Real-Time FMCW Radar System for Waveform Optimization using SDRs

Shammi A. Doly SDOLY@ASU.EDU
Gerard Gubash GERARD.GUBASH@ASU.EDU
Mikko Heino MIKKO.HEINO@TUNI.FI
Alex Chiriyath ACHIRIYA@ASU.EDU
Daniel W. Bliss D.W.BLISS@ASU.EDU
Center for Wireless Information Systems and Computational Architectures (WISCA), Arizona State University, Tempe, AZ, 85281, USA

Abstract

We develop a highly flexible real-time FMCW radar system for designing and testing different radar waveforms (e.g., triangular, sawtooth) and radar signal processing algorithms (e.g., stretch processing) without the need for extensive hardware modifications and MATLAB codes. We implement an adaptive waveform co-design technique in a single real-time feedback loop for multi-user networks applications leveraging low-cost SDRs. To implement a feedback loop in real-time, an asynchronous message-passing interface is employed in this experiment. Furthermore, we show the benefits of radar waveform optimization, particularly by increasing RMS bandwidth and significantly increasing target detection performance by enhancing range resolution. To demonstrate real-time spectrum optimization, we use the GNU Radio block for real-time spectrum analyzer (RTSA)-like spectrum visualization.

1. Introduction

The "Spectrum Congestion" problem in wireless networks has led researchers to investigate the potential use of available radio detection and ranging (RADAR), commonly known as "radar" bands to share with communications users, leading to the development of a wide range of cooperative radio design techniques under the label of "Joint Sensing and Communications" or "Network as Sensor (Nas)" (Tarassenko et al., 2006; Bliss & Govindasamy, 2013; Paul et al., 2016; Labib et al., 2017; Liu et al., 2019). This forces wireless systems to employ adaptive and intelligent waveform co-design algorithms which can dynamically adjust their characteristics based on the environment and dynamic user requirements (Hassanien et al., 2016; Chiriyath et al., 2019; Doly et al., 2020; 2022).

Moreover, traditional sensing and communication systems, operating in rigid configurations and dedicated spectrum allocation, are naturally resource-inefficient and inflexible (Bliss & Govindasamy, 2013). Recently, radar has spread its application areas more for civilian applications such as in air traffic control, naval, automotive, health, and IoT devices (J. Li, 2009; Heunis et al., 2011; Bliss, 2014; Paul et al., 2016).

However, designing an adaptive waveform optimization algorithm for dynamic environments, diverse user demands, and fluctuating spectrum availability remains a significant challenge (Aulia et al., 2015; Liu et al., 2019; Doly et al., 2023b). Furthermore, designing an end-to-end electromagnetic radio frequency (RF) system integrated with an adaptive tracking system (Dang, 2008; Akhlaghi et al., 2017; Kalman, 1960) is essential for the real-time implementation of waveform design algorithms, allowing complete testing and providing insights into user benefits and computational complexity (Su et al., 2023; Tan & Wang, 2021).

Developing real-time implementations of such new and emerging systems over-the-air (OTA) is highly nontrivial. The authors discuss the implementation of GNU Radio-based software-defined radio (SDR) to design a frequency-modulated continuous wave radar (FMCW) (Mathumo et al., 2017) 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 radar is studied for weather surveillance applications.

In our previous work, we showed a path towards conducting a Hardware-In-The-Loop (HWIL) OTA experiment to demonstrate the feasibility of the waveform co-design technique (Doly et al., 2023b) in pseudo-real-time. In (Doly et al., 2023a), we implemented an RF convergence system that can simultaneously transmit and receive data using USRP (Universal Software Radio Peripheral) B210s

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with GNU Radio acting as command software for SDRs. We used BPSK or QPSK modulated signals as the transmit waveforms (Doly et al., 2023a).

In this paper, we aim to develop a real-time FMCW radar system that accommodates different chirp types, highlighting the waveform co-design technique in a single real-time feedback loop for multi-user networks applications. We also explore how optimizing bandwidth can reshape the waveform to resolve issues with range resolution.

1.1. Key Contributions

The key contributions of this paper are listed below:

- develop a highly flexible real-time FMCW radar system for designing and testing different radar waveforms (e.g., triangular, sawtooth),
- highlight the waveform adaptive co-design technique in a single a real-time feedback loop for multi-user networks applications leveraging low-cost SDRs,
- explore the benefits radar waveform optimization, particularly through increasing RMS bandwidth, significantly boosting target detection performance by enhancing range resolution.

2. Frequency-Modulated Pulse Compression Waveforms

In this section, we will discuss pulse compression techniques to decouple the energy and resolution of radar waveforms. There are a large number of pulse compression forms in the literature (Richards, 2014; Levanon & Mozeson, 2004). A simple pulse has only two parameters, its amplitude A and its duration τ. These two parameters are coupled, because there is only one free parameter in the design of the simple pulse. Increasing range resolution requires a shorter pulse, while improving detection performance requires a longer pulse (Richards, 2014; Levanon & Mozeson, 2004). The pulse compression technique decouples the range and resolution by adding frequency or phase modulation to a simple pulse. Therefore, the pulse compression waveform has a bandwidth B that is much greater than the "Rayleigh bandwidth" which ensures a "time-bandwidth" ($B\tau$) product much greater than one.

2.1. Linear Frequency Sweep

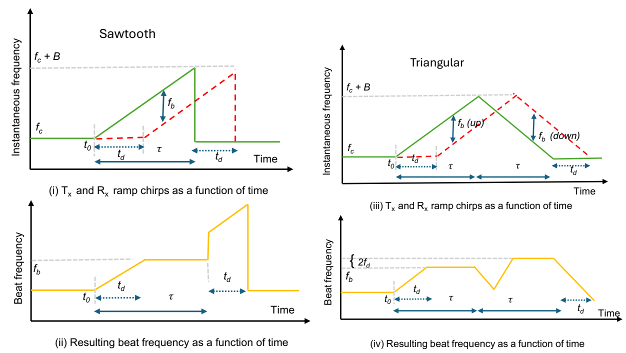
The complex envelope of unimodular linear frequency modulation (LFM) waveform is

$$x(t) = e^{j\theta(t)} = e^{j\pi Bt^2/\tau}. \quad (1)$$

Here, τ is the pulse duration, B is the total available bandwidth, $\theta(t)$ is the phase function. The instantaneous frequency of this waveform is the derivative of the phase function

$$F_i(t) = \frac{1}{2\pi}\frac{d\theta(t)}{dt} = \frac{B}{\tau}t. \quad (2)$$

This linear relationship shown in Fig. 1 assumes the chirp bandwidth $B > 0$. Clearly, $F_i(t)$ sweeps linearly across the total bandwidth B during the τ pulse duration. If the product of $B\tau >> 1$ then, the LFM pulse qualifies as the pulse compression waveform. For a low $B\tau$, the spectrum is relatively poorly defined.



(a) Frequency of transmitted and received (i) sawtooth chirps as a function of time, the (ii) resulting beat frequency for chirps as a function of time.

(b) Frequency of transmitted and received (iii) triangular chirps as a function of time, and (iv) the resulting beat frequency as a function of time.

Figure 1. Sketches of a sawtooth, and triangular chirp modulation schemes and corresponding beat frequencies.

2.2. LFM Waveform Selection

In RADAR systems, different linear modulation slopes are employed for LFM purposes, depending on the specific applications. A simple illustration of sawtooth and triangular linear frequency modulation schemes is shown in Figure 1. The solid lines represent the transmitted signal as a function of time, while the dashed lines represent the reflected signal from a single stationary target. The delay introduced by the stationary target is indicated by the round-trip delay t_d, and the chirp duration is denoted by τ.

A sawtooth is very similar to a ramp function except that after the bandwidth has been swept, the frequency is immediately returned to the carrier frequency as seen in Fig. 1(c,e). This rapid frequency change results in an undershoot (Koivumäki, 2017). This can cause difficulties if the application is tightly limited to a certain bandwidth. Beat frequency behaviors are also very similar to the ramp function in Fig. 1(d,f), except that there is a sudden very high frequency region.

It is not feasible to estimate both the unknown quantities, range and radial velocity of a moving target using a single ramp or sawtooth, which is why the Doppler shift is often initially ignored. By introducing an additional lin-

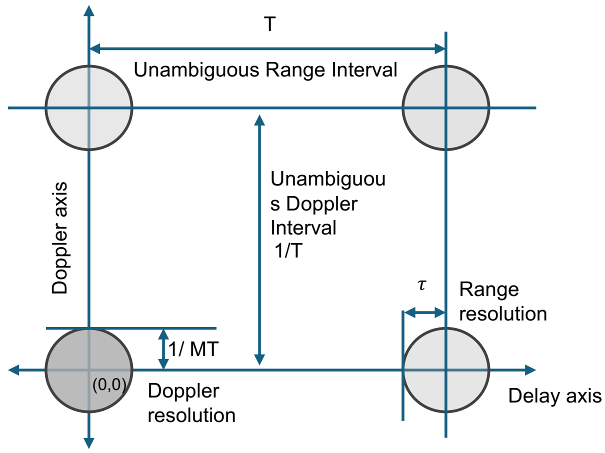


Figure 2. Notional illustration of the pulse burst waveform design parameters and range-Doppler resolution and ambiguities.

ear ramp section of opposite slope to the chirp to form a triangle (Rohling & Meinecke, 2001), it is possible to estimate both quantities from a single chirp. For the triangular chirp, the received waveform is drawn with a small positive Doppler shift in Fig. 1(b). A quick comparison of three LFM modulation techniques is presented in Tab. 1.

3. FMCW RADAR Design

The graph in Fig. 2 illustrates the concept of FMCW radar signal processing at the receiver end, highlighting how target parameters are extracted and used to determine resolution and ambiguities in both range and Doppler. Once the desired modulation technique is determined, the radar bandwidth B, is selected to achieve the desired range resolution ΔR. The pulse repetition interval $PRI = T$ sets the ambiguity interval in both the range ($\frac{CT}{2}$) and the Doppler range ($\frac{1}{T}$). Finally, the number of pulses in the burst determines the Doppler resolution ($\frac{1}{MT}$) (Richards, 2014).

3.1. Dechirp Processing

The output of the "dechirp/stretch" receiver contains a different "beat frequency" tone for each scatterer (Richards, 2014; Levanon & Mozeson, 2004; Koivumäki, 2017). In an FMCW radar, the beat frequency is calculated as:

$$f_b = f_t - fr,$$

where f_t, f_r are the transmitted and received frequency components in the receiver. For a triangular chirp, the Doppler shift can be calculated fairly straightforwardly from the difference between two beat frequency peaks as

$$f_d = \frac{f_{b,down} - f_{b,up}}{2}.$$

Similarly, an unshifted beat frequency can be calculated from the mean of the up and down ramps canceling the Doppler components, which can be expressed as

$$f_b = \frac{f_{b,down} + f_{b,up}}{2}.$$

The bandwidth of the receiver output can be obtained considering the difference in the beat frequencies for the scattered edges near and far the edges of the range window (Richards, 2014). The receiver bandwidth equation is obtained as

$$f_{b_{\text{near}}} - f_{b_{\text{far}}} = \left[-\frac{B}{\tau}\left(-\frac{T_w}{2}\right)\right] - \left[-\frac{B}{\tau}\left(\frac{T_w}{2}\right)\right] = \frac{T_w}{\tau}B. \quad (3)$$

Here, T_w is the range interval where the reference LFM chirps are expected to completely overlap the echo from the scatterers anywhere within a range window (Richards, 2014; Levanon & Mozeson, 2004).

4. Waveform Spectrum Shaping

There are two common methods for shaping the radar spectrum (Richards, 2014). Both approaches are based on the concept of application-oriented redistribution of uniformly distributed spectral energy, which results from a linear sweep rate with constant pulse amplitude in the LFM method.

4.1. Spectral Masking

To reshape the spectral energy as desired, different linear filtering methods are used. Methods include window functions (rectangular, Hann, Hamming, etc.), known as spectral masking (Richards, 2014; Chiriyath et al., 2019). Another method is to reduce the signal amplitude at the edge of the pulse while maintaining a constant sweep rate known as amplitude weighting (tapering) (Doerry, 2006; Chiriyath et al., 2019; Doly et al., 2022). However, the amplitude modulation technique requires operating the power amplifier at less than full power over the pulse width (Richards, 2014). This requires more complicated transmitter control but, more importantly, results in a pulse with less than the maximum possible energy for a given pulse length (Chiriyath et al., 2019; Doly et al., 2022).

4.2. Non-Linear Frequency Sweep

In linear FM, the transmitter spends equal time at each frequency, hence the nearly uniform spectrum (Doerry, 2006). Another method of shaping the spectrum is to deviate from the constant rate of frequency change and to spend more time at frequencies that need to be enhanced. This approach was termed as Non-linear frequency modulation (NLFM) (Levanon & Mozeson, 2004; Richards, 2014). The discrete frequency modulation equation is typ-

Table 1. Feature Comparison of Sawtooth, and Triangular Waveforms

Feature	Sawtooth Chirp	Triangular Chirp
Chirp Duration	τ	2τ
Range Resolution	constant	constant
Doppler Resolution	fixed	improved

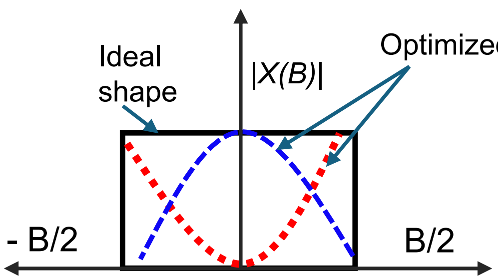
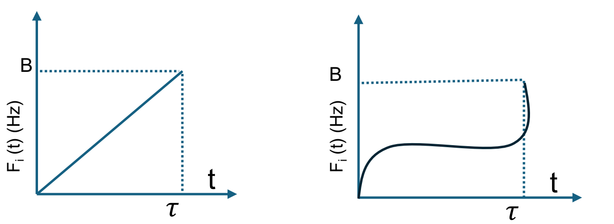


Figure 3. Optimized radar spectral shape vs. ideal spectral shape.



(a) Instantaneous frequency LFM (b) Instantaneous frequency NLFM

Figure 4. Frequency-Modulated pulse compression waveforms. Instantaneous frequency function for (a) LFM pulse, (b) NLFM pulse.

ically represented as

$$f[n] = \sum_{n=1}^{k} (f_0 + \kappa n^p). \tag{4}$$

The variable $f[n]$ denotes the discrete frequency of the chirp signal at time k, f_0 represents the initial frequency of the chirp signal and κ signifies the constant chirp rate. The index $p = 1, 2, \ldots, m$ represents the order of the chirp rate and $p!$ denotes the factorial of p.

5. Problem Setup

In Fig. 5, we show the block diagram of the OTA experimental setup for FMCW radar waveform in real time. The problem is set up as follows.

We begin with a fixed LFM chirp generator, which can be employed with various sweeping methods (e.g., sawtooth, triangular). The LFM chirp has a bandwidth ranging from $-B/2$ to $B/2$ with a duration of τ.

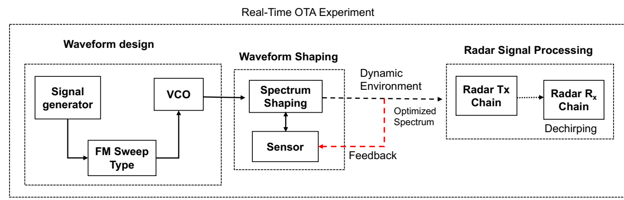


Figure 5. Block diagram of the OTA experimental setup for real-time FMCW radar waveform optimization.

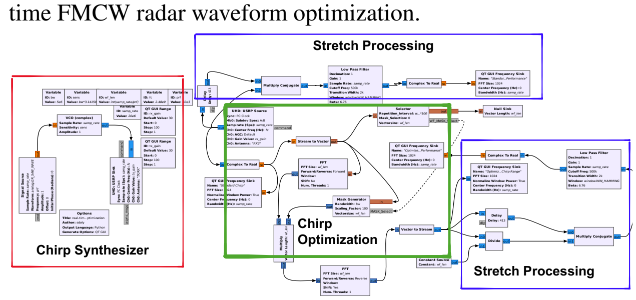


Figure 6. GNU Radio Flow-graph for OTA adaptive FMCW radar waveform design.

Next, we apply a frequency domain spectral mask, $W(f)$, to the chirp to reshape the energy distribution of the power spectral density (PSD) of the ideal waveform. This approach allows for an adjustable root mean square (RMS) bandwidth with a variable shaping filter derived from a conventional fixed-bandwidth chirp generator.

Finally, we conduct a target tracking experiment to demonstrate the advantages of the adjustable RMS bandwidth in resolving ambiguities in closely spaced multi-target scenarios. The signal-to-noise ratio (SNR) of the optimized waveform is proportional to its energy, which is the product of $A^2\tau$ of its power and duration. The performance of the ambiguity of the range of the Radar depends on the achievable RMS bandwidth of the waveform (Richards, 2014).

The problem setup is presented as the three main experimental blocks in Fig. 5.

6. OTA Experiments & Analysis

The GNU Radio flow graph for this experiment is illustrated in Fig. 6. Table 2 shows the parameters that are used during the experiments to design the adaptive radar system. In this setup, two USRP B210 devices are used as the transmitter and receiver, respectively, to transmit

Table 2. Parameters of the FMCW radar being studied

Parameter	Value
Center frequency (f_c)	2.48 GHz
Swept Bandwidth (B)	10 MHz
Sampling Rate (F_s)	25 MHz
Pulse Repetition Frequency (PRF)	50 KHz
Time-Bandwidth Product (TB)	200
Number of Frequency Weights (N)	400
Radar duty factor (δ)	1.0
VCO sensitivity (ϵ)	31.43e6

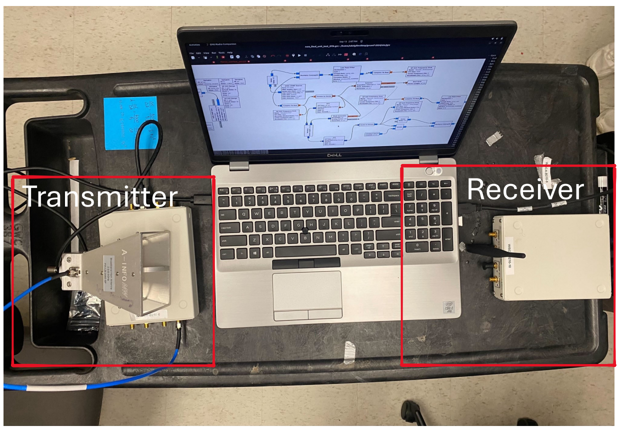


Figure 7. FMCW radar adaptive waveform design real-time experimental setup.

and receive the reflected echoes from the environment, as shown in Fig. 7. Both USRPs are equipped with antennas that offer directional patterns that improve the strength of the received echo signals.

6.1. Results and Analysis

GNU Radio is originally designed as a streaming system without a built-in mechanism to pass data between blocks in a feedback loop. To implement a feedback loop in real-time, the asynchronous message-passing interface is employed in this experiment. However, there is a non-deterministic delay in the signal generator receiving messages from the feedback, instructing it on which waveform to transmit. To synchronize the feedback with each chirp repetition interval (CRI), a fixed number of samples ($w_{len} = 400$) is used, which are equal to the number of masking weightings generated for chirp optimization purposes, as shown in Fig. 6.

In Fig. 8, an unweighted chirp spectrum is compared with a standard chirp spectrum. Original unmasked chirp is depicted and compared with the optimized waveform in Fig. 9. The optimized waveform spectrum is communication optimal when it has more energy in the center of the bandwidth in Fig. 9(a). The optimized waveform spectrum

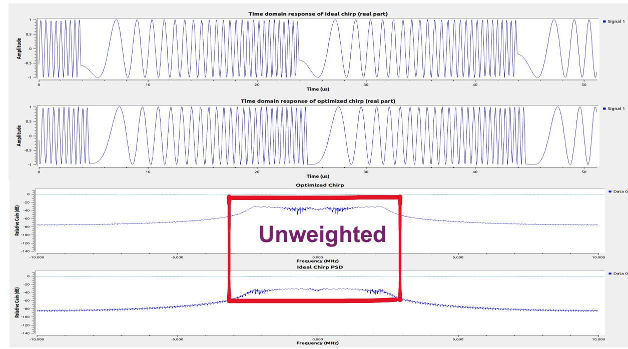


Figure 8. Unweighted chirp vs. the standard chirp spectrum.

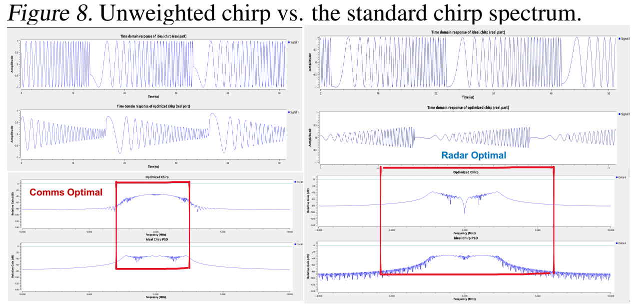


Figure 9. GNU Radio Flow-graph for OTA adaptive FMCW radar waveform design.

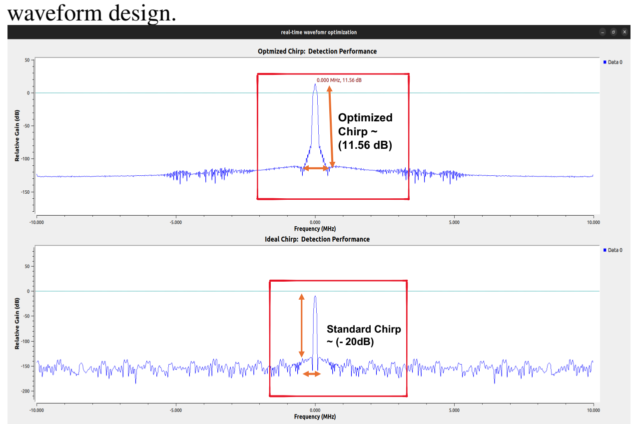


Figure 10. The output of the stretch processing for zero-Doppler range.

is radar optimal and has more energy in the edges of the bandwidth in Fig. 9(b).

In this experiment, stretch processing is used for matched filtering at the radar receiver. Stretch processing is a specialized technique used in industry for real-world problem solving applications for matched filtering wideband LFM waveforms.

The output of the stretch processing receiver is shown in Fig. 10, containing only the "*beat frequency*" tone for the zero-Doppler range of the scatter. If there are multiple scatterers distributed in range, the stretch processing receiver output is simply the superposition of the output of multiple mixers.

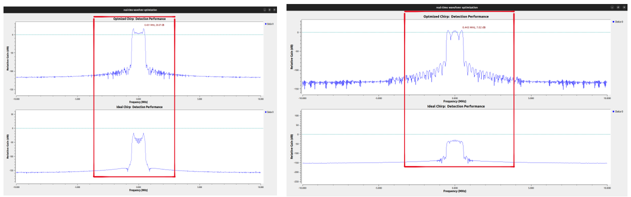


Figure 11. The concave-up (radar optimal) mask increase the RMS bandwidth of the optimized waveform. Which boost the radar's ability to detect weak or small targets, leading to a more reliable and accurate detection system.

As shown in Fig. 10, the optimized chirp's peak detection performance improves by approximately 30 dB compared to a standard chirp. However, the width of the optimized chirp increases, which could present challenges in detecting smaller targets. On the other hand, this wider chirp is advantageous for communication users as it aggregates more power. Higher bandwidth signals have more spectral content, which improves the effectiveness of matched filtering, leading to a higher gain in SNR and better target detection in Fig. 11.

7. Conclusion

In this paper, we showed a highly flexible real-time FMCW radar system for designing and testing different radar waveforms (e.g., triangular, sawtooth) and radar signal processing algorithms (e.g., stretch processing) without the need for extensive hardware modifications and fetching MATLAB codes. We implemented an adaptive waveform co-design technique in a single real-time feedback loop for multi-user networks applications leveraging low-cost SDRs. To implement the feedback loop in real time, an asynchronous message-passing interface is employed. We also presented the benefits of radar waveform optimization, particularly through increasing the RMS bandwidth, which significantly boosts the target detection performance by enhancing the range resolution. We implemented the system using USRP (Universal Software Radio Peripheral) B210s with GNU Radio acting as command software for the SDRs. In future work, we will evaluate the performance of the adaptive FMCW radar system for real target detection in a real-world scenario.

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