Project No.501
Communication Track

Development of a New Method for Integrated Sensing and Communication Systems

פיתוח שיטת שידור-גילוי חדשה למערכות תקשורת משולבת חישה

Preliminary Report

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1 Project Goal

Integrated sensing and communication (ISAC) [1] is an emerging paradigm in wireless systems where the same hardware, spectrum, and waveforms are used simultaneously for communication and for sensing the environment. Instead of separating radar and communication systems, ISAC aims to merge them to improve efficiency, reduce costs, and enable new applications such as autonomous driving, smart cities, and high-precision localization in future 6G networks.

The goal of the project is to design, realize and test a new transmitting method for ISAC, involving spectral nulling a chirp sensing signal and combining it with an orthogonal frequency-division multiplexing (OFDM) signal, at the frequencies where the chirp is nulled. After designing such a transmitting method, it is needed to design a matching receiver and analyze it in the presence of white Gaussian noise, using pre-defined metrics (probability of detection, bit error rate, etc.).

This method offers several key advantages over existing ISAC approaches. By creating controlled spectral nulls within the bandwidth of a conventional frequency modulation (FM) chirp, it enables the insertion of OFDM communication subcarriers without significantly degrading the autocorrelation properties of the chirp signal, which are essential for high-quality radar imaging. This approach avoids the high sidelobes and sensing performance loss typically caused by directly embedding complex communication waveforms into radar signals. In addition, we introduce mechanisms for precise control of null depth and width using regularized least squares and derivative constraints-providing far greater flexibility than traditional coexistence or DFRC techniques (Dual-Function Radar-Communication). Overall, the waveform maintains radar performance while supporting high-rate data transmission, achieving a more effective balance between sensing and communication.

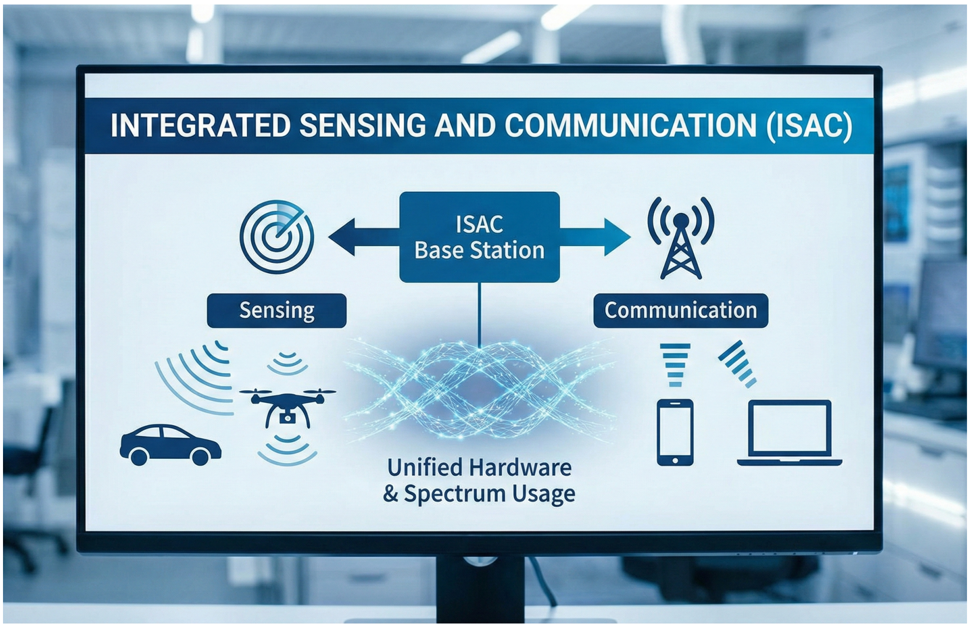

Figure 1: Conceptual illustration of ISAC technology.

2 Project Contents and Deliverables

2.1 Literature review

2.1.1 Spectral Nulling

Nowadays, the RF spectrum is increasingly crowded by multiple users, such as radar, communication, and navigation systems that are required to transmit within shared environments. While these users are generally assigned specific frequency bands, their transmissions are rarely perfectly contained. consequently, a user's emissions can "leak" into other regions via spectral sidelobes, disrupting the operation of neighboring RF systems even when their allocated bandwidths do not technically intersect.

To mitigate this interference, traditional radar waveform design has often relied on amplitude tapering to uniformly suppress spectral sidelobes. however, this approach inherently reduces the total transmitted energy, resulting in a loss of signal power. As an alternative that avoids this efficiency penalty, [2] proposes a method of spectral nulling that modifies only the phase structure of the pulse. By introducing a small, time-varying phase offset while maintaining a constant amplitude, this technique creates precise nulls at the frequencies of other RF users without sacrificing any transmit energy, effectively resolving the interference issue while preserving the radar's operational range and detection capability.

2.1.2 The ISAC Technology

ISAC (e.g., [1]) is the act of combining a sensing system with a communication system to significantly improve size, cost, power consumption, robustness and performance. Existing methods to do so can be seen, e.g., in [1], and include three types: Co-exist, co-operation and co-design. The differences between the three are explained in [1]:

- **Co-Existence**: The communication function and the sensing function are separately designed, using completely non-dependent hardware and spectrum. In this case, ISAC technologies are mainly reflected in the integration of functions, that is, the perception function obtains the information of users and the surrounding environment to improve communication performance. The only improvement is the ability to schedule communication resources.
- **Co-Operation**: The communication function and the sensing function share the same hardware resources in the form of time-division multiple access (TDMA), frequency division multiple access (FDMA), and antenna division.
- **Co-Design**: The communication function and sensing function share the same hardware resources and also the signal design, waveform, and modulation technology. This can meet future speed, delay, scaling, connectivity and reliability communication needs, and the complex and diverse sensing needs.

2.1.3 Using Spectral Nulling for ISAC

While the method in [2] focused on interference suppression, [3] extends this technique to actively utilize the created spectral nulls for data transmission. By embedding communication signals, such as Orthogonal Frequency Division Multiplexing (OFDM) subcarriers, directly into these 'silent' regions, the radar waveform can simultaneously image the environment and convey information.

The critical trade-off explored in [3] lies between achieving a deep spectral null to house communication signals and preserving the radar-waveform spectrum's integrity for effective imaging. While creating a deep null is essential for inserting OFDM subcarriers without interference, achieving this depth requires applying a more aggressive phase offset to the original chirp. However, excessive phase manipulation, specifically high variation, "damages" the spectrum by distorting the waveform, resulting in elevated and asymmetrical autocorrelation sidelobes that degrade the radar's ability to detect weak targets.

To manage this conflict, [3] employs a regularized least squares algorithm that uses a penalty parameter to limit the phase excursion. This effectively sacrifices the maximum possible null depth to ensure that the sensing properties remain robust enough for high-quality environmental imaging. In addition, the width of the null can also be modified, either by crowding several nulls with frequencies close to each other or by requiring the two first derivatives equal to zero in said frequencies.

2.2 Extensions and Variants

While [3] conceptually suggests the insertion of an OFDM signal into the nulled chirp, our project advances the work by implementing this configuration in practice to evaluate its performance. Another distinction in our approach lies in the optimization methodology. The existing framework in [3] relies on linearizing the spectral constraints via Taylor expansion to facilitate an analytical solution
The optimization problem brought up in [3] is:

$$\begin{aligned} &\min \|\phi\| \\ &\text{s.t. } S(\omega_k) = 0, \end{aligned} \tag{1}$$

where ϕ is the added phase, $S(\omega)$ is the spectrum of the adapted chirp signal, and ω_k represents the specific frequencies intended to be nulled (these can be viewed as the OFDM subcarriers).
After Taylor's expansion, $S(\omega_k)$ is approximated to be:

$$S(\omega_k) = S(\omega_k; \phi(t) = 0) + \int_0^T \frac{\partial S(\omega_k)}{\partial \phi}\bigg|_{\phi=0} \cdot \phi(t)\mathrm{d}t \tag{2}$$

and the appropriate, linearized, constraint reads:

$$\begin{aligned} &\min \|\phi\| \\ &\text{s.t. } \langle \mathbf{z}(\mathrm{t}), \phi(\mathrm{t}) \rangle = \langle \mathbf{z}(\mathrm{t}), 1 \rangle \end{aligned} \tag{3}$$

This approximation transforms the non-linear constraint $S(\omega_k) = 0$, into a simplified linear form, which, while computationally convenient, is theoretically suboptimal. In our project, we plan on solving **the non-linearized problem**, using a DNN model.

2.3 Performance Evaluation

After adding OFDM both to the baseline nulled chirp of [3] and to our extension, it is nothing but natural to test both systems in the presence of noise, more specifically, additive white Gaussian noise (AWGN). We will compare between the two solutions via different metrics for the **detection probability** of the Chirp, and the **bit error rate (BER)**.

2.4 Public Code Repository

The simulation codes will be written in Python and will run on Bar Ilan's GPU servers. The final code scripts will be available on a public repository on GitHub, as well as a README text file explaining how to run them. Some of the main libraries we will use include the following:

- Numpy - For efficient numerical and vectorized computations.
- PyTorch - For automatic differentiation, GPU acceleration, and building optimization routines.
- Matplotlib - For visualization of waveforms and graphs.

2.5 Simulation results

The initial phase of the project focused on reproducing the core "phase-only nulling" capability. We have successfully implemented the linearized spectral nulling algorithm described by [3] using Python. The following result demonstrates the implementation of the baseline spectral nulling algorithm. After generating a standard Linear Frequency Modulated (LFM) waveform, we employed the analytical linearized method derived from [3] to calculate the phase offset ($\hat{\phi}(t)$) required to enforce a spectral null at 0.4 MHz. The resulting adapted spectrum, shown in Fig. 2, validates that the applied phase offset effectively eliminates signal power at the designated 0.4 MHz frequency, producing the expected spectral null.

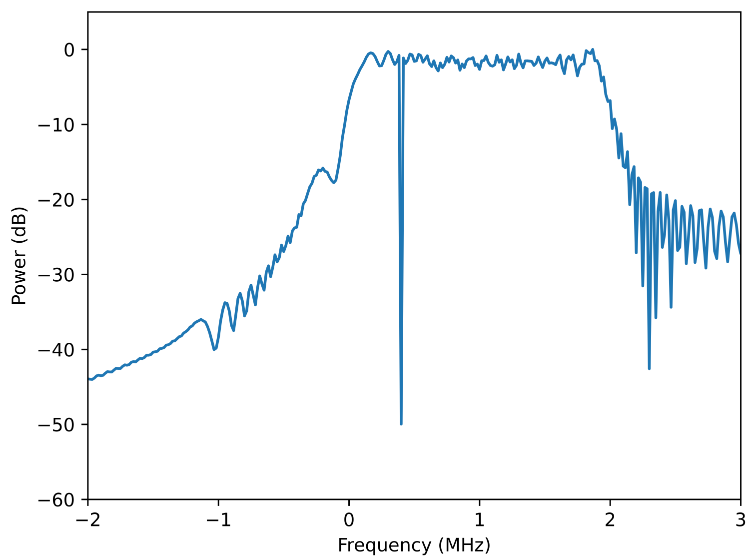

Figure 2: Adapted LFM spectrum for example, as shown in [3] and achieved by us

3 Project Work Plan

In the following table, we listed the different milestones of our project, including a description and the estimated completion time:

Task	**Description**	**Estimated Completion**
Literature review	• Review the core principles of Integrated Sensing and Communication. • Read [3] and understand it perfectly. • Study and practice the framework of solving optimization problems and Deep Neural Networks (DNNs), specifically for solving complex, non-linear optimization problems.	beginning of December
Baseline Implementation	Implement the baseline solution, simulating a chirp signal and nulling it, as shown in the article. • Simulating the chirp. • Optimizing for $\hat{\phi}$ and nulling the chirp in specific frequencies. • Implementing the algorithms for controlling null's depth and width. • Reproducing the known baseline results from the literature.	End of December
Computing environment setup	• Access to Bar-Ilan's GPU server • Installation and testing of relevant Python libraries (Numpy, Pytorch, Matplotlob etc.)	Midterm presentation
Implementation of proposed extension(s)	• Dropping the linear approximation of the constraints. • Adding the OFDM signal with the frequencies where the chirp is nulled. • Developing matched filter and hypothesis decision rule.	End of May

Task	**Description**	**Estimated Completion**
Noise + analysis	• Adding AWGN to our model • Testing and analyzing our model • Potentially learning the distortion made by the OFDM to the LFM and changing the receiver accordingly to preform as an optimal receiver.	Final presentation

Added here is a more detailed Gantt chart outlining our project plan, including projected milestones and an estimated timeline for completion:

	9.25	10.25	11.25	12.25	1.26	2.26	3.26	4.26	5.26	6.26	7.26	8.26
Literature review												
ML practice												
Baseline implementation												
Learning LaTeX												
Adding OFDM												
Exact Solution												
Receiver												
Noise + Analysis												
Book writing and editing												

References

[1] H. Ma, ``Integrated sensing and communication-the isac technology,'' in *2024 IEEE 2nd International Conference on Sensors, Electronics and Computer Engineering (ICSECE)*, 2024, pp. 225--229.

[2] K. Gerlach, M. R. Frey, M. J. Steiner, and A. Shackelford, ``Spectral nulling on transmit via nonlinear fm radar waveforms,'' *IEEE Transactions on Aerospace and Electronic Systems*, vol. 47, no. 2, pp. 1507--1515, 2011.

[3] P. Vouras, ``Frequency modulated waveforms for integrated imaging and communications,'' in *2024 58th Asilomar Conference on Signals, Systems, and Computers*, 2024, pp. 894--897.

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Bar-Ilan University

נספח מס' 1 – הצהרה על שימוש בכלי בינה מלאכותית יוצרת (במ"י – Generative Artificial Intelligence)

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שם המרצה: ד"ר אמיר וייס, שם ומספר הקורס: פרוייקט- 8340101

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חתימה: ____ תאריך: 8/12/2025