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Design and Development of Radar Signal Emulator for Electronic Warfare Scenario Simulation

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***Abstract*— The objective of this project is to design and develop software based Radar Signal Emulator (RSE) to generate various classes of modern radar signals synthetically and simulate complex electronic warfare scenarios. This involves formulation of time, frequency and spatial domain properties of radar signals such as frequency, modulation bandwidth, modulation slope, instantaneous amplitude, frequency and phase, waveform pattern, scan modulations etc. in the presence of additive white Gaussian noise. Analytical formulation followed by Matlab implementation of the candidate signal set has been carried out followed by actual generation of the same using vector signal generators. Proposed RSE provides a developmental platform for various electronic warfare systems, concepts and algorithms. RSE facilitates performance quantification under realistic threat scenarios with a broad class of signals and modulations.**

***Keywords:* Additive White Gaussian Noise, Barker Code, Electronic Warfare, Frank Code, Frequency Modulation, Frequency Hopping, Spectrogram, Time Frequency Analysis.**

I. INTRODUCTION

Electronic warfare (EW) is defined as the usage of electromagnetic spectrum to detect, interpret, analyse and locate the enemy assaults via the spectrum and to impede the enemy attacks through spectrum. The purpose of electronic warfare is to deny the opponent advantages and ensure friendly unimpeded access to the electromagnetic (EM) spectrum. Generally, determination of parameters or characteristics of emitter is not easy because in practice radars emit energy in predefined sequences of pulses and these pulse trains from a number of sources are received at a time. Each of these pulse trains has different parameters. The modern Radar signals are characterized by random/high pulse repetition frequency and frequency agilities. The Radar signals contain the information like Carrier frequency, Pulse width (PW), Pulse amplitude etc. All these parameters collectively form the pulse descriptor word (PDW).

II CLASSIFICATION OF EW SYSTEMS

EW systems are classified into electronic support measure (ESM), electronic attack (EA) and electronic protection (EP).

Electronic support measure is an action which detects, identifies, locates and interprets the electromagnetic (EM) emissions which are unfriendly. It can detect and identify radar mode, scan, modulations etc. from parameters of the received pulse such as pulse width, pulse amplitude, direction of arrival, time of arrival, pulse repetition interval (PRI), etc.

Electronic attack is defined as the usage of directed EM energy intended towards the enemy systems in order to reduce their combat capabilities. It involves technique like noise jamming and deception jamming. ESM gives information required for EA and attack will be done with the directed EM energy. Noise jamming is the technique in which noise is added to the intended EM spectrum to reduce the efficiency of enemy's spectrum usage. Deception jamming is the technique in which the received copy of spectrum is stored and retransmitted at random intervals of time to confuse the opponent with false indications of our range and position.

Electronic protection is defined as the ability to use the EM spectrum efficiently even in the presence of enemy's assaults with intended EM emission aiming us. It provides the better environment for our warfare in the EM environment where we can deny the assaults of opponent and can use the spectrum efficiently. EP is also called as electronic counter counter measures (ECCM).

From the EW perspective, ESM requires analysis of various kinds of signals; modulation and codes, while EA signifies capability of EW system to reproduce those signals with pre-determined parametric modifications and EP signify higher level signal design and modulation efforts.

III RADAR SIGNALS AND MODULATION

A radar signal is designed with a distinct signature in time, frequency and space to achieve a host of operational objectives like probability of detection/false alarm/sensitivity etc. They are designed to achieve longer range to target and fine target resolution, which is achieved by various types of pulse and angle modulations. A typical pulsed radar signal is depicted in Figure-1.

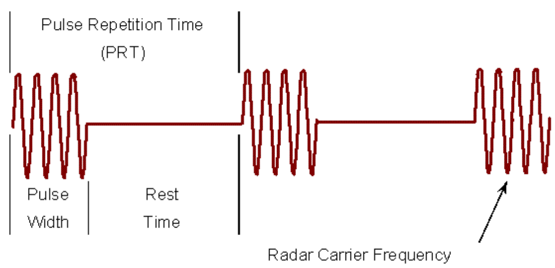

Figure-1: radar pulse

In fact in radars, range resolution will be better when we have narrow pulse width (PW). But there is a limit up to which PW can be reduced in order to have sufficient power for reliable echo detection. The alternative solution to this problem is achieved by the use of intra-pulse modulation (IPM), which gives advantages of a very narrow PW for achieving longer range to target, while simultaneously achieving fine target resolution. The candidate IPM methods include various forms continuous time and discrete time frequency modulation (FM), bi-phase and poly-phase modulation and frequency hopping. These techniques are also known as pulse compression.
Unmodulated radar signal & its Instantaneous frequency are mathematically defined in eqns.1&2

$$S(t)=A.ej2\pi[Fn+\varphi]+w[n]\ldots\ldots(1)$$

$$F+v[n]=p0+v[n]\ldots\ldots(2)$$

A. Linear Frequency Modulation

When a radar signal undergoes linear frequency modulation maximum compression of pulse takes place. In a linear frequency modulation [3] the frequency of a carrier increases instantaneously called Chirp up or instantaneously decreases called Chirp down.
The LFM and its instantaneous frequency is mathematically defined as shown in eq. 3 and eq. 4.

$$S(t)=A.ej2\pi[(F\mp B2)n\pm B2Tn2+\varphi]+w[n]\ldots\ldots(3)$$

$$(F\mp B2)\pm BTn+v[n]=p0+p1n+v[n]\ldots\ldots(4)$$

The QFM and its instantaneous frequency is mathematically defined as shown in eq. 5 and eq. 6.

$$S(t)=A.ej2\pi[(F\mp B2)n\pm B3T2n3+\varphi]+w[n]\ldots\ldots(5)$$

$$(F\mp B2)\pm BTn2+v[n]=p0+p1n2+v[n]\ldots\ldots(6)$$

Hence, any FM can be expressed using Taylor Series expansion as

$$f[n]=p0+p1n+p2n2\ldots\ldots+pqnq+v[n]\ldots\ldots(7)$$

$$v[n]:Noise\,\forall n\in[0\ N-1].$$

Typical examples of unmodulated, LFM, and QFM signals along with their DFT and probability mass function of their instantaneous frequencies (IF) are shown in the Figure2.

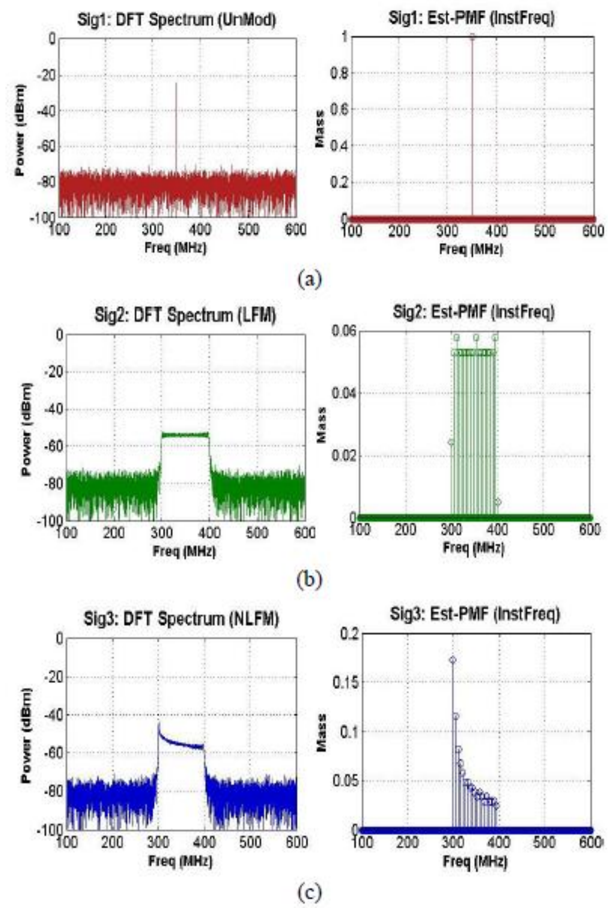

Figure2: DFT and PMF of IF for Unmodulated, LFM & QFM radar signals with Center Freq=350MHz, Mod BW=100MHz at 15dB SNR.

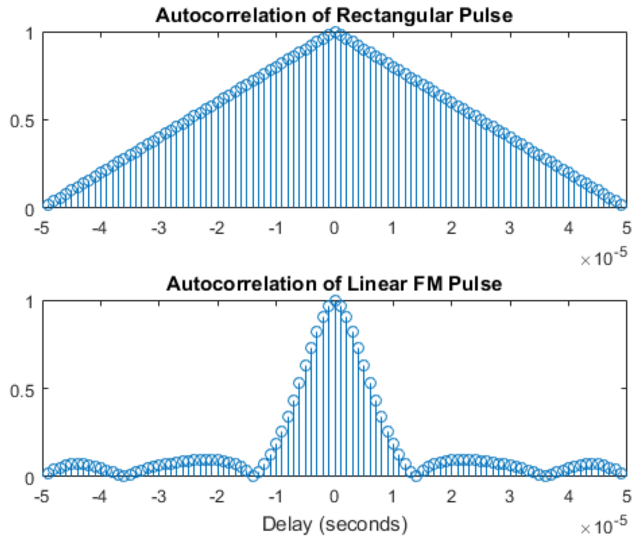

Figure-3: Autocorrelation of Rectangular Pulse and Autocorrelation of Linear FM Pulse

B. Barker Coded Radar Signals

Barker codes [3] are the finite sequence of +1 and -1 also represented can be in + and - , which indicates phase changes. In barker sequences the pulse compression ratio is small compared to LFM. The fixed barker code sequences are 2, 3, 4, 5, 7, 11 and 13. The barker coded radar signal is shown in the Figure-4.

LENGTH	CODES	
2	-1 +1	+1 -1
3	+1 +1 -1	
4	+1 +1 +1 -1	+1 +1 -1 +1
5	+1 +1 +1 -1 +1	
7	+1 +1 +1 -1 -1 +1 -1	
11	+1 +1 +1 -1 -1 -1 +1 -1 -1 +1 -1	
13	+1 +1 +1 +1 +1 -1 -1 +1 +1 -1 +1 -1 +1	

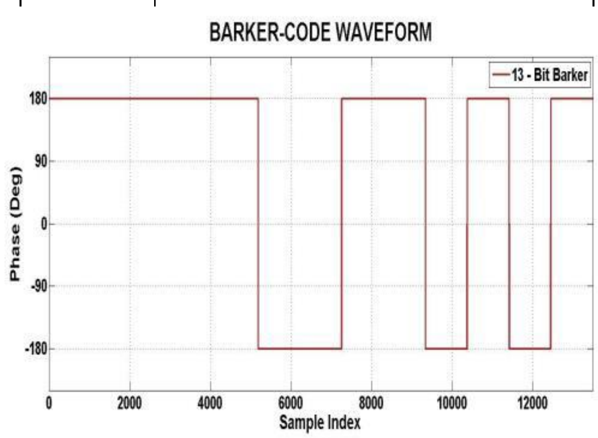

Figure-4: Barker code sequences and barker coded radar signal waveform 13 Bit

C. Frank Polyphase Codes

R.L. Frank devised a poly phase code that is closely related to LFM and Barker codes. Successfully used in LPI radars. The Frank code is derived from a step approximation to a linear frequency modulation waveform using M frequency steps and M samples per frequency. The length of the Frank code is$N=M2$. Consider that a local oscillator is at the start of the sweep of the step approximation to the linear frequency waveform. The first M samples of the polyphase code are 0 phase. The second M samples start with 0 phase, and increase with phase increments of $(2\pi/M)$ from sample to sample. The third group of M samples start with 0 phase and increase with $(3-1)(2\pi/M)$ increments from sample to sample and so on.

$\varphi i,j= 2\pi M(i-1)(j-1)$………………………….(8)

Where $i=1,2,\dots,M, and j=1,2,..,M$.

The frank code can also be written as an M x M matrix as shown

$$\begin{bmatrix} 0 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 2 & \cdots & M-1 \\ 0 & 2 & 4 & \cdots & 2(M-1) \\ 0 & \vdots & \vdots & & \vdots \\ 0 & (M-1) & 2(M-1) & \cdots & (M-1)^2 \end{bmatrix} \ldots.(9)$$

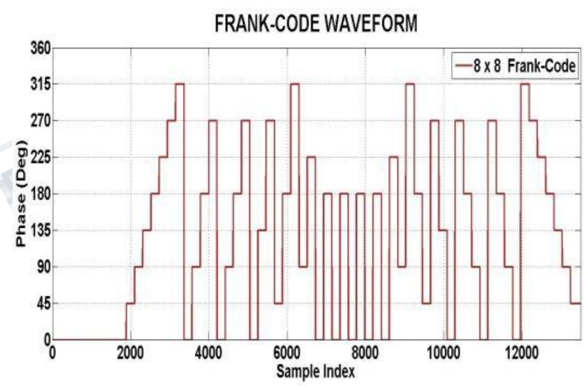

Figure-5: 8 X 8 Frank Coded Waveform

D. Need For Amplitude Modulation

Radar antenna steers electronically or mechanically in space. Every radar uses different search and track strategies. These search strategies are called antenna scan type (AST) of the radar. The commonly encountered scan types are circular, helical, raster, sector, conical etc. On reception of radar pulse the ESM system analyse, calculate and interpret the parameters so that it can determine the mode of operation such as search or tracking, antenna scan pattern, frequency of radar, position and modulations involved. Those parameters are pulse amplitude, pulse repetition interval (PRI), pulse width (PW), direction of arrival (DOA), TOA (time of arrival).

These parameters give information about type of radar which emitted the pulse that EW system received. By using difference between TOA of radar antenna power levels or peaks received antenna scan period (ASP) can be determined. Similarly by calculating difference between TOAs of successive radar pulses PRI can be determined. Different types of radar antenna scans are shown in the Figure-6.

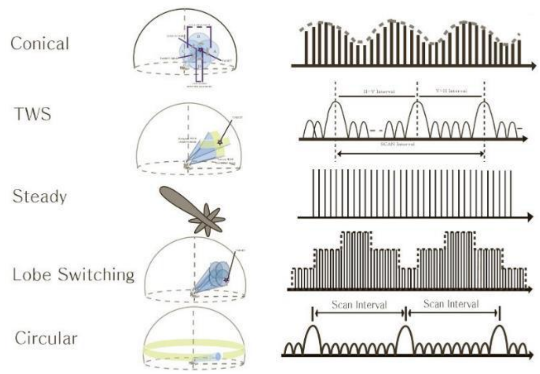

Figure-6: Scan patterns of different scans [6]

In order to generate these kinds of patterns synthetically here we use FIR window functions like Kaiser, Gaussian etc. which are multiplied to the pulse to get these patterns. Gaussian amplitude modulated pulse and Step amplitude modulated pulse of width 10uS with noise 20dB is shown in Figure-7.

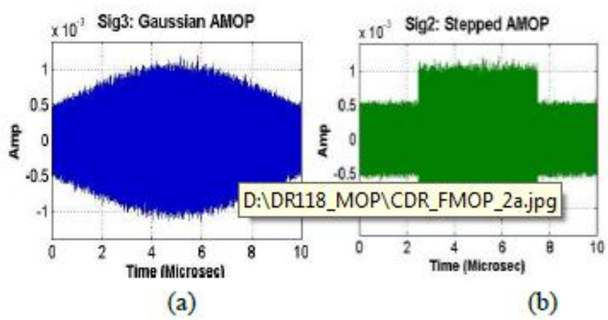

Figure-7: (a) Gaussian AMOP, (b) Stepped AMOP

IV RADAR PULSE MODULATIONS

Pulse Modulation (PM) is the basic form of modulation in a radar signal and is designed with characteristic on/off amplitude shift keying, varying pulse repetition interval and/or pulse width according to pre-determined pattern. In the present work only PRI modulation is considered. Typical radars use four types of pulse modulations viz. Fixed PRI, Staggered PRI, Switched PRI and Jittered PRI. Each of these are analytically explained below.

A. Fixed PRI

In this type of PM, radar employs a constant PRI along with a constant PW. The same is analytically expressed as,

$S(t) = \alpha\ .\ ej[2\pi Ft+\emptyset]$; $t \in [0\ \tau - 1]$**.......(10)**

$S(t) = 0$; $t \in [\tau\ T - 1]$**.......(11)**

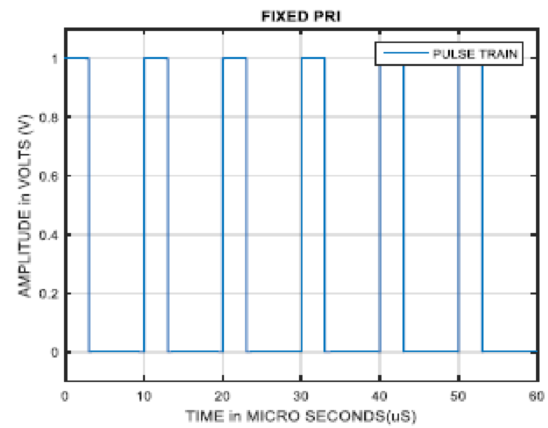

Figure-8: Fixed PRI with Pw 3uS, PRI 10uS

B. Staggered PRI

A staggered PRI radar signal is characterised by a constant PW and a set of PRIs, appearing in a sequential pattern in the pulse train, with each pattern repeating only once. Analytical expression for PRI staggered signals is given by, $S(t) = \alpha\ .\ ej[2\pi Ft(m)+\emptyset]$;

$t(m) \in [\Sigma\ Tm\ ; [\Sigma Tm\ N\ m=0\ ] + \tau - 1\ Nm=0\ ]$**......(12)**

$S(t) = 0$;

$tm \in [[\Sigma Tm\ N\ m=0\ ] + \tau\ ;\ \Sigma\ Tm\ N+1\ m=1 - 1]$**........(13)**

Where ; $m \in [1\ M]$ **.**

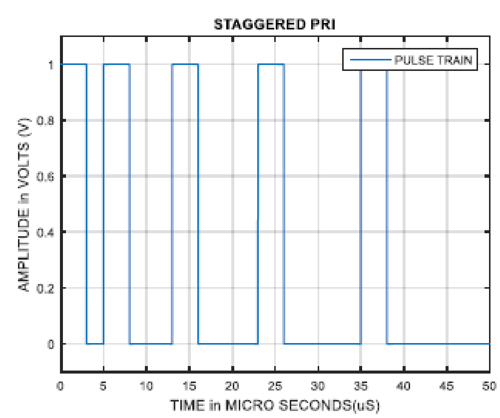

Figure-9: Staggered PRI with Pw 3uS, level 5

C. Switched PRI

A switched PRI radar signal has a fixed number of levels and a fixed number of pulses per level, with PW remaining constant for all pulses. Number of levels signifies distinct PRI values and number of pulses per level is a count of repetitiveness of that PRI consecutively. This type of modulation offers long pulse modulation trains. Switched PRI Signal is expressed as,

$S(t) = \alpha \,.\, ej[2\pi Ft(m)+\emptyset]$;
$t(m) \in [\ \Sigma \mathrm{Tm}(n(m) - 1)$; **M m=1**
$\Sigma \mathrm{Tm}(n(m) - 1)$ **M m=1** $- 1 + \tau$]….(14)

$S(t) = 0$;
$t(m) \in [\ \Sigma Tm(n(m) - 1)\ M\ m=1 + \tau$;
$\Sigma Tm(n(m))\ M\ m=1 - 1$]…………..(15)

Where $n\ \epsilon\ [1\ N(m)]$; $m \in [1\ M]$.

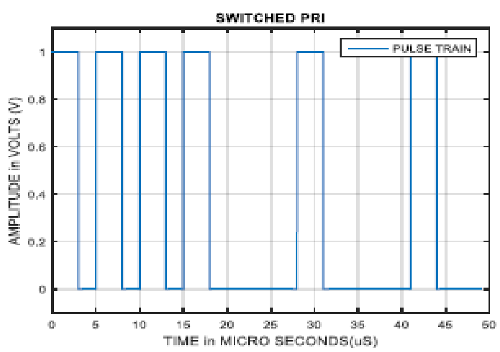

Figure-10: Switched PRI with switcher level 3, Pw 3uS, PRIs 5uS, 10uS, 15uS.

D. Jittered PRI

Radar signals with jittered PRI have their PRI values from a pre-determined range selected randomly with a specific probability distribution for each pulse. Analytically,

$S(t) = \alpha .\ ej2\pi Fcti$; $ti \in [tlow : thigh]$……….(16)

$tlow = t - jitp{*}t\ 100$ ……………………..…(17)

$thigh = t + jitp{*}t\ 100$ …………………....(18)

i= 1, 2, 3, ….n, Where,jitp: jitter percentage

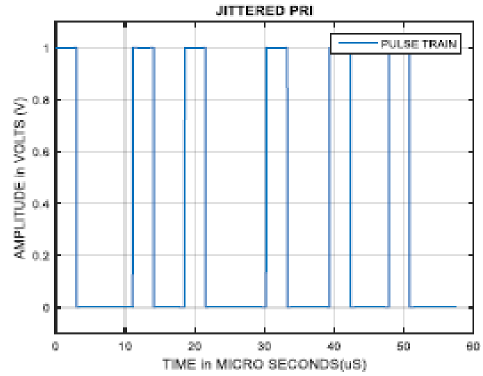

Figure-11: Jittered PRI with Pw 3uS, PRI 10uS and Jitter percentage of 30%.

V. RADAR SIGNAL EMULATOR

Radar Signal Simulator (RSE) EMULATES different radar signals with user defined modulations, Amplitude patterns (scan patterns). At first RSE simulates radar signals using software system MATLAB. These waveforms are transformed to real time scenario using vector signal generator (VSG). From the VSG, the RF output is given to the travelling wave tube amplifier (TWTA). The amplified version of output is given to the Log Periodic Dipole Antenna (LPDA) or parabolic reflector antenna from where it is radiated into space. Vector Signal Generator (VSG) has input option like in phase, quadrature phase, and differential in phase and differential quadrature phase.

A. Simulation Schematics Developed With Matlab

We developed some simulation schematics of Linear Frequency Modulated (LFM) Pulse, Phase Modulated and Amplitude Modulated Radar Signals with different PRI's such as Fixed, Staggered, Switched, and Jittered. GUIDE in MATLAB is used to develop an application which has 4 different channels, i.e. four individual signals can be generated and viewed. Both CW and pulsed radar signals can be generated and analysed individually in time, frequency and joint Time Frequency domains. Finally the interleaved structure of all the four signals can be generated. AWGN is user specified with the option of clean signal conditions. A typical multi threat EW scenario simulated with 4 different radar signals is presented below:

- ❖ Barker coded pulse with barker no 11, Fc 500MHz, Pw6uS, No of repetition 2.
- ❖ Non LFM pulsed with Fc 300MHz, BW 100MHz, Pw 3uS, PRI 12uS.
- ❖ Pulsed RADAR with Discrete AM with 5 steps, Fc 550MHz, Pw 4uS, with Staggered PRI of Stagger level 3, with PRIs 12us, 14uS, 9uS.

- LFM Pulsed with Kaiser Window, Fc 150MHz, Pw 3uS, Jittered PRI of 10uS with jitter percentage 30%.

Fig.12 presents time and frequency description of the scenario. Fig.13 gives spectrogram representation of the various signals.

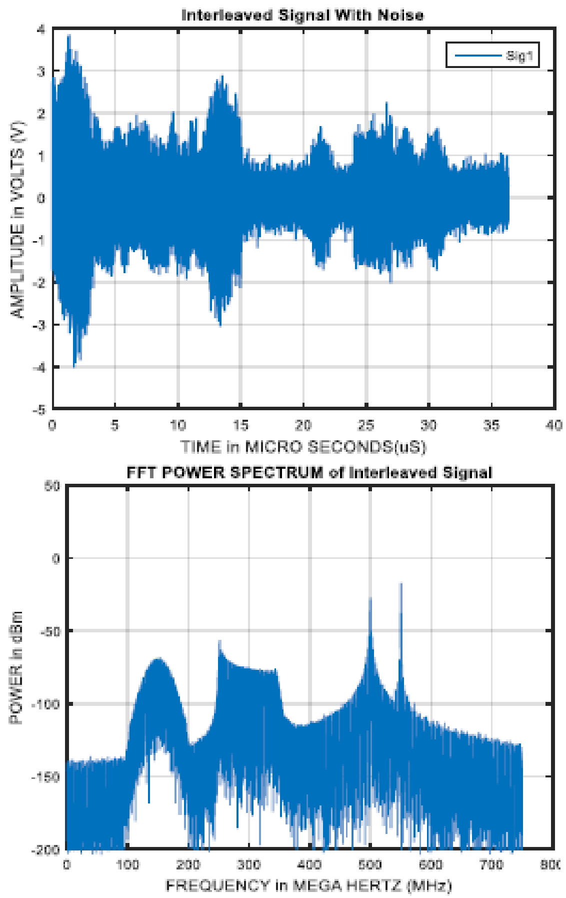

Figure 12: Time and Frequency representations of the Multi Threat EW Scenario

Any of the four channels can be selected or deselected, thus facilitating single signal or multi signal scenario generation. Provision is made for generation of CW and pulsed radar signals, with parameter and scenario validation features. Utility function like saving the scenarios generated for future use, loading scenarios directly from a priori generated files, default parametric option, validation of individual parametric combinations etc. is provided to aid users in efficient and fast application. Noise and its statistics are user defined, as also the number of bits for ADC.

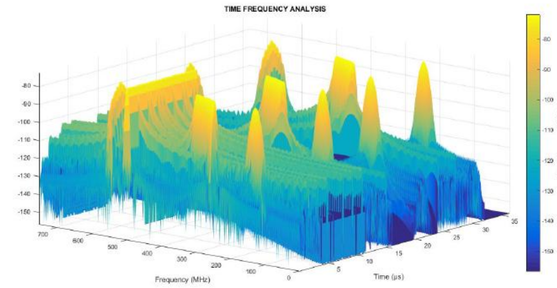

Figure 13: Joint Time-Frequency Representation of the Multi Threat Electronic Warfare Scenario

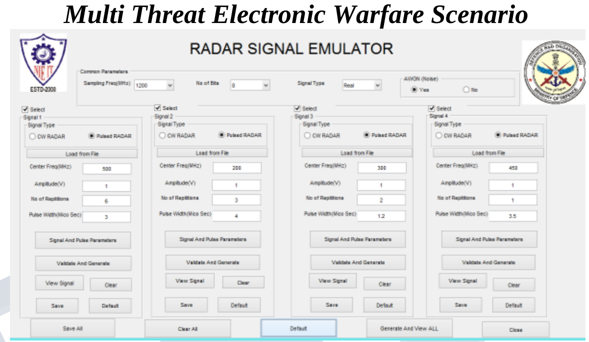

Figure 14: Radar Signal Emulator Application

VI. CONCLUSION

Current work has been carried out with well-defined analytical background of the various signals and their modulations in all three domains viz time, frequency and space. Matlab simulations and synthetic scenario generation has been ensured to be in agreement with theoretically expected results. This gives performance guarantees on correctness & completeness of scenarios. Software Application developed as part of this work is designed with a host of utilities along with visualization capabilities. Joint Time Frequency analysis using spectrogram and visualization in 3- dimensions is a unique feature of this project. Unknown signals generated from other sources can be analysed in this software using spectrogram.

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