sentinel-1B mission ended in July 2022, but a third satellite (Sentinel-1C) is planned to be launched during 2023.

As introduced earlier, the choice of Sentinel-1 is due to the possibility to access the data acquired by the Sentinel-1 satellites; in particular, ESA distributes all the data acquired by the satellites under three different products: Level-0, which consists of compressed and unfocused SAR raw data (hence I/Q components received by the satellites), Level-1, which are the focused data produced in two different versions, the Single Look Complex (SLC) that preserve the phase information and the Ground Range Detected (GRD) with only information about the amplitude, and the Level-2 which consists of geolocated geophysical products available as Ocean Wind Field (OWI), Ocean Swell spectra (OSW) and surface Radial Velocity (RVL). This research activity refers only to Level-0 products, as described in the following section. All these products and the relative types are available for each acquisition made by each satellite at every point of the globe, making ESA Sentinel-1 an extraordinary source of data for research activities linked to remote sensing and, in the last years, ISAC.

Regarding the development of the SDR target, several considerations are needed. Referring to the general physical radio features of ESA Sentinel-1 satellites, i.e. carrier frequency of 5.405GHz and 100MHz of maximum instantaneous bandwidth, the SDR target must be capable to meet these requirements; for this reason, referring to the SDR platform investigated in [81] the decision ended up to the NI USRP 2954R, since its features fulfill the requirements while offering high performance, like 2x2 MIMO possibility with four I/O interfaces (two TX/RX and two only RX), operative frequency from 10MHz to 6GHz, 200MSps of maximum sample rate with 160MHz of maximum instantaneous bandwidth, 16bit DAC and 14bit ADC, and Xilinx Kintex-7 FPGA for high-performance processing in the hardware domain. Moreover, this SDR platform does not simply satisfy the requirements but offers the possibility to implement both hardware-oriented and software-oriented design methodologies. In this sense, the choice of the USRP 2954R is optimal because of the reduced latency (i.e., less than 0.6μs [81]), enabling a hardware-oriented design methodology with both functionalities that can be performed into the FPGA. The software-oriented approach cannot be considered for this activity due to the delay involved, which is much higher than the hardware-oriented design and comparable with the time window in which the SDR target is illuminated by the SAR system, corresponding to a large shift of the SDR target in the final SAR image.

J1.5 Framework Emulation and Results

In this section the proposed ISAC framework is described and tested in a real scenario based on the acquired data available from the reference SAR system of this activity. The main objective would have focused on a real test, using two SDR targets displaced in different positions (corresponding to different pixels of the final SAR image) to implement both functionalities (Fig. J1.6 A). Nevertheless, different critical issues are present with this approach, like the impossibility to emit signals over the air in licensed frequency bands such as the 5.405GHz carrier frequency of ESA Sentinel-1, or the well-known difficulties to operate with real satellite systems, especially with amplitudes of hundreds of kilometers. Moreover, Sentinel-1 SAR satellites operate in the entire globe, acquiring the majority of SAR images through IW acquisition mode, which is based on TOPSAR technique. As described previously, this technique is based on

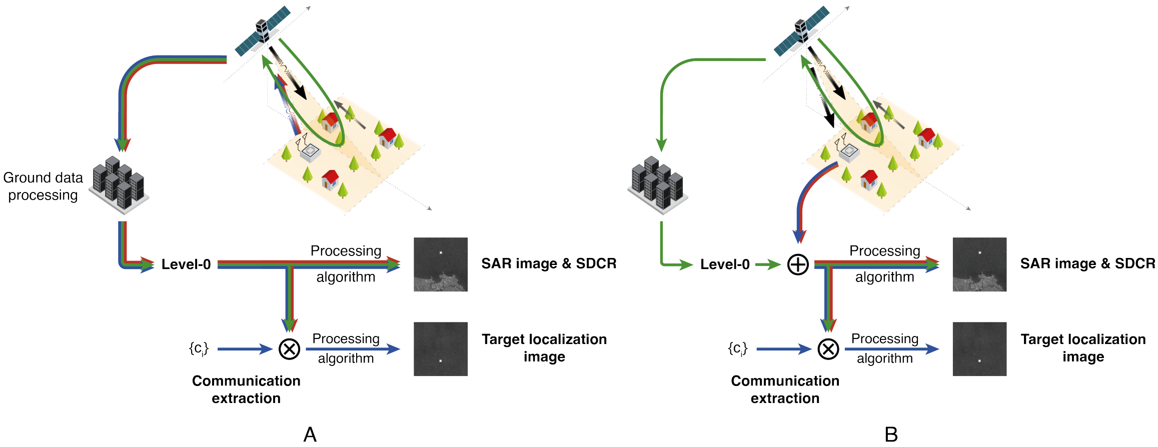

Figure J1.6: Schematic representation of proposed framework for both functionalities (communication integration in blue, SDCR in red) for real test scenario (**A**) and emulated scenario where the SDR target contribution is added directly into the Level-0 raw data (**B**).

three sub-swath each one with different parameters(i.e., chirp bandwidth, duration, PRI, orientation, etc.), and each area inside the sub-swath is acquired through burst, each one with a certain number of PRI, based on beam steering techniques, making the image processing algorithms extremely difficult to manage [85]. For this reason, the choice of this testing operation has fallen to the stripmap acquisition technique, since is one of the four acquisition methods supported by ESA Sentinel-1 satellites. The drawback is that stripmap technique is used by Sentinel-1 satellites only in remote islands and few cities around the globe, with no stripmap coverage in Europe. For this reason, considering the impossibility to displace SDR targets in those areas, the analysis of both functionalities with real SAR data has been conducted through an emulation process instead of a real test, as shown in Fig. J1.6 B. In this case, is possible to validate the entire framework without requiring a real test with the emission of signals in licensed frequencies.

This approach has been fulfilled by creating a local copy of the chirp signal transmitted by S1A satellite in stripmap acquisition mode. The area selected for this emulation is the city of São Paulo, Brazil (Fig. J1.7); this choice is justified by the fact that half image acquired by the satellite includes the Atlantic Ocean, giving the possibility to test the effectiveness of the functionalities even in dark areas compared to the cities, since water has low reflectivity at C-band frequency. For this operation, the Level-0 raw data, available from the ESA Copernicus platform, has been downloaded and processed to decompress the Flexible Dynamic Block Adaptive Quantisation (FDBAQ), which is a compression technique used to reduce the instrument data

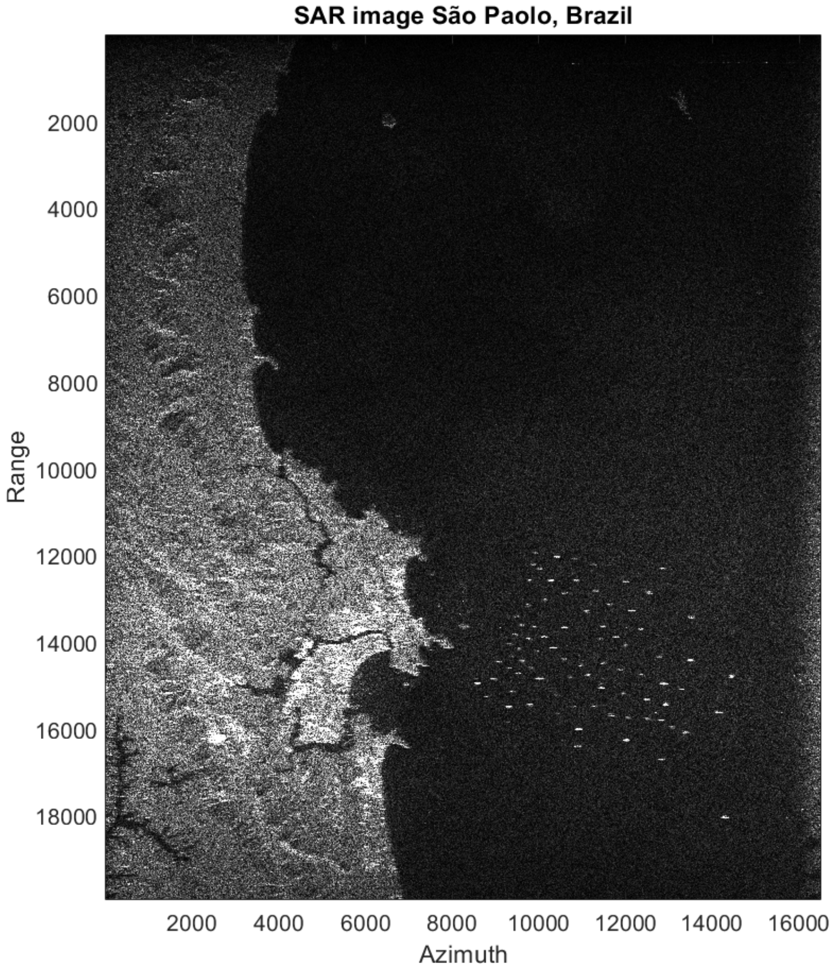

Figure J1.7: Final SAR image of São Paulo, Brazil, processed from S1A stripmap raw data.

rate of the satellite; after the FDBAQ decompression, the I/Q components of each PRI is available. Then, the local copy of S1A signals is added into each PRI, for a total number of 836 PRIs; this number is the outcome of a computation related to several parameters for S1A acquisition in stripmap mode, among which the azimuth angle of S1A antenna, the satellite speed, the satellite incident angle (the center of the swath has been considered for this operation), the antenna azimuth beam width of S1A, and the PRI. For each PRI of the set containing the local chirp signal, three different effects have been considered to emulate the behavior of a real scenario:

- i) the amplitude of each local chirp inside the PRIs is lower at the beginning and the end, while is maximum in the middle, which is needed to emulate the maximum amplitude in the central PRI corresponding to the one where the SDR target is centered in the azimuth direction, meaning that S1A is near to

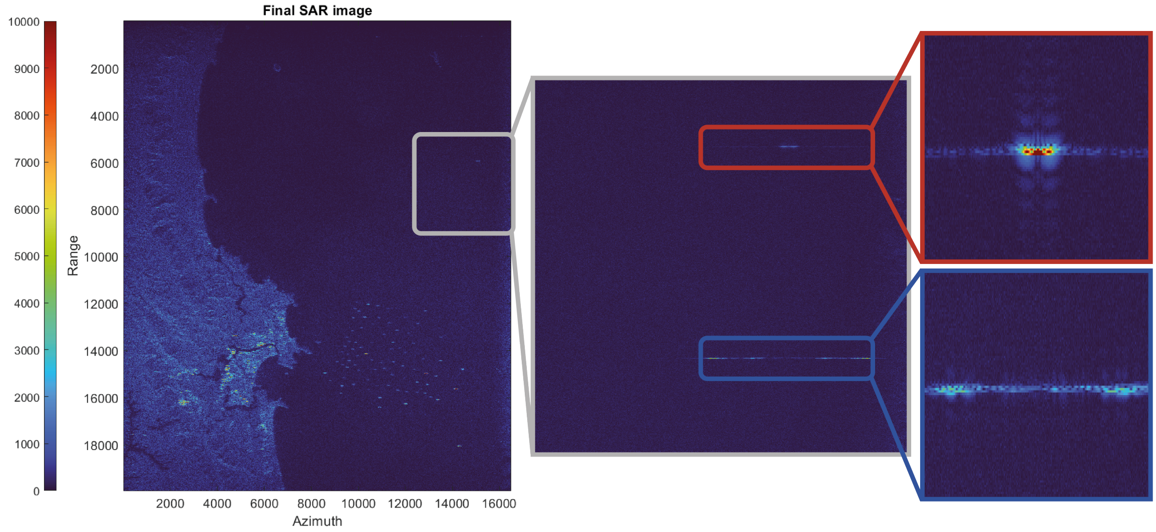

Figure J1.8: Emulation results for final SAR images starting from S1A raw data; in red is highlighted the behavior of the emulated SDCR functionality, while in blue is the emulated communication integration functionality.

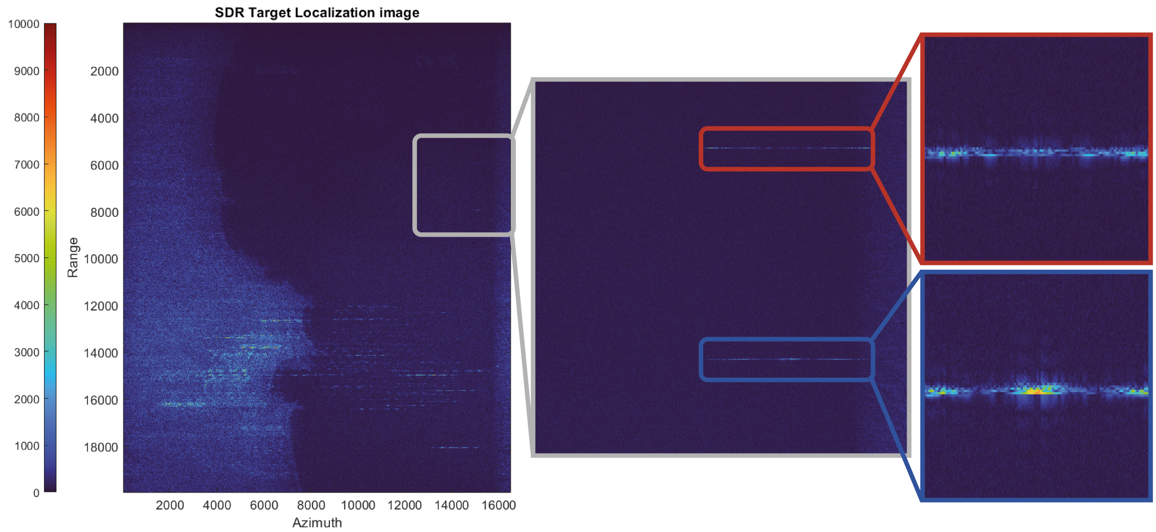

Figure J1.9: Emulation results for SDR target localization images, obtained applying the code to the S1A raw data; in red is highlighted the behavior of the emulated SDCR functionality, while in blue is the emulated communication integration functionality.

the SDR target;

- ii) the phase offset of each local chirp changes in each PRI depending on the movement of the S1A satellite;
- iii) the position of the local chirp in each PRI (i.e. the duration between the time instant in which S1A starts to collect the chirp replicas to the start of the

local chirp) changes hyperbolically, since at the beginning of the set of PRIs the distance between S1A and the SDR target is farther than the central PRI, similarly to effect i).

For what concern the SDCR, this functionality has been emulated simply by adding the local chirp with the features previously described; on the other hand, the communication integration has been emulated by applying the code modulation to local chirps in each PRI, with the assumption that each code bit is applied to one PRI (i.e., one code bit per chirp). The code selected for this task is the Kasami code with two possible code bits, 0 and 1; the Kasami code has been conveniently adapted to be locally balanced, mapping each code bit with four symbols, so that the balancing property is guaranteed every 4 bits (i.e., 4 PRI): the code bit 1 is mapped as $[+1, -1, +1, -1]$, while the code bit 0 is mapped as $[-1, -1, +1, +1]$, which are orthogonal sequences. Therefore, the final balanced code contains only the symbols $+1$ and -1, corresponding to the emulation of the SDR target's backscattering with a reflection coefficient $+1$, corresponding to no phase modification, and -1, with 180 degree phase offset. Further investigation of this research activity will include the analysis of codes in order to find the sequences that will outperform this simplified approach.

The outcome of this emulation is shown in Fig. J1.8 and J1.9. Starting from Fig. J1.8, the raw data with the additive SDR target responses for both functionalities have been processed as usual, indeed in red is possible to see the effect of the SDCR functionality, whose presence is highlighted in the final SAR image, while in blue is shown the effect of the communication integration functionality; in this case, the contribution of the SDR target is reduced due to the code modulation, and spread in the azimuth direction. Further work of this research will include the analytical analysis of the code modulation in the final image.

In Fig. J1.9 are shown the final images of the S1A emulated raw data where the code has been applied before the image processing; in this case, is evident that the code effect on the raw data is similar to a shifted repetition of the image in the azimuth direction with lower amplitude compared to the final SAR image. Moreover, observing the emulated SDR targets, the SDCR (in red) has the same behavior of the communication integration functionality in Fig. J1.8, with a spread effect with reduced amplitude, while (in blue) the other functionality stands out, demonstrating the validity of this approach for real satellite SAR systems already on-air. In this case, the communication integration SDR target is not perfectly reconstructed, which is probably due to the code adopted for this purpose. In this sense, further investigations are required.

J1.6 Conclusions

Considering the modern technological advancements of wireless communications networks, the joint development of sensing and communication services is becoming popular for plenty of purposes and applications. In particular, the integration of radar and communication techniques is attracting the attention of the research community. In this sense, SAR represents a fertile land to exploit for ISAC purposes, in particular using the advantages and opportunities enabled by SDR technology. In this paper, a novel use of SDR technology has been proposed and described for a dual purpose in satellite SAR systems: support modern SAR systems already on-air for calibration and high-level applications through the SDCR functionality, and the integration of an embedded communication link through a code-modulation technique without any interference in classic SAR imaging process. Both SDR functionalities have been fully described and tested in an emulated environment using real S1A raw data acquired in stripmap mode. The results have demonstrated the validity of the proposal, showing that is possible to execute both functionalities with SDR targets displaced to the ground without negatively affecting the classic SAR operation. Further investigations are required, starting from an analytical analysis of the code in the SAR imaging process together with a research of the optimal code for this operation. Then, the next step will be a real test in a real environment, eventually in TOPSAR mode.

Conference C1

SDR-Based Distributed System for Mobile Communication Network Monitoring and Support

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Abstract

Nowadays, in contexts where communication technologies are always more oriented to the wireless approach, mobile communications are not just systems to connect devices but enablers for several heterogeneous services depending on the demand, starting from 5G networks. Sensors and massive IoT scenarios are introducing a higher order of complexity, making the situation more difficult for wireless technologies, even considering the high resource demand of the present days. For this reason, the use of a distributed system can be the most suitable to interface this complex environment for monitoring and support purposes, in particular taking advantage of Software Defined Technology (SDR) advantages. In this paper is proposed an SDR-based distributed system capable to execute several services, depending on the necessity, to monitor and support a generic wireless communication system. After the overall presentation of the proposed system, a prototype capable to execute a monitoring service for spectrum analysis, interference detection and localization will be described and tested.

C1.1 Introduction

With the evolution of wireless communications in the past decades, many services moved toward the mobile approach, particularly with 5G networks and all the possibilities offered by this new technology. Compared to the previous mobile communication standards, 5G (and 6G in the future) offers the possibility to allocate different resources for the execution of a wide range of services. Following the International Telecommunication Union (ITU) recommendations [3], all the services enabled by 5G networks are grouped into three main categories:

- enhanced Mobile Broadband (eMBB), focused on performance enhancement for high data-rate services;
- ultra Reliable and Low Latency Communications (uRLLC) for mission and safety critical services that requires a network with very high reliability and minimum latency;
- massive Machine Type Communications (mMTC) with all services involved in high-density connectivity, i.e. massive Internet of Things (IoT) and Industry 4.0.

As a consequence, 5G in general is defined service-enabler, and this line will carry on in future systems starting from 6G; this comes from the flexibility offered and the variety of heterogeneous services that can be executed. In this sense, different applications are present in literature, as in [7] where a sound spatialization application for cultural heritage services in 5G networks is presented. Another important aspect of 5G innovation is the concept of Network Function Virtualization (NFV), where specific network equipment is replaced by Virtual Machines (VMs); this approach follows the modern software-oriented approach of the future mobile communication systems starting from 5G. Referring to mMTC, the technology evolution and the wireless expansion in everyday scenarios has brought an exponential increase in the number of devices per user; in massive IoT 1 million devices per square km are expected to be connected to the network [4], and this estimation will rise even further in the future. This escalation in connected IoT devices is also related to the exploitation of sensors and wireless sensor networks, which are mostly used for practical cases of prevention and monitoring in several fields. An application is described in [5] within the context of structural health monitoring, where sensor nodes are connected to the 5G network and distributed in constructions to monitor their health state and prevent disasters in critical events like earthquakes. Another scenario connected to structural health monitoring is presented in [6] with the description of the 5G disaster management system for earthquake early warning.

Several unwanted effects are present, like the emergence of interference effects and the increase in resource demand, just to name a few. As a matter of fact, the usage of spectral resources is becoming critical, in particular regarding spectrum saturation due to the increasing bandwidth demand. These aspects have been extensively studied in [86] where the authors detailed the challenges related to spectral usage and addressed the need for spectrum monitoring supported by a measurement campaign. Moreover, the necessity of spectrum monitoring systems is becoming obvious, in particular to reduce and mitigate the interference and evaluate the radio resources usage in a certain area, even supported by localization processes to identify the interfering source position. This purpose has been investigated by the research community, as in [87] where signal detectors have been proposed taking advantage of Software-Defined Radio (SDR) technology. Furthermore, is clear the necessity of feature extraction in addition to detection techniques to better understand the nature of the interfering source, as in [88] where a signal recognition technique focused on modulation classification has been described.

In this background, the aim of this work is to present a distributed system to implement heterogeneous services in real-time to support modern mobile communication networks taking advantage of SDR technology and its flexibility and interoperability, which can be an added value compared to previous works presented in literature. In this direction, a prototype will be described and tested in a simplified scenario, focused on the spectrum resources monitoring for interference detection and localization. The rest of the paper is structured as follows: in section C1.2 is detailed the reference context with a general description of the proposed system and its practical scenarios, while section C1.3 presents the prototype and its assessment; finally, some conclusions are reported in section C1.4 together with future development of this activity.

C1.2 SDR-based distributed system

The proposed system falls into the paradigm of smart cities, which is one of the key factors of the INCIPICT project, acronym of INnovating CIty Planning through Information and Communications Technology. This project is revolved around the concept of a living lab testbed for smart city applications in the city of L'Aquila, which was one of the first cities hosting the 5G experimentation trials in Italy. The project has three main objectives, surrounded by diversified services and applications: the construction of an experimental optical network to build a Metropolitan Area Network (MAN) through an optical ring that connects the most important sites of the city (e.g., public administration buildings, the University of L'Aquila, etc.), the development of innovative wireless technologies to reduce the energy consumption and increase the transmission speed integrating real time tracking and localization applications, and the development of middleware for the abstraction of heterogeneous network components, adapting the access method for a certain technology as independently as possible. More information about INCIPICT project can be found in [89] and [90]. Part of INCIPICT objectives meets the goals of SICURA project, acronym of caSa Intelligente delle teCnologie per la sicURezza - L'Aquila, whose purpose is the development of a living lab to support business models oriented to cyber security, IoT, and artificial intelligence. Additive information about SICURA is available at [91].

In this context, the proposal of this research activity is to develop a novel distributed system that is able to support mobile communication systems. The core idea is a distributed system based on SDR devices, which is capable to be reconfigured in real-time depending on the application that needs to be executed. For this reason, the use of SDR technology can be an added value, especially in terms of performance, flexibility, and scalability, thanks to the reconfigurable hardware equipped on SDR platforms and their possibility to be programmed in hardware or software domain, depending on the required performance. The use of a remote controller, connected with the SDR devices through an ad hoc network, allows to switch between the set of services that can be implemented, as shown in figure C1.1 with a simplified representation. Moreover, the ad hoc network for the SDR devices and controller connection allows to place the SDR devices in a very large area (i.e., an entire city), giving the possibility to monitor and support the mobile communication system through a certain number of SDR devices and applying different policies depending on the necessity of specific sub-areas.

A service classification can be defined in terms of standard and critical scenarios, as in figure C1.1. The standard scenario collects all the possible situations where a mobile communication system can operate without criticality; in this case, the proposed system aims to support the mobile network through monitoring services for an efficient use of the resources. Power emission analysis can be useful to monitor the power radiated in a certain area, eventually supported by directional antennas to identify areas with higher power emissions; another service is spectrum analysis,

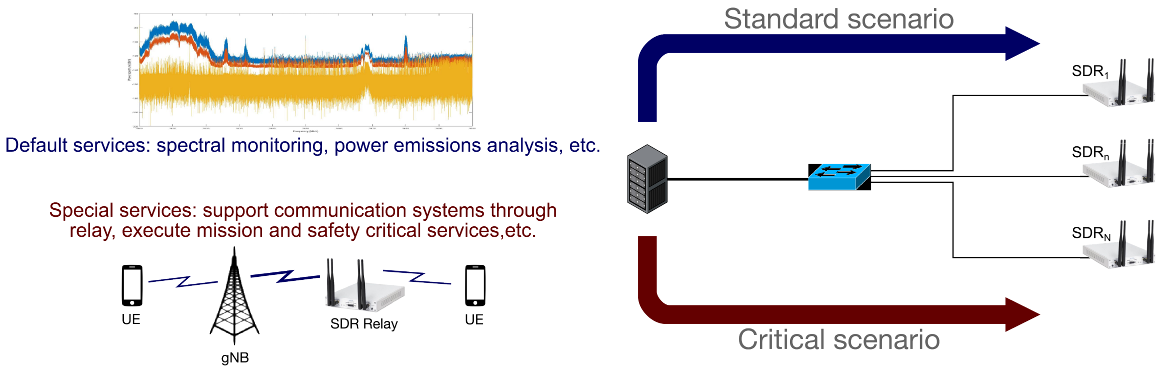

Figure C1.1: Simplified representation of the proposed distributed system.

which allows to monitor the status of a certain radio spectrum in terms of present signals and perform techniques for interference detection, localization using algorithms based on different parameters (received power, time of arrival, etc.), and recognition. Other interesting solutions integrate sensing techniques to monitor the surrounding environment for information acquisition like activity detection, movement recognition and analysis, in particular in contexts of 5G massive MIMO for energy-saving purposes. Sensing services will have a key role in future mobile communication systems, in particular for integrated sensing and communication purposes.

Referring to critical scenarios, this category represents exceptional situations where the network operability cannot be guaranteed for final users, like in the presence of critical disasters or unusual events. In this circumstance, the aim is to employ the proposed SDR network to support the mobile communication system. Repeater service is the first task the proposed system needs to execute, in particular the low-level relay method like amplify-and-forward or high-level methods like compress-and-forward or decode-and-forward depending on the performance required, avoiding situations in which the users cannot connect to the mobile network. Moreover, through the proposed system is possible to replace Radio Access Network (RAN) elements, i.e. gNBs or Remote Radio Units (RUs) in general, in case of outages or service interruptions. Other services that could support the mobile networks in critical scenarios can integrate specific PHY or MAC functionalities for ad hoc tasks, for example, to support the propagation of warnings in case of disasters like earthquakes. Besides, the remote control of the SDR devices enables their use for more services at the same time in different sub-areas, even for a hybrid scenario where some SDR devices execute a critical service in a certain zone while others continue to operate in a standard scenario.

C1.3 Prototype and testing

During the writing process of this paper, a prototype for the proposed system is under advancement. The focus is on the development of one default service that the proposed system can execute in a standard scenario; for this reason, the choice has fallen to the spectrum monitoring and interference detection and localization services. To validate it, a test has been conducted using a static interfering source in a controlled scenario.

C1.3.1 Prototype analysis

In the actual context of mobile communication NFV and software-oriented approach, the idea is to virtualize the proposed system. Therefore, the system controller has been developed through a VM that can be executed on different devices like computers or servers. The system, programmed through LabVIEW software, is composed of three identical high-performance SDR Universal Software Radio Peripheral (URSP) by National Instruments (NI), the NI USRP 2954R, equipped with a user-programmable FPGA, the Xilinx Kintex-7. Other noteworthy features are 2x2 MIMO device with four I/O interfaces (two Tx/Rx and two only-Rx), 10MHZ to 6GHz frequency range, up to 200MSps sample rate (maximum 100MSps for one channel) with 160MHz of maximum instantaneous bandwidth, 16 bits DAC and 14 bits ADC.

In this first stage, the system management and the service processing are relegated to the software domain; the system controller sets all the parameters needed by the SDR devices (e.g. sample rates, carrier frequencies, etc.) and the start command. Then, the SDRs are responsible for the signals acquisition and transfer to the controller, where the acquired samples will be processed for spectrum monitoring, interference detection and localization services. The hardware-oriented development and the offloading of some functionalities in the FPGA are left as part of further advancement, in particular for low-latency services; in this sense, some tests have been conducted in [81] to evaluate the minimum delay introduced by the NI USRP 2954R, whose range is between $0.5\mu s$ and $1.5\mu s$. A limitation of this prototype is the SDR firmware and its FPGA processing update; due to technological limitations, up to now is possible to update the device firmware only through a proprietary cable in loco.

Once the system is active, the three NI USRP 2954R acquire the signals in the spectrum under analysis and the samples are encapsulated and transferred to the system controller. In this first stage, the controller, i.e. a VM executed into a PC, is directly connected with each SDR device through 10Gbps fiber connection, allowing a maximum sample rate of 200MSps for each device; in future development, where the entire system will rely on a dedicated network, a trade-off must be considered between the controller link capacity and the maximum sample rate of each SDR device. The controller works under the assumption of RF synchronization between the three devices; considering that the level of synchronization depends on requirements needed for the specific service, in this prototype this assumption is still valid. The first analysis executed by the controller is spectrum monitoring, where the Power Spectrum (PS) is processed for every sample frame acquired by each SDR device; the maximum, average, and minimum PS are computed for each SDR device with multiple acquisitions. This first stage enables the analysis of the spectrum status to identify the signals that are always present through the minimum PS; the maximum PS allows the identification of all the frequency bands, even the sporadic ones, that are present in the maximum PS but not in the minimum. Then, the average PS can be an indication of how much a signal is present in the acquired frames: if is closer to the minimum PS it can be a sporadic signal, while if is closer to the maximum the occurrences are more frequent, as long as its amplitude has low variability.

Successively, the detection algorithm is applied to identify the interfering signals in the selected spectrum, based on the z-score. In general, for a data set x, its z-score is computed as:

$$z = \frac{x - \mu}{\sigma} \tag{C1.1}$$

where μ is the data set mean value and σ its standard deviation. The z-score standardizes the data set distribution making it with zero mean and standard deviation equal to 1. Taking advantage of equation C1.1, the prototype detection algorithm evaluates the differences between the actual PS with the average one so that every new signal will be detected through the comparison of its z-score

$$z^* = \frac{|PS - PS_{avg}| - \mu}{\sigma} \tag{C1.2}$$

with a threshold λ [92]. Then, the threshold is used as a comparison enabling two possible situations:

$$\begin{cases} H_0: & |z^*| < \lambda \\ H_1: & |z^*| \geq \lambda \end{cases} \tag{C1.3}$$

If the absolute value of the z-score is equal or greater than λ (i.e., case H_1), it corresponds to a point distant at least λ standard deviations from the mean value, and a signal has been detected in that frequency; otherwise there is no detection (H_0). A trade-off is required to reduce the false alarm rate; it can be done by choosing a higher λ, with a drawback of a higher miss rate in the detection. In this step, the focus is on narrowband signals, since the detection algorithm based on the z-score cannot guarantee the detection of wideband signals, since a wideband signal will affect the PS mean reducing its effect in the z-score. The detection of wideband signals will be taken into account in further development.

The detected signals of each SDR device are compared so that only the merged detection is taken into account, focusing only on those signals that are detected by all the devices at the same time. Through this operation, is possible to apply a technique to localize a static signal source. For this prototype has been considered a range-based localization algorithm to estimate the distances between the source and the receivers; in general, localization is performed in two steps: the distance calculation and the position solution. Regarding the first step, the distance calculation is performed using a model based on the Friis formula and adjusted experimentally; the following simplified formula is used to explain the relationship between distance and PS:

$$PS(d) = PS_0 - \beta \log_{10}(d) \tag{C1.4}$$

where $PS(d)$ is the detected PS at distance d in dBm, PS_0 is the PS at a distance of one meter, β is the path loss parameter. PS_0 and β are determined empirically, and they strongly depend on the environment and the channel. The localization is performed through a multilateration technique, which is based on a system of equations where the solution corresponds to the source coordinate (x_s, y_s, z_s) [93], as shown in figure C1.2. After the distance estimation for each SDR receiver through

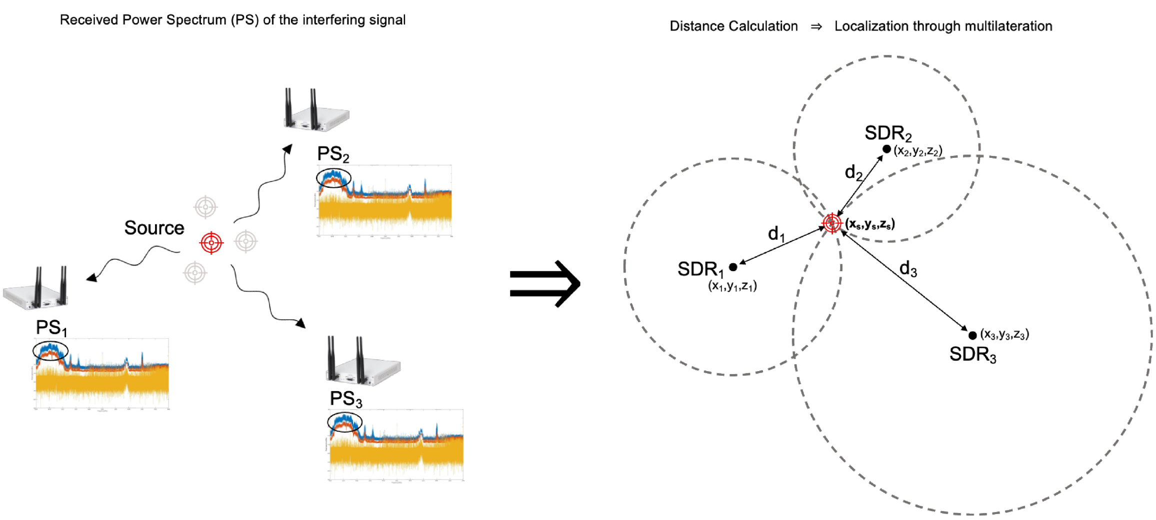

Figure C1.2: Default service representation: from spectral analysis with interference detection to position solution through multilateration.

the beforehand described model based on the detected PS, the localization is fulfilled by solving a non-linear equations system:

$$(x - x_n)^2 + (y - y_n)^2 + (z - z_n)^2 = d_n^2 \tag{C1.5}$$

for $n = 1, 2, 3$ where (x_n, y_n, z_n) are the coordinates of $n - th$ SDR device and d_n is its distance from the source evaluated through the PS with equation (C1.4). Manipulating (C1.5), the result is

$$\begin{aligned}&(x^2 + y^2 + z^2) - (2xx_n + 2yy_n + 2zz_n)\\&= d_n^2 - (x_n^2 + y_n^2 + z_n^2)\end{aligned} \tag{C1.6}$$

The expression C1.6 identifies the $n - th$ term of an equations system represented in the matrix form $A\mathbf{s} = \mathbf{b}$, where A is the coefficient matrix, $\mathbf{b}$ is a constant vector, and $\mathbf{s}$ is the solution vector with the coordinates (x_s, y_s, z_s) [94]. It must be taken into account that the values of A and $\mathbf{b}$ are provided by the SDR devices, with the estimated distance d_n and their coordinates (x_n, y_n, z_n).

C1.3.2 Testing operation

Due to the beginning stage of this work, the purpose of this paper is to give the reader a basic presentation of the prototype alongside with the proposal of the distributed system, validating the default service that is able to execute rather than describing the performance of each detection and localization algorithms or trying to improve the outcome. Once the prototype is up, is possible to select a certain spectrum where execute the default monitoring application. For this testing operation, the 2.4GHz ISM radio band has been selected with 100MSps sample rate and 100MHz bandwidth. Besides the effectiveness of the spectrum monitoring through the maximum, average and minimum PS, a static interfering source has been used to test the validity of the prototype. A frequency modulated signal, also known as chirp, has been used as interference source, with 10MHz bandwidth and 100μs duration, transmitted at 2.45GHz carrier frequency; the choice of the chirp results from the reduced fluctuations in the power spectrum compared to other narrowband signals.

To test the effectiveness of the prototype, the three SDR devices have been placed in the scenario represented in figure C1.3 (in red), while the interfering source has been placed in five different positions (in blue) to test the detection and localization. This scenario has been considered with the assumption of static environment, without considering the fluctuations due to the channel; future development will include a more accurate analysis taking into account the effect of the channel. Moreover, due

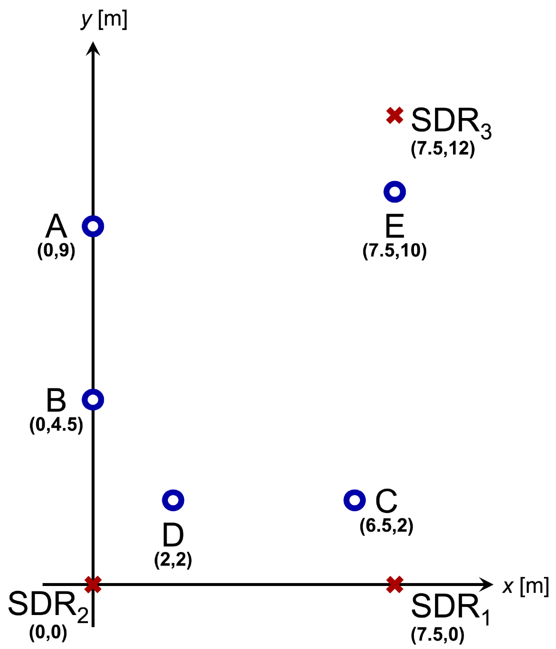

Figure C1.3: Scenario adopted for the prototype test with the three SDR devices specified with the red cross, while the five positions of the interfering source specified with the blue circle.

to the limited number of SDR devices, the localization has been considered only on the xy-plane with $z = 0$. Once the system is up, the interfering source can be noticed in the PS of both devices with different power levels, as reported in figure C1.4a. Besides the interfering source, other signals can be appreciated, e.g. Wi-Fi and other standards. Then, the source has been detected through the z-score computation like in equation C1.2 with and without the source, and then compared with a threshold. Referring to the trade-off introduced before, a threshold equal to 3 has been considered acceptable for this test. Finally, the comparison between the detection of each SDR device enables the interfering source detection, as in figure C1.4b where the static source can be clearly observed. It must be noticed that an interfering source could not be detected by every SDR device in a large environment scenario; in this case, a different detection policy is required for the entire system, and this will be part of future enhancement together with the implementation of wideband interference detection.

After the detection, the source position is computed through the aforementioned algorithm. Before the real time execution of the localization algorithm, for the localization model adopted a measurement campaign is required to estimate the general behavior of the channel that will affect the localization error. Moreover, the early

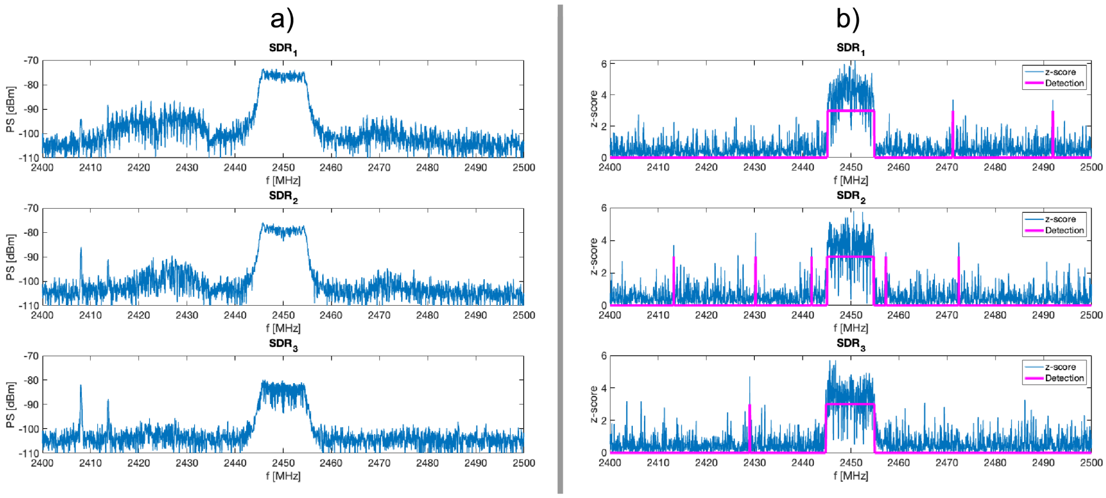

Figure C1.4: Power Spectrum frame acquired in the range 2.4-2.5GHz from all three SDR devices with the chirp interfering source in position C (**a**) and the corresponding z-score absolute value of the difference between the PS with and without the source, with the detection overlapped for each SDR device (**b**).

stage of this activity and the testing purpose of the overall system limit to having a priori knowledge of the interfering source in the measurement campaign, with the constraint of the term PS_0 in equation C1.4. A different approach based on the ratio between the distances estimated by each SDR device allows the removal of the term PS_0 with the localization of any type of interfering signal, but this operation is left as future development. After the measurement campaign, the localization has been tested by placing the interfering source in the five positions of figure C1.3 using the empirical parameters $PS_0 = -64.96dBm$ and $\beta = 18.96dB$. The source positions estimated by the prototype are reported in table C1.1. Due to the complexity of the

Table C1.1: Source localization results.

Positions	**Reference [m]**	**Localized [m]**	**Error [m]**
A	$(0, 9)$	$(3.16, 6.28)$	$(+3.16, -2.72)$
B	$(0, 4.5)$	$(2.94, 6.42)$	$(+2.94, +1, 92)$
C	$(6.5, 2)$	$(4.19, 5.95)$	$(-2.31, +3.95)$
D	$(2, 2)$	$(3.66, 5.92)$	$(+1.66, +3.92)$
E	$(7.5, 12)$	$(4.87, 6.28)$	$(-2.63, -3.72)$

environment selected for the test, the empirical parameters may bring to errors in the model that increase the localization error. This can be noticed in the final column of table C1.1, where the average absolute error is $2.54m$ for the x variable and $3.25m$ for the y. It must be highlighted that these are well-known issues related to the range-based localization algorithms, which is not the main purpose of this activity but simply a part of it, and a more accurate measurement campaign is required to reduce them. Therefore, these will be part of future testing operations, even through the use of more accurate localization algorithms depending on other parameters than PS, like time of arrival, angle of arrival, and so on.

C1.4 Conclusions

Considering the novelty introduced by modern communication systems like 5G and 6G, and the flexibility offered to implement a variety of heterogeneous services, this work has presented a novel distributed system capable to support mobile communication networks taking advantage of SDR technology. The proposed system can execute different services, starting from default applications like power emissions analysis and spectrum monitoring, to critical services in uncommon scenarios where all the fundamental operation cannot be guaranteed. In this context, a first prototype has been described, capable to execute a default service based on spectrum monitoring, interference detection and localization. The prototype, based on three NI USRP 2954R SDR devices, has been tested through an interfering source in a limited scenario to evaluate the validity of the system.

The further steps of this activity will look in several directions. The main focus will include the implementation of new services, starting from 5G relay in critical scenarios, through the offloading of some functionalities in the FPGA. At the same time, the aim will be the enhancement of the spectrum monitoring service, integrating techniques for signal recognition such as automatic modulation classification, and the refinement of the adopted interference detection and localization algorithms. These future developments will be supported by tests in a real environment through the displacement of the SDR devices in a large area like the city of L'Aquila, where the aforementioned USRP devices are planned to be distributed. This will include the connection of controller and SDR devices by means of ad hoc networks like MAN; it will be an opportunity to integrate sensing techniques to monitor the entire network together with the analysis of the radio environment.

Conference C2

SDR-Based Ground Target for Identification and Tracking through Satellite SAR Systems

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Abstract

This paper presents a new approach to integrate communication process in satellite synthetic aperture radar (SAR), without the necessity of updates in systems already on-air, through a software defined radio (SDR) based ground target. Nowadays, in the actual context of fast technology evolution, wireless communication integration is becoming popular in commercial and research domains, and from this point of view, SAR is the perfect candidate because of its appeal that increases constantly.

Through the flexibility and versatility of SDR technology, a novel ground target is proposed in order to emulate the ground backscattering of SAR waveforms with the implementation of a coding technique that allows the integration of a transparent wireless communication link in SAR devices already on-air, enabling the classic SAR image process without interferences but also the simultaneous ground target identification and tracking. In this paper, the features and the design strategies of the SDR-based ground target are described followed by the presentation of the prototype.

C2.1 Introduction

Synthetic aperture radar (SAR) is one of the most popular radar techniques used in remote sensing for many applications, included localization and earth surface information acquisition through 2D or 3D images; as the name suggests, it takes advantage of a large synthetic antenna aperture to obtain high-resolution images of the earth surface. Typically, SAR is applied in different airborne or spaceborne civilian fields, e.g. forestry and deforestation, oceanography, meteorology, geology analysis of natural disaster effects, agriculture, or military applications as surveillance, reconnaissance and enemy detection and classification. SAR technology is particularly used because provides daylight and weather independent images but also higher spatial resolution compared to conventional radar systems [51].

Nowadays satellite services are growing exponentially; besides imagery and SAR satellite applications for weather and earth monitoring tasks in civilian and military applications, as for high-resolution SAR like COSMO-SkyMed system but also open satellites as Sentinel group of ESA Copernicus project, from a smart cities perspective new services supported by satellites are becoming popular, as imagery satellites for street lighting monitoring and control. Moreover, commercial satellites are planned to be launched to support communication services as 5G and IoT but also for SAR services, as Starlink satellite constellation.

Today the use of SAR satellite systems only for classic functionalities may be reductive; actually, the technology evolution is strongly oriented to communication services, and this is valid even for SAR but also for radar in general, where this dual approach has well-known fundamentals. In recent years, in radar and SAR domain several research activities have been carried out to improve some critical aspects, i.e. image resolution, flexibility, complexity. Different solutions have been proposed, like bistatic systems, multiple-input-multiple-output SAR (MIMO-SAR), digital beamforming SAR (DB-SAR), spotlight and scanSAR [51].

MIMO-SAR, DB-SAR and bistatic SAR solutions have been introduced to enhance, among other things, the range resolution; through that, it is possible to improve image resolution for localization purposes. Bistatic SAR system was proposed firstly in the middle 1980s, whose aim was to improve SAR performance with the spatial separation of transmitter and receiver. This strategy led to significant improvement in performance and system design flexibility, with the drawback of increased complexity, as described in [95] where the bistatic spaceborne-airborne TerraSAR-X/F-SAR system is analyzed.

MIMO-SAR is a different kind of SAR architecture that has been proposed in order to increase spatial coverage and geometric resolution; in fact, spatial diversity through multiple transmitters and receivers brings the opportunity to increase image resolution concurrently with range extension [96]. MIMO-SAR architecture is often correlated with DB-SAR, because of several advantages like high efficiency in image acquisition combined with lower power consumption and distributed irradiated power; DB-SAR is a technique where is possible to manage the received beam by controlling bandwidth and sidelobes, increasing SAR performance, efficiency and flexibility [97] [98].

Basically, SAR can be considered as a radar application used differently. Both SAR and radar have in common the backscattering, and its importance is based on the concept that every wave is backscattered in a certain manner which depends on the surface and its reflectivity: a rough surface backscatters in every direction while a smooth one acts as a mirror; therefore, rough surface has lower reflectivity that results in wrong measurement for radar application and vice versa. Nowadays backscattering is constantly linked to wireless communications and sensor-based systems, in particular IoT, because allows passive device usage related to low-power techniques, as in ambient backscattering [99] and radio frequency identification (RFID) applications [100].

Different from SAR, radar is a service that is studied in relationship with communication; moreover, radar systems are more frequently developed with software defined radio (SDR) platforms. Within this background, this paper presents a new approach to integrate a communication link in SAR systems without requiring any modifications in satellite systems already on air. Through an SDR-based ground target, the aim is to integrate a communication link that is transparent for SAR imaging process and does not require any modifications in hardware or software equipment already on-air, which is a well-known difficult operation. With the SDR versatility, the purpose is the backscattering emulation in order to increase the degrees of freedom, evolve and test this system in a more efficient way. To do this, the SDR-based ground target performs coding operation in received SAR signals, enabling localization and ground target identification with coding, but it is also capable to act as a corner reflector without coding process because it can simply operate as a repeater with an additive transmission gain.

C2.2 Radar & Communication

Nowadays the utilization of shared resources is challenging the research community; in particular, bandwidth is the real test because of increasing spectrum demand due to technology evolution of wireless communications, like IoT and 5G. In this sense, also radar technology requires higher bandwidth resources for improving, among other things, range resolution for target detection or imaging process in remote sensing applications. In this background, the combination of wireless communication and radar technology has critical importance, most of all for the possibility to use the same resource for both, but also because one could contribute to research improvement for the other and vice versa, as presented in literature over the years.

One of the first publication on joint wireless communication and radar application was carried out by NASA Space Shuttle program at the end of 1970s [30], while in recent years USA Defence Advanced Research Projects Agency (DARPA) starts the Shared Spectrum Access for Radar and Communications (SSPARC) program [31] [45]; these activities could be classified in communication and radar spectrum sharing (CRSS). In CRSS applications, the aim is the RF convergence of these two services in order to coexist in the same shared resource; radar and communication are organized in primary and secondary service according to three categories [101]:

1) radar is the primary service with bandwidth allocation, while communication is the secondary service without any degradation in radar performance, making the communication a cognitive service like in cognitive radio applications;

2) the combination of radar and communication services with techniques to mitigate the interferences for radar service;

3) the cooperation of radar and communication with techniques of interference mitigation that act for both services.

In literature, CRSS is usually considered as a general way to gather all the combined radar-communication applications where, except for system development, the distinction between them is preserved through the sharing of the same resources.

Theoretically similar but with significant differences, dual function radar communication (DFRC) can be considered as a sub-group of CRSS applications which presents a deeper level of combination; this means that DFRC application is based, but not only limited, to the simple resource sharing, extending the coexistence toward some common features to operate simultaneously without interference. An example of DFRC application is presented in [102] with a strategy to implement both radar and communication services without interferences using a hardware approach based on frequency diverse array (FDA); this allows the development of a system capable of sidelobes management to achieve the orthogonality between far-field patterns excited by radar and communication waveforms. A different solution is proposed in [103], where a new DFRC approach based on multi-carrier frequency modulated continuous waveform (FMCW) MIMO system can obtain similar radar performance in addition to phase modulation process for communication integration.

A completely different strategy is what is typically called joint radar and communication (JRC). Generally, in JRC (sometimes indicated as CoRadar, which stands for Communication Radar) converge all the applications that combine radar and communication oppositely with respect to CRSS: the main purpose is to realize only one service that could operate both radar and communication activities at the same time; this means that JRC development is based on the combination of some features of radar and communication, without any distinction between primary and secondary service.

In the literature many research activities have been carried out in the JRC domain; in [45] the term JRC is used to indicate a more general view of coexistence between radar and communication, with the differentiation between uncoordinated coexistence (in physical isolation), cooperation (at the same level), coordinated co-design (hence a deep level of cooperation which includes some features like waveform, etc.) and coordinated collaboration (hence a complete joint operation); it should be noted that uncoordinated coexistence and cooperation can converge to CRSS definition.

In [27], the JRC coexistence is exhaustively explained with a distinction between four different kinds of joint sensing radar and communication approaches in multi-user topology: multi-user detection radar, monostatic broadcast channel, bistatic broadcast channel, in-band full-duplex; besides the different way to develop joint radar and communication transmitters and receivers, in this case is very interesting the use of shared waveforms for both services.

As explained in [27], these kind of strategies are also extended to remote sensing applications based on SAR systems, as in [66] where an airborne MIMO SAR system is proposed and the purpose is to model SAR waveforms in order to implement orthogonal frequency-division multiplexing (OFDM) and space-time coding (STC) scheme for the communication side. In [56] there is a proposed uplink communication channel integrated into SAR system in a planar simulation environment; in this case, the communication link is implemented with an antenna backscattering approach based on impedance matching network used to spreading, similarly to UWB RFID systems [104] [105].

Since SAR is a radar application, as already introduced the purpose is to implement communication techniques in SAR systems in the same way as for radar. With respect to radar, in SAR several constraints that depend on the specific design strategies must be taken into account. In this sense, all those techniques related to the observation time window become extremely important. Differently in aerial or UAV, in satellite SAR there is the strong influence of its timings and settings, such as pulse repetition interval (PRI) and pulse repetition frequency (PRF) that depend on satellite-earth distance but also on the pulse used, which is a frequency modulated waveform called chirp where the frequency sweeps from f_1 to f_2; hence, any modification in chirp features as duration or bandwidth can afflict the PRI but in general the SAR resolution, while the chirp itself represents a degree of freedom: SAR is independent of sweep type (up for $f_1 < f_2$, down for $f_1 > f_2$) or sweep type (linear, exponential, etc.).

In this context, a good choice in SAR design can regard the operation mode: ScanSAR and spotlight are two different kinds of operation modes compared to stripmap, which is the basic one; in stripmap, the swath (i.e. ground range extension of SAR coverage perpendicular to azimuth direction) is continuous due to fixed antenna, while in scanSAR the antenna is guided to different elevation angles (i.e. angle between nadir and radar-target line) which result in multiple sub-swaths that increase the overall swath range, with the drawback of degraded azimuth resolution because of reduced observation time in every sub-swath compared to stripmap. Instead, spotlight mode can illuminate a ground region for a longer time interval with a consequently better resolution; nevertheless, this mode leads to discontinuous swath [51]. Those different behaviors lead to different tradeoffs: increase the observation time window (which can be important in a communication approach) could follow in discontinuous observation and high range resolution, and vice versa.

C2.3 Framework analysis

As already introduced, the idea of this proposal is to combine a communication link, for identification and localization purposes, in SAR imaging systems using an SDR-

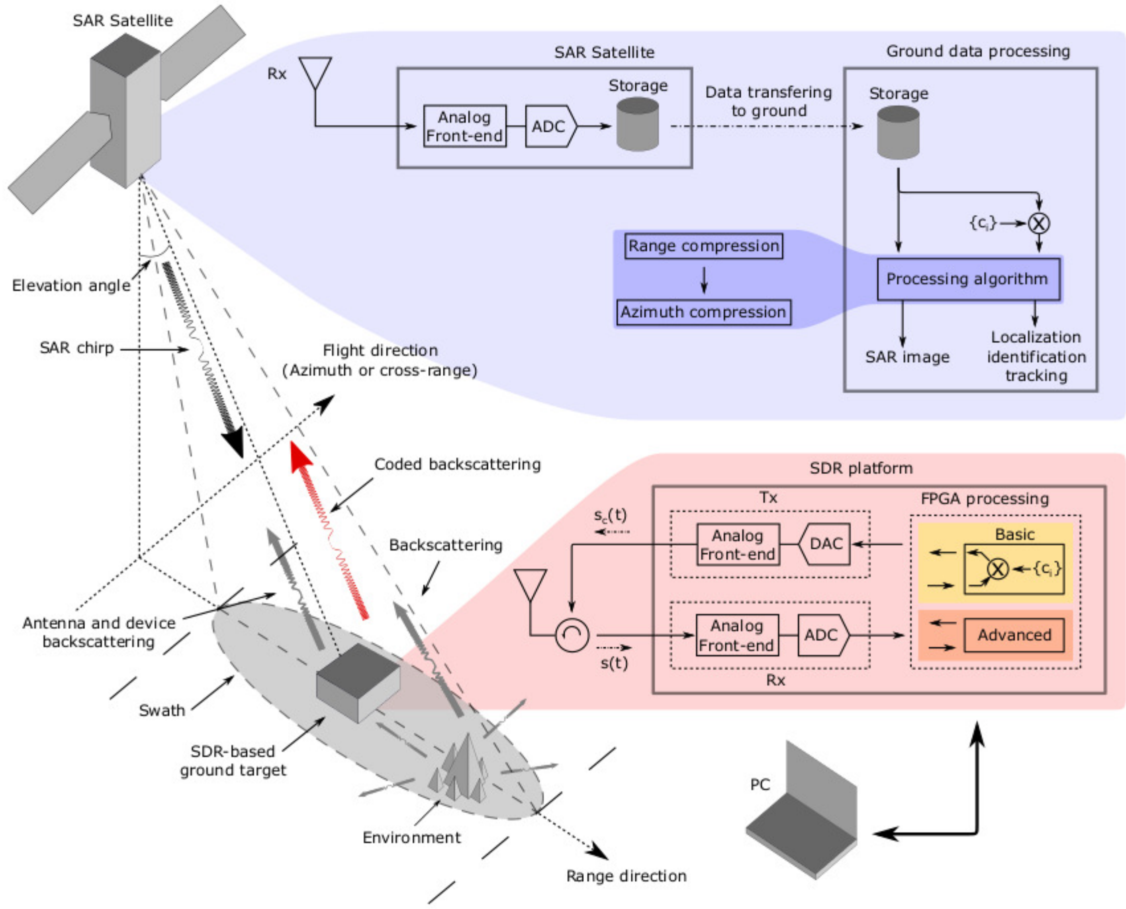

Figure C2.1: The proposed scheme of satellite SAR system behavior, with the proposed ground target and the integration of communication link.

based ground target to emulate the backscattering process in combination with coding technique, as illustrated in Fig. C2.1. In this framework, the purpose is to go beyond the antenna backscattering approach with the support of SDR platforms, which give additional possibilities and capacities.

SDR versatility allows to operate in different ways, but in real environment is often necessary a license released by a government agency; for this reason, SDR is the optimal choice to emulate backscattering in a testing environment without any license, but also to implement a more complex system in case of legal emission of signals. Moreover, SDR allows the proposed ground target to act as a simple corner reflector using the platform as a repeater.

To realize this proposal in a real SAR environment, two concepts must be taken into account: integration and transparency. Integration defines the wireless communication link implementation in satellite SAR system, highlighting the fact that this operation must be realized without any modification in every on-air equipment; hence, this process can be done in every satellite SAR system already in use or under development. Transparency implicates that the communication link must not interfere with sensing process, which means that the final image must not have variations compared to the resulting image of classic SAR.

The real environment also forces to operate with time constraints that are defined by SAR system, hence in this integration the communication window is decreased because of reduced time in which the ground target is illuminated by the SAR, and this behavior limits the amount of information that can be transmitted; so the communication can be transparently integrated into classic imaging process through identification with coding procedure in an emulated backscattering scenario. In this way, simultaneously with the classic imaging process, communication is achieved with the identification process through coding techniques while localization is implemented similarly to the imaging process. Furthermore, if the observation time increases, then a more complex communication link can be realized.

Synchronization between target and satellite is often an issue in SAR system design; in general, two different synchronization approaches can be considered: all the system information is extracted from SAR waveform with a matched filter in order to synchronize with it, otherwise an external signal is used. For this proposal, the synchronization is assumed to be implemented using an external signal with a frequency bandwidth that can be different with respect to SAR, as ultra-high frequency (UHF) range; since typical PRF values are around 1000 Hz while chirp duration is in the order of tens of μs, synchronization can be considered a soft constraint, as typically happens in backscattering systems.

To develop the proposed ground target, SDR platforms have been selected due to the flexibility in hardware-software design that they offer and versatility to use these devices in different application domains; this technology is constantly growing because of its capacity to update tasks in a very simple way compared to classic systems. The choice of SDR platform for the ground target extends the set of possible solutions to deal with waveform receiver and transmitter; for this purpose, considering the assumption of synchronization, three different solutions have been identified.

One solution is based on the simple generation of a coded waveform, that is transmitted after the detection on the receiver side of the ground target, which requires a matched filter design; since SDR platforms are typically equipped with field-programmable gate array (FPGA), which is a particular circuit configurable with hardware description language (HDL), waveform generator can be developed in the

FPGA to achieve optimal performance, given the well-known higher performance of hardware with respect to software.

Another solution is based on digital radio frequency memory (DRFM), a technique proposed in the early 1990s which is under analysis still today, especially for military purposes. In DRFM techniques, radio and microwave signals are stored through high sampling rate and digital memory, in order to recreate the same signals for false target response generation in electronic countermeasures (ECM) applications with the drawback of additional delay [106].

Neglecting the hypothesis of a priori ground target knowledge of SAR features, the DRFM approach is a better solution than the previous one, due to the capacity to store SAR signal and transmit back delayed replicas which are SAR independent. For this solution, the drawback is the necessity of storage memory, which leads to a tradeoff between cost, capacity and performance (since unwanted delay is a consequence of slow memory). Moreover, in presence of high bandwidth constraints, the huge amount of data to storage and transmit back could generate a bottleneck; a possible solution is an ad-hoc system based on FPGA supported by RAM, but is out of interest for this paper.

The last solution is based on a digital backscattering-like approach; as previously introduced, backscattering-oriented communication is obtaining increasing interest from the research community that explains the backscattering emulation choice made in this paper. Compared to the other solutions, this approach does not need a storage memory, neither the FPGA-based matched filter (it could be needed for a more complex backscattering-like approach, but this is not the case); besides, this solution guarantees coherence between received and transmitted signals.

While the analog backscattering is achieved with the control of antenna impedance that leads to changes in its reflection coefficient, the backscattering emulation is performed through SDR platform with a connection between Rx, processing block and Tx; this scheme allows to operate in different ways, from the simplest strategy with the product of every sample with the code up to more complex strategies like techniques based on OFDM, amplitude, phase, up and down sweep, frequency and doppler coding. Compared to analog backscattering, there are two main drawbacks: the necessity of additional RF components (two antennas or one antenna and one circulator) and the additional delay, which will be analyzed in the next section of this paper.

C2.3.1 Transparency

With the synchronization assumption, which implies the knowledge of when the ground target is illuminated but also when SAR is listening, in order to integrate the identification process is necessary to map the identification bit sequence in a specific code, as introduced before, in a way similar to the direct sequence spread spectrum (DSSS) modulation.

To make identification a transparent process, the same code must be used to extract the information from SAR data without degrading the resulting image; with the assumption of no modification in on-air SAR systems, communication extraction can be realized only in SAR ground data processing system.

Assuming that the satellite does not perform any process but only stores the digitalized data before sending them to earth for processing, to decode the communication is possible to apply the code in a parallel way with respect to the classic SAR in order to extract identification information. Since SAR system coherently adds the received echoes of every observation points, in order to make the identification a transparent process, this contribution must be zero; hence, considering the coding applied chirp by chirp, this condition is valid only if the code is balanced with zero mean inside the time window in which the SAR is listening for echoes:

$$\sum_{i=1}^{N} c_i = 0 \tag{C2.1}$$

where $c_i \in \{-1, +1\}$ is the code of length N. Because the effect of coding reflects in signal as a phase shift of π, then in matched filter coding contribution is low and negligible. Since SAR can be assumed to operate at wide bandwidth, the use of balanced zero-mean codes is not casual, because these codes are applied in a similar way to ultra-wideband (UWB) RFID applications based on antenna backscattering, in particular in decoding phase [104] [105].

C2.3.2 Localization and identification

Localization is the intrinsic process of this proposal; under the assumption of communication link integration without modification in SAR systems already on-air, is possible to distinguish different cases, determined by the type of approach and by the number of ground target that implements the communication channel. The single-target scenario is the easiest case because allows the use of only one code, as the simple alternation of $+1$ and -1; in this case the localization is implemented with

Table C2.1: List of different services that can be introduced with the proposed ground target.

Services	Requirements	Constraints
Localization	$\sum_{i=1}^{N} c_i^{tag} = 0$	Multi-target distance > SAR resolution
Group identification	Set of N_{group} codes to identify any ground target that belongs to a specific group	Limits in code selection
Tag identification	Data packet-based structure for identification with known preamble, payload and error detection method	Higher SNR

the identification of the proposed ground target through the decoding process with a resolution that is determined by the satellite SAR system.

Multi-target context can be seen as a generalization of the single-target scenario, because of the relationship between the target distance and SAR resolution: if the targets have a distance between them greater than SAR resolution, then the multi-target case can be limited to a situation of multiple single-target with the same code; otherwise, the identification process can be limited to group identification, in order to detect how many targets belong to a specific group; in this case, the transparency is maintained using orthogonal, zero mean and balanced group code.

A more sophisticated identification approach can be used in order to identify multiple targets at a distance lower than the range resolution, where each target communicates with a packet-based data structure; in this case, the transparency can be maintained also with orthogonal, zero mean and balanced group code, but the overall code must contain different components that increase the complexity and require higher SNR: a preamble code, which can be simple and known, the payload code that must be unique for each target, and a code for the error detection method. Both the approaches described are summarized in Tab. C2.1.

C2.3.3 Bidirectional link

If the assumption of inalterable on-air system is dropped, then it is possible to develop a bidirectional communication link, with the drawback of increased complexity in system design. In this case, the identification process is assumed to be RFID-like, with satellite SAR acting as a reader that is capable to send query commands to the target population simultaneously with the classic imaging process, while each target can answer to commands in an organized way. In this case, the main constraint remains the observation time window: any kind of communication can be implemented only inside the observation time window that is determined by the SAR system.

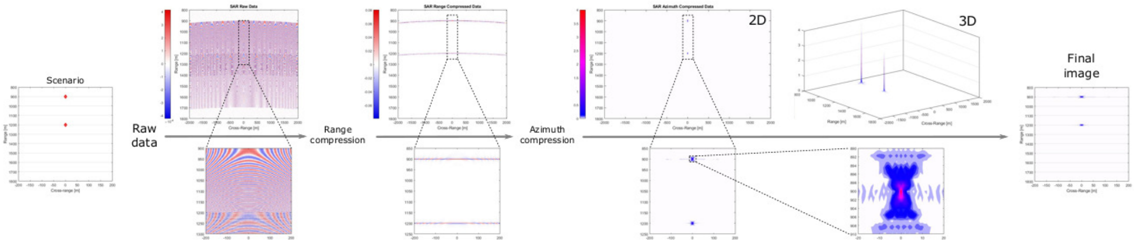

Figure C2.2: Range compression and azimuth compression algorithms to obtain the final image from acquired raw data.

C2.3.4 Tracking

Tracking operation can be considered as a natural consequence of localization and identification processes; in fact, independently of what kind of identification approach is implemented, tracking can be performed by the satellite consecutive paths over the same ground target. Moreover, tracking operation can be performed more efficiently if the satellite SAR constellation is dense: if the constellation increase in number then is possible to increase the number of paths over the target, reducing the time between two different SAR acquisitions and identifications.

C2.4 Design choices evaluation

All the design choices presented in this paper have been evaluated through MATLAB software. The design choices evaluation describes all the effects of this proposal in SAR systems, but also all the critical issues, and this is performed with the support of MATLAB Phased Array System Toolbox that allows the simulation of the standard SAR systems behavior: SAR satellite emits a chirp waveform that is backscattered by the environment and received by the SAR; the raw data are then processed in order to obtain the final image, as showed in Fig. C2.2, with the range compression algorithm and the range migration algorithm to perform azimuth compression. This simulated behavior does not represent a real satellite SAR system but is just a simplified stripmap model [107]. The scenario implemented in this operation is based on two targets that represent the environment alongside the proposed target, as illustrated in Fig. C2.3; in this simple scenario, two different images can be extracted: the final SAR image of the environment where can be distinguished two peaks, and the final image for the localization that results from decoding operation, with only one peak that corresponds to the proposed ground target.

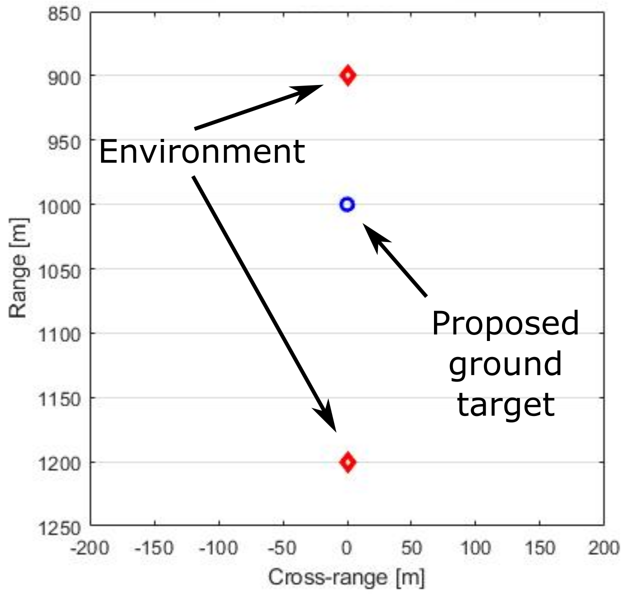

Figure C2.3: The scenario considered in this paper for the evaluation of the design choices, where two targets represent the environment in addition to the proposed ground target.

To evaluate the performance, a radar cross-section (RCS) equal to 1 has been selected for the environment and the ground target. In a real scenario, the RCS depends on the antenna for the ground target, while the environment depends on ground topology, and in both cases RCS influences the backscattering effect; with the proposed approach, this problem can be solved including transmission gain, if necessary. In this approach, a PRF of 1000Hz, so 1ms PRI, and a linear chirp of 3μs duration have been selected. Two different aspects have been investigated: the effect of coding and the transparency in SAR images, and the effects of different system delays in the proposed ground targets.

C2.4.1 Coding

Coding is performed with the assumption that the ground target transmits only one code in the time window; moreover, is assumed that each code bit corresponds to a single chirp. The transparency is maintained if and only if the chirps are modulated with balanced codes inside the observation time window. In this case, two different approaches can be considered: each information bit corresponds to a specific code, or one information bit corresponds to one code and the other one to the opposite code. In this case, the assumption of balanced code could not be sufficient for transparency

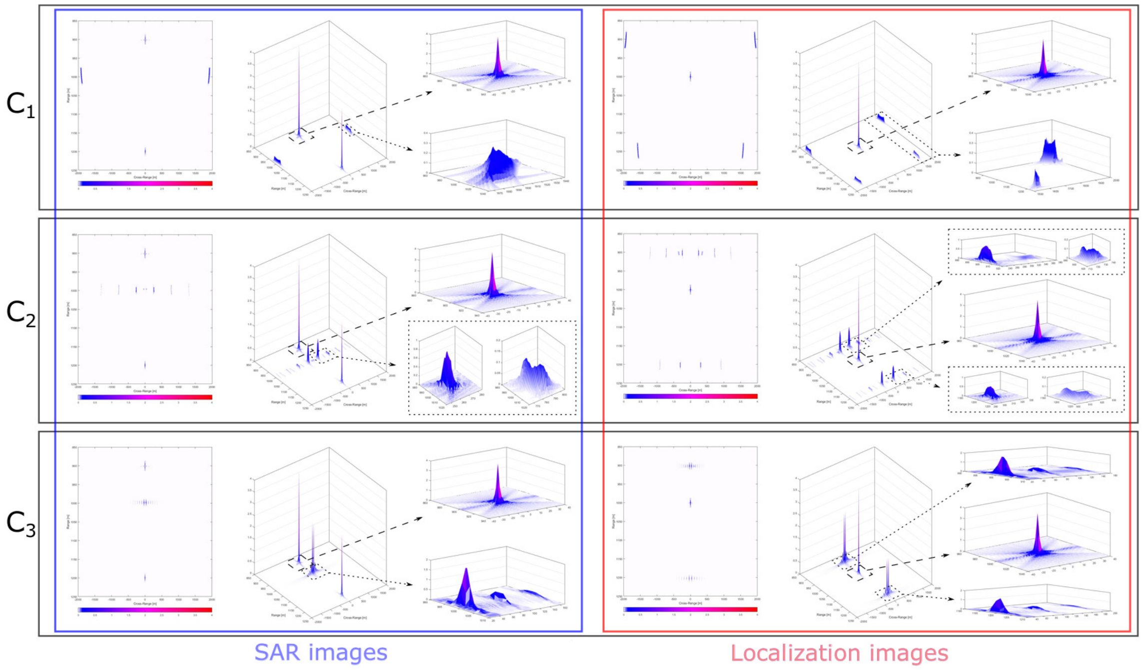

Figure C2.4: Effects of three different codes, $\mathbf{c_1} = [+\mathbf{1}, -\mathbf{1}, +\mathbf{1}, -\mathbf{1}, ...\,]$, $\mathbf{c_2} = [+\mathbf{1}$ (8 times) $, -\mathbf{1}$ (8 times) $, ...\,]$, $\mathbf{c_3} = [+\mathbf{1}$ (64 times) $, -\mathbf{1}$ (64 times) $, ...\,]$, applied by the proposed ground target in the scenario illustrated in Fig. C2.3; the resulting 2D and 3D SAR images are highlighted in blue, while the 2D and 3D ground target localization images are highlighted in red.

due to the possibility that the two information bits have not the same code aspect, which results in an unbalancing effect.

A critical issue that must be taken into account is the type of the code: the coding operation to a single chirp can be considered as a filtering operation that includes in the final images some unwanted replicas in cross-range direction that are limited in amplitude; as the code becomes slower in terms of commutations, the replicas of this windowing effect occur with higher amplitude and closer in cross-range direction, with a symmetry in the real position of environment targets and ground target, that lead to a fall of transparency assumption. This effect is illustrated in Fig. C2.4 where three codes have been considered: c_1 is the code with a commutation at every chirp, c_2 is the code with commutation every eight chirps (commutation eight times slower) while c_3 is the code with commutation every sixty-four chirps (commutation sixty-four times slower).

To solve this critical aspect, a different approach could be used: instead of classic balanced codes, the use of bipolar codes can be useful to prevent this effect. Actually, through the assumption of one code bit mapped into two chirps is possible to imple-

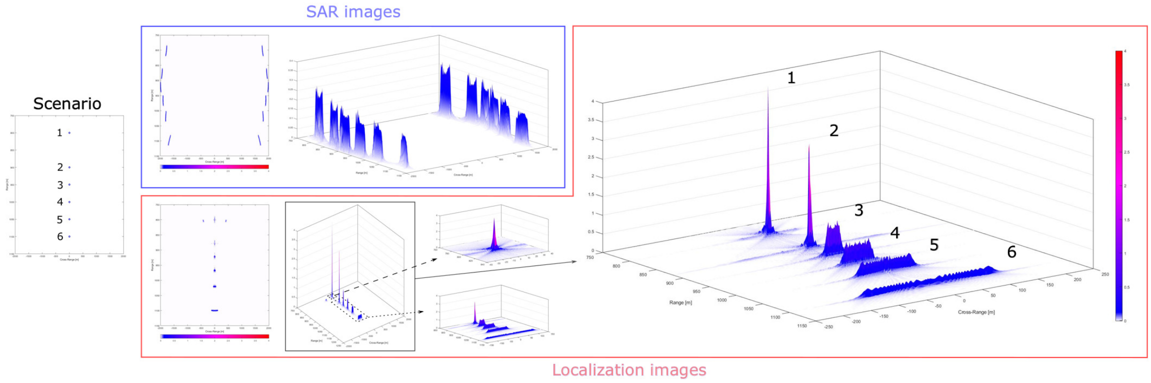

Figure C2.5: Effect of system delays in SAR image, highlighted in blue, and localization image, highlighted in red, for a specific scenario with six ground targets with no delay in target **1** up to **500** ns delay in target **6**.

ment codes as the alternate mark inversion code where the worst case is represented by the commutation of two informative bits, that corresponds to two consecutively equal code bit.

C2.4.2 Delay

Another aspect that must be taken into account to implement a controlled backscattering is the effect of system delay, especially in presence of digital systems as SDR platforms. In this case, without considering the analog front-end of the device, the minimum delay that must be considered is equal to the sum of ADC-DAC time, the time required to transfer digital data on FPGA and the time for any process that is performed inside the FPGA.

This effect has been implemented in MATLAB environment with a delay in echoes; to perform this, a different scenario has been considered with six proposed ground targets that implement the coding operation with code c_1 in six different conditions, respectively no delay for the first target, 10ns delay, 50ns, 100ns, 200ns and finally 500ns for the last target, as showed in Fig. C2.5. While in the imaging process the delay has low amplitude effects that can be easily neglected, with the assumption of transparency that is still valid, on the localization side all the critical issues emerge: the greater is the delay, the lower is the amplitude of the ground target combined with an increasing spreading effect in cross-range direction.

C2.5 Ground target prototyping

As previously introduced, the proposed ground target is based on SDR platform with transmitter and receiver interfaces connected to a single antenna towards a circulator used as a duplexer, which acts as a switch between the antenna and transmitter or receiver, isolating the direct path between them.

In order to operate with the wide bandwidth that SAR applications typically required, the SDR platform selected to prototype the ground target is the 2954 RIO developed by National Instruments, which is a platform that belongs to the universal software radio peripheral (USRP) family; moreover, RIO is the acronym of reconfigurable input-output, which indicates all those SDR platforms that are equipped with FPGA boards. Some of NI USRP 2954R features are four I/O interfaces (two Tx - Rx and two only Rx) for a MIMO 2x2 system, frequency range from 10MHz up to 6GHz, sample rate up to 200MSps with a maximum instantaneous bandwidth of 160MHz, 16bits DAC and 14bits ADC (digitally mapped into 16bits) and Xilinx Kintex-7 FPGA.

This device is programmable with LabVIEW, which is a development environment and system-design platform based on graphic language and virtual instrument (VI) concept. LabVIEW graphic programming is achieved through two interfaces, front panel with VI inputs and outputs and block diagram with VI core implementation. Moreover, LabVIEW can integrate other software and has available some additional modules, as the LabVIEW FPGA module that allows the design of FPGA functionalities and hardware description language (HDL) scripts as VHDL or Verilog.

Working with SDR platforms to operate with specific performance implicates different design methodologies that are strongly influenced by the development constraints. In fact, while soft constraints can be managed with both hardware or software-oriented design choice, hard requirements such as high instantaneous bandwidth are followed by high data rate processing for SDR platform that can be easily managed in a hardware-oriented design in order to achieve high system performance, while a software-oriented design can bring bottlenecks related to PC architecture but also PC-SDR connection. Hence several factors must be taken into account in the design strategy choices for SDR-based development.

Due to bandwidth constraints of SAR technology, this prototype has been designed with a hardware-oriented design, also because the performance and capacities of Kintex-7 FPGA are appropriated to this approach. In the writing step of this paper the prototype is under development with LabVIEW software, LabVIEW FPGA

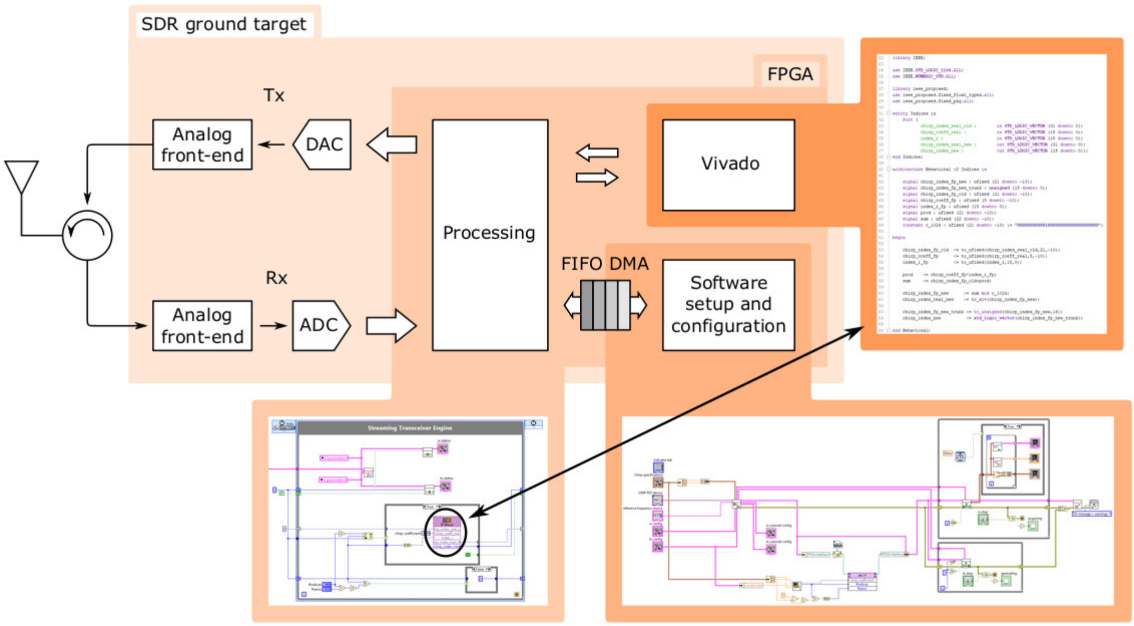

Figure C2.6: Low-level scheme of the proposed SDR-based ground target prototype.

for the design of FPGA operations and Vivado software to integrate external VHDL scripts in LabVIEW FPGA, as shown in Fig. C2.6.

While the backscattering emulation with coding is implemented in LabVIEW FPGA with Vivado support, data are transferred between FPGA and software domains in a bidirectional way through FIFO DMA; due to the hardware-oriented design strategy, the use of software is limited only to the steps of initial setup and configuration.

C2.6 Conclusions

In this paper, a transparent approach to integrate a communication link in satellite SAR systems through an SDR-based ground target has been proposed. In a world always more oriented on communication, its integration in other technologies is an attractive challenge; while the joint radar-communication approach has a solid basis in literature, the integration with SAR technology, because of its growing interest, is becoming a real test. In this sense, the SDR-based approach allows the use of versatility and flexibility of this technology for integration purposes.

It has been illustrated that the backscattering simulation approach based on coding technique can be an optimal solution to implement a transparent communication link without adding any interferences in classic imaging processes, allowing this implementation in every classic satellite SAR systems without modifications. Moreover, the communication, that in this paper has been limited to the identification approach, allows also the localization of the proposed ground target through the application of decoding technique before the classic SAR image processing. Different strategies have been presented to implement the transparent identification process also in a multi-target scenario and for tracking purposes. Nevertheless, some critical aspects must be taken into account to develop the ground target transparently and efficiently, as the type of sequence to use in the coding technique, and some tradeoffs must be considered, as the design choices for the ground target correlated to the effect of system delay in the localization process.

The next challenge will be the design of a real testbed for the ground target prototype presented in this paper, eventually with the support of an open SAR satellite already on-air.

Conference C3

Software-defined Corner Reflector for Satellite SAR Systems

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Abstract

Satellite SAR systems are becoming an important source of information for several types of remote sensing applications because they allow the analysis of this planet that is always changing; in this sense, the research is constantly focused on this technology to increase the performance. Ground targets are key factor in SAR applications since they support the image acquisition process mainly with calibration and remote sensing geopositioning, and corner reflectors are one of the most frequently used for this purpose. In this paper a new approach is proposed for the corner reflector design; through the advantages of software-defined radio technology, the novel software-defined corner reflector (SDCR) takes all the benefits from the SDR technology and the classic corner reflectors design. After the presentation of the features of this new device, different SDCR prototypes will be described and tested in a controlled environment to verify the performance from a satellite SAR systems perspective.

C3.1 Introduction

Remote sensing has a fundamental role in many civilian and military fields like meteorology, oceanography, geology but also intelligence, security and humanitarian applications. One of the most important techniques used for this purpose is the Synthetic Aperture Radar (SAR), which is based on a large synthetic antenna aperture to acquire high-resolution images of earth environment that are independent of daylight and weather conditions [51].

The main advantage of satellite SAR systems is the capacity to obtain large-scale images with high resolution compared to ground-based or UAV-based systems. In this sense, the usage of satellite devices has constantly raised in the last decades where several devices have been launched, e.g. the Italian COSMO-SkyMed or the ESA Sentinel project constellations; simultaneously, the interest for satellite applications is raising also for communication purposes, in particular in smart cities point of view, as for 5G and 6G communication standards and massive IoT applications.

Nowadays the technology evolution is increasingly oriented to communication processes; since the satellite strategy is full of potential both for SAR and communication purposes, in the last years different approaches have been proposed to implement a shared application between radar or SAR and communication, even in satellite systems as proposed in [74].

Different techniques have been developed to improve the performance of satellite SAR; among all the features of this technology, in general the research is focused on a wider swath (i.e. ground extension of SAR coverage perpendicular to the flight direction) and a better spatial resolution of the final image. ScanSAR, spotlight and TOPSAR are solutions to achieve better performance besides stripmap, which is the classic mode where the swath, hence the antenna beam, is fixed and the acquisition is continuous compared to the flight direction [51].

ScanSAR, instead of stripmap mode, is a more dynamic technique used to obtain a wider swath; basically, the antenna beam moves to produce multiple sub-swath, mechanically or through beam steering, that jointly illuminate a wider region with respect to the stripmap mode, with the drawback of a degraded spatial resolution [58]. Conversely, through the steering technique in flight and swath direction, in spotlight mode a specific region is illuminated for a longer time with the drawback of discontinuous image acquisition in flight direction, as in [59] where the TerraSAR-X satellite and the spotlight mode are fully described; typically this acquisition mode is used to acquire small areas that require higher spatial resolution than stripmap and scanSAR as for COSMO-SkyMed constellation. TOPSAR mode takes advantage of the antenna beam steering in flight direction and the sub-swath division to increase the performance of the imaging process together with the burst-mode acquisition; TOPSAR provides a higher resolution compared to stripmap and scanSAR with continuous imaging with respect to the spotlight mode [60].

In general, independently of the acquisition technique adopted, SAR technology requires calibration phases to correct some features during the imaging process, i.e. frequency, gain and localization correction; these procedures can be implemented with the internal calibration, which the satellite can execute by itself, or the external calibration, where an outer device with known and static features can support the imaging process [62].

Ground devices are typically employed for external calibration; in this operation are executed processes like the geometric calibration, which is used to map the geographic position to the final image, or the radiometric calibration to evaluate the measurement of the satellite with respect to standard and known targets as the corner reflectors. Another important use of ground targets is the support for remote sensing geopositioning, where they are used as a reference to evaluate the movement of an object or an area. Ground targets are also used for communication purposes in radar and SAR domain, as reported in [74] where a software-defined radio (SDR) based ground device enables a transparent communication link in a generic satellite SAR systems without any interference in the imaging process.

Corner reflector (CR) is one the most frequently used ground device for calibration and particularly for remote sensing geopositioning since it has good performance and visibility for satellite SAR applications. In this proposal, a new type of CR is proposed through the support of SDR technology; the aim is to characterize the proposed software-defined CR enlightening all the features and the limits of this implementation, and also test and compare the prototypes developed with two different commercial SDR platforms.

C3.2 Corner Reflectors

As already introduced, CRs are devices that facilitate the calibration process and can also act as benchmarks for the images acquired by the SAR satellite, especially in remote sensing geopositioning. In general, CRs are located in particular positions, usually in areas without natural reflectors in which these devices can reflect the SAR signal with high radar cross-section (RCS), i.e. an indication of the object visibility

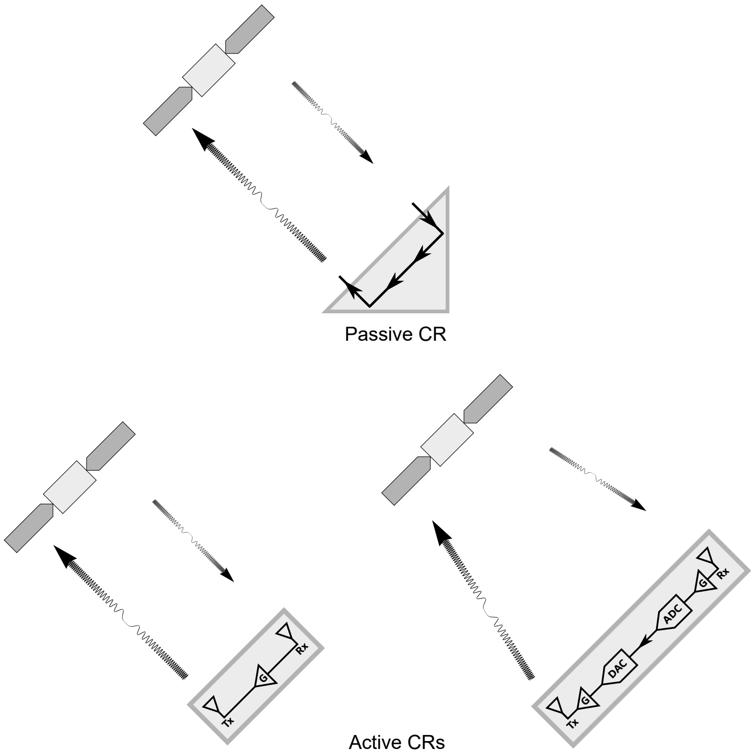

Figure C3.1: Schematic representation of passive and active corner reflectors.

by the radar, which makes it visible for the SAR; with this strategy, the positioning of CR allows the final images to be mapped with respect to the geographic coordinate system currently used.

CRs are classified into two main categories, passive CR and active CR (Fig. C3.1), depending on the power source and also on other design choices adopted during the device development.

C3.2.1 Passive CR

Passive CRs are devices that are studied by the research community with particular interest; typically, these CRs are cheaper compared to active CRs, since they are developed with metal plates that are combined to operate in specific frequency bands with a certain analog gain.

In general, these devices are developed with a larger size compared to the working wavelength and with the orientation that allows the maximum power reflection towards the SAR satellite. Different shapes are developed for this purpose, like the triangular CR, the rectangular CR but also the circular CR, as explained in [64] where three different shapes, perforated or not, have been analyzed also in real test with the ESA Sentinel-1 SAR satellite. In [80] the triangular CR, which is the most common shape, has been fully investigated with several sizes in different real satellite tests. The choice between them is based on the constraints over the RCS, which is the key factor in the development of these devices.

The main advantage of passive CRs is the capacity to reflect the SAR signal with high RCS and an analog gain; moreover, since they are devices without batteries or power supply, they can be located anywhere independently of the environment and weather conditions. The drawbacks are the size, since passive CRs have dimensions typically in the order of meters, and the weight, due to the fact that they are based on metals; these drawbacks increase the complexity in the positioning, especially in remote and mountain areas.

C3.2.2 Active CR

This category of CRs, sometimes also called electronic corner reflector (ECR), is based on a different development approach due to the active elements required, like direct power supply, batteries or solar panels. Active CR, operate in a simple manner: unlike passive CRs that backscatter the satellite signal, active CRs receive the signal, execute operations as amplification and filtering and then transmit it back to the satellite.

The choice of the antenna is a key factor in active CR design and its development but also for the design of any satellite application; horn antennas and patch antennas are in general the most used since they have a narrow directivity, which avoids the effect of interference coming from other directions, supported by high antenna gains.

Active CR outperforms passive CR in terms of RCS due to the high gain involved in this kind of device through the presence of the antennas and the amplifiers, in addition to a design that is smaller and compact compared to the passive one. The disadvantages are mainly based on the power source, which limits the possibility to install these devices in any environment and increases the complexity.

In literature many studies have been fulfilled and implemented; in [108] a low-cost active CR has been designed and tested for ESA Sentinel-1 constellation with the purpose of snow-monitoring application, while in [65] the same prototype has been tested also in a controlled environment to completely analyze its behavior.

These devices have been studied in the last years for new design and development approaches; in this work, a new category of CR is proposed, based on all the benefits that SDR technology offers.

The introduction of signal sampling in CR design allows new operations that take advantage of SDR approach, which has become a mature and trustworthy technology.

This new design approach, which is based on several commercial-off-the-shelf (COTS) SDR devices, will be described and analyzed in the next section.

C3.3 Software-defined Corner Reflector

As already introduced before, in this project the aim is to design and analyze a new kind of CR based on a digital approach; for this reason, the SDR technology has been chosen to develop a new category of CR defined as software-defined corner reflector (SDCR); the choice of SDR is due to the fact that is a very flexible and versatile technology since allows the implementation of any kind of application depending on the constraints required through a low-cost development.

This design choice is based on the versatility of this technology that allows to operate in different frequency bands, and this feature enables the implementation in several satellite constellations. Moreover, considering that SDR devices are equipped with amplifiers both on the transmitter and receiver side, they enable the gain management which is an interesting feature even for satellite applications. For this reason, the proposal of SDCR can be considered as a generalization of passive and active CR: without the gain management, SDCR can be considered as a compact passive CR that act in the same way; conversely, through gain management SDCR behave like a classic active CR with different performance depending on SDR features.

The proposed SDCR must be capable to do the same tasks implemented by the passive and active CRs, hence the support for geopositioning and calibration operations; moreover, in the same way of passive and active CR, SDCR is not aware of satellite transition and is independent of the nature of the transmitted signal. Compared to passive CRs, the advantages are focused on the compact design, which allows the positioning even in high-complexity environments since they are lighter and smaller, but also on the high gain provided by the antennas employment; despite that, SDR devices require a power source, but it must be noticed that the power consumption are limited and depends on the SDR platform itself, hence some trade-off must be considered during the prototyping process.

Regarding active CRs, SDCR provides a more flexible device capable to operate with several satellite SAR constellations; in addition, the SDR technology allows the implementation of high-performance processing of SAR signals through the equipped FPGA, even for more complex applications [74]. In Tab. C3.1 are summarized all the advantages and disadvantages of each category previously described.

Table C3.1: Comparison between passive CR, active CR and SDCR.

	Advantages	**Disadvantages**
Passive CR	No power supply required	Limited analog gain, large size and heavy, no signal control
Active CR	High gain	No operations on satellite signal, fixed gain, power supply required
SDCR	Compact device, automatic controlled gain, possibility to operate with several satellite constellations, interference mitigation, satellite signal monitoring	Require a power supply, additive latency

The main difference compared to the previous categories is the digitalization since the received SAR satellite signal pass through the ADC on the receiver side and the DAC on the transmitter side. The outcome of this operation is an additive delay to the signal that can be mapped into a spreading effect of the SDCR in SAR image acquisition, as described in [74]; since this spreading effect depends only on the features of SAR imaging process, it can be counteracted in this step of image acquisition. Considering that these effects are strongly dependent on the performance of the SDR platform, different platforms with diverse performance and costs will be used for the prototype operation to fully describe all the limits of this novel proposal.

In the next section the testing procedure will be fully explained, supported by the analysis of the COTS devices involved in this process and its performance for the prototype development of this novel group of CRs.

C3.4 SDCR development and testing

After the full analysis of the novel SDCR category, in this step are described the design choices in terms of hardware and software; three different prototypes have been developed through COTS SDR platforms with diverse costs and performance; this operation has been conducted to show all the advantages but also the trade-offs that are necessary to operate with this technology, especially in satellite SAR domain.

C3.4.1 Prototype design

For the development of SDCR prototypes, two different SDR platforms have been chosen; the reason for this distinction is dual: firstly, the aim is the development of a working SDCR capable to operate in a real environment through a high-performance

SDR platform; secondly, is to prove that is possible to design a SDCR with a low-cost COTS platform.

National Instruments (NI) USRP 2954R has been selected for the high performance prototype, which belongs to the Universal Software Radio Peripherals family; RIO is the acronym of Reconfigurable Input-Output, which is a group of NI SDR platforms equipped with an FPGA board. Some USRP 2954R features are: is a 2x2 MIMO device (four I/O interfaces, two TX/RX and two only RX), operative frequency from 10 MHz up to 6 GHz, up to 200 MSps sample rate with 160 MHz of maximum instantaneous bandwidth, 16bit DAC and 14bit ADC (digitally mapped into 16) and Xilinx Kintex-7 FPGA.

This SDR platform has been programmed in LabVIEW, which is a development environment and system-design platform based on graphic language and virtual instrument (VI) concepts, and LabVIEW FPGA, an additional module to design hardware functionalities in hardware description languages such as VHDL or Verilog.

In the second case, the ADALM PLUTO SDR platform from Analog Device Inc. has been used to develop a low-cost SDCR prototype, since it is an easy to use and portable device very cheaper compared to the previous platform. This SDR platform is equipped with a Xilinx Zynq Z-7010 FPGA, and is based on the AD9363 transceiver with one TX and one Rx channel, frequency range from 325 MHz to 3.8 GHz, up to 61.44 MSps with 20 MHz of maximum instantaneous bandwidth, 12bit DAC and ADC; moreover, since the AD9363 is responsible for the analog front-end, it must be taken into account that is not possible to operate changes like FIR filter design, etc., but only on the operative parameters like carrier frequency, gain, etc. The ADALM PLUTO can be programmed in different environments like GNURadio or MATLAB and Simulink; in this work, this device has been programmed in MATLAB environment.

In order to develop the SDCR prototypes and reduce the latency of the device, the SDR platforms have been programmed in the hardware domain, since the software approach is not contemplated due to the strict time constraints. For the USRP, two different prototypes have been realized to evaluate different latency: in the first prototype the data incoming in the FPGA is transmitted back bypassing any digital processing, while in the second prototype the digital samples experience digital processing to optimize the signal with the drawback of higher latency. Digital down converter (DDC) and digital up converter (DUC) are used as interpolators, decimators and filters to allow the data stream reduction between the SDR platform and the external control systems.

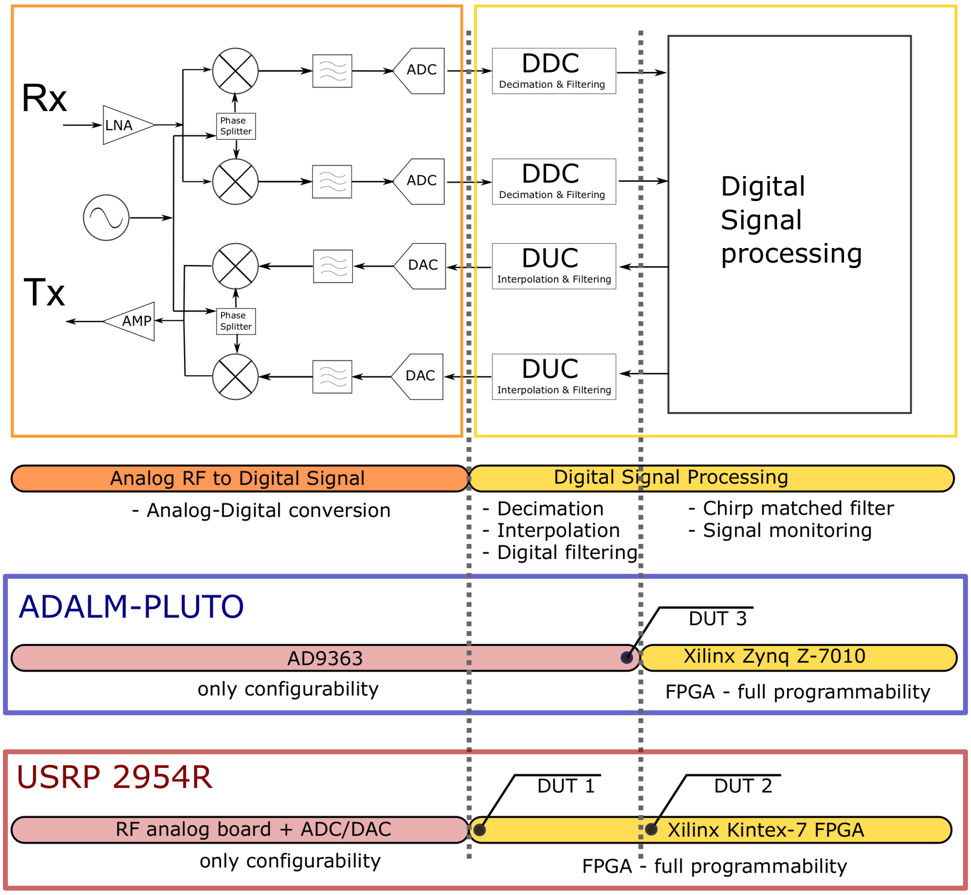

Figure C3.2: SDR architecture diagram with the representation of the characterizing constituent elements. The level of the chain used for the realization of the prototypes is highlighted.

On the other hand, the third prototype has been developed through the ADALM PLUTO and its built-in self-test loopback RF function, which implements the loopback operation, including some digital processing, inside the transceiver bypassing the FPGA; the different prototyping levels are represented in Fig. C3.2.

It must be noticed that the second prototype is evaluated both to understand the latency for necessary reduction of the stream flow but also for a direct comparison with the ADALM PLUTO platform in which the elements DDC and DUC are not by-passable and this point is the first in which the received data can be processed.

C3.4.2 Testing

The prototypes described in the previous section have been tested in a real environment to analyze the performance. In this step, the ESA Sentinel-1 constellation has been selected as a reference environment, but many complexities are involved in a real

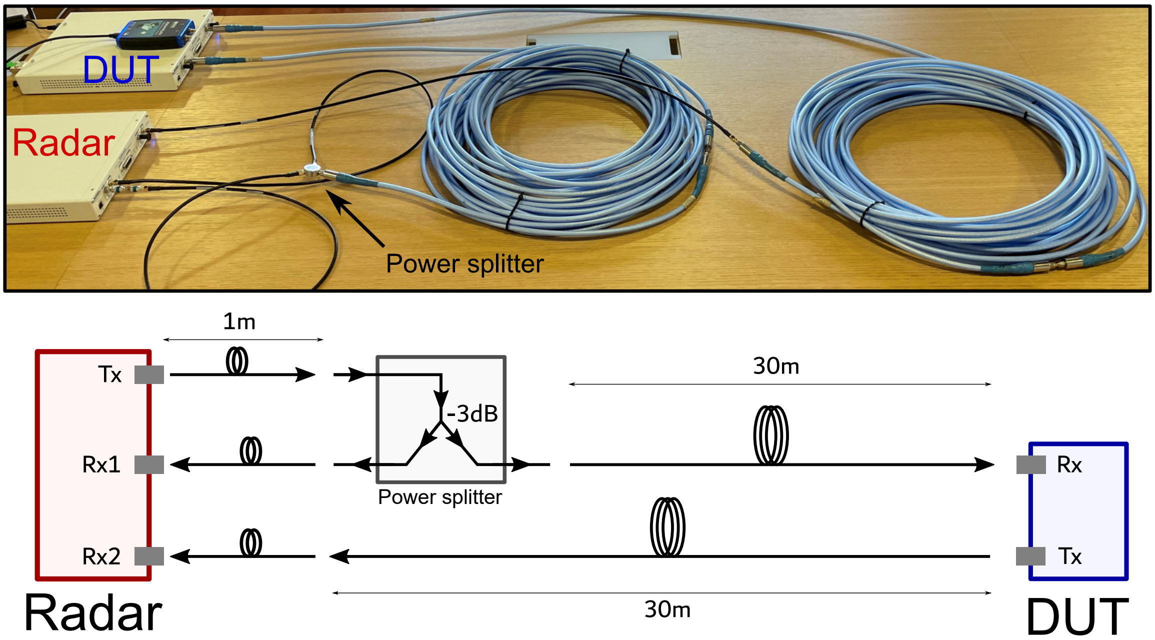

Figure C3.3: Testing environment and related block diagram.

satellite scenario, in particular the revisit time of a generic satellite, which is about six days for Sentinel-1, but also the requirement of suitable antennas.

For these reasons, the testing operation ended up with the choice of a controlled environment in the laboratory. Moreover, since SAR is a particular technique that derives from radar technology with the additional synthetic antenna aperture due to the SAR movement, the testing operation has been conducted in a static radar scenario, because the interest is on the proposed SDCR behavior and not in the image acquisition process.

The testing scenario, shown in Fig. C3.3, is composed of a radar and the device under test (DUT); the radar has been developed with a USRP 2954R SDR device, that transmits the typical SAR and radar chirp waveform (i.e. frequency modulated signal where the frequency sweeps linearly, exponentially, etc. from a frequency f_1 to f_2), and then it collects the replies from two channels.

Three different DUT has been analyzed in this process, which are the three prototypes previously described; the USRP 2954R without (DUT 1) and with (DUT 2) DDC and DUC and the ADALM PLUTO (DUT 3); in Fig. C3.3 is also showed the block diagram of the scenario: the radar transmits the chirp waveforms, which are split into two paths through a power divider in order to collect the direct path, as a reference to analyze the latency of any DUT, and the second path where the waveforms travel inside 30 meters cables (composed of two 15 meters Sucoflex 106

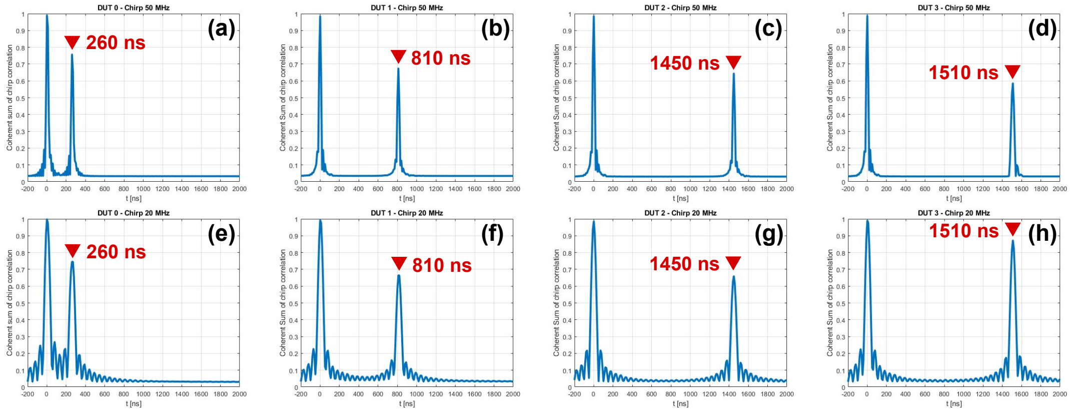

Figure C3.4: Results of dechirping operation; (a) and (e) are the results for the reference DUT 0, corresponding to a simple SMA adapter among the two 30-meters cables, while the others are the three DUT analyzed. (a), (b), (c) and (d) are the analysis with 50 MHz chirp while (e), (f), (g) and (h) with 20 MHz chirp.

cables connected through an SMA adapter) to reach the DUT, then are transmitted back to another 30 meters cables and are acquired by the radar; therefore, the second path is delayed with a total of 60 meters between the DUT compared to the direct path.

The choice of this delayed path is due to the performance of the radar, because it is capable to acquire two channels simultaneously with a maximum sample rate of 100MSps, corresponding to 10ns between two samples. Since the signal inside these 60 meters cables propagates at 77% of the speed of light, this path guarantees at least 260ns of delay, as indicated in graphs (a) and (e) of Fig. C3.4 for DUT 0, corresponding to an SMA connector for the direct link between the two 30 meters cables, that allow to clearly distinguish these two paths during the correlation analysis. Furthermore, the result of chirp correlation, also known as dechirping, is a peak whose width is inversely proportional to the chirp bandwidth with an amplitude proportional to the chirp bandwidth and duration, therefore also these limits forced the use of additive cables to implement this delay in order to clearly distinguish the peak corresponding to the DUT in the dechirping operation.

In this test, the parameters chosen are close to the ones used in the reference satellite SAR system: C-band carrier frequency at 5.405GHz and chirp bandwidth of 50MHz with a sweep rate of 1MHz/μs. While the USRP 2594R is capable to operate whit these features, it must be kept in mind that ADALM PLUTO technically cannot work in C-band and it has only 20MHz of instantaneous bandwidth; to exceed these limits, the firmware device was hacked by software to operate like the AD9364

Table C3.2: Latency summary for the DUT.

	Latency
DUT 1: USRP 2954R (without DSP)	550 ns
DUT 2: USRP 2954R (with DSP)	1190 ns
DUT 3: ADALM PLUTO	1250 ns

transceiver up to 6GHz; additionally, a second chirp waveform with 20MHz bandwidth has been analyzed for all the DUT.

For conciseness purposes, both DUT have been configured to have a power ratio between input and output power equal to one; this means that no gain has been set, so that every DUT behaves like a passive CR without passive gain, since in this scenario no antenna has been used.

The dechirped signals, as illustrated in Fig. C3.4, have been summed coherently to analyze the effects of the three DUT compared with the DUT 0; without considering the 260ns additive delay, the USRP 2954R without digital signal processing (DSP) with DDC and DUC is the most performing SDCR as expected, since its latency is about 550ns, while the USRP 2954R and the ADALM PLUTO both with DSP require higher timing up to, respectively, 1190 and 1250ns, as summarized in Tab. C3.2. It must be noticed that these performance can be considered as benchmarks for more complex development: once the latencies of the devices are known, is possible to develop applications in the FPGA with deterministic timing that depend on the number of clock cycles required.

Besides the latency analysis, from Fig. C3.4 can be assumed that both DUT satisfy the requirements of the test since they are capable to be identified, even the ADALM PLUTO that has an instantaneous bandwidth up to 20MHz despite the variation in the dechirping amplitude, as in the graphs (d) and (h) of Fig. C3.4; this means that the ADALM PLUTO can be used also in real environment considering the losses due to the filter that is narrower compared to the SAR bandwidth typically used.

The prototypes have been tested through the Anritsu MS2037C vector network analyzer (VNA) to verify the behavior as a SDCR. As shown in Fig. C3.5, the scattering parameter S_{21} highlights the features described for the COTS devices used for the prototypes. While the USRP 2954R has an almost-flat behavior due to the 160MHz of instantaneous bandwidth, in the figure is shown the 20MHz filter of ADALM PLUTO, which has a degradation outside the 20MHz of about 1dB/MHz; despite the 20MHz

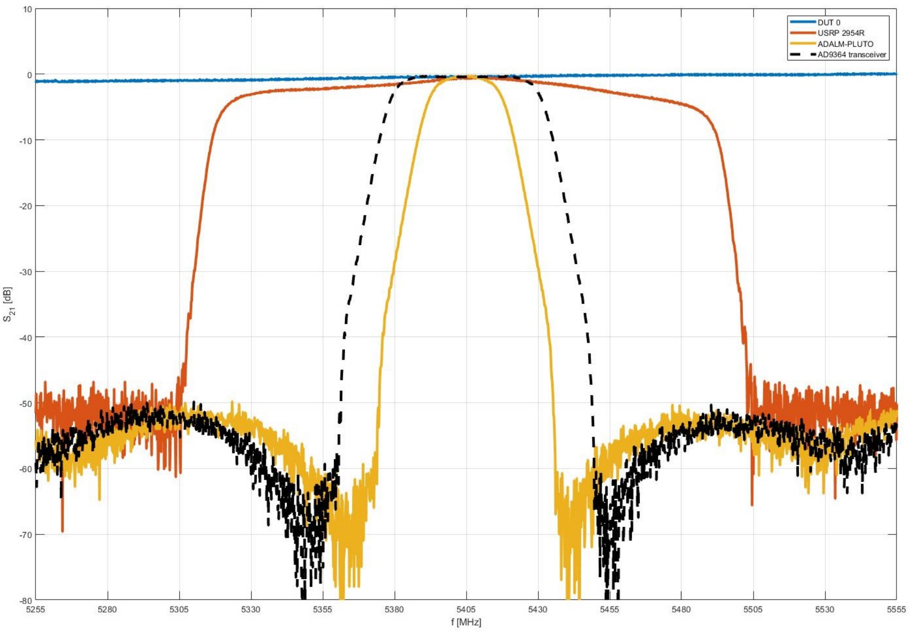

Figure C3.5: Scattering parameter S_{21} plots, centered at 5.405GHz, acquired with the VNA for both USRP 2954R and ADALM PLUTO devices compared with DUT 0 condition (direct link between the VNA ports) and the hypothetical bandwidth of AD9364 transceiver.

filter, is possible to use the ADALM PLUTO for real satellite SAR systems, but to overcome this limit the AD9363 transceiver has to be physically substituted with the AD9364 since it has a 50MHz filter. Finally, both devices are compared with the DUT 0, which is the direct connection between the VNA ports through an SMA adapter, in order to show the power ratio between input and output equal to 1; in the figure is possible to notice the behavior of the filters for both devices with some losses at the end of the guaranteed bandwidth, compared with the DUT 0 and the expected bandwidth with the AD9364 transceiver.

C3.5 Conclusions

In this work a new group of CR has been proposed; passive and active CR are devices whose importance is constantly increasing at the same pace with satellite SAR systems, because of the support that CR supply to the imaging processes. In this context the proposed SDCR can be an innovative alternative to the previous, even considering all the limits of the classic CR groups.

The purpose of this work was not the enhancement of SAR technology but the development of this novel group of CR that combines all the advantages of SDR and classic CRs; for this reason the analysis proposed in this paper is not based on SAR point of view and its services, but is focused on the comparison between SDCR and active and passive CRs.

Moreover, the novel SDCR is a basic element that allows a subsequent step, represented by the possibility to implement an additive digital signal processing inside the FPGA equipped in the SDR devices, even for more complex applications.

Therefore, this possibility can bring this kind of device to a further level in which implement other services like backscattering communication inside a satellite technology that is not suitable for. In this operation, SDCR can be a crucial element to this purpose with the demonstration of SDCR advantages and its workability with real satellite SAR systems.

Said that, the next step to reach this new level will be the test in a real environment like the Sentinel-1 constellation, in which test the prototypes described in this paper; this will be the real challenge due to the high complexity involved in a real satellite system.

Conference C4

SDR SAR Target: Corner Reflector and Communication

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Abstract

This paper presents a novel target based on software-defined radio (SDR) technology that allows the support of remote sensing processes and enables a transparent communication link in synthetic aperture radar (SAR) systems. In the actual context of increasing communication demand, the integration of communication services in technologies that are not developed for this purpose can be an interesting solution, even for airborne and spaceborne systems. Through the flexibility of SDR technology, the novel target acts in two different ways for SAR systems: as software-defined corner reflector (SDCR) to support calibration and remote sensing applications but also to enable target localization, but also as SAR target to integrate a communication link without any interference or modifications in the classic SAR imaging process, enabling new services like identification and target tracking.

C4.1 Introduction

Nowadays the importance of remote sensing is growing constantly due to the variety of airborne and spaceborne applications where it is involved. One of the most important techniques is Synthetic Aperture Radar (SAR), where the radar movement enables a large synthetic antenna aperture for high-resolution images acquisition of earth surface independently of weather and daylight [51].

The research community is always oriented to the satellite approach. Besides remote sensing satellites as COSMO-SkyMed and ESA Sentinel constellations, in smart cities perspective new services supported by satellites are becoming popular, in particular for new communications standards as 5G and 6G with massive IoT applications.

Backscattering is the common point between radar and SAR, and it is constantly linked to wireless communications and sensor-based systems because it allows the use of passive devices for low-power applications as ambient backscattering [99] and radio frequency identification (RFID) [100].

Nowadays there is a growing interest in communication services implementation, even into technologies that are not supposed for this purpose, like radar and SAR. Moreover, targets have an important role in the validation of the results of acquisition processes made by the SAR satellite; in general, they are used to support satellites in calibration processes and also for geopositioning and localization in remote sensing applications. Corner reflector (CR) is a device frequently used for these purposes.

In this paper is presented a novel target for a generic SAR system already on air, referring to satellite SAR systems without loss of generality; through software-defined radio (SDR) flexibility, it can act in two different manners, as software-defined corner reflector (SDCR) but also as modulator for transparent communication link integration. The transparency reduces the interference of the communication link in the classic imaging processing, and the communication can be extracted in the received SAR signals to implement services like identification and tracking.

C4.2 Radar and communication

The use of shared resources is the real challenge for the research community, in particular bandwidth due to the increasing spectrum demand in wireless communications but also radar technology; hence, the joint approach of wireless communication and radar can be an optimal solution.

This joint approach is long-standing, and today these activities are classified in several manners; a first classification is indicated as communication and radar spectrum sharing (CRSS) where they share the same resource and are classified in primary and secondary service [101].

Dual-function radar-communication (DFRC) can be considered as a sub-group of CRSS applications with a deeper level of combination where the coexistence is extended toward some common features to operate simultaneously without interference, as described in [102].

Finally, in joint radar and communication (JRC) is designed a joint service that can operate both as radar and communication at the same time, without any distinction between primary and secondary service, as indicated in [45].

This dual approach is also extended to SAR remote sensing applications as in [56], where the communication is integrated into a planar SAR system through an antenna backscattering approach based on spreading techniques as for UWB RFID systems [104] [105].

Targets play a fundamental role for satellite approach in SAR systems, due to the support for geopositioning and calibration but also for new communication services implementation as in [74], and CR are an optimal solution.

C4.3 Corner reflectors

CR is an object that supports satellite SAR for calibration but also for image quality purposes and geolocalization. Usually a CR is located in places without natural reflectors so that it can backscatter the SAR signal with a certain gain to have a high radar cross-section (RCS).

In general CRs are classified between passive and active CRs; passive CRs are big and cheap since are made by metal plates with sides up to meters. Several shapes have been studied and the most used are the triangular CR, the rectangular CR and also the circular CR, as shown in [64].

The great advantage is the absence of power supply so that they can be located everywhere independently of weather conditions, but the main drawback is the size and weight.

Active CR is powered with power supply, battery or solar panels; differently from passive CR, active CR is smaller and compact, and it executes amplification, filtering and then transmits the signal back to the SAR satellite with better performance [65].

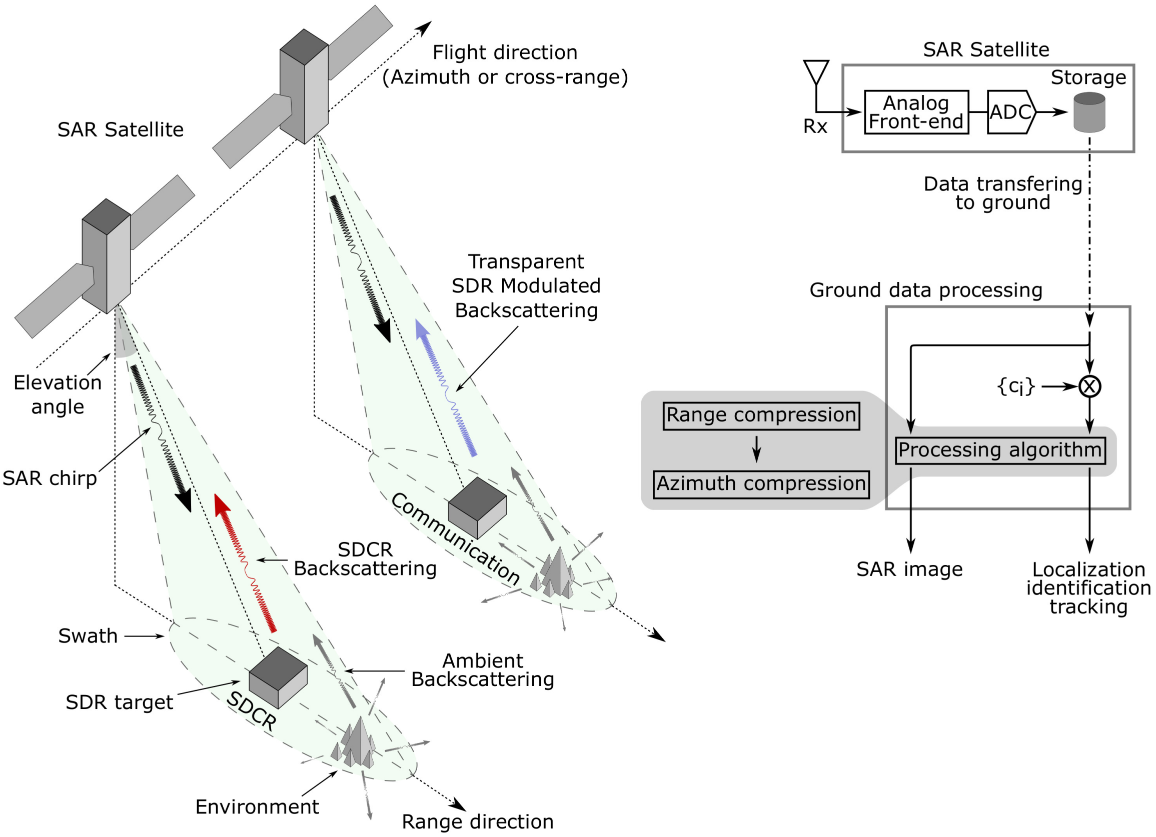

Figure C4.1: Simplified schematic representation of the proposed SDR target with both functionalities.

The main disadvantage is the power source that limits the possibility to locate it everywhere.

C4.4 SDR SAR target

As previously introduced, in this paper is presented a novel target that can execute two different functionalities for support a generic satellite SAR system but also to integrate a transparent communication link without interference in the classic imaging process; these two approaches are illustrated in Fig. C4.1 with a simplified representation.

The first functionality is the software-defined corner reflector (SDCR) that takes advantage of SDR technology jointly with the advantages of active and passive CRs. The SDCR transmits back the signal received by the satellite SAR as a classic CR, but the SDR choice enables a set of additive features: it can operate at different carrier frequencies to operate with several satellite constellations, and it enables the gain management.

The advantages of SDCR compared to passive CR are the compact design that allows its positioning even in high-complexity environments, and the higher gain due to amplifiers and antennas. Differently from active CR, SDCR enables interference mitigation, satellite signals monitoring and digitalization through the SDR FPGA, which allows also the real-time processing of the received signal.

Nevertheless, digitalization is also a drawback since is responsible for an additive latency that will be investigated in the following section; another drawback is the power source requirement, but they have low power consumption, thus some trade-offs must be considered.

The second functionality is the transparent communication link integration into a generic satellite SAR system already on air. This approach is focused on transparency, such that the contribution of the proposed communication target must be negligible. The idea is to operate in a way similar to SDCR with the integration of a transparent communication link. Due to the reduced time window, identification is the first strategy and it is implemented through a modulation of the signals received and backscattered to the satellite SAR with a specific code similar to CDMA or DSSS

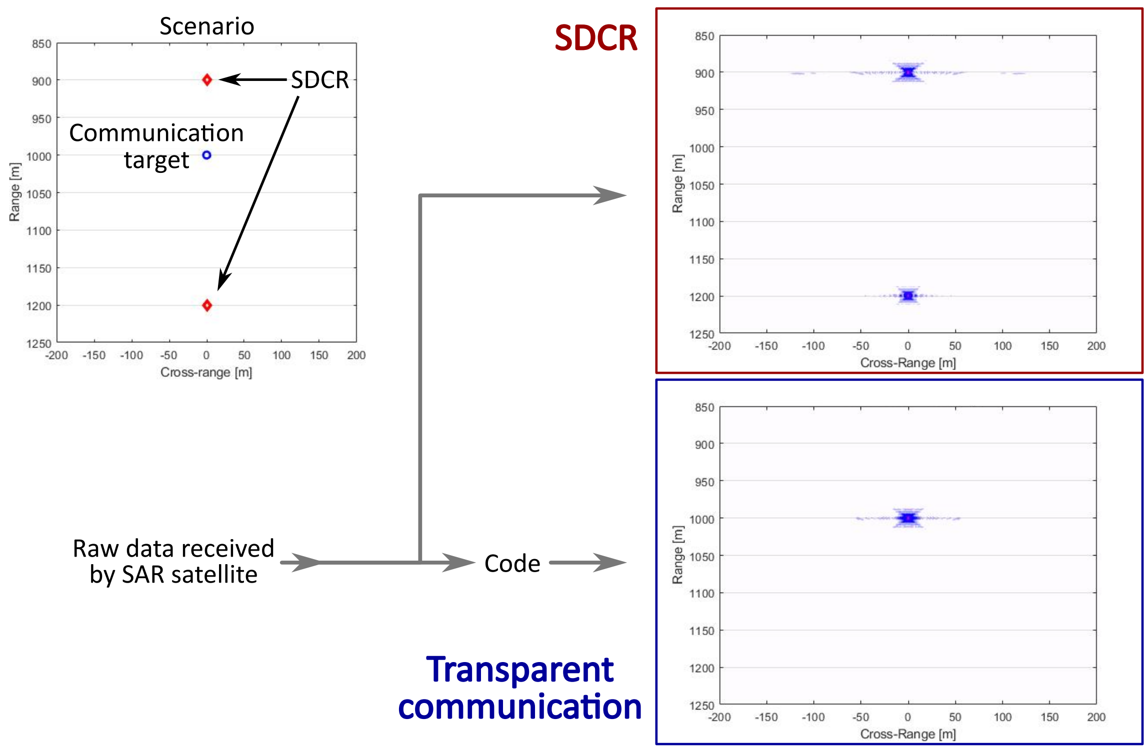

Figure C4.2: Simulation of both functionalities in a reference scenario with two red targets as SDCR and the blue one that implements the transparent communication.

techniques.

The signals received by the SAR satellite can be processed as usual to obtain the final image without interference due to the transparency; otherwise, applying the same code the contribution of the environment is reduced and the one of the target is highlighted, enabling the identification through code matching, target localization and also tracking with multiple localization images. An example is shown in Fig. C4.2 with a simple scenario.

The real challenge for the transparency is the choice of the code; the main requirements are the zero mean and the balancing property during the time window in which the SAR is receiving the modulated replicas of the transmitted signal, expressed as $\sum_{i=1}^{N} c_i = 0$ where $c_i \in \{-1, +1\}$ is the code of length N. Since π is the phase shift resulting from the code bits, in the processing algorithms for the final image the contribution of the code can be neglected; moreover, to preserve transparency, the balancing property must be valid in a short time window due to the SAR movement.

It must be highlighted that the two functionalities are implemented in the same object which can perform them together in real-time or separately switching between them, since these execute conceptually the same task.

C4.5 Analysis and critical issues

In this section are described the issues related to the proposed SDR target development for both SDCR and communication integration functionalities. Since this activity is in its early stage, the purpose is to present them with the description of their behaviors and all the advantages and drawbacks related to the classic technologies supported by simulations and analysis in a controlled environment.

The first issue to deal with is the delay introduced by the SDR platform used for the target prototype, which is related to both functionalities since it depends on the level of design inside the SDR device. The test has been conducted with several SDR platforms, but for conciseness purpose just NI USRP 2954R has been reported in this paper; the USRP has been programmed through LabVIEW and LabVIEW FPGA. Both functionalities have been developed in hardware domain to reduce the delay introduced by the device; it must be considered that the SDR platform introduces a minimum constant delay based on the analog front-end and analog-digital conversion blocks (ADC and DAC) involved in the receiver-transmitter chain, and this assumption is valid for both functionalities since it depends on the SDR device itself.

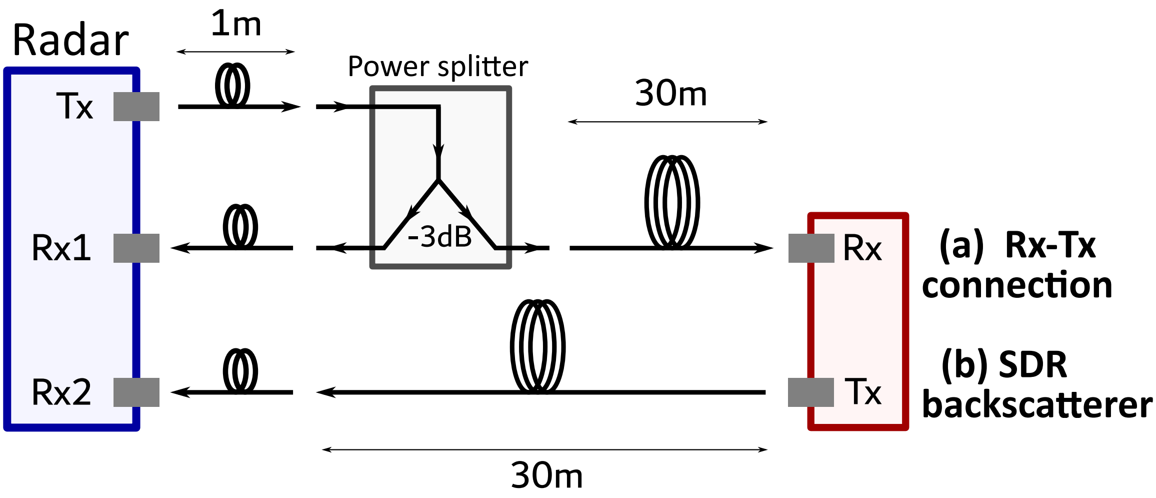

Figure C4.3: Block scheme of the scenario under test and the two paths with $60m$ cables (a) in addition to the SDR delay (b).

To analyze the delay effect, two different approaches have been studied; in the first approach, a test has been conducted in a controlled environment to quantify the amount of delay introduced by the system. Since SAR is based on radar technology, the test has been conducted through another USRP which acts as a radar that transmits a chirp waveform similar to real SAR satellites, and acquire it back in two channels, the first as a direct path and the second as the reflected path with additive $60m$ cables and the devices under test. The higher distance of the reflected path allows to distinguish the delayed path since the SDR sample rate could not be enough; the block scheme of the scenario under test is shown in Fig. C4.3.

The minimum delay introduced by the SDR device is equal to $550ns$ but it must be taken into account that any further processing inside the FPGA has a deterministic delay that can be computed as multiple clock cycles depending on the operations to implement. In Fig. C4.4 are shown the results of the test, where the direct and reflected paths have been correlated through a matched filter and the correlation has been coherently summed in the entire signal acquisition to reduce the contribution of the noise.

While the first approach has quantified the minimum delay of the proposed target, the second approach allows to understand the effect of this delay in the final SAR image; hence, a simulation has been conducted through MATLAB software and its Phased Array System Toolbox in the same scenario of Fig. C4.2, where the three targets reflect the satellite SAR signal with three different delays: the first with no delay, the second with $550ns$ which is the same quantity measured with the previous test and the third with a higher delay of $1200ns$. In this case, as shown in Fig. C4.5,

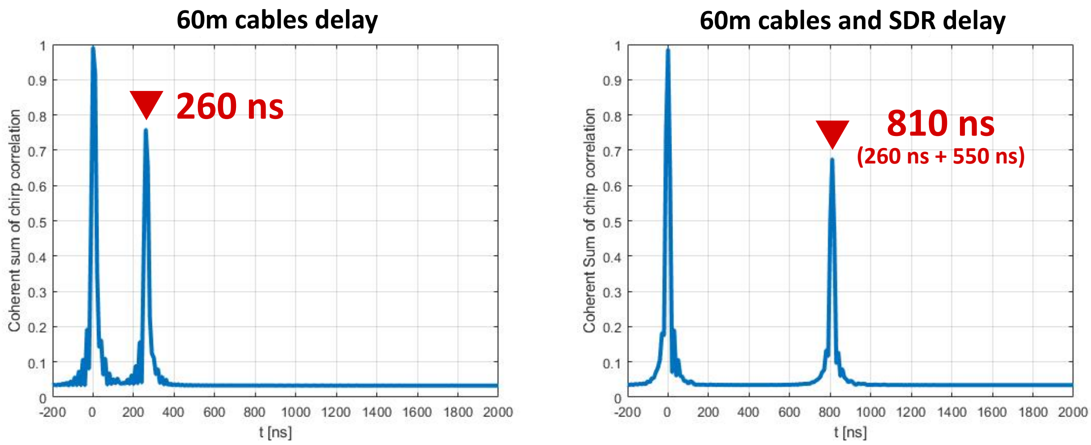

Figure C4.4: Coherent sum of signal correlation, with only the 60m cables to the left and with the addition of the SDR platform to the right.

the delay introduced by the SDR platform corresponds to a spreading effect of the target contribution in the cross-range direction of the satellite that increases with higher delays. At the writing step of this paper, this spreading effect of the delay is under investigation to find a proper solution.

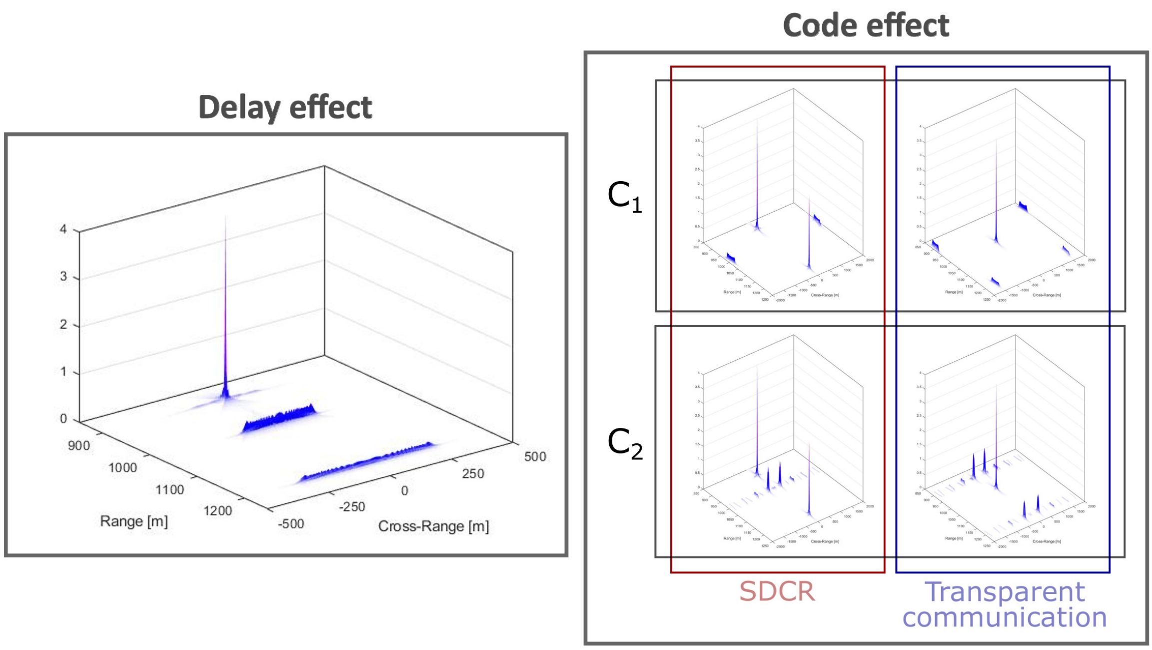

Figure C4.5: Simulation of the scenario presented in figure 2 to analyze the effects of delay independently of the functionality implemented, and the effects of the code for the transparency communication; two codes has been tested, c_1 with the commutation between $+1$ and -1 every one chirp signal, and c_2 with the commutation every eight chirps.

The second main issue of this proposal is the effect of the code used to implement the communication process. Since the time window in which the target is illuminated by the satellite is short, the first assumption is that a code, required for the identification process, must be transmitted in a single time window. Moreover, it is assumed that each code bit corresponds to a single chirp waveform; with these assumptions, transparency is guaranteed if the code has zero mean and is balanced during the observation time window. In this case, the integration of communication link has been simulated in the same way as for the delay analysis; two different codes has been used based on the switching between +1 and −1, c_1 with the commutation of the code bit at every chirp and c_2 with the commutation at every 8 chirp, as shown in Fig. C4.5. The simulation results show in Fig. C4.5 that the effect of the code is a filtering operation that leads to unwanted replicas in the cross-range direction that are limited in amplitude but can interfere in the final image. Also this issue is currently under investigation, and a solution can be the use of different codes like the bipolar or alternate mark inversion, but different assumptions regarding the code bit mapping are required.

C4.6 Conclusions

Nowadays the importance of satellite systems is constantly increasing for remote sensing applications but also for communication purposes due to the increasing demand for connectivity; the trend of communication integration in technologies that are not designed for this purpose is becoming popular, in particular in radar and SAR systems. In this background, SAR targets are one of the most important solutions to integrate communication services and also to support satellite SAR systems in calibration and remote sensing operations.

In this paper has been proposed a novel target based on the versatility of SDR technology that implements two different functionalities, the SDCR for target localization and to support SAR technology and the processes that it has to implement, but also the integration of a transparent communication link that enables services like identification and tracking; these two functionalities are implemented in the same target and it can perform them together in real-time or separately. It has been shown that both functionalities have drawbacks in the target design, like the additive delay introduced by the SDR platform or the choice of the code and its properties to guarantee the transparency to avoid interference in the imaging process. These issues have been described and analyzed through software simulations and tests in a controlled environment.

The further analysis of this work will be focused on prototype tests in a real environment with real SAR satellites like the ESA Sentinel-1 constellation, with all the complexities that will be included.

Part III

Conclusion

Concluding remarks and future directions

Considering the novelty introduced by modern communication technologies like 5G and 6G and the plethora of heterogeneous services enabled, different side effects must be taken into consideration to avoid communications failures or outages. In this sense, referring to the well-known physical issues like spectrum congestion or the RFI increase, in this dissertation two main solutions have been investigated, the spectrum analysis and the ISAC approach, taking advantage of SDR and all the benefits involved with this technology; indeed, it is becoming a paradigm in which is possible to develop every type of communication systems that afford the RF propagation.

Regarding the spectrum analysis, this thesis has shown that spectrum monitoring through maximum, average and minimum power spectrum can be an interesting solution to have an overview about the presence of evident signals, supported by specific algorithms for signal detection and recognition. Referring to the activity realized in the LNGS, is evident the necessity of an automatic system able to monitor the radio spectrum for the detection and recognition of unknown signals. In this direction, this dissertation has shown that the use of distributed systems can be an optimal solution to enlarge the spectrum area under analysis and to integrate source localization algorithms in real time between different devices, moving the attention even to a security point of view; moreover, the deployment of a distributed system can be an feasible also for the execution of additive services to monitor the spectrum status and to support mobile communication systems with other standard and critical services. This activity is quite near to the concept of ISAC, since spectrum monitoring is a sensing operation made to detect its status. In this sense, further investigations will include the refinement of these systems together with the implementation of signal recognition algorithms.

Concerning ISAC development, this dissertation has been focused on the integration of communication links in radar technology, in particular on SAR systems for imaging purposes. Referring to satellite SAR systems without lost in generality, this work demonstrated that is possible to integrate additive ISAC functionalities in SAR systems already on air taking advantage of SDR technology. In particular, it demonstrates that is possible to integrate a transparent communication link by means of code modulation techniques similarly to CDMA and DRSS techniques. In this sense, is possible to integrate a communication process through SAR signal backscattering with code modulation techniques, without any modification and interference in the classic SAR imaging process. Moreover, through the code matching and the successive SAR processing of the demodulated RAW data is possible to enable the target identification and its localization and tracking (with multiple images). Two main issues are present in this activity; the first one is related to the choice of the code since the side effect corresponds to an image replica spread on the azimuth direction (i.e. the SAR moving direction), whose effect is more evident as the code became slower in the commutation. The second issue is related to the additive delay introduced by the SDR technology, whose minimum delay corresponds to the time required for the analog front-end and the digitalization.

The effects of the SDR-based delay have been tested accurately with a second functionality tested in this work, the so-called SDCR, whose effect is to purely backscatter the SAR signal as a classic CR, integrating all the advantages due to SDR technology. In this sense, the additive delay (tested through two COTS SDR devices) is in the order of μs and its effect in the final SAR image corresponds to a spreading of the SDCR contribution in the azimuth direction with an amplitude decrease of the target contribution.

These activities will be part of the future investigation in ISAC context, in particular taking advantage of SDR paradigm and all the benefits that derive from this technology. The importance of ISAC will increase in the development of future mobile communication systems, an example is reported in the last ITU-R report toward 2030 [2] where an entire section has been dedicated to ISAC. In this sense, the further research activities will be focused on the prototype development of SDR target for ISAC application in SAR and radar context, where SDR technology represents an interesting solution; the prototypes will be tested in a real environment with real SAR systems like ESA Sentinel-1 constellation, supported by an accurate analysis of the code modulation techniques to refine the SDR target transparency.

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