

High Accuracy Parameter Estimation for Advanced Radar Identification of Electronic Intelligence System

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ABSTRACT

Radar identification is one of the vital operations in an electronic intelligence system. The conventional methods based on basic parameters comparison of unique identification of a radar in a cluster of similar radars, is prone to ambiguities. To meet the current tactical requirements of unique identification of a radar, the methodology needs to be based on better feature extraction, even in low SNR conditions. The paper explores a novel technique based on moving autocorrelation for the extraction of intra-pulse and inter-pulse radar parameters. Extensive simulation and empirical studies have been carried out to establish the approach to extend accurate radar parameters in noisy and low SNR conditions. The technique is found to be promising even in field data conditions. The paper describes the methodology, simulation results, FPGA implementation using system generator and resource utilisation summary.

Keywords: ELINT system; Electronic intelligence; Intra-pulse parameters; Autocorrelation

NOMENCLATURE

$x(n)$	Time domain signal
X_m	Restored signal spectrum
N_m	Noise spectrum
Y_m	Noisy signal spectrum
$x(m)$	Restored time domain signal
m, n	Index number
k	Bin number
θY_k	Phase of the Frequency Spectrum
F_s	Sampling Frequency
$\Phi(n)$	Phase of the signal
$\Delta\Phi(n)$	Phase difference
$F_m(n)$	Multilevel Frequency

1. INTRODUCTION

The modern electronic intelligence (ELINT) system should be capable to identify radar signal emissions uniquely in a dense environment. The evolving radar technology, utilising frequency, pulse width (PW) and pulse repetition interval (PRI) agility requires complex signal processing techniques to facilitate unique emitter identification. The dense electromagnetic environment, with complex radar waveforms, results in pulse on pulse in radar signals being overlapped in time, frequency and azimuth. It poses serious challenge to ELINT reconnaissance process.

The efficient emitter identification system is vital which extracts distinctive and accurate intra-pulse and inter-pulse parameter to handle the above challenges. The radars of the same kind exhibit slight differences in their transmitted pulses¹. The identification system needs to classify and identify

similar radars i.e. radars of the same make and model using the unintentional intra-pulse parameters in addition to the intentional parameters. These extracted features constitute the finger print or signature of the radar. Based on signature of the radar, the decision making and correct identification of the radar can be established.

The intra-pulse parameters include frequency, amplitude, rise time, fall time, type of modulation for each pulse. As part of intra-pulse analysis, instantaneous variations in frequency, amplitude, phase and their first and second order statistical variations are computed²⁻⁴. Instantaneous frequency is an important parameter to describe the characteristics which changes with time. The identification was presented using various methods⁵⁻⁹. Michel & Adams¹⁰ presented the FPGA implementation aspects for radar system. Accurate measurement of parameters ensures the correct radar identification. Measurements carried out using proposed approach improve the identification as discussed⁵⁻⁹.

The conventional method of handling pulse on pulse signals is given based on extraction of basic parameters, viz frequency, PW and direction of arrival (DOA)¹¹⁻¹². This method is prone to ambiguities and often result in erroneous identification. To overcome this, the intra-pulse parameters of the radar also need to be extracted. With the advent of radars exhibiting agility in frequency, PW and PRI, there is a need to measure the intra-pulse group parameters. And also with the rapid deployment of LPI radars¹³⁻¹⁴, it is crucial to handle these radars and identify them correctly.

A better methodology is based on digital in phase and quadrature phase (DIQ) for intra-pulse analysis. This technique performs reasonably well for SNR conditions better than 12 dB as demonstrated¹⁵. Pulse detection approach is discussed

which needs about 3 dB SNR¹⁶. Digital instantaneous frequency measurement technique is presented for frequency measurement¹⁷⁻²⁰. However they measure the frequency with high accuracy at high SNR. But their performance is not good at lower SNR.

This paper proposes for unique identification a much better methodology, in a low SNR condition of order of 0 dB. The signal is preprocessed, prior to the extraction of parameters. As part of preprocessing, noise cancellation is employed for signal enhancement to improve the quality of the signal. Noise cancellation is done by estimating the noise from electromagnetic environment. The estimated noise magnitude is subtracted from the magnitude of noisy signal without affecting the phase to get restored signal²¹. Noise cancellation is applied on both in phase and quadrature phase components and restored signal is computed for both. Thereafter, moving autocorrelation with different delays is performed on the complex signal to further enhance the signal and reduces the effect of noise. Performing autocorrelation is computationally intensive. So, an efficient technique for implementation has been devised. The intra-pulse parameters so extracted are highly accurate even at low SNR conditions.

The efficacy of the algorithms has been tested with live radar data. The analysis has been conducted on different radar modes and different radar signals to verify the robustness of the features extraction algorithm. In subsequent section, the instantaneous measurement techniques based on autocorrelation alongwith noise cancellation and noise estimation, simulation results and implementation of FPGA hardware is discussed.

2. FINE GRAIN PARAMETER MEASUREMENTS TECHNIQUES

The accurate intra-pulse information amalgamated with the inter-pulse information of RF, PRI, PW and scan provides the comprehensive characterisation of the emitter thereby arriving at the fine grain parameters of each emitter, which are highly accurate and grain parameters of each emitter and stable for identification of the emitter. Intentional parameters are measured using time domain and frequency domain techniques.

Figure 1 shows the block diagram of Fine Grain Parameter (FGP) measurement. The algorithms shown are applied on digitised baseband or IF signal and finally instantaneous amplitude profile, instantaneous frequency profile and fine grain parameters are generated using both autocorrelation approach and DIQ approach. The signal is also pre-processed using noise cancellation technique before applying these algorithms. Noise estimation is carried out for finding out the noise riding threshold which is used for pulse detection and FGP are measured.

2.1 Noise Cancellation

Subtraction of noise from the noisy signal is done to get a restored signal which reduces the SNR requirement at the

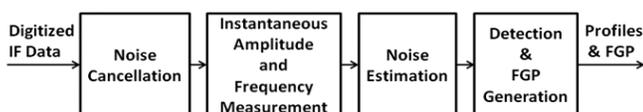


Figure 1. Fine grain parameter measurement.

input signal. Noise samples are collected from the system chain when front end is connected to built-in test equipment (BITE) port in signal off condition for minimum time of 50 us for better estimate. Then estimated average of noise spectrum N_m is subtracted from the noisy signal spectrum Y_m to get estimate of the instantaneous magnitude spectrum of restored signal X_m .

$$X_m = Y_m - N_m \quad (1)$$

Restored time-domain signal (X_m) is obtained by combining an estimate of the instantaneous magnitude spectrum of restored signal (with phase of the noisy signal), and transforming via an inverse discrete Fourier transform to the time domain²¹.

$$x(m) = \sum_{n=0}^{N-1} (X_k e^{j\theta Y_k}) (e^{\frac{j2\pi km}{N}}) \quad (2)$$

Noise estimate subtraction technique is applied to the input signal, to produce the output restored signal as shown in Fig. 2. The 66650 samples are taken for pre-trigger region which consists mainly noise and 8000 samples are taken for pulse signal which consists signal as well as noise. The additive white Gaussian noise (AWGN) is considered. It is visible in output restored signal that has reduced noise and thus helps in improving accuracy of further analysis. Restored signal is applied on both baseband signals of in-phase (I) and quadrature-phase (Q) components.

2.2 Instantaneous Amplitude and Frequency Measurement

Autocorrelation is performed on the baseband signal to reduce the effect of noise¹⁶. Thirty two samples autocorrelation is performed in a recursive way to reduce the computational

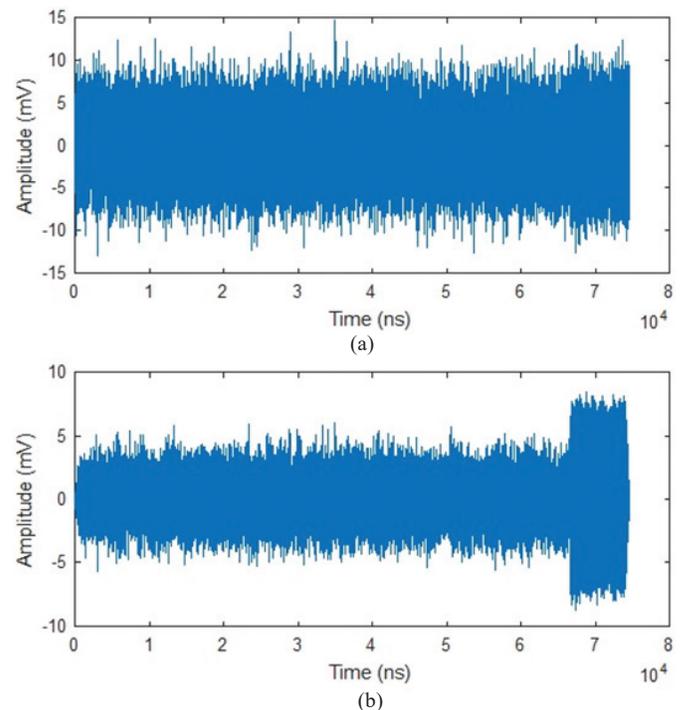


Figure 2. (a) Input at 1 GHz with 0 dB SNR and (b) Restored signal.

requirement. Thirty two samples autocorrelation is selected to cater the minimum pulse width requirement of 50 ns when sampling time is 1.5 ns. Delay m is 1 in case of amplitude measurement. First element of thirty-two samples auto correlation is calculated as:

$$X(1) = \text{mean}(x(1:32).x^*(1+m:32+m)) \quad (3)$$

where x^* is a conjugate of x . It is implemented in recursively as below:

$$X(n+1) = x(n) + |x(n+32).x^*(n+32+m)| - |x(n).x^*(n+m)| \quad (4)$$

where n varies from n to the size of samples. This equation is further optimised by replacing first element of thirty-two samples auto correlation with fixed value:

$$X(1) = a + jb \quad (5)$$

where a and b are constant values. This does not require the measurement of initial average of thirty-two samples auto correlation output. Measurement of frequency parameters involves calculation of autocorrelation variables with different delays using baseband signal. Four autocorrelation variables $X1$, $X2$, $X4$ and $X8$ with four different delays $m = 1, 2, 4$ and 8 are calculated from the correlated signal with different delays. Multilevel phase differences are calculated from the correlated signals with different delays, which in turn are used to compute the frequency. Frequency ($F_1(n)$) is measured as:

$$F_1(n) = F_s \left(\frac{\Delta\Phi(n)}{2\pi} \right) \quad (6)$$

where F_s is sampling frequency and $\Delta\Phi(n)$ is the phase difference derived from $X1$. Now $F_1(n)$ measurement determines the zone in which phase belongs according to the following equation.

$$Z_m = \text{Ceil} \left(\frac{mF_1(n)}{F_s} \right) \quad (7)$$

Here unwrapping of phases which is required for complex signals is not required as different phases are calculated from auto-correlated variables with different delays and are mapped to appropriate zones which are obtained with the help of frequency $F_{m-1}(n)$ ¹⁷⁻¹⁸. Likewise $F_2(n)$ serves as a guide for Φ_4 by determining the zone it should be merged to. Similarly, $F_4(n)$ determines the zone for Φ_8 . The final frequency parameter $F_8(n)$ is based on the mapping of Φ_8 .

$$F_m(n) = \left(\frac{F_s}{2\pi m} \right) (\Delta\Phi_m(n) + 2\pi Z_m) \quad (8)$$

Using the improved instantaneous frequency, the various intra-pulse modulations. Bi-phase, quad-phase and poly-phase signals are also classified. The instantaneous frequency is median filtered to suppress impulses caused due to the noise, but to retain the main trend. The standard deviation of the median filtered instantaneous frequency profile is utilised to differentiate conventional bi-phase and quad-phase signals from poly-phase signals.

2.3 Noise Estimation

Estimation of noise is done for pulse detection which reduces the computation requirement and storage requirement. Mean of the modulus of the noise samples are taken and approximate standard deviation is computed. The absolute of input signal samples $x(n)$ are taken which makes all negative samples positive. The shape of probability density function (PDF) will be same but doubles the peak value.

$$\sigma = \sqrt{\sum_{n=0}^{N-1} \frac{(x(n) - x_{avg})^2}{N}} \quad (9)$$

$$\sigma_1 = \left(\frac{k_1}{2} \right) \sum_{n=0}^{N-1} |x(n)| \quad (10)$$

$$\sigma_2 = \left(\frac{k_2}{2} \right) |x(n) + x(n+1)| \quad (11)$$

The Eqn. (9) shows standard deviation (σ) of signal $x(n)$ which is obtained by computing mean of noise. Absolute value of signal $x(n)$ is computed and multiplied with constant ($k_1/2$) and result (σ_1) is derived as Eqn. (10) which is approximately equivalent to standard deviation of signal $x(n)$. Similarly, based on two point averaging also approximate standard deviation (σ_2) is calculated using Eqn. (11). Constants k_1 and k_2 are decided based on minimum error. The random noise is computed and results are tabulated using both the approaches as shown in Table 1. Error is also computed with standard deviation. The error ($E1$) computed is less than 10% using first approach whereas error ($E2$) is less than 20 % using second approach. Usually, two level threshold is used which will have difference of 6 dB. Hence the first approach is appropriate as error computed is less and it is efficient also in hardware implementation.

2.4 DIQ Technique

Equations given below describes the DIQ approach for calculating instantaneous phase, frequency, and amplitude. The detection is carried out on this amplitude profile $R(n)$ and pulse is detected.

$$\Phi(n) = \tan^{-1} \left(\frac{q(n)}{i(n)} \right) \quad (12)$$

Table 1. Comparison of noise estimation approach

Iteration No.	Standard deviation A	Approach-1 (σ_1) B	Error-1 E1=A-B	Approach-2 (σ_2) C	Error-2 E2=A-C
1	5.825	5.296	0.529	5.593	0.232
2	5.784	5.343	0.441	5.339	0.445
3	4.852	5.305	-0.453	5.756	-0.904
4	5.567	5.281	0.286	5.838	-0.271
5	4.787	5.256	-0.469	5.598	-0.811
6	5.063	5.323	-0.26	6.008	-0.945
7	5.629	5.324	0.305	5.663	-0.034
8	5.276	5.196	0.08	5.576	-0.3
9	5.091	5.195	-0.104	6.023	-0.932
10	4.466	4.789	-0.323	5.213	-0.747

$$F(n) = \left(\frac{F_s}{2\pi} \right) \Delta\Phi(n) \quad (13)$$

$$R(n) = \sqrt{i^2(n) + q^2(n)} \quad (14)$$

There is a requirement of above 8 dB SNR using DIQ technique for instantaneous amplitude and frequency measurement of pulse.

A novel technique based on optimised autocorrelation and noise estimation has been developed to calculate accurate intra-pulse parameters and to overcome the effect of noise at low SNR conditions. It can be utilised for feature extraction and identification of LPI signals also. Using this technique the instantaneous amplitude and frequency parameters of a pulse can be measured with 0 dB.

3. SIMULATION RESULTS

The input signal generated at 0 dB and 9 dB SNR is plotted in Fig. 3. The same signal is used in simulation for generating autocorrelation and DIQ technique outputs.

The envelope or instantaneous amplitude is computed using correlated signal $x(n)$ at SNR conditions of 0 dB and 9 dB which is plotted in Fig. 4. First the input signal is improved using noise cancellation technique. The envelope computed using DIQ technique is plotted in Fig. 5 at SNR conditions of 0 dB and 9 dB. It is observed from Figures, that there is a improvement of 9 dB to 10 dB in the correlated signal as compared to the DIQ technique.

Figure 6 shows the instantaneous frequency output calculated from multilevel correlation coefficients and Fig. 7 shows the instantaneous frequency output as computed from the conventional DIQ technique using the same input pulse

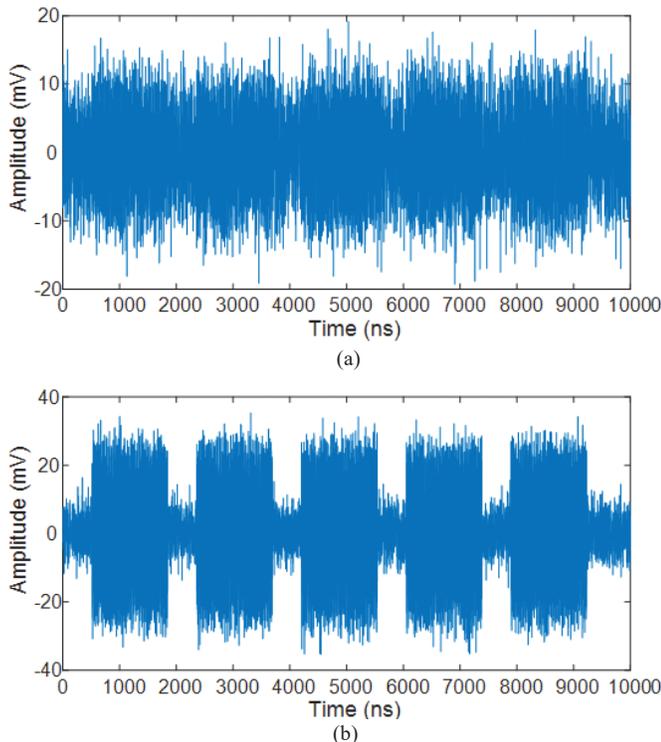


Figure 3. Input signal at (a) 0 dB and (b) 9 dB SNR.

signals at 0 dB SNR and 9 dB SNR. Frequency measurement accuracy of 500 kHz at 0 dB SNR has been achieved using the multilevel correlation technique as we see in Fig. 6.

Improvement in frequency measurement accuracy with reduction in SNR requirement at the input is achieved in comparison with DIQ technique as observed through Fig. 7.

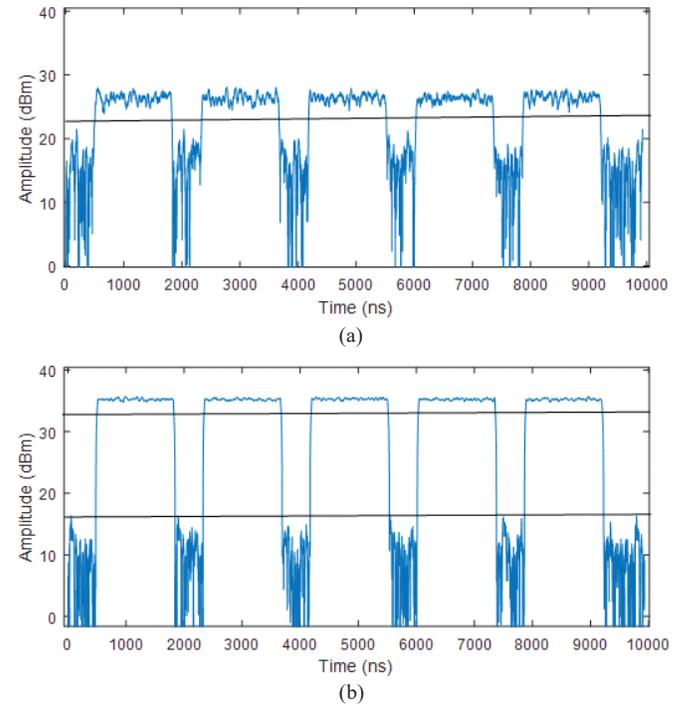


Figure 4. Amplitude profile using autocorrelation approach at 0 dB and 9 dB SNR.

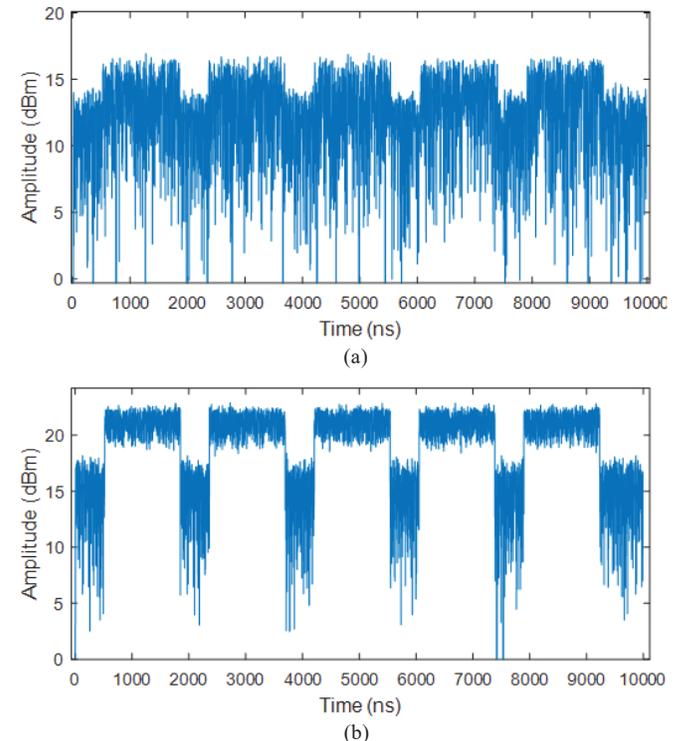


Figure 5. Amplitude Profile using DIQ approach at (a) 0 dB and (b) 9 dB SNR.

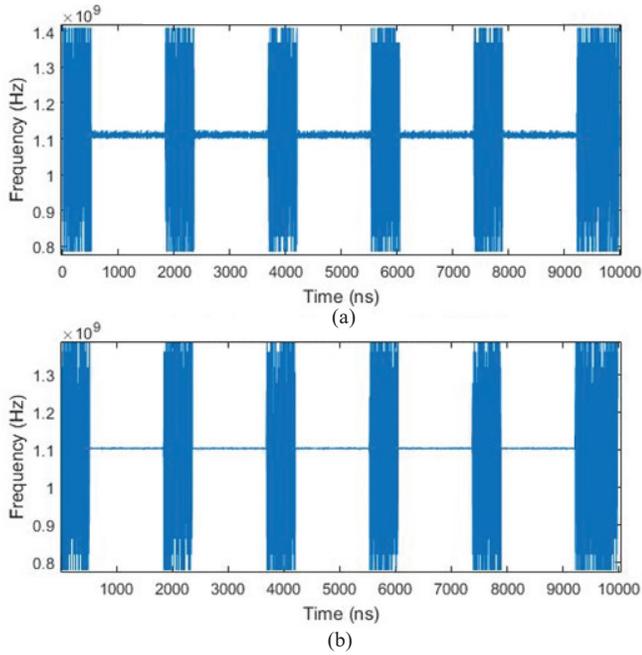


Figure 6. Frequency profile using autocorrelation approach at (a) 0 dB and (b) 9 dB SNR.

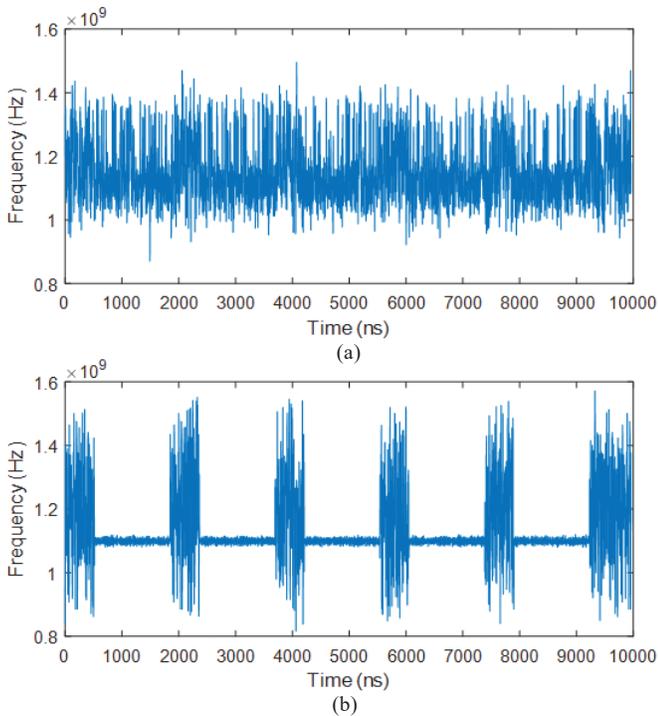


Figure 7. Frequency profile using DIQ approach at (a) 0 dB and (b) 9 dB SNR.

Figure 8 depicts the frequency accuracy with respect to SNR using both the techniques. This shows that autocorrelation technique is able to process the signal at 0 dB SNR, whereas DIQ technique fails. The DIQ technique requires the SNR more than of 9 dB.

The field data is also introduced to check the efficacy of the proposed algorithms. The same data is used for DIQ approach and results are provided as shown in Fig. 9. It is clearly evident from instantaneous amplitude and

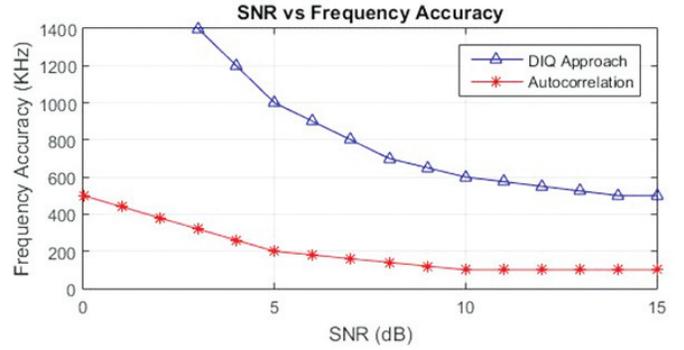


Figure 8. SNR vs frequency accuracy plot.

instantaneous frequency profiles generated using proposed approach having better results compared with DIQ approach.

4. IMPLEMENTATION ON FPGA HARDWARE AND SIMULATION RESULTS

Conventional and Proposed approaches are implemented using System generator, Matlab and Xilinx Vivado 2016.4 tools. The system generator models are generated as shown in Fig. 10. The design is implemented on Xilinx Virtex-7 XC7VX415T FPGA device. The synthesis for netlist generation, mapping, place and route is carried out. The comparison of FPGA resource utilisation summary is shown in Table 2. The overall requirements of resources are reduced in proposed approach. Total eight DSP48E1 component are required as proposed approach is having only two complex multiplications. Whereas DIQ approach requires more multiplications as it require low pass filters.

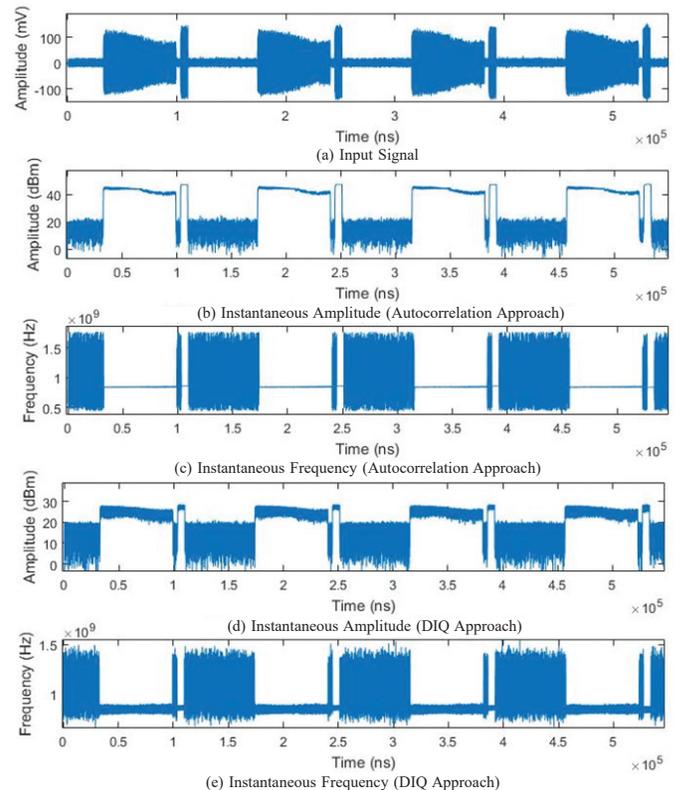


Figure 9. Field data result using Autocorrelation and DIQ approach.

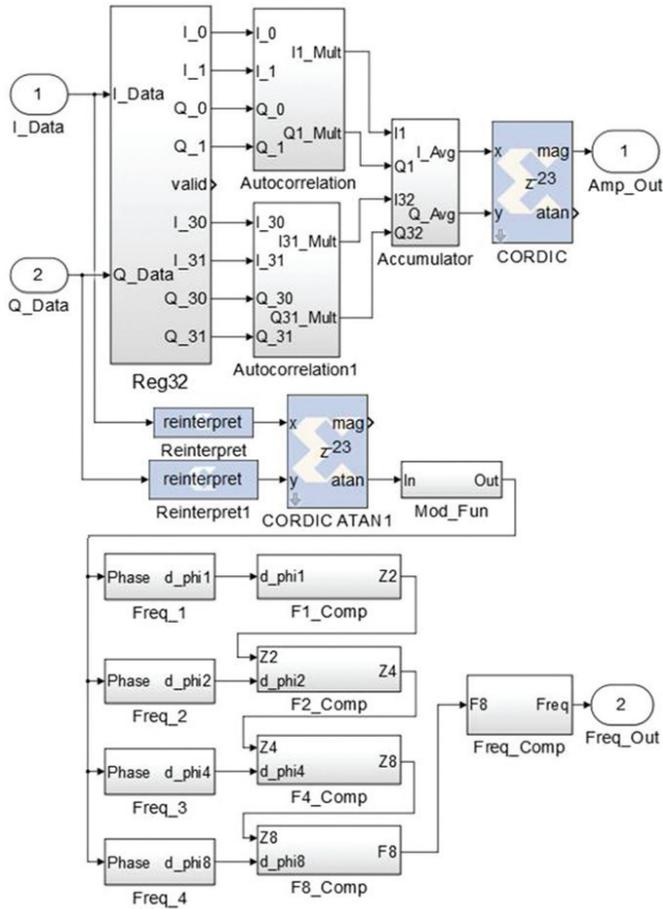


Figure 10. System generator model.

Simulation result using proposed approach is shown in Fig. 11 at 0 dB SNR. Only pulse on time along with pre and post region is shown to facilitate the simulation for multiple pulses. Amp_Out shows the instantaneous amplitude profile which is clearly visible and Freq_Out is the instantaneous frequency profile.

Table 2. FPGA resource utilisation summary (Device: XC7VX415T)

FPGA resource utilisation with max operating Freq.	Proposed approach	DIQ approach	Savings in %
Maximum clock frequency (MHz)	238.1	231.8	2.72
Slice F/Fs	2003	4052	50.52
LUT (4 Inputs)	2546	3799	32.98
DSP48E1	8	38	78.94
Total power (mW)	472	708	33.33

5. CONCLUSIONS

The proposed technique based on moving autocorrelation and noise estimation has significantly improved the measurement accuracy of intra-pulse parameters of instantaneous amplitude and instantaneous frequency at low SNR conditions. The scheme along with finger printing system has lead to a very efficient and accurate emitter identification system. The advancement in signal processing algorithms,



Figure 11. Simulation result at 1100 MHz.

coupled with high performance FPGA has enabled to improve the unique emitter identification and also achieves a real time performance. It is planned for real time modulation classification based on instantaneous frequency profile in future.

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