International Journal of Engineering and Applied Sciences (IJEAS)
ISSN: 2394-3661, Volume-11, Issue-10, October 2024

DDS-PLL Based Programmable Radar Waveform Generator

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Abstract— **Different types of radar systems are developed to serve specific applications such as surveillance, fire control, air-defense tracking, missile guidance, and low probability of intercept (LPI) operations. Each type utilizes a distinct set of pulse and frequency parameters, shaped by its operational requirements. To simulate these diverse radar types for testing and evaluation purposes, programmable radar simulators are employed. Effective radar simulation requires the generation of radar signals with configurable waveform parameters, such as pulse width, bandwidth, modulation, PRF, power, and frequency, to accurately replicate different radar emitters. In this paper, architecture of a programmable radar waveform generator based on a DDS-PLL hybrid design, intended for use in radar simulation systems is presented.**

Index Terms— **Radar Waveform, Simulation, Waveform Generation, DDS, LFM, FMCW, Barker, FPGA.**

I. Introduction

Radars are fundamentally ranging devices that operate by transmitting electromagnetic signals and analyzing the echoes reflected from targets to determine their range, velocity, and angular position. The core principle of radar operation is based on measuring the time delay between transmission and reception of the signal. In its simplest form, even an unmodulated continuous wave (CW) signal can be employed for ranging purposes, particularly in bi-static radar configurations where the transmitter and receiver are located at different positions. Thus, a wide variety of waveforms can be utilized to fulfill the basic functional requirements of radar systems. However, in modern combat and surveillance scenarios, radar systems often operate in hostile electromagnetic environments (EME), where electronic warfare (EW) threats such as jamming, deception, and detection by enemy receivers are prevalent. In such settings, radar systems are not only expected to carry out their primary functions—such as target detection, classification, tracking, and engagement but must also possess the capability to defend themselves against intentional interference and exploitation. To counter these challenges and enhance survivability and operational effectiveness, modern radars incorporate a range of electronic protection (EP) techniques. These techniques are designed to mitigate the impact of hostile EW systems and to reduce the likelihood of detection by enemy sensors. A significant portion of these EP strategies involves the manipulation and optimization of the transmitted radar waveforms. By varying key signal parameters such as pulse width, pulse repetition frequency (PRF), modulation scheme, peak power, frequency agility, and time-on-target, radar systems can become more resilient to jamming and more difficult to detect or classify.

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In this context, the ability to simulate such diverse and dynamic radar waveforms becomes critically important for the design, testing, and evaluation of radar and EW systems. For this purpose, programmable radar waveform generators are developed. These systems must offer high flexibility and configurability to accurately replicate the behavior of a wide spectrum of radar emitters operating under various mission scenarios and electronic threat environments.

In this paper, we present the architecture of a versatile radar waveform generator designed specifically for the simulation of different types of radar transmitters. The proposed system enables the generation of customizable radar signals with programmable parameters, thereby supporting comprehensive testing and validation of radar and electronic warfare systems under realistic conditions.

II Programmable Waveform Generator

A generic radar waveform can be given by the following equation.

$$Y(t) = A(x)*\sin(\omega(x)*t + ø(x)) \quad (1)$$

Where, x is a time-dependent variable, and the functions A(x), ω(x), and ϕ(x) denote the amplitude, angular frequency, and phase, respectively, as they vary with time. By appropriately selecting these functions, a radar system can modulate its transmitted signal in terms of amplitude, frequency, phase, or any combination thereof. Programmable waveform generator thus should be able to evaluate eqn (1) in real time to emulate generic radar. However, real-time computation of sinusoidal function with variable amplitude, phase and frequency is computationally expensive, consuming significant logical resources and increasing latency.

Various techniques have been developed for efficient generation of radar waveforms, particularly for approximating sinusoidal functions. Among them, the lookup table (LUT) approach is widely used due to its simplicity and speed, where precomputed values of the sine function are stored and accessed in real time. This method significantly reduces computational load but is limited in flexibility, as it typically supports only a single waveform per table. Algorithms like CORDIC offer more versatility with lower hardware complexity, yet they are still tailored for specific waveform types. Consequently, these conventional methods often fall short when simulating a broad range of radar waveforms that require dynamic control over parameters such as frequency, phase, and amplitude.

To address these challenges, Direct Digital Synthesizer (DDS) architectures have emerged as a powerful solution. DDS enables fine-grained, real-time programmability of waveform parameters using a phase accumulator and a sine LUT, supporting rapid frequency switching and multiple modulation schemes. However, DDS performance can degrade at higher frequencies due to spurious content and phase noise. A hybrid DDS-PLL approach overcomes these limitations by using DDS as a tunable reference source for a phase-locked loop, which multiplies the frequency while preserving spectral purity. This combination leverages the agility of DDS and the high-frequency stability of PLLs, making it ideal for generating versatile, high-quality radar waveforms across a wide frequency range.

Let's now investigate the possibility of programmatically controlling each of modulation parameters of generic waveform given in eqn (1) using DDS. First consider evaluation of eqn (1) for un-modulated case i.e. A(x), ω(x) and ø(x) constant. To further simplify the discussion, let's consider A(x) = 1 and ø(x) = 0, the eqn (1) then reduces to

$$Y(t) = \sin(\omega t) \qquad \text{--- (2)}$$

Eqn (2) represents a sine wave of constant angular frequency 'ω' and term ωt is instantaneous phase. Thus by storing values of sine function in a lookup table, for phase values 0 to 2π at interval corresponding to required resolution, waveform of eqn (2) is generated. Frequency is related to phase as given in eqn (3).

$$\omega = 2\pi f_0 = d\theta/dt \qquad \text{--- (3)}$$

It is clear from eqn (3), that by changing the rate of phase increment, frequency is changed. Lookup table is accessed at rising or falling edge of clock edge, so dt is repetition time of clock signal, so by changing dθ which is accessed at consecutive clock pulses, frequency of output is changed and eqn. (3) can be modified to represent output frequency in terms of clock frequency, f_{clk}.

$$f_0 = f_{clk} * d\theta/(2\pi) \qquad \text{--- (4)}$$

Logical block diagram for waveform generator to programmatically generate singleton sinusoids is given in fig. 1. This architecture is known as Direct Digital Synthesizer or DDS.

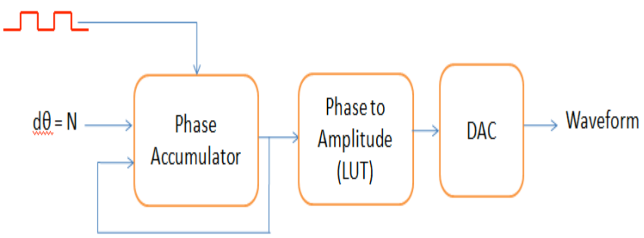

Fig. 1: Direct Digital Synthesizer

The architecture shown in fig.1 implements eqn (2) for programmable output frequency ω. To change the frequency of output, input N, (=dθ) calculated as per eqn. (3), to phase accumulator is changed and frequency is changed from next clock cycle. This simplicity of operation makes this an ideal architecture for digital implementation of programmable single tone generation.

We will now consider implementation of eqn (1) to realize generic waveform generation. In DDS architecture shown in fig 1, phase accumulator is designed to have initial output of '0' (zero initial condition), so that the output waveform start at zero phase. To have this phase to some other programmable value, another input to accumulator may be added to have custom initial phase. If this phase is varying as a function of time (phase modulation), as given in eqn (1), ø(x) is given as input to this point.

To implement ω(x) in the output waveform, function to generate time varying phase increment corresponding to ω(x), as given by eqn (3), be connected to dθ input of the phase accumulator.

As discussed earlier, A(x) is time dependant variation in amplitude of the signal, and to implement this in DDS architecture, LUT output is modulated with suitable function. Modified architecture for generic waveform synthesizer, as per the discussion, to implement eqn (1) is shown in fig 2.

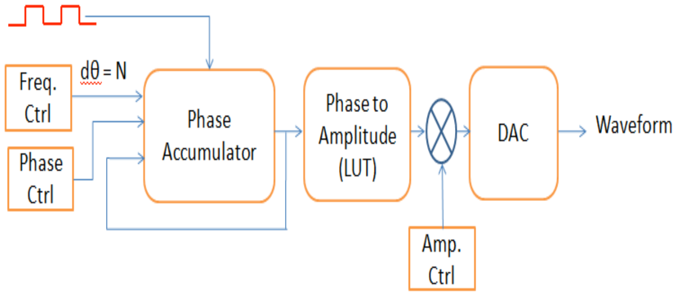

Fig. 2: Generic Waveform Synthesizer

III Realisation Architecture

Realization architecture of programmable radar simulator to simulate radar operating in different frequency band is presented in fig 3.

The architecture is based on DDS-PLL Hybrid generation to take advantage of fast switching and programmability of DDS and phase noise and SFDR performance of PLL circuitry.

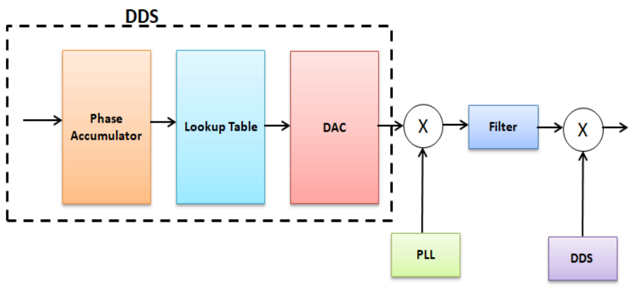

Fig. 3: Realization Architecture of Programmable Radar Simulator

V Conclusion

In this paper, architecture of a programmable radar waveform generator, capable to generate radar waveforms, whose parameters *viz.* frequency, modulation, PRT, PW etc. can be controlled programmatically in real time, is presented. The architecture uses a single LUT to store sine-function and all the parameters of output are controlled using modifying the input function to this LUT. DDS-PLL hybrid architecture is employed to for programmable modulation and frequency band selection offering advantages of fast switching of DDS and spectral purity of PLL.

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