# GNU Radio realization of Waveform Co-design for Joint Radar-Communications system using SDRs

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## Abstract

Combining Software Defined Radios (SDRs) with the GNU Radio software development toolkit can enable rapid prototyping of integrated sensing and communications (ISACs) systems. In this paper, we conduct a Hardware-In-The-Loop (HWIL) Over-The-Air (OTA) experiment on a low-cost SDR platform testbed to demonstrate the feasibility of cooperative waveform design for a joint radar-communications system. We implement the system using USRP (Universal Software Radio Peripheral) B210s with GNU Radio acting as command software for the SDRs. A joint radar-communications node acts as a mono-static radar trying to detect a target in the environment, while also acting as a communications relay. A separate SDR transmits a complete BPSK or QPSK modulated signal that is implemented completely in GNU Radio. The joint radar-communications SDRs, equipped with high gain horn antennas, simultaneously performs radar processing to detect an emulated target in the environment and decoding of a communications message. Different modulation schemes for the communications transmitter, such as BPSK and QPSK are also implemented to verify the soundness of the joint radar-communications system.

## 1. Introduction

Congested spectrum for wireless communications users has led many to rethink the current method of spectral access, leading to the development of a wide range of cooperative radio design techniques under the label of "Integrated Sensing and Communications" or "RF convergence" (Bliss, 2014; Paul et al., 2016; Labib et al., 2017). One facet of ISAC or RF convergence research is geared towards cooperative waveform design, in which several types of waveforms are jointly optimized to simultaneously enable multiple RF capabilities, such as communications, radar, and positioning, navigation, and timing (PNT). (Hassanien et al., 2016; Zheng et al., 2017; Peng et al., 2021; Sturm et al., 2009; Chiriyath et al., 2019; Doly et al., 2022). In Fig. 1, we consider a simple multiple-access scenario in which radar and communications users compete for spectral access. This scenario includes a communications transceiver, a radar transceiver, a joint radar-communications transceiver, and an external interferer. At this point, this is a well studied problem with several existing solutions.

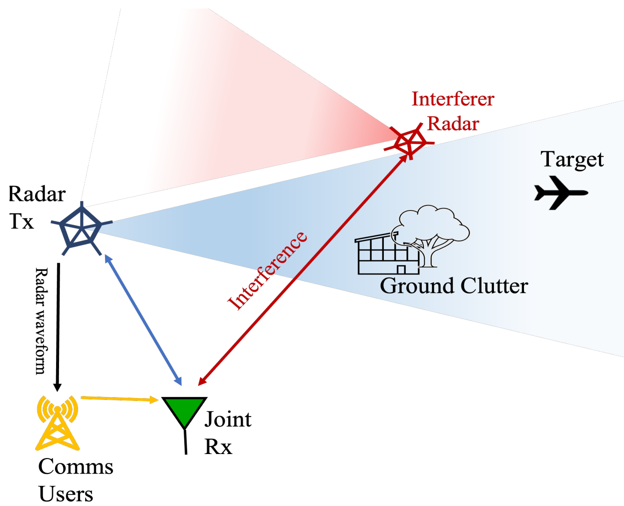


*Figure 1.* Example joint radar-communications system configuration in which a joint transceiver simultaneously receives transmissions from a radar transceiver, communications transceiver, and an interferer.

While a considerable amount of research exists that ex-

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plores waveform co-design, most of the results (including our own) have been obtained via simulation. Developing real-time implementations of such novel and emerging systems over-the-air is highly non-trivial. In (Liu et al., 2019) authors performed a joint radar-communication Software Defined Radio (SDR) platform with GNU-Radio as command software and USRPs as its front-end. Orthogonal Frequency Division Multiplexing (OFDM) is used as the wireless communications system. Authors discuss the implementation of GNU Radio-based software defined radio (SDR) for designing a frequency modulated continuous wave (FMCW) radar to detect stationary and moving targets discussed in (Aulia et al., 2015; He et al., 2017). In (Prabaswara et al., 2011) a GNU Radio based software-defined FMCW (Frequency Modulated - Continuous Wave) radar is studied for weather surveillance application.

Through this paper, we start building a path towards evaluating waveform co-design methods in real-time, over-the-air experiments.

### 1.1. Key Contributions

In this paper, we conduct a Hardware-In-The-Loop (HWIL) Over-The-Air (OTA) experiment on a low-cost SDR platform testbed to demonstrate the feasibility of cooperative waveform design for a joint radar-communications system.

Specifically, we implement a RF convergence system that can simultaneously transmit and receive data and perform both radar processing and communications decoding simultaneously at the receiver chain. We implement the system using USRP (Universal Software Radio Peripheral) B210s with GNU Radio acting as command software for the SDRs. A joint radar-communications node acts as a mono-static radar trying to detect a target in the environment, while also acting as a communications relay. A separate SDR transmits a complete BPSK or QPSK modulated signal that is implemented completely in GNU Radio. The joint radar-communications SDRs, equipped with high gain horn antennas, simultaneously performs radar processing to detect an emulated target in the environment and decoding of a communications message. Different modulation schemes for the communications transmitter, such as BPSK and QPSK are also implemented to verify the soundness of the joint radar-communications system.

This simple system set-up can be used to test the joint radar-communications performance of any type of waveform employed. In this paper, we evaluate the performance of un-optimized modulated (BPSK or QPSK) communications signal and an ASK radar signal.

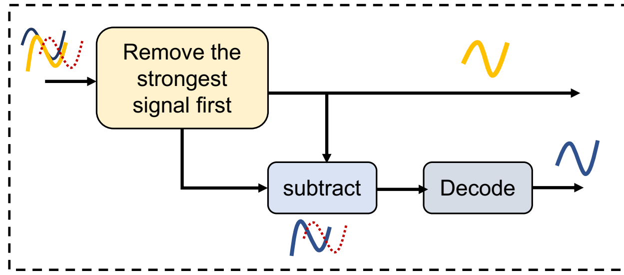


*Figure 2.* Simple block diagram of Successive Interference Cancellation algorithm SIC.

## 2. Prior Solutions of Waveform Co-design Problem

The joint radar-communications system has two effective transmitting channels and the output of the transmitting nodes converge to a single receiver node at the joint radar-communications receiver end. The stronger radar signal is predicted and removed from the composite return. An optimal multi-user receiver model employing *Successive Interference Cancellation* (successive interference cancellation (SIC)) (Bliss & Govindasamy, 2013) is used to separate both the signals from composite form as showed in Fig. 2.

### 2.1. SIC Receiver Model

SIC is an optimal multi-user receiver model called SIC (Chiriyath et al., 2017) to remove the communication signal from the radar return described in Fig. 2. Based on the prior observations of the radar target range (or time delay) up to some random fluctuation (also called process noise) $n_{\text{proc}}(t)$ as a zero-mean random variable, we generate the radar return. Then we subtract the predicted radar return from the joint radar-communications signal received.

### 2.2. Waveform Co-design via Dynamic Programming

In our previous papers, (Doly et al., 2020; 2022), we posed the waveform codesign problem as a decision-making problem and solved the problem via dynamic programming. To set up any problem in the POMDP, we need to define the POMDP ingredients, namely states, actions, state-transition law, observations and observation law, and reward function, in the context of the particular problem at hand. So, we model the system dynamics as a discrete event process, where $k$ represents the discrete time index. We formulate the problem through the state, action, and reward functions. The reward function rewards the decision $u_k$ taken at time $k$ given the state of the system is $x_k$ as defined below:

$$R(x_k, u_k) = \alpha R_{\text{est}}(x_k, u_k) + (1-\alpha) R_{\text{comm}}(x_k, u_k), \quad (1)$$

where $R_{\mathrm{est}}$ is the radar estimation rate, $R_{\mathrm{comm}}$ is the communications rate, and $\alpha \in [0, 1]$ is a weighting parameter (Doly et al., 2020; 2022).

### 2.3. Waveform Co-Design Over-the-Air Using the WISCANet Network

In (Doly et al., 2023) the joint radar-communications problem was implemented using the WISCANet SDR test-bed Network. In the experiments, a target response is emulated by encoding a time delay and carrier frequency shift of a predefined target path into the transmission waveform described in (Doly et al., 2023). The joint-receiver utilizes the Kalman filter to track the range and range-rate of the target. The Kalman filter provides a state-space solution to the Wiener problem (Kalman, 1960).

## 3. GNU-Radio realization of Waveform Co-design Problem

### 3.1. Problem Scenario

In Fig. 3 we showed the entire system block diagram of the joint radar-communications OTA experiment. We simplify the complex joint radar-communications waveform Co-design decision-making problem as described in Section 2.2 with a real-time signal processing problem. We use the SDRs within the GNU Radio algorithm development environment as shown in Fig. 3. The radar and communications node have their own transmitting chain with a dedicated transmitter SDR as shown in the Fig. 3. The receiver SDR receives the joint signal. Then we apply SIC to determine the correlation estimation and then remove the strongest signal. We consider free radar return, a communications node, and a single joint node (joint receiver).

### 3.2. Correlation Estimator and Peak Removal

We implement a simplified version of SIC receiver model in GNU Radio algorithm development platform. The GNU Radio flowgraph of SIC receiver model is shown in Fig.4.

Correlation estimator block correlates the input signal against the provided reference signal. It compares an incoming stream of samples against a known pattern or reference signal, peaking when there is a match. This block is designed to search for a sync word by correlation and uses the results of the correlation to get a time and phase offset estimate. These estimates are passed downstream as stream tags for use by follow-on synchronization blocks. The users need to define a $time_{est}$ (estimate of phase offset) and $phase_{est}$ (estimate of symbol timing offset) tag marking delay from the start of the correlated signal segment, in order to mark the proper point in the sync word for downstream synchronization blocks.

The $corr_{est}$ contains the correlation value of the estimates and the very first value of the $corr_{est}$ is the start sample of the correlation and its tagged value. The $corr_{tag}$ information as the output of the "Correlation-Estimator" block is sent to our designed "Est-Remove-Peak" block to remove the estimated peak of the joint received signal as shown in Fig. 4. The "Est-Remove-Peak" block works on a simple peak-removal algorithm by removing the estimated peak from the jointly received signals.

The result of the "Est-Remove-Peak" (in Fig. 4) block is the post SIC signal which is only the communications. After the subtraction, we can restore the original radar returns from the composite signals.

### 3.3. Over-The-Air Experiment

GNU-Radio is an open-source software to implement software-defined radios. The transceiver flow diagram used to control USRPs in our experiments is developed based on signal processing blocks provided by GNU Radio. We use GNU Radio algorithm development environment to implement the joint-multiple access system topology using two software-defined radio nodes.

The network topology consisted of a communications transmitter node, radar transmitter node, and joint communications-radar receiver node as shown in 3. In Fig. 5 each radio node consisted of an Ettus Research universal software radio peripheral (USRP) B210 transceiver. Two of the transceivers were equipped with high gain horn antenna and a single monopole antenna for joint receiver. The monopole antenna frequency range is from 1.7- 2 GHz, with a 3.7 dBi average gain. Each radio node could be tuned upto 900 MHz and 20 MSPS sampling rate. The SDR network testbed utilizes a low-duty cycle signal processing approach to emulate continuous-time operation within the GNU Radio algorithm development environment. The antennas are separated by a partition to mitigate the crossover interference as shown in Fig. 5.

## 4. Experimental results and Discussions

### 4.1. Experimental Setup

The radar-communication system is established with two USRPs B210 SDR Kit -Dual Channel Transceiver. The USRP B210 provides a fully integrated, single-board, Universal Software Radio Peripheral (USRP) platform with continuous frequency coverage from 70 MHz – 6 GHz.

One USRP B210 is used as the transmitter, where we used RF channel A:A (Tx/Rx) as the communications transmitter and RF A:B (Tx/Rx) as the radar transmitter. Both of the USRPs are equipped with horn antennas, which have directional patterns thus we could acquire stronger echo signal.

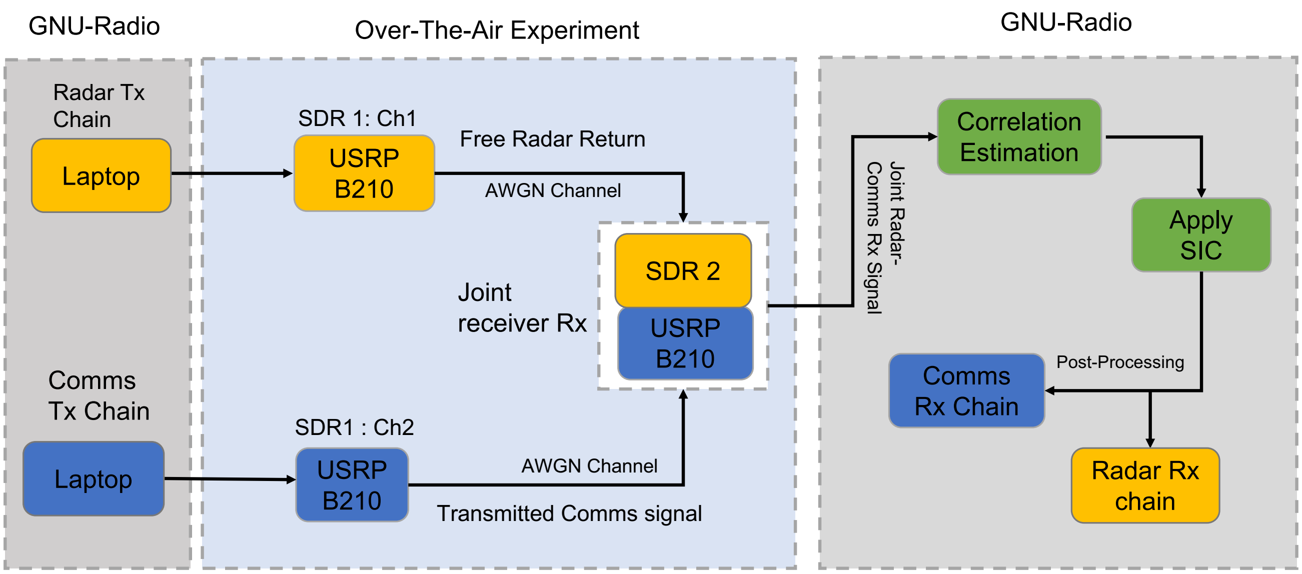


*Figure 3.* Entire system block diagram of the joint radar-communications OTA experiment.

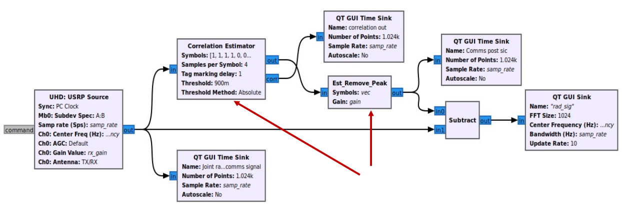


*Figure 4.* GNU-Radio schematic design of correlation and peak Removal.

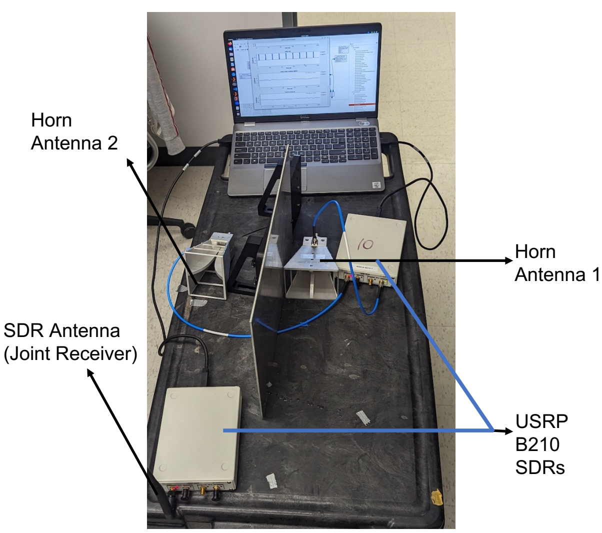


*Figure 5.* OTA experiment of waveform co-design problem using SDRs within the GNU-Radio algorithm development environment.

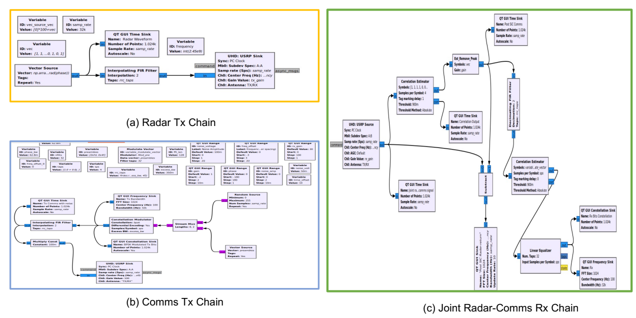


*Figure 6.* Entire GNU-Radio flow-graph of joint radar-communications waveform design problem.

Another USRP is used as the joint radar-communications receiver with a single monopole antenna with a 3.7 dBi average gain.

Each of USRPs is connected to one Linux machine using Ethernet cable. Radar detection experiments must be conducted under the condition of time synchronization between transmitter and receiver. For the sake of simplicity and we do not consider any target range or Doppler estimation in our experiment. Instead, we use a free echo or radar return from the environment (wall in-front of the transceiver in this experiment) as the radar returned.

### 4.2. Waveform Separation

We use the 'QT-GUI-Time-Sink' block to see the original radar signal and the correlated peak of the returned signal as shown in Fig.7. As we can see, the first estimated peak is detected at about 2.5ms and then continued at 5ms, 7ms,

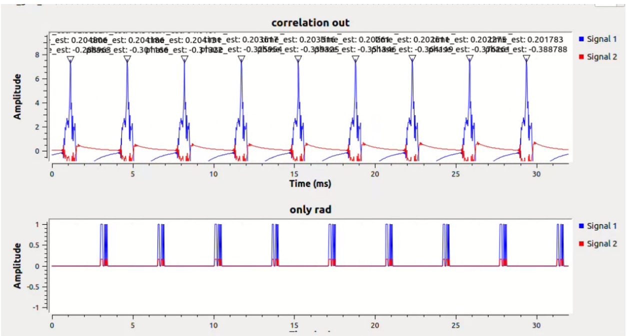


*Figure 7.* (upper) Output of the correlation estimator block and peak detection, (lower) only radar transmission.

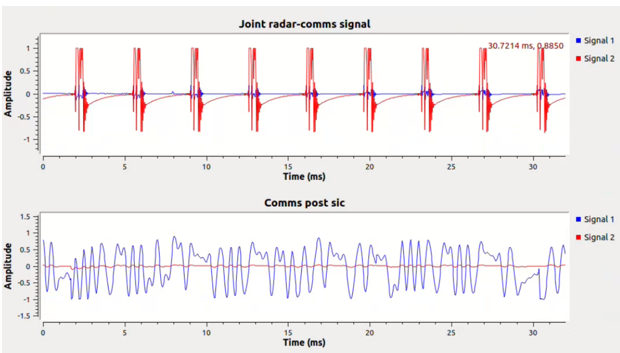


*Figure 8.* (upper)Joint radar-communications signal at the joint receiver end, (lower) result of the post SIC. Only communications signal with noise.

and so on in Fig.7 (upper). In Fig.7 (lower) we plot the original radar waveform.

In Fig.8(upper) we can observe an overlap between radar returns with the communications signals. The red and blue lines denote the real and imaginary parts of a signal. In Fig.8(lower) we can see the resultant output of post SIC. As expected, the result of the post SIC is only the communications received signal with some noise.

### 4.3. Communications Signals Restore

In Figs. 9, 10, we plot the results of communications signals after SIC receiver end post signal processing. The BPSK modulated header and message bits are sent through the transmission chain as shown in Fig. 9(lower). The constellation of BPSK modulated signal at the transmitting and receiving ends are shown in Fig. 9.

The BPSK modulated header and the QPSK modulated message bits are sent through the transmission chain as shown in Fig. 10(lower). The constellation of QPSK modulated signal at the transmitting and receiving ends are shown in Fig. 10.

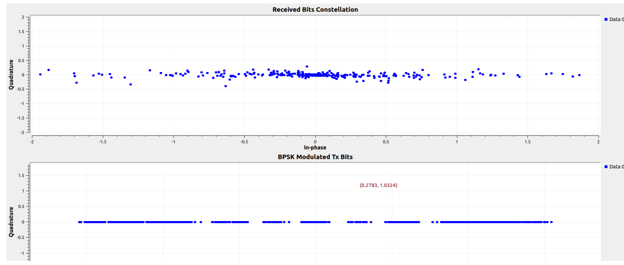


*Figure 9.* The constellation of BPSK modulated header and message bits at the transmitting and receiving ends.


*Figure 10.* The constellation of the BPSK modulated header and the QPSK modulated message bits at the transmitting and receiving ends.

## 5. Conclusion

The goal of this paper, we build a path towards evaluating waveform co-design methods in real-time, over-the-air experiments. We conduct a Hardware-In-The-Loop (HWIL) Over-The-Air (OTA) experiment on a low-cost SDR platform testbed to demonstrate the feasibility of cooperative waveform design for a joint radar-communications system. We implement a RF convergence system that can simultaneously transmit and receive data and perform both radar processing and communications decoding simultaneously at the receiver chain. We implement the system using USRP (Universal Software Radio Peripheral) B210s with GNU Radio acting as command software for the SDRs. We use our system setup to evaluate the performance of un-optimized, modulated (BPSK or QPSK) communications signal and ASK radar signal. This simple system set-up can be used to test the joint radar-communications performance of any type of waveform employed.

In our future studies, we will address challenges including time-varying communication demand and real-time target detection probability while evaluating the performance of optimized waveform.

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