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ISAC Simulation Framework

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***Abstract*—In integrated sensing and communication (ISAC), the radar and communication functionality share the same channel and resources. Therefore resource allocation strategies are needed to satisfy radar and communication performance simultaneously. This TD introduces an ISAC simulation framework to quantify the ISAC performance in a mobile network for a given multi-dimensional resource allocation to develop new ISAC resource allocation strategies. The considered domains are time-frequency, spatial, and network. The aim is to have an appropriate trade-off between computational complexity and realistic results for proper training of machine learning techniques. Therefore the ISAC-nodes base stations (BS), user equipment (UE), and radar targets are represented in a geometrical environment to determine the relevant channel parameters, while clutter components are modeled stochastically. Furthermore, ISAC signal processing steps are implemented in a modular way. This End-to-End simulation allows the evaluation of the ISAC performance in terms of detection and data transmission by modeling effects like multi-path propagation and the impact of antenna directivity.**

I. INTRODUCTION

In recent years, communications and radar technologies have been developed as separate systems in parallel. To avoid interference between the two systems, they are separated in the spectrum and by infrastructure. In ICAS, the communication and radar functionalities are integrated into a joint system, reducing the need for spectral resources and infrastructure. This is important in today's world as more and more broadband services are offered over radio channels (including mobile communications, automotive radar, TV, etc.), making radio resources a limited and rare commodity.

Due to parallel development, radar and communication systems were optimized separately to optimize their performance. Therefore, the signal shapes and hardware implementations differ from each other. Communication systems are designed to reliably transmit data from a transmitter over a transmission channel (e.g., wireless) to a receiver. In radar, a signal is emitted into the environment to be monitored to detect targets from the backscattered signal and to estimate their parameters such as distance, speed, or angle.

When operating both functionalities in one system, a joint waveform and a shared infrastructure are to be used. Therefore, new approaches have to be developed to satisfy the performance of both functionalities. In this context, resource allocation plays a crucial role. The aim of the ISAC simulation framework is to provide an environment to develop algorithms with which an intelligent resource allocation optimizes/satisfies the desired performance of the communication and radar functionality.

This TD describes the principles of the ISAC simulation framework. It determines the ISAC performance for communication and radar based on multi-dimensional resource allocation in time, frequency, spatial, and network. The assumed waveform is OFDM-A as it is normally used in mobile communication. Furthermore, the simulation is implemented in an end2end manner, including the relevant ISAC signal processing steps, to consider disturbing effects like multipath propagation on the ISAC performance.

The TD includes the introduction of the ISAC channel, the considered multi-dimensional resources, the implemented signal processing steps for the end2end simulation, the ISAC performance parameters, and an outlook.

II. ISAC CHANNEL MODEL

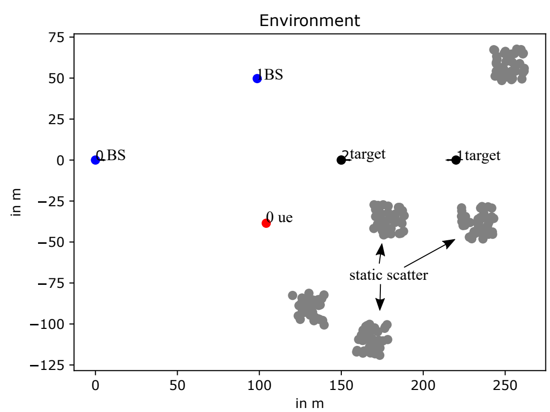


Fig. 1: ISAC environment in 2D with an BS (blue), radar targets (black), ue (red), and static clutter (grey) .

Channel modeling is a crucial part of the simulation. The requirements for communication and radar have to be considered. The channel must be suitable to simulate the data transmission and at the same time represent the relevant parameters estimated for the radar application. For this purpose, a multipath channel model with the following parameters is used:

- Amplitude
- Delay
- Doppler
- Direction of arrival (DoA)
- Direction of departure (DoD)

These parameters are considered for multi-path propagation, including the LOS component and multiple NLOS components arising from radar objects or random static scatter (clutter).

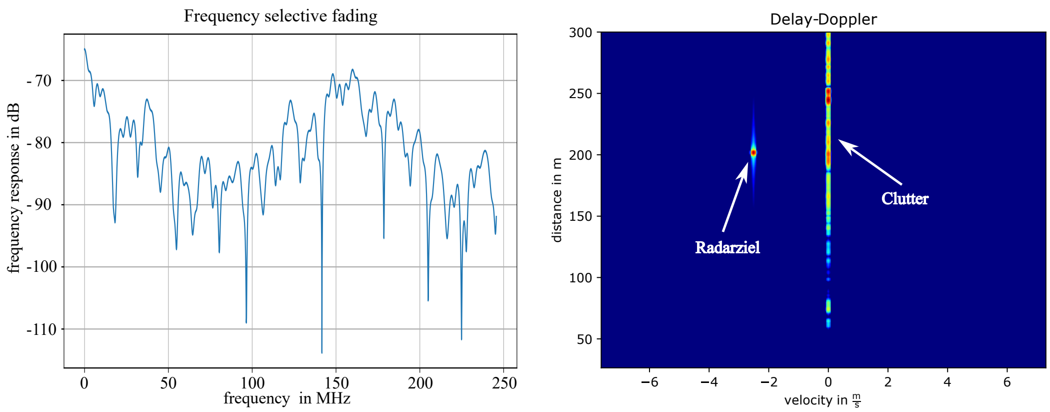


Fig. 2: Channel of radar target and clutter in frequency domain (left) and as delay-doppler-map (right).

A. Geometric Model

To determine the channel parameters, the pose of the ISAC nodes are defined geometrically in the 3D Cartesian coordinate system. It includes the position, velocity and orientation and is updated for every observation time. In figure 1 the ISAC nodes and random scatter are visualized.

Pose of ISAC nodes:

- **position**: The position is necessary to determine the delay and amplitude and it is defined as:

$$\mathbf{p} = [p_x, p_y, p_z]^{\mathrm{T}} \tag{1}$$

- **velocity:** The velocity is necessary to determine the bi-static doppler and it is defined as:

$$\mathbf{v} = [v_x, v_y, v_z]^{\mathrm{T}} \tag{2}$$

- **Orientation:** The orientation is necessary to transform the local coordinate system into a global coordinate system and vice versa to determine the DoD and DoA. It is defined by the Euler angles yaw, pitch, and roll:

$$\mathbf{\Psi} = [\psi, \phi, \theta]^{\mathrm{T}}. \tag{3}$$

Transformation between coordinate systems: The two following coordinate systems are used to consider the orientation for calculation of the channel parameters:

- The **global Cartesian coordinate system** is used to determine the distance, delay, bi-static doppler between the nodes.
- the **local spherical coordinate system** is used to determine DoA and DoD, with respect to the orientation which sets the antenna gain and bi-static rcs.

B. Channel Parameters

The channel parameters are determined based on the geometric pose of the ISAC nodes.

- **amplitude:** The complex amplitude b contains the following elements:

$$b = b_{\text{path}} \cdot b_{\text{rcs}} \tag{4}$$

The scattering of a multi-path component is described by point scatter and its bi-static RCS. If the scatter is a radar object the bi-scatter is derived from a lookup table, which is generated based on 3D rcs simulation. The rcs of a static scatter (clutter) is generated randomly.

$$b_{\text{rcs}} = \text{lookup\_table}(\text{DoA}, \text{DoD}) \tag{5}$$

Furthermore, the distance is proportional to the distance between the nodes.

$$b_{\text{path}} \propto \frac{1}{d_{\text{tx,s}} \cdot d_{\text{s,rx}}} \tag{6}$$

- **Delay:** The delay is defined by the propagation velocity c_0 and the distance between the nodes.

$$\tau_{l,s} = \frac{d_{\text{tx,s}} + d_{\text{s,rx}}}{c_0} \tag{7}$$

- **Doppler:** The doppler shift is determined by projecting the velocity vector on the direction vector between the nodes. Note that the vectors are defined in the global coordinate system.

$$f_{\text{D}} = \left(\frac{\mathbf{v}_{tx}^{\mathrm{T}} \cdot (\mathbf{p}_{\text{s}} - \mathbf{p}_{\text{tx}})}{d_{\text{tx,s}}} - \frac{\mathbf{v}_{rx}^{\mathrm{T}} \cdot (\mathbf{p}_{\text{rx}} - \mathbf{p}_{\text{s}})}{d_{\text{s,rx}}} \right) \cdot \frac{f_0}{c_0} \tag{8}$$

- **DoD:** The DoD is defined in the local spherical coordinate system of the node and includes azimuth and elevation.
- **DoA:** The DoA is defined in the local spherical coordinate system of the node and includes azimuth and elevation.

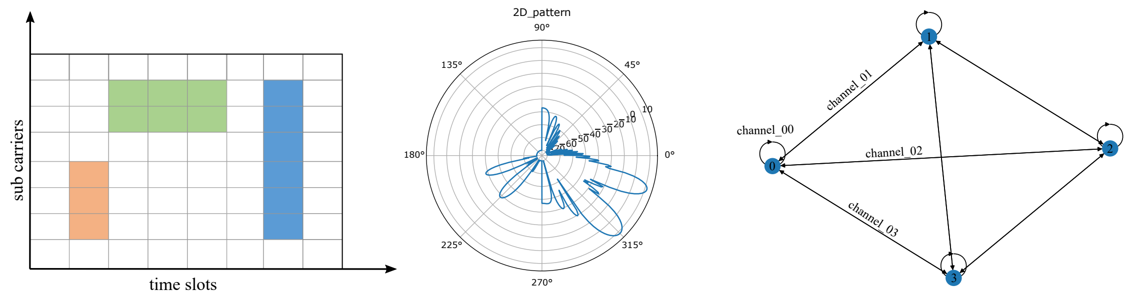


Fig. 3: ISAC resources: resource blocks in time-frequency-domain (left), beam-pattern of antenna array in spatial domain (middle), network constellation (right).

C. *transfer function*

The received signal is defined by the transmitted signal and the transfer function of the channel. In figure 2 the channel of a radar object and clutter is shown in frequency domain and delay-doppler domain.

$$\mathbf{y}_{n,t} = \mathbf{H}_{n,t} \cdot \mathbf{x}_{n,t} \tag{9}$$

Channel model: The transfer function is defined by the channel matrix which contains the channel parameters coming from the geometrical formulation of the ISAC nodes.

$$\mathbf{H}_{n,t} = \sum_{q}^{Q} \sum_{l}^{L_q} b_{q,l} \mathrm{e}^{-j2\pi n\tau_{q,l},\Delta f} \mathrm{e}^{\mathrm{j}2\pi t, f_{\mathrm{D}q,l}, T_{\mathrm{s}}} \cdot \mathbf{a}_{\mathrm{rx},q,l} \cdot \mathbf{a}_{\mathrm{tx},q,l}^{\mathrm{T}} \tag{10}$$

The model contains path components from Q transmitting BSs and L_q multi-path component. The path component is modeled with the channel parameter introduced before.

The steering vector for every path $\mathbf{a}_k \in \mathcal{C}^{M_C \cdot M_R \times 1}$ is determined by

$$\begin{aligned} \mathbf{a}_k = &[1, \cdots, \mathrm{e}^{\mathrm{j}(M_C-1)\frac{2\pi}{\lambda} d \cos(\phi_k)\sin(\theta_k)}, \cdots, \\ &\mathrm{e}^{\mathrm{j}\frac{2\pi}{\lambda} d(M_C-1)\cos(\phi_k)\sin(\theta_k)+(M_R-1)\sin(\phi_k)}]^{\mathrm{T}}. \end{aligned} \tag{11}$$

Where d is the element distance, λ is the wave length, M_{C} is the number of column elements, M_{r} is the number of row elements, and ϕ_k and θ_k are the azimuth and elevation angles of path k, respectively.

An uniform rectangular array (URA) is assumed to create beams. The beams are designed by weighting the tx signal at the array elements with a precoding matrix.

$$\mathbf{x}_{n,t} = \mathbf{B}_{n,t} \cdot \mathbf{s}_{n,t} \tag{12}$$

III. ISAC Resources

The ISAC simulation framework aims to determine the ISAC performance for a give resource allocation. The ISAC resources which are considered in the simulation environment are listed below and described how they can be adapted. Additionally the resources are visualized in figure 3.

- **Resource Blocks:** For data transmission and or illumination of radar targets, resource blocks are allocated in the time-frequency radio frame. The shape and size of the RB affect the data throughput and the ambiguity function, which is crucial for the parameter estimation of the radar objects.
- **Power:** The tx power can be adjusted depending on the sub-carrier. Thus the SNR at the receiver as well as the ambiguity function can be influenced.
- **Modulation**: The modulation type can be selected from QAM-M and PSK. With it the data throughput can be increased depending on the SNR.
- **Spatial:** Beams can be generated with the antenna arrays and the pre-coding matrix to reduce the SNIR at the receiver. The implemented methods to caluculate the pre-coding matrix are ”Digital Beam Steering” and ”Zero forcing”.
- **Network:** In the network domain, the BS are selected to beam ISAC nodes.

IV. Signal processing

Metrics to evaluate the performance of radar and communication can be described as theoretical boundaries for specific technical conditions. They can easily be obtained based on theoretical information theory (e.g. CRLB or Shannon Capacity). The disadvantage is that simple channel conditions are assumed which are not realistic in real measurements.

The idea is to integrate a end2end simulation considering the relevant ISAC signal processing steps. The advantage is that more realistic disruptive effects (e.g. clutter due to multi-path propagation) on the ISAC performance can be investigated. Furthermore, because the signal processing steps are modular, they can easily replaced by new ones, which makes it usable to develop ISAC signal processing. The implemented

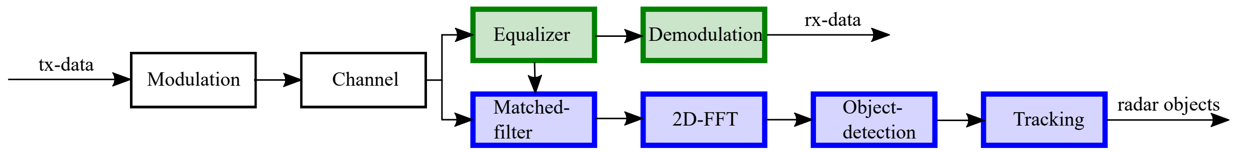


Fig. 4: Flow-graph of signal processing steps. Radar components in blue, communication in green.

signal processing steps are shown as a flow-graph in figure 4

In summary the ISAC signal processing steps of the ISAC simulation framework are:

- Modulation/Demodulation
- Equalizer (Zero forcing)
- Matched filter (Deviation)
- Clutter suppression (Notch filter, Exponential Background Subtraction)
- Object detection (CFAR)
- Parameter estimation (parabolic fitting)
- Multi Target Tracking (Kalman filter)

V. ISAC Performance Evaluation

The quantification of the ISAC performance is done via quality of service (QoS) parameters. They are used as feedback for the resource allocation to ensure a defined performance. On the one hand, the ISAC performance is derived from the end2end simulation of the implemented signal processing steps. On the other hand, the theoretically achievable performance boundary is given, which is listed below. In figure 5b the PAPR and the BER are shown with respect to the distance.

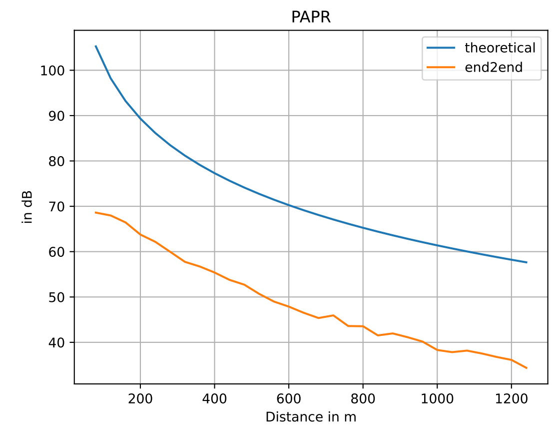
- **Peak to Average Power Ratio (PAPR)** The PAPR describes the ratio of echo level to the power level of the vicinity of the echo. It is an important parameter on which the detection probability is based. In reality, several multipath components can reduce the PAPR. For an ideal channel ratio it corresponds to the SNR of the following radar equation:

$$\mathrm{SNR} = \frac{P_{\mathrm{tx}} G_{tx} G_{rx} G_p \lambda^2 \sigma}{(4\pi)^2 d^4 k T_0 B F} \tag{13}$$

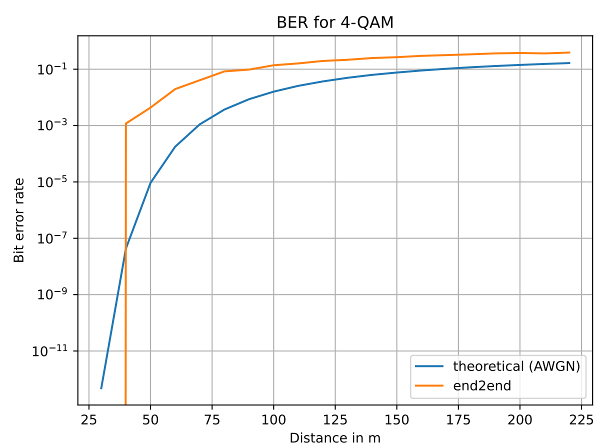
- **Detection:** The detection performance can be formulated as the detection probability for a given false alarm. A theoretical boundary can expressed if the assumptions that the signal contains only AWGN and no interference are true. The end2end result can be obtained by applying the detection algorithm CFAR. The theoretical detection probability with CFAR is

$$p_D = p_{\mathrm{fa}}^{\frac{1}{1+snr}}. \tag{14}$$

- **Accuracy:** The accuracy of an estimated parameter can be formulated by its variance. The theoretical



(a) Peak to average power ratio (PAPR) based on theoretical boundaries and on end2end simulation in heavy multi-path scenario.



(b) Bit error rate (BER) based on theoretical boundaries and on end2end simulation.

boundary of the variance of an estimated parameter can be obtained by the Cramer Rao lower bound (CRLB). After the end2end simulation the variance can be obtained from the covariance matrix of the state vector, estimated by the tracking unit (Kalman filter).

$$\mathrm{var}(d) = \frac{6 * \sigma^2}{(N^2-1) * M * N} * \left(\frac{c_0}{(4 * \pi * \Delta F)}\right)^2 \tag{15}$$

- **Throughput:** The throughput describes the number of correct transmitted bits in a certain time period. A theoretical boundary can be obtained by the Shannon capacity. Furthermore after the demodulation the number of correct transmitted bits are compared with the transmitted bits, to obtain the throughput from the end2end simulation. The Shannon capacity is defined by

$$C = B \cdot \log_2 \left(1 + \frac{P}{\text{SNIR}} \right). \tag{16}$$

- **Bit error rate:** The Bit error rate quantifies the relation of successfully transmitted bits to incorrect bits. The theoretical achievable BER by assuming an AWGN channel can be determined based on the modulation schema and the symbol energy.

$$p_b = \frac{2}{\text{ld}(M)} \left(1 - \frac{1}{\sqrt{M}} \right) \text{erfc} \left(\frac{3\text{ld}(M)}{2(M-1)} \cdot \frac{E_B}{N_0} \right) \tag{17}$$

VI. Outlook

The next step is using the ISAC simulation framework as a basis to develop intelligent resource allocation algorithms. An appropriate method is deep reinforcement learning. There an agent selects actions based on the observed environment and a neuronal network. The agent learns a ”good” behavior by receiving feedback (reward) from the environment and adapting the neuronal network.