Satellite SAR Testing Framework for Integrated Sensing and Communication

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Abstract

Modern advancements in wireless communication and sensing technologies are driving the integration of different services, enhancing overall performance through automation and situational awareness concepts. Consequently, Integrated Sensing and Communication (ISAC) has emerged as a promising research field, in particular for radar-based technologies such as Synthetic Aperture Radar (SAR). In this background, this paper presents a novel ISAC target that exploits code modulation backscattering to integrate transparent communications in consolidated satellite SARs, without requiring updates or modification in systems already in operation. Insights into the ISAC target and the transparent communication link are provided, supported by the evaluation of the proposal through a novel testing framework that emulates the ISAC target using real data from ESA Sentinel-1 SAR satellites.

1 Introduction

In recent years, Integrated Sensing and Communication (ISAC) have risen as a novel paradigm to mutually integrate services in sensing and communication systems, aiming to improve the overall performance. Despite communication and sensing represent technologies developed with different resources (i.e., hardware, frequency spectrum, etc.), the demand for new tasks as well as the higher performance requirements are encouraging the development of ad hoc systems capable to perform both technologies simultaneously while sharing the same resources.
From the communication point of view, ISAC is becoming a relevant topic for modern mobile networks like 6G [1]. Situational awareness and automation functionalities, such as movement recognition and location awareness, enable the integration of sensing techniques, making mobile networks aware of the surrounding environment for optimization and energy-saving strategies [2]. Furthermore, communication integration represents an opportunity for information exchange in sensing technologies, which benefit from ISAC through the novel concept of "network as a sensor", where each sensing device cooperates by sharing acquired information to improve performance [3, 4].
Radar is one of the most popular sensing technologies, and radar-based ISAC has a well-established research activity. Nevertheless, the integration of communication in derived radar technologies like Synthetic Aperture Radar (SAR) is still in its initial stage. Unlike radar, SAR specifically operates for remote sensing applications, and the ISAC approach is exploited on the coexistence level. Communication embedding in SAR waveforms is a common approach for ISAC [5], while other approaches leverage SAR principles to extract information in modern communication systems [6].
Similarly to radar, SAR exploits a frequency-modulated signal known as chirp to obtain high-resolution, daylight, and weather independent images of the illuminated area through a very large synthetic antenna aperture [7]. In spaceborne SAR systems, referring to satellite solutions without loss of generality, ground targets play an important role. They support traditional SAR operations like geometric and radiometric calibration, but also the integration of novel functionalities like geopositioning [8] or ISAC tasks [9]. Corner Reflectors (CRs) are commonly used for these purposes, offering a trade-off between performance and the flexibility to be placed anywhere. They are classified into passive CRs (i.e., metal plates without power supplies) or active CRs, where the power source enables higher performance. Recently, a novel category based on Software-Defined Radio (SDR) technology has been proposed, providing flexibility and high performance [10].
In this context, this paper introduces the integration of a communication task in a consolidated SAR technology without requiring modification in systems already in operation, referring to the European Space Agency (ESA) Sentinel-1 satellite constellation as the reference SAR platform. This integration is achieved through an ISAC ground target that exploits code-modulated backscattering of the received SAR signal. This approach guarantees transparency in the final SAR image avoiding additive interference. Considering the testing challenges involved with such ground targets, like the impossibility of emitting signals in licensed spectrum and the different acquisition techniques adopted by the Sentinel-1 system (i.e., stripmap, TOPSAR,

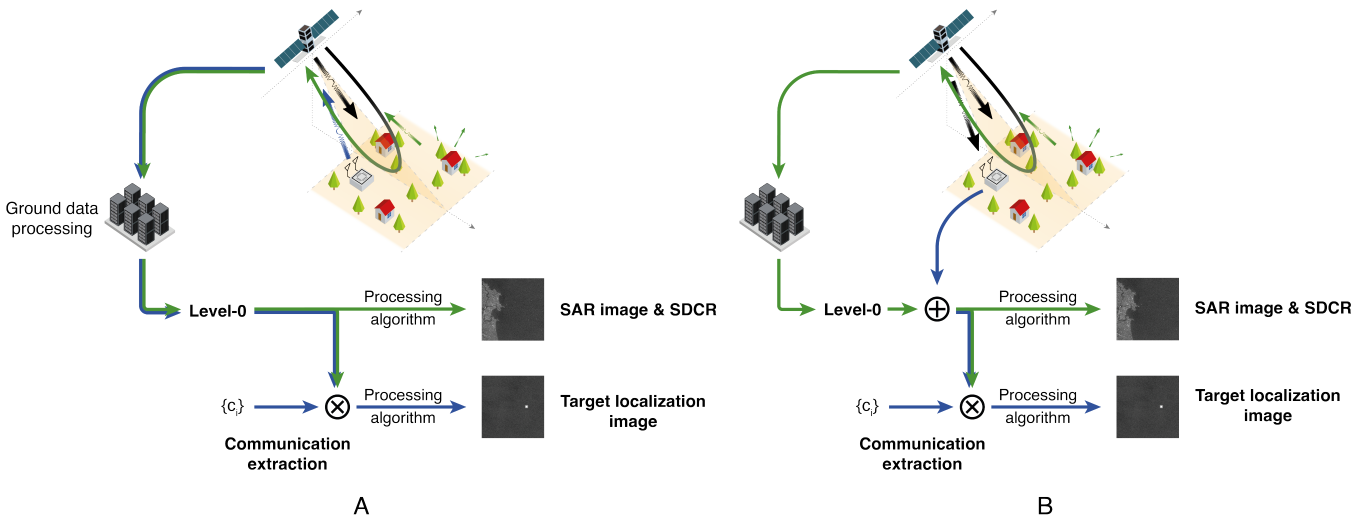

Figure 1. Schematic representation of the proposed ISAC target (**A**) and the testing framework (**B**).

etc.), this paper introduces a novel testing framework that exploits real data to validate the ISAC functionality assuming the SDR-based ground target proposed in [9]. The structure of the paper is organized as follows: Section 2 provides a description of the proposed ISAC functionality, Section 3 presents a general overview of the testing framework, while Section 4 shows the framework evaluation and presents the results obtained. Finally, Section 5 reports some conclusions.

2 ISAC Functionality Description

The proposed ISAC task is performed by exploiting communication embedding based on a code modulation approach, as summarized in Fig.1-A. In this scenario, the ISAC target backscatters the chirps toward the SAR satellite, embedding information contents through the code. Assuming a code $C = \{c_1, ..., c_L\}$, where L is the code length and $c_i = \{0, 1\}$ with $i = 1, ..., L$, an encoding operation is required to balance the code and ensure transparency; hence the Manchester encoding technique has been selected for this purpose. Defining the encoded sequence as C_e with $c_{e,k} \in C_e$ and $k = 1, ..., 2L$, we have

$$[c_{e,j}, c_{e,j+1}] = \begin{cases} [-1,+1] & \text{if } c_i = 1 \\ [+1,-1] & \text{otherwise} \end{cases} \quad (1)$$

where $j = 2i - 1$, and $i = 1, ..., L$. The balancing property is ensured with (2):

$$\sum_{k=1}^{2L} c_{e,k} = 0, \quad \text{with } c_{e,k} \in \{-1, +1\} \quad (2)$$

Thus, the ISAC target backscatters the SAR chirps applying an encoded bit to each chirp. This assumption is valid under the condition of synchrony between the ground target and the SAR satellite, meaning that the ground target is aware of the time instant when it is illuminated by the SAR and the SAR Pulse Repetition Interval (PRI), such that the encoded code bit duration T is equal to the PRI, $T = \text{PRI}$. Besides, the encoded code bit values $+1$ or -1 prevent additive interference in the final image, resulting in a code-modulated backscattered chirp with a phase shift of 0 or π, respectively.

The outcome of this operation is the traditional SAR images along with three additive results: the **communication extraction** obtained by demodulating the code of the ISAC target in the raw data, the **target localization** image obtained by processing the demodulated raw data to generate the SAR image, where the contribution of the environment is reduced while the target one is highlighted due to the effect of the applied code, and the **target tracking** through multiple localization images.

3 Framework Definition

As introduced previously, validating the effectiveness of the ISAC target presents several challenges. In addition to limitations due to licensed frequencies, the stripmap mode is only adopted by Sentinel-1 in select areas of the globe, which restricts the possibility of testing the proposed ISAC target in real environments. To address these challenges, this work proposes a novel testing framework focused on emulating the ISAC target, leveraging real raw data acquired by the Sentinel-1 system, as summarized in Fig.1-B. The emulation involves a set of local code-modulated chirp replicas added to the In-phase and Quadrature (I/Q) components of the raw data available from the ESA Copernicus platform, simulating the presence of the ISAC target. Each modulated chirp replica in the set is modelled under two assumptions: (i) emulating the SAR movement to achieve optimal antenna matching and lower target-satellite distances, resulting in low chirp amplitude at the beginning and end of the set and maximum amplitude in the middle, and (ii) varying the position of each local chirp within each PRI, simulating the changing ISAC target-SAR distance, which is minimum in the middle of the set and maximum at the edges, resulting in delayed chirp replicas.

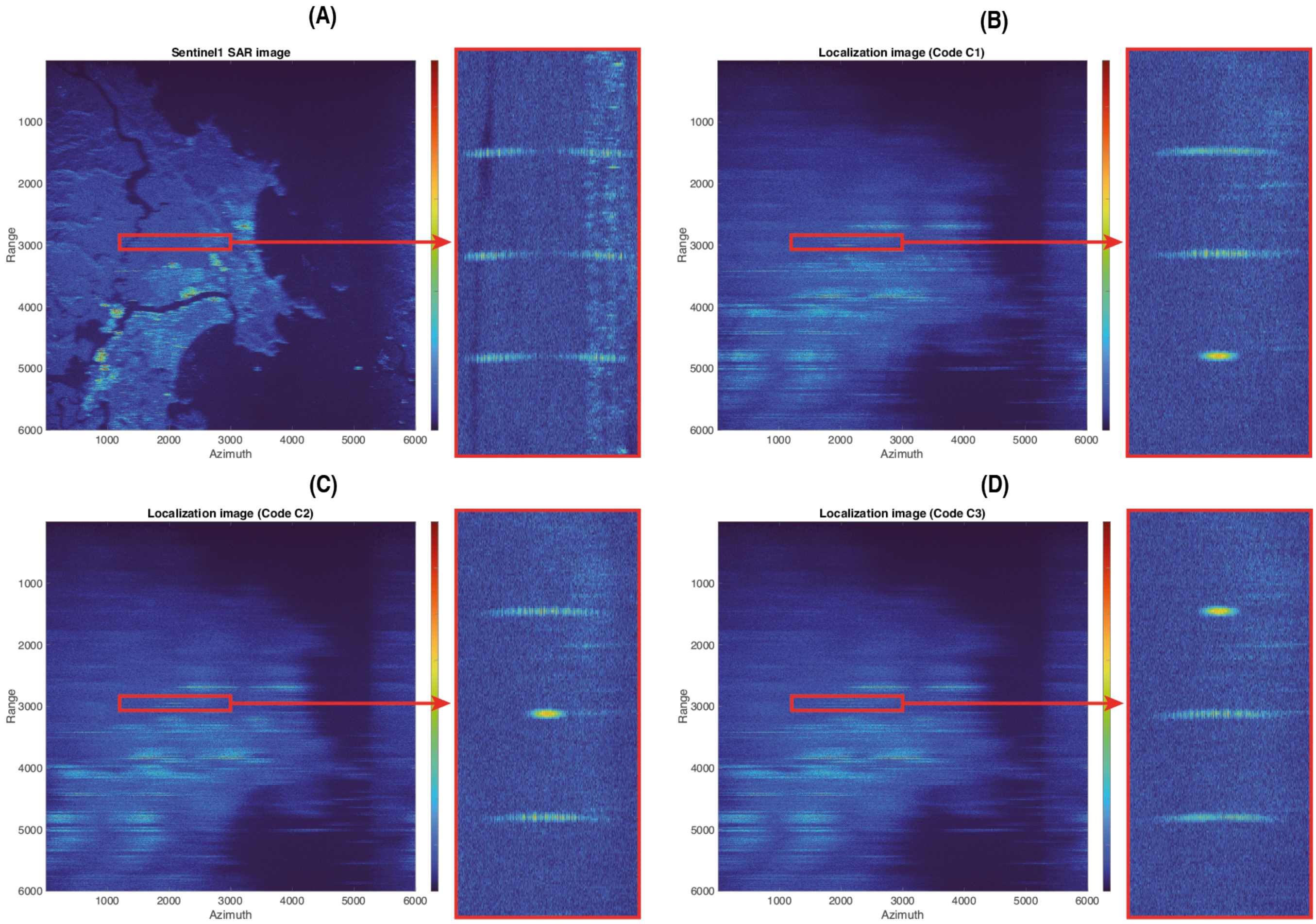

Figure 2. Emulation results with the traditional SAR image (**A**) and the image obtained from the data demodulated through the code C_1 (**B**), C_2 (**C**) and C_3 (**D**).

4 Emulation Results

The proposed testing framework has been employed to evaluate the ISAC target using real raw data of the city of São Paulo, Brazil. The raw data have been processed to generate the final image using the range migration algorithm [11]. Three ISAC targets have been emulated, implementing three different codes of the same length $L = 63$: Kasami code (C_1), Gold Code (C_2) and Pseudo-Noise code (C_3). Each code has been balanced through Manchester encoding. Considering specific parameters, including stripmap antenna azimuth beamwidth, satellite speed, and incident angle, a local replica set of 817 PRIs was considered for each ISAC target PRI set. The raw data have been demodulated by applying the code C_i with $i \in \{1,2,3\}$ to match the code-modulated replicas of the ISAC targets, maximizing the code correlation. Thus, three different images derive from the demodulated raw data, each corresponding to a specific code.

Upon observing the zoom in Fig.2-A, the ISAC targets successfully integrate a transparent code-based communication link with limited interference in the final image due to residual contributions in the azimuth direction. All codes ensure transparency since no contributions are present at the target positions, only residual components in the azimuth direction. While Kasami code C_1 appears to slightly outperform C_2 and C_3, further analysis is required for optimal code selection. Demodulating the raw data for each code reduces the contribution of the environment, highlighting the ISAC target using the specific code as shown for codes C_1 (Fig.2-B), C_2 (Fig.2-C) and C_3 (Fig.2-D). A particular mention is needed for the cross-code demodulation: each localization image presents an interfering factor in correspondence of the emulated ISAC target implementing a different code, resulting from the cross-correlation between different codes that cannot be neglected. The mitigation of cross-code residuals is left for future development.

5 Conclusions

Recent advancements in wireless communications and technological evolution of sensing techniques are driving the research for innovative solutions to improve the performance while implementing new functionalities. In this regard, ISAC represents a meeting point providing high-performance solutions, particularly for radar-based sensing technologies like SAR. Therefore, this paper presents a novel ISAC approach for the transparent integration of code

modulation technique in SAR satellites without requiring updates or modification.
Due to limitations in testing with real satellites, this work proposed a novel testing framework to evaluate the effectiveness of the ISAC target using real data acquired by Sentinel-1 satellites. The results demonstrate the possibility of implementing code-based communication links with limited interference from residual components in the azimuth direction. Future development will focus on optimal code selection to mitigate both residual components due to the codes and cross-code interference resulting in the images from demodulated data.

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