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Embedded Design, Simulation and Implementation of Threat Detection in Radio Receivers by Stastistical Signal Processing

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***Abstract*- This paper focuses on design, simulation and practical implementation of threat detection in radar warning receivers (RWR), by estimation of radar parameters using pulse descriptive words (PDWs). The author discusses detection of radar type by utilizing information such as pulse repetitive interval (PRI), time of arrival (TOA), angle of arrival (AOA), radio frequency (RF) and pulse width (PW). The author also discusses the digital signal processing (DSP) algorithms implemented during the research. For this purpose, the software employed were MATLAB and LabVIEW, and practical implementation was done using FPGA and DSP hardware.**

Keywords—Radar Warning Receiver (RWR), Time of Arrival (TOA), Pulse Repetitive Interval (PRI), MATLAB Simulation, DSP Algorithms, FPGA Hardware.

I. INTRODUCTION

Observing the signals transmitted by radar systems to ac- quire information about their capabilities is termed as Electronic Intelligence. It is possible to obtain valuable information while remaining remote from the radar itself (remote sensing) [1]. RWR system designed for this purpose is a high bandwidth radio receiver. The high bandwidth of the receiver is targeted to receive all the possible threat emitters, covering from 2 GHz to 14 GHz signals. The system will listen for radar signals striking the aircraft. It will then attempt to determine the location and movement of the signal sources [2]. An optimal Electronic Warfare (EW) system will extract maximum information from received signals, and will alert the aircraft pilot about EM activity that is nearby.

An RWR system in the vicinity of multiple unsynchronized radars, having different radiation patterns (depending on their PRI value and the PRI patterns) shall receive interleaved pulse trains. Thus, the signals received by the aircraft are not sorted according to the source, but are overhanging over each other in time. Before we can extract any useful information about radar, its associated signals have to be separated from the amalgam of information received from multiple emitters [3].

Until now, the dilemma of generating synthetic data for real time scenario was unaddressed. The only way was to generate different scenarios to record data while the system is still airborne, which is costly and infeasible. The research includes generation of real time scenarios such as pulse on pulse, multiple target detection, etc.

II. AN OVERVIEW OF VARIOUS DESIGN PARAMETERS

Design parameters for required for emitter signals detection and identification require in-depth analysis of radio frequency, angle of arrival, pulse amplitude, pulse width and time of arrival. Interleaved signals have multiple emitters signals, as depicted in Fig. 1.

After de-interleaving, signals are separated on the basis of design parameters, as shown in Fig. 2. When the pulse transmitted by radar reaches the intercept receiver at the aircraft, the information can be measured by analysis of the parameters [4]. Each one of these parameters has its own importance in de-interleaving, which is explained in the later passage.

A. ANGLE OF ARRIVAL

The angle of arrival (AOA) can be measured on a single pulse basis. The one parameter that modern radar systems do not modulate is their location; therefore, the AOA holds a special place in de-interleaving schemes. In case of an airborne radar, the above statement is true, as an airborne radar cannot change its position. In other words, we can say that AOA measured by an intercept receiver has a relatively stable value for the interval of interest.

B. PULSE AMPLITUDE

Pulse amplitude is often deemed less useful due to its variability within a pulse train. However, the amplitude difference from one pulse to the next within a pulse train is not that significant. It is rather certain that adjacent pulses with a large amplitude variation do not originate from the same emitter [7]. For simulated data using constant pulse interval scanning radars, the results obtained using just amplitude for de-interleaving are similar to those obtained using pulse interval alone. Since pulse amplitude is a strong function of distance with the emitter, it can often de-interleave signals that would otherwise be quite complicated. Therefore, the amplitude parameter may prove crucial in distinguishing emitters.

C. RADIO FREQUENCY

An intercept receiver measures the center of the carrier frequency of a pulse. In general, the distribution of the spectrum is not needed. Carrier frequency is a very powerful sorting parameter [5]. As a matter of fact, radars physically close to each other cannot operate on same frequency. The main shortcoming of using frequency information is the occasional time overlapping of pulses, which can give an erroneous discriminator output in case of both signals having nearly equal strength. However, the benefits of having frequency available as a parameter, far outweigh this minor problem. Frequency agility on pulse to pulse basis or pulse group to pulse group basis is common, so our algorithm must cater for it while using the frequency in de-interleaving process [6].

D. PULSE WIDTH

Pulse width, if available, should be used along with the amplitude. However, pulse width is less effective as a de-interleaving parameter, since many types of radar are similar in this respect. Moreover, pulse duration of a given emitter (as measured) also varies with amplitude. In addition, multi-path causes variations in measuring pulse duration values. In contrast, it is well-known that amplitude does not vary considerably from pulse to pulse. Hence, a change in pulse width will not have a major effect for a short time of interest, and thus becomes a relatively stable parameter.

E. TIME OF ARRIVAL

Time of arrival is a widely used parameter for de-interleaving. TOA difference is used for determination of PRI(s). Many techniques, such as Delta Histogram, Cumulative Difference Histogram, Sequential Histogram and Sequence Searching have been developed that rely solely on TOA for de-interleaving. However, these techniques are less effective due to the increasing use of PRI-agile waveforms used by radar systems. PRI stability is only incidental to many radars performance, and even some MTI systems can use PRI-agility if deemed necessary. In this case, involvement of other parameters for de-interleaving becomes essential.

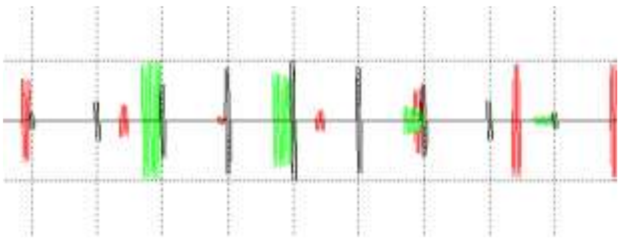

FIGURE. 1. Interleaved Pulse Train.

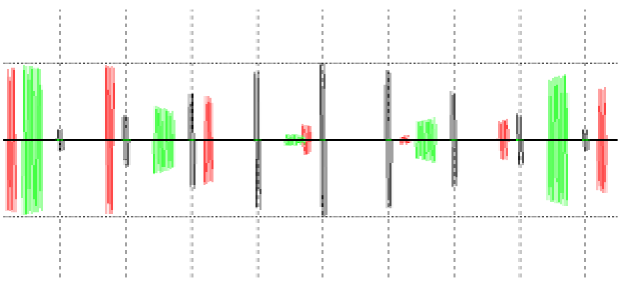

FIGURE. 2. De-Interleaved Pulse Train.

III. STOCHASTIC DYNAMIC MODELLING OF EMITTER PARAMETERS

In order to process and estimate parameters of emitter signals of threat, stochastic dynamic model of pulse amplitude, time of arrival, radio frequency and pulse width is formed using state space approach [8].

A. PULSE AMPLITUDE

Non-linear trajectory is a major constraint for modeling of this parameter. Fortunately, an airborne EW system will not experience drastic variations in pulse amplitude for consecutive pulses. Hence, we may approximate it by a third order dynamic state space model. However, to reduce complexity, we have employed a second order linear model. This approximation is modeled as an additional process noise in the stochastic linear estimator. Fig. 3 shows the plot of dynamic amplitude modeling, while mathematical representation is provided in (1) and (2).

$$\begin{bmatrix} x_{amp}(k+1) \\ x^{\Delta}_{amp}(k+1) \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} x_{amp}(k) \\ x^{\Delta}_{amp}(k) \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \end{bmatrix} x_{amp}(k) + \begin{bmatrix} 1 \\ 1 \end{bmatrix} v_{amp}(k) \quad (1)$$

$$\hat{x}_{amp} = \begin{bmatrix} 1 & 1 \end{bmatrix} \begin{bmatrix} x_{amp}(k) \\ x^{\Delta}_{amp}(k) \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \end{bmatrix} w_{amp}(k) \quad (2)$$

B. TOA AND PRI MODEL

Emitter’s pulse TOA model is quite straight forward, as the next TOA is equal to the sum of previous TOA and the emitter’s PRI. Emitters having a staggered PRI have to be modeled by frame period instead of usual PRI. Additionally, the staggered emitter model is supposed to have same number of values of last TOAs as the staggered levels (staggered intervals). Equations (3) to (7) illustrate TOA dynamic model for a constant PRI emitter.

$$\begin{bmatrix} x_{PRI}(k+1) \\ x_{TOA}(k+1) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} x_{PRI}(k) \\ x_{TOA}(k) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} v_{TOA}(k) \quad (3)$$

$$x_{TOA}(k) = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} x_{PRI}(k) \\ x_{TOA}(k) \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \end{bmatrix} w_{TOA}(k) \quad (4)$$

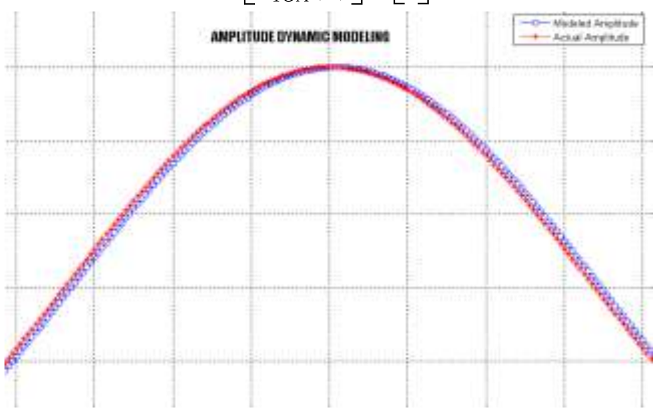

FIGURE 3. Amplitude Dynamic Modeling.

$$\begin{bmatrix} x_{frame}(k+1) \\ x_{TOA}^{n}(k+1) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} x_{frame}(k) \\ x_{TOA}^{n}(k) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} v_{TOA}(k) \quad (5)$$

$$x_{TOA}^{n}(k) = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} x_{frame}(k) \\ x_{TOA}^{n}(k) \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \end{bmatrix} w_{TOA}(k) \quad (6)$$

$$x_{TOA}^{n} = \begin{bmatrix} x_{TOA}^{1} & x_{TOA}^{2} & \cdots & x_{TOA}^{n} \end{bmatrix}^{T} \quad (7)$$

Note that the superscript 'n' in above equations indicates the TOA of nth staggered PRI. Jittered emitters are modeled by introducing process noise. Thus, a jittered emitter has a single mean PRI. Variations in the PRI are modeled by process noise which appears in the TOAs for that emitter.

C. RADIO FREQUENCY AND PULSE WIDTH MODEL

Radio frequency of emitter is deemed as the most stable parameter of an emitter. Moreover, the propagation effects do not change the transmitted frequency. Any variation observed in RF by an RWR receiver is due to the measurement inaccuracies [9].

Pulse width of an emitter in a certain mode is also constant, but the channel through which a pulse travels induces certain variations. These variations depend on myriads of variables associated with the channel. Accurate modeling of these channel variations is difficult to accomplish. However, as the time span is minimal, hence the PW variable doesn't vary significantly in the observation window. It is sufficient to introduce a little process noise in the model which helps in tracking the so- called long term variations in the pulse width.

Models for the RF and pulse width are more or less similar. The difference lies only in specification of process and measurement noise. Radio frequency model is shown in (8) and (9). Whereas, (10) and (11) show the model for pulse width. State vector for the integrated tracker is given by (12).

$$x_F(k+1) = x_F(k) + v_F(k) \quad (8)$$

$$x_F(k) = x_F(k) + w_F(k) \quad (9)$$

$$x_{PW}(k+1) = x_{PW}(k) + v_{PW}(k) \quad (10)$$

$$x_{PW}(k) = x_{PW}(k) + w_{PW}(k) \quad (11)$$

$$x = \begin{bmatrix} TOA & PRI & PA & d\_PA & PW & RF \end{bmatrix}^{T} \quad (12)$$

D. DSP ALGOTRITHMS AND DESIGNS

PDWS are streamed to DSP processor, which applies statistical signal processing techniques. These techniques include cluster formation on TOAs, histograms formations, auto-correlations, sequence searching, integration and extraction of pulses [10]. For multiple emitter cases, trackers are formed in order to correlate upcoming emitter with previously detected threat signals. Fig. 4 shows the flow of statistical digital signal processing algorithms.

Autocorrelation is a well-known method of finding the period of repeating patterns. In autocorrelation process, histogram of the nth-order differences of pulses is created [11]. The process of autocorrelation results in peaks which carry the information about the characteristics of PRI frame. Noise floor is computed by finding the mean of all values in autocorrelation array 'H' in the histogram, as shown in (13) and (14).

$$\text{Noise Floor} = \left\{ \sum_{k=0}^{HistogramSize-1} H[k] \right\} / \, HistogramSize \quad (13)$$

$$\textit{Peak integral} = \textit{Peak integral} + H[k] \quad (14)$$

Subsequent consecutive peaks (in an envelope) above noise floor are integrated and their locations in the histogram are also kept, as shown in Fig. 5. Once the peaks are obtained by process of forming histogram, they are analyzed in the subsequent modules of algorithm for the existence of candidate dwell and its related density of pulses in the buffer [12]. PDWs analysis results in trackers formation, while upcoming emitter signals parameters are compared with already formed trackers. Fig. 6 shows the block diagram of trackers formation.

FIGURE 4. Algorithm flow for Threat Detection.

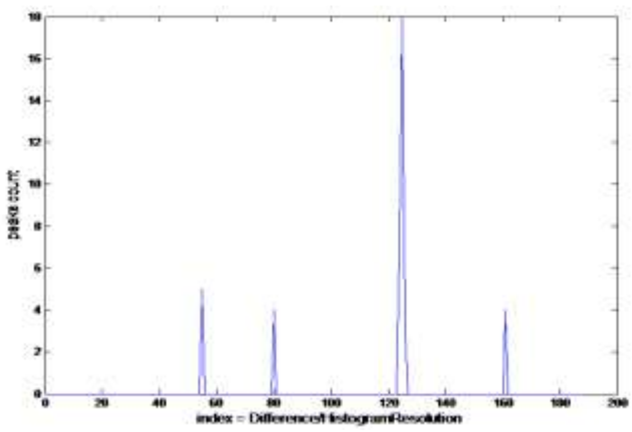

FIGURE 5. Histogram Plot of Time of Arrival Differences.

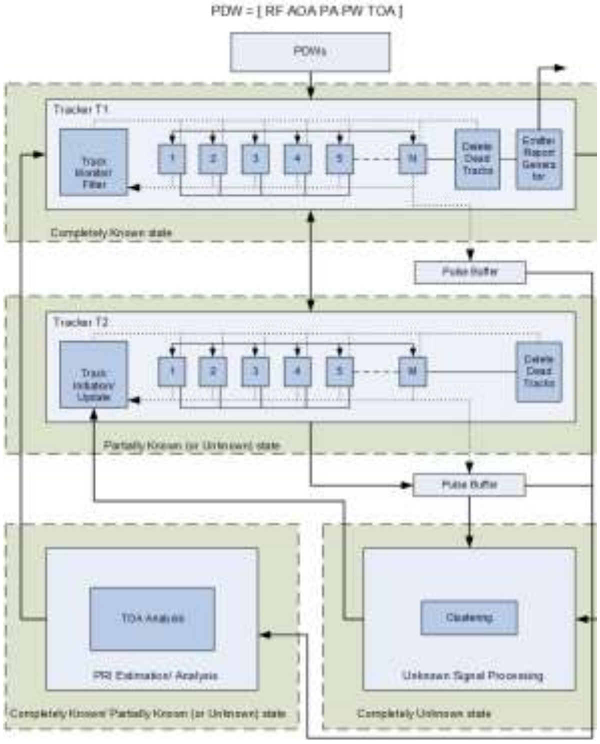

FIGURE 6. Block Diagram of Trackers formation and Clustering from PDWS.

E. SIMULATION AND RESULTS OF SYNTHETIC DATA GENERATION OF RADAR WARNING RECIEVER

In order to realize and test the algorithms in real time environment, simulation and implementation of algorithms was performed for different scenarios of emitter signals [13]. The emitter signals were generated by developing synthetic data generator, which was able to generate real time PDWs for threat processor.

F. THREAT EMITTER SIGNALS OF AGILE, STEP, SWEEP AND DWELL-SWITCH RADIO FREQUENCY

Fig. 7 explains the different RF patterns. Emitter signal in agile and jitter RF signals shows frequency deviation of up to 5% from the mean value. Emitter signals with sweep radio frequency start form specific frequency with slide rate and reach maximum radio frequency. Afterwards, patterns again jump to initial radio frequency forming saw-tooth wave. In RF step and jump, specific spots of radio frequency appear in consecutive pulses which repeat the pattern in an order. Synthetic data can generate up to 16 levels of RF step and jump [14]. Dwell-switch RF emitter signals have specific radio frequency for some interval and then another for the next interval as depicted in the figure.

i) THREAT EMITTER SIGNALS OF PULSE PULSE WIDTH

Pulse width emitter signal have deviation in central pulse width which forms fix and agile patterns. In fix PW emitter signals, there is almost zero deviation. However, in agile and complex cases, deviation in pulse width is up to 5% form the mean value. Fig. 8 shows fix and agile pulse width patterns.

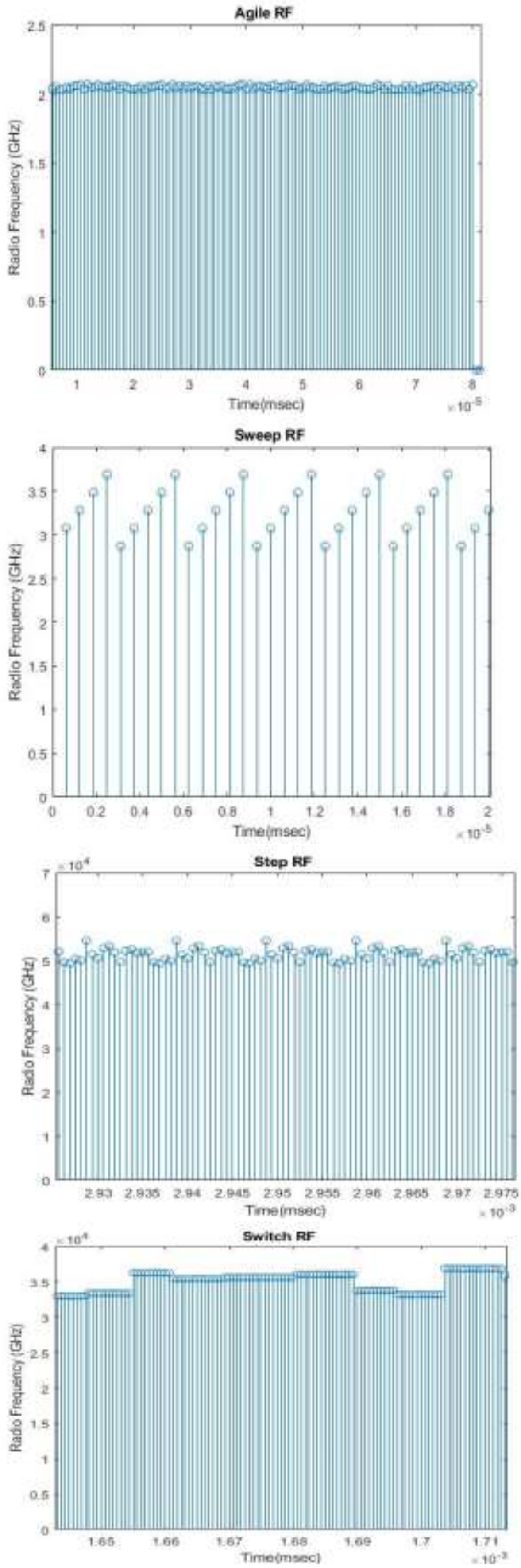

FIGURE. 7. Agile, Sweep, Step and Switch RF Patterns.

ii) THREAT EMITTER SIGNALS OF PULSE REPETITIVE INTERVAL

In radar warning receivers, PRI estimation is done by processing the Time of Arrival (TOA) factor. TOA Analysis module is an integrated block of algorithms to detect different sort of PRIs and accurately estimate parameters associated with them. Four different PRI signatures that integrated TOA analysis can identify and report are: Jittered PRI, Dwell & Switch PRI, Stagger PRI and Sliding PRI.

Jittered PRI has deviation of up to 15% from central value of PRI. In dwell & switch PRI, specific PRI retains its value, and after some interval changes to another. In design, up to 16 level of dwell-switch patterns can be generated. Switching among them is done automatically and rapidly to perform certain radar functions.

In Stagger PRI, two or more PRIs are selected in a fixed sequence. The sequence may contain more than one of the several intervals before it repeats. A Stagger PRI sequence is described by Stagger PRI frame. Moreover, the number of different positions (stagger phases) or stagger intervals in a single stagger frame (along with its PRI signature) is maintained against particular threat's track [15]. Sliding PRI is characterized by monotonic increase or decrease in the PRI, followed by a rapid switching upon reaching one extreme limit to the other extreme limit. The parameters of interest in Sliding PRI are Initial PRI, terminal PRI and Slide Rate. Fig. 9 shows the Jitter, Dwell-switch, stagger and slide PRI patterns.

In order to test the algorithms for real time radar signals, synthetic data was generated for PRI, PW and RF to form PDWs for the testing and implementation of DSP algorithms. Synthetic data also included practical scenarios like spurious pulses, band filtering, antenna filtering, blanking and low pass filtering of signals, as depicted in Fig. 10. Band value, RF, PW & PRI are combined to form PDWs packets, which are then transmitted to DSP processor.

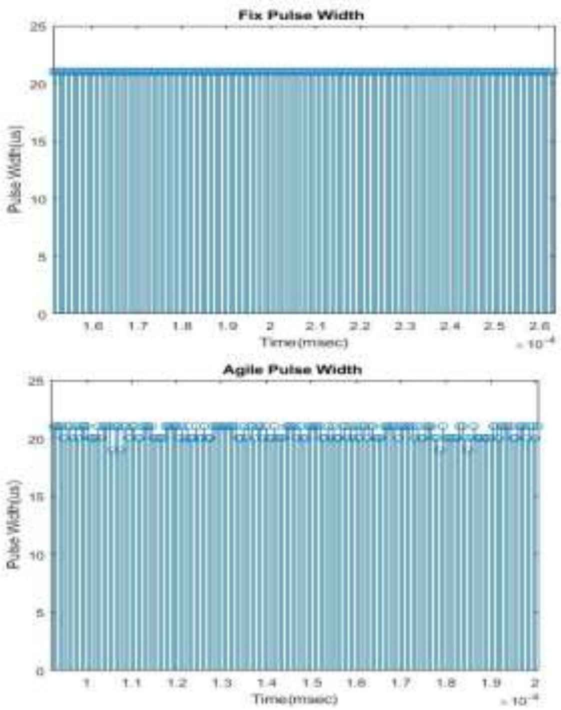

FIGURE 8. Fix and Agile Pulse Width Patterns.

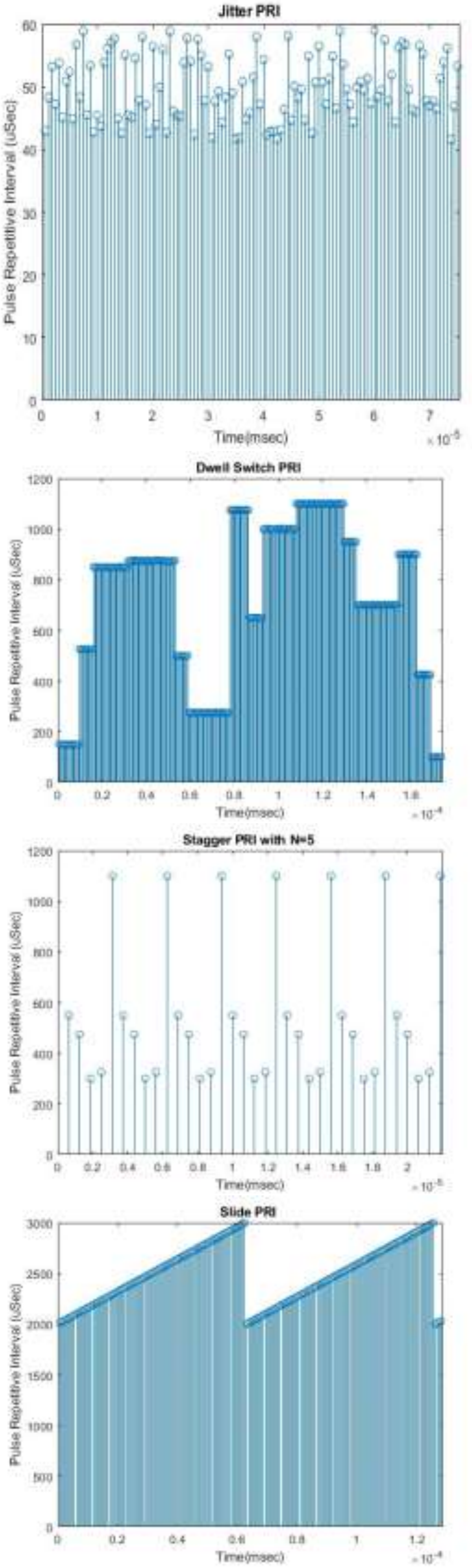

FIGURE 9. Jitter, Dwell, Stagger and Slide PRI Patterns.

iii) HARDWARE IMPLEMENTATION

System design algorithms were implemented on FPGA, DSP and ARM processors. STM32, TI Keystone II and Xilinx KC705 evaluations kits were utilized. Moreover, NI PXI 5644R was used for real time RF signal generation with frequency band from 1 to 6 GHz, after sampling of signal using analog to digital conversion (ADC) in KC705 FPGA hardware. Multiple emitter signals were also generated in order to test the system performance. Hardware employed in the research is shown in Fig. 11.

Analysis on generated RF signal and pulsed signals was carried out in FPGA, which measured the accurate frequency of carrier signals using FFT (Fast Fourier Transform) algorithms. Reported RF with other parameters like power, TOA, PW and PRI were combined to form packets of PDWs, which were provided to TI Keystone processor for applying statistical DSP algorithms including clustering, histogram and trackers formation. Synthetic data generated with different emitter signals was given to threat processor and results were compared with response from real time signal generation using NI PXI.

IV. CONCLUSIONS

Design, simulation and hardware implementation of threat detection in radar warning receivers has been presented in this paper. Synthetic formation of various emitter signals is discussed, including jitter, slide, stagger and dwell-switch. PDWs were used for statistical algorithms implementation and identification of threat type. Multiple emitter cases were also generated and tested using DSP algorithms for threat detection and identification of emitter type. It is noteworthy that synthetic data generation addresses the issue of recording data in real time, which is infeasible. Upon comparison with the original airborne data, the synthetically generated data was found to be quite close.

V. FUTURE WORK

De-interleaving of multiple emitter signals is challenging due to complexity. Multiple emitter signals give rise to pulse on pulse scenarios, in which parameters are difficult to calculate, and identification of threat type becomes cumbersome. Future research should be done on improvement of algorithms for de-interleaving. Moreover, radio frequency calculation and pulse repetitive interval estimation methods need further work in terms of having higher accuracy.

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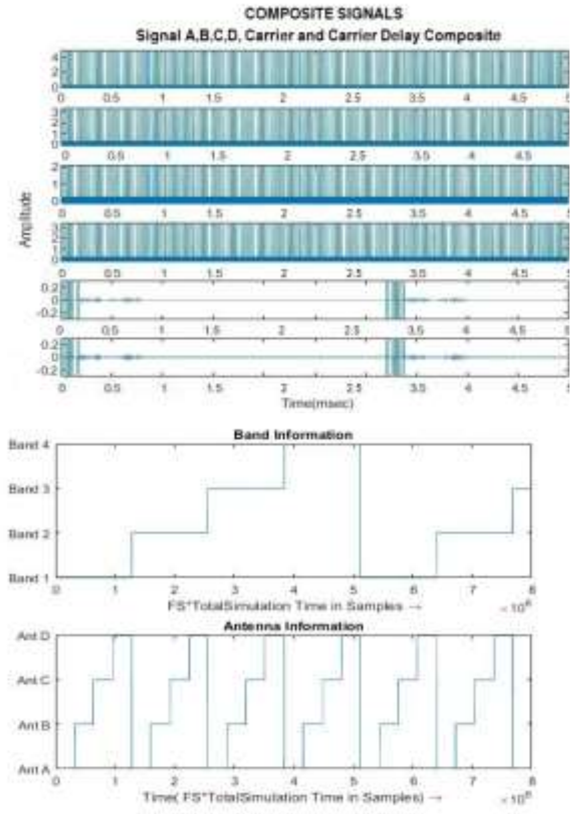

FIGURE 10. Antenna and Band Information.

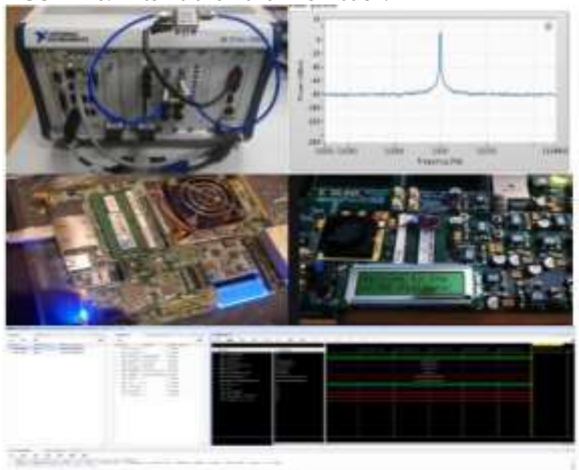

FIGURE 11. NI PXI FPGA and DSP Hardware.

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