Defence Science Journal, Vol. 71, No. 1, January 2021, pp. 79-86, DOI : 10.14429/dsj.71.15705

FPGA based Identification of Frequency and Phase Modulated Signals by Time Domain Digital Techniques for ELINT Systems

R.K. Niranjan[#,@,*], C.B. Rama Rao[#], and A.K. Singh[@]

[#]*Department of ECE, National Institute of Technology, Warangal - 506 004, India*
[@]*DRDO-Defence Electronics Research Laboratory, Hyderabad - 500 005, India*
[*]*E-mail: niranjanrk2004@gmail.com*

ABSTRACT

In this paper, a decision tree algorithm based on time-domain digital technique is developed for the identification and classification of diverse radar intra-pulse modulated signals for the electronic intelligence system in real-time. This includes linear frequency modulation, non-linear frequency modulation, stepped frequency modulation and bi-phase modulation. The received signal is digitised and the instantaneous phase and high accuracy instantaneous frequency are estimated. The instantaneous amplitude is also estimated to get the start and stop of the pulse. Instantaneous parameters are estimated using a moving autocorrelation technique. The proposed algorithm is employed on the instantaneous frequency and the modulation is identified. The modulation type and modulation parameter are important for unique radar identification when similar radars are operating in a dense environment. Simulations are carried out at various SNR conditions and results are presented. The model for algorithm is developed using a system generator and implemented in FPGA. These results are compared when the proposed algorithm is used with the existing digital in-phase and quadrature-phase (DIQ) technique of instantaneous frequency and amplitude estimation.

Keywords: Complex radar signals; Instantaneous frequency profile; Intra-pulse modulation; moving autocorrelation technique; Digital in-phase and quadrature-phase technique

NOMENCLATURE

$x(t)$	Continuous-time signal
$x(n)$	Discrete-time signal
t_s	Sampling time
f_s	Sampling frequency
ϕ	Initial phase of the signal
τ	Fixed time period
α	Ascending chirp rate
β	Descending chirp rate
T	Time duration
f_c	Centre frequency of IF signal
F_{max}	Maximum frequency of FMCW signal
F_{min}	Minimum frequency of FMCW signal
F_{LE}	Leading edge frequency
F_{TE}	Trailing edge frequency
F_{CNT}	Center frequency during the pulse
F_{IP1}	Frequency at the first intermediate point
F_{IP2}	Frequency at the second intermediate point
δf	Frequency deviation
f_m	Sinusoidal modulating frequency
Δf	Frequency tolerance limit
$\Delta\phi$	Phase tolerance limit

1. INTRODUCTION

Modulation on radar pulse is one of the most important features and one of the vital problems in the analysis of non-cooperative radar signals is modulation classification for emitter identification[1-2]. The modulation classification plays a very important role in electronic intelligence (ELINT) systems[4-5]. Firstly, the modulation type of a signal is important to identify the radar type. Second, on identifying the correct modulation type the carrier frequency is re-estimated. Third, it helps to distinguish similar radars deployed in proximity. But for radar signals, the modulation classification in real-time is very challenging due to the possibility of various modulations within a very short pulse.

An earlier generation of electronic support (ES) systems was based on instantaneous frequency measurement (IFM) receiver and pulse measurement using log video. The time-domain technique was used for noise estimation and signal detection[6] and frequency were measured using time-frequency analysis[7-9]. But during conversion from radio frequency (RF) or intermediate frequency (IF) to log video, the phase and hence the modulation information is lost. Due to this reason these systems measure only basic parameters like RF, Pulse width (PW), pulse repetition interval (PRI) and pulse amplitude (PA). These parameters broadly are called inter-pulse parameters. But the measurement of these parameters alone is not sufficient against modern RADARs.

Conventional radars have simple pulsed waveform or continuous waveform with no modulation. These pulsed radars sometimes have the variations in PW or PRI. But complex radars are having various modulations within the pulse along with the above variations. These intra-pulse modulations can be linear frequency modulation (LFM), non-linear frequency

Received : 14 May 2020, Revised : 28 August 2020
Accepted : 09 October 2020, Online published : 01 February 2021

modulation (NLFM), stepped frequency modulation (SFM) and bi-phase modulation (BPM). Typically, these modulations are identified by the ELINT system using offline analysis[10-15]. Till the earlier generation of electronic warfare (EW) systems, these offline analysis tools are either add-on or they are integrated with the main ES systems or ELINT systems. Identification of modulations by the ELINT system in real-time is still a challenge. Various digital methods are discussed for modern digital implementation[16-21] and decision-theoretic approaches are mentioned for modulation classification[22-26].

Modulations can be identified using frequency domain techniques using offline systems[27-28]. Implementation of these techniques in Field Programmable Gate Array (FPGA) for real-time applications is not a viable solution as they consume a lot of hardware resources. Due to this reason, the implementation of signal classification techniques is attempted in FPGA using time-domain technique for real-time applications. IF signal is digitised in ADC and samples are captured, processed and further analysed in FPGA. These are possible to implement in FPGA due to parallelism, high density and high-speed component cores.

In this paper, an algorithm to identify modulation in real-time has been discussed and elaborated. The decision-tree based algorithm is proposed to identify the modulation. The RF pulse (RFP) is generated based on the instantaneous amplitude profile. The complete instantaneous frequency profile data is stored in the random access memory (RAM) during RF pulse. The frequency at different points in the pulse region is fetched from RAM and the algorithm is applied in real-time. The modulation is measured within shadow time based on the frequency parameters.

The validity of the algorithm has been tested with various modulated signals at different SNR conditions. In section-2, modelling and characteristics of various radar signals are given. The proposed modulation recognition algorithm is discussed in section-3. The performance and effectiveness of the algorithm are presented in section-4 through simulations and implementation on FPGA hardware is given in section-5.

2. MODELLING AND CHARACTERISTICS OF VARIOUS RADAR SIGNALS

The RF signal is down-converted to the IF signal using a superhet receiver and it is digitised. The instantaneous amplitude, phase and frequency are estimated. Pulse is detected using amplitude and modulation is identified using phase and frequency. The block diagram of FPGA based modulation identification is shown in Fig. 1.

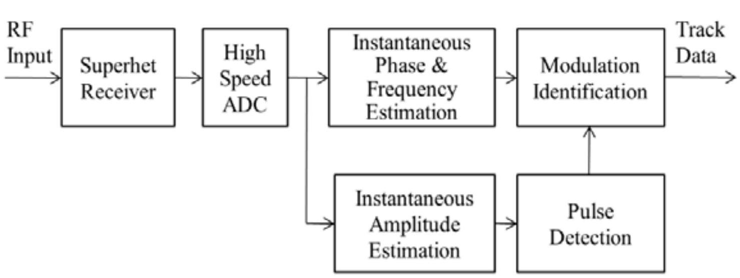

Figure 1. FPGA based modulation identification.

Modern radars are exhibiting complex radar waveforms. These waveforms include No-Modulation Continuous Wave (NMCW), Frequency Modulated Continuous Wave (FMCW), No-Modulation On Pulse (NMOP), LFM, NLFM, SFM and BPM. The following signals are considered and modelled. They are described as below:

(i) *Signal with No Modulation*: NMCW and NMOP signals do not consist of any modulation. The discrete version of the time-domain signal $x(t)$ is given as[29],

$$x(n) = Ae^{j(2\pi fnt_s + \phi)} \tag{1}$$

where, A denotes the carrier amplitude, ϕ denotes the initial phase, f denotes carrier frequency, t_s denotes sampling time and for $n = 1, 2, 3..., N$ for NMOP signal.

When $n = 1, 2, 3..., \infty$ and signals are with PW more than predefined time duration T considered as continuous wave (CW). If PW is below T, they are considered as pulsed signals.

(ii) *Linear Frequency Modulation (LFM)*: LFM ascending (LFMa), LFM descending (LFMd), LFM ascending-descending (LFMad) and LFM descending-ascending (LFMda) chirp signals are considered as LFM signals. These signals are also known as Triangular FM.

(a) LFMa signal is generated as given by[29]

$$x(n) = te^{j(2\pi fnt_s + \phi + \pi\alpha n^2 t_s^2)} \tag{2}$$

$$\text{for } n = \left(\frac{-N}{2}\right), \left(\frac{-N}{2}\right) + 1, ..., -1.$$

where, α is the slope of the LFMa.

(b) LFMd signal is generated as given by[29]

$$x(n) = te^{j(2\pi fnt_s + \phi - \pi\beta n^2 t_s^2)} \tag{3}$$

$$\text{for } n = 0, 1, 2, ..., \left(\frac{N}{2}\right) - 1.$$

where, β is the slope of the LFMd. Usually, LFMa and LFMd signals have the same slope, i.e. $\beta = \alpha$.

(c) LFMad and LFMda signals are generated using a combination of the above two equations. The frequency f is the instantaneous frequency at the peak of the triangular frequency variation, which is the maximum instantaneous frequency within the observation duration in the case of LFMad. The slope α and β is calculated as $2\delta f / \tau$, where the δf is the bandwidth within the time period τ . The parameter τ is a fixed value. The waveform is characterised by f, δf, α and β .

(iii) *Non-Linear Frequency Modulation (NLFM)*: NLFM signal is generated as given by[29].

$$x(n) = Ae^{j(2\pi fnt_s + \phi + \left(\frac{\delta f}{2 f_m}\right)\sin(2\pi f_m nt_s))} \tag{4}$$

where, the $\delta f / 2$ is the peak deviation, f_m is the sinusoidal modulating frequency, $n = 1, 2, 3...N$, if the signal is narrowband, it means $\delta f / 2 f_m \ll 1$. It is assumed that only a fraction of the cycle is sampled over an observation time. In case of the wideband FM signal, $\delta f / 2 f_m \gg 1$. NLFM forward and NLFM reverse is represented as NLFMf and NLFMr respectively.

(iv) *Stepped Frequency Modulation* (SFM): SFM is generated as below

$$x(n) = e^{j(2\pi f_h n t_s + \phi)} \tag{5}$$

for $n = 1, 2, 3, ..., N$

where, f_h is the frequency of h^{th} step, and $h = 1, 2, 3, ..., H$ is the number of steps. Usually H is in the sequence of $2, 4, 8, ...$ etc. For $H = 2$, $h = 1, 2$ similarly for $H = 4$, $h = 1, 2, 3, 4$, and so on. SFM ascending and SFM descending signals are represented as SFMa and SFMd, respectively.

(v) *Phase Modulation (PM)*: Bi-Phase Modulation (BPM) is one of the phase modulations and it is generated as given by[29]

$$x(n) = Ae^{j(2\pi f n t_s + \phi + \theta(n))} \tag{6}$$

where, $\theta(n) = \pi(1 - n)$, when the zero bits of the code sequences are sampled and $\theta(n) = \theta$, when the one bits of the code sequence are sampled. The phase shift θ can be 0° or 180° in the case of BPM.

3. PROPOSED DECISION TREE MODULATION IDENTIFICATION ALGORITHM

The IF signal is down-converted signal of RF signal digitised at the sampling frequency f_s which is equivalent to $f_s = 4f_c / 3$, where f_c is the center frequency of the IF signal[30]. Four samples are latched into FPGA coming from ADC at the clock rate of $f_s / 4$. The samples are latched at both the clock edges. All eight samples are processed in parallel at $f_s / 8$ clock rate and results are combined at the output. The instantaneous frequency profile generated using the moving autocorrelation approach[31] is given by

$$F_m(n) = \left(\frac{F_s}{2\pi m}\right)\left(\Delta\Phi_m(n) + 2\pi Z_m\right) \tag{7}$$

where, F_s is the sampling frequency, $\Delta\Phi_m(n)$ is the phase difference derived from zone Z_m of phase and m is 16. The instantaneous amplitude profile is generated as given by[31]

$$X(n+1) = x(n) + |x(n+32).x^*(n+32+m)| - |x(n).x^*(n+m)| \tag{8}$$

where, x^* is a conjugate of signal *x, n* is the sample number and delay *m* is 1. The Eqn (8) is optimised by keeping $X(1) = a + jb$ where, *a* and *b* are constant values.

In Fig. 2, LFMad and FMCW signals frequency profiles are shown for presentation purposes. In the case of pulsed signals, pre-trigger and post-trigger region of the pulse is also captured to get the complete intra-pulse information including rise time and fall time. The pre-trigger region is captured based on the circular buffer memory concept which is implemented in first-in-first-out (FIFO) memory. The instantaneous frequency profile is used to extract frequency at various points. The frequency is extracted at an equal time interval at five different points from stored instantaneous frequency profile as shown in Fig. 2. These frequencies are known as leading edge frequency (F_{LE}), trailing edge frequency (F_{TE}), center frequency during the pulse (F_{CNT}), frequency at the first intermediate pint (F_{IP1}) and frequency at the second intermediate point (F_{IP2}). The F_{LE} and F_{TE} are latched at the leading edge (LE) and trailing edge (TE) of the RFP pulse. The RFP is generated using an instantaneous amplitude profile. Whereas to extract frequency at other three points the frequency data is stored during the pulse region in RAM which is generated using block RAM resource of FPGA. The frequency at these three points i.e. F_{IP1}, F_{CNT} and F_{IP2} are fetched from RAM based on the address calculated from the pulse region.

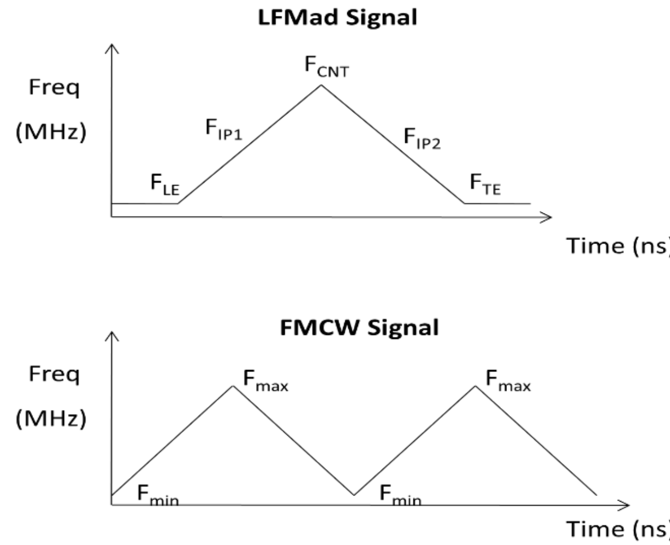

Figure 2. Frequency profiles of LFMad and FMCW signals.

In the case of the FMCW signal, the maximum frequency (F_{max}) and minimum frequency (F_{min}) are computed in real-time and stored. The frequency tolerance limit (Δf) and phase tolerance limit ($\Delta\phi$) are used during comparisons and windows are fixed.

The amplitude and frequency profiles are computed from the digitised signals using the moving autocorrelation technique. The approximated standard deviation (σ_1) is computed for noise estimation[31] using the instantaneous amplitude profile $X(n)$ as given below.

$$\sigma_1 = k\sum_{n=0}^{N-1}\frac{X(n)}{N} \tag{9}$$

where, k is constant which is determined based on the minimum error between standard deviation and its approximated value and *N* is the number of samples. High-level threshold (T_H) is computed using estimated noise and accordingly, low-level threshold (T_L) is set during the noisy region. T_H is used to detect pulse leading edge (or pulse start) and T_L for the pulse trailing edge (or pulse end). The threshold is adaptive for better detection and analysis of pulses. Based on the adaptive threshold the pulse detection is carried out. The signal power and noise power is also measured[32]. Accordingly, signal-to-noise (SNR) is declared.

The flow chart for the proposed decision tree modulation recognition algorithm is shown in Fig. 3. First, the IF signal is captured and amplitude and frequency profiles are computed. The pulse start and pulse end are detected based on high and low-level threshold respectively. As per the flow chart initially, the signal is distinguished between pulsed and CW signals. If PW is greater than the predefined time limit *T*, it is declared as CW, otherwise, this is considered as a pulsed signal. If the signal is CW, the algorithm will look for frequency variations

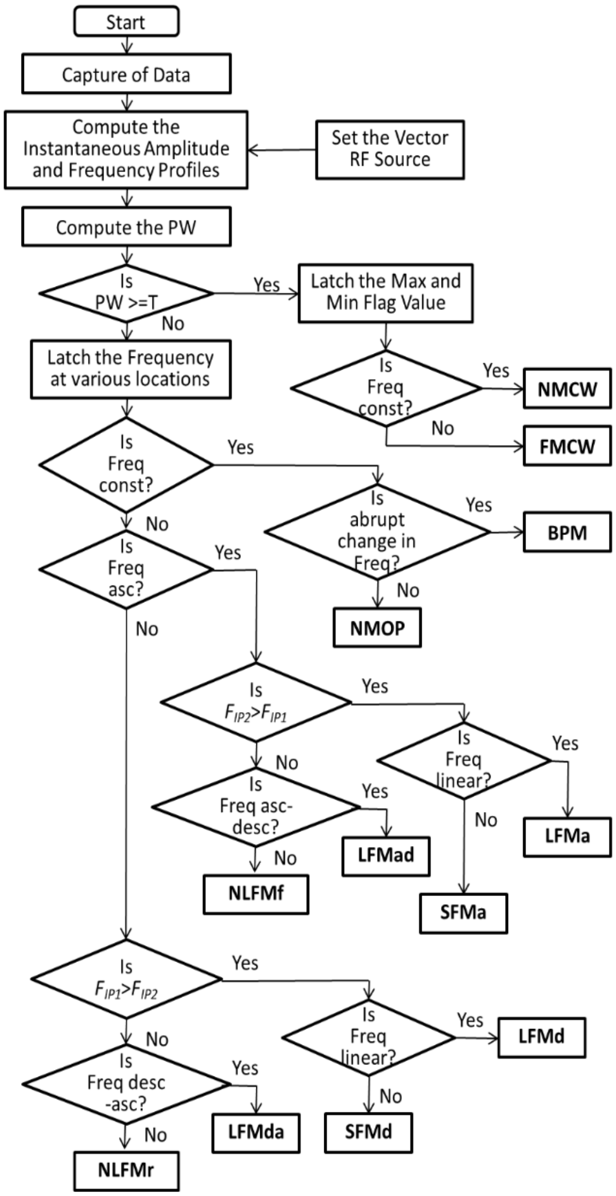

Figure 3. Proposed decision tree algorithm flow chart for modulation identification.

within that period. If F_{max} and F_{min} are within the set tolerance limit (Δf) i.e. frequency is constant, it will be declared as NMCW signal. Whereas, if the difference of F_{max} and F_{min} is more than the Δf, it will be declared as FMCW signal. When the signal PW is below predefined time limit *T*, it is known as a pulsed signal. If the frequency is constant in pulse region and there is no frequency discontinuity it is declared as No nodulation on pulse (NMOP). When there is an abrupt change in frequency due to sudden change in phase, it will be declared as BPM in which phase changes occur closed to pi. Phase changes and their numbers are detected. The minimum duration between two phase changes is measured and stored. The total width of the signal is divided by the minimum duration and the BPM pattern is identified. BPM pattern starts with 1's and each phase change is represented by 0's from 1's and 1's from 0's and when there is no phase change it will continue with the same 1's or 0's. The representation of the 13-bit BPM code is "1111100110101". The frequency profiles of NMCW, FMCW, NMOP and BPM are represented in Fig. 4.

The signal is declared as NLFMf when F_{IP2} is greater than F_{IP1} as well as frequency is sinusoidal. Whereas, if F_{IP1} is greater than F_{IP2} as well as frequency is sinusoidal, the signal is declared as NLFMr. SFMa is declared when F_{IP2} is greater than F_{IP1} as well as frequency changes in steps. If F_{IP1} is greater than F_{IP2} as well as frequency changes in steps, the signal is declared as SFMd. In SFM signals, there will be a step change in the frequency. NLFM signals are generated based on the approximation of SFM signals. The frequency profiles of NLFM and SFM signals are represented in Fig. 5.

When the linear change of frequency trend is ascending, descending or both in pulse region the modulation present is known as LFM. Modulation is declared as LFMa when F_{IP2} is greater than F_{IP1} as well as frequency changes linearly.

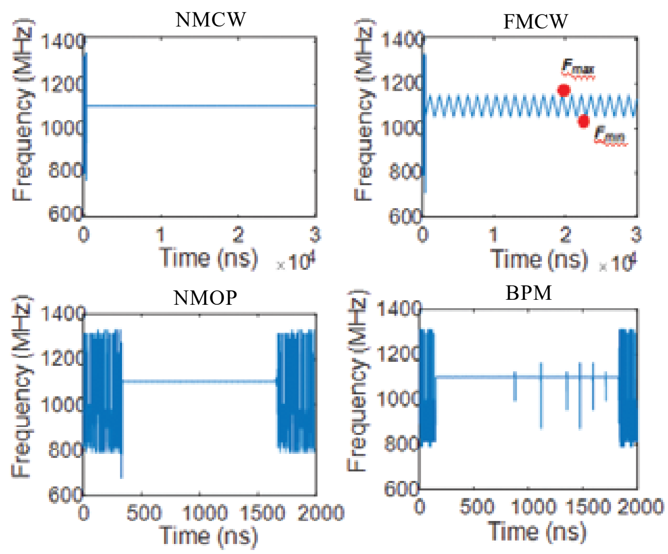

Figure 4. NMCW, FMCW, NMOP and BPM signals frequency profile.

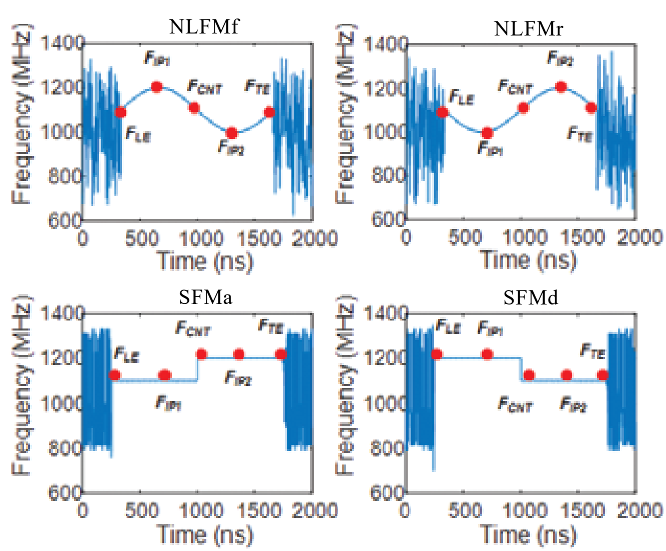

Figure 5. NLFM and SFM signals frequency profile.

Whereas, if F_{IP2} is less than F_{IP1} and frequency changes in ascending-descending order, the signal modulation is declared as LFMad. When F_{IP1} is greater than F_{IP2} and frequency changes linearly, the signal modulation is declared as LFMd. If F_{IP1} is less than F_{IP2} and frequency changes in descending-ascending order, the signal is declared as LFMda. Above mentioned LFM signals frequency profile is illustrated in Fig. 6.

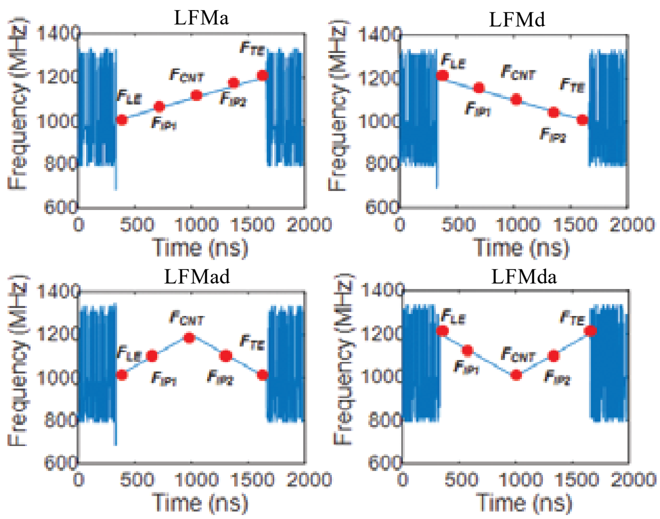

Figure 6. LFM signals frequency profile.

Once the type of modulation is found out, their parameter is also estimated like slope in the case of LFM, which is known as chirp rate in MHz/us. Similarly, the number of steps and BPM code are the parameters in the case of SFM and BPM respectively. Both modulation type (MT) and modulation parameter (MP) are represented using five nibbles in Table 1. Each MT is bit encoded and represented by one nibble, whereas, MP is represented by four nibbles. In Table, frequency deviation, frequency modulation rate, ascending chirp rate and descending chirp rate are represented as FD, FMR, ACR and DCR.

4. SIMULATION RESULTS

In this section, simulation at various SNR is presented to demonstrate the effectiveness and performance of the proposed decision tree algorithm for modulation identification. The input signal is generated with widely used additive white Gaussian noise (AWGN). A similar signal is used in the simulation for computing instantaneous frequency profile using moving autocorrelation[31] and DIQ techniques for generating results for various signals.

The detection performance of modulation identification is given in Table 2. An extensive simulation is carried out to test the performance. Total of 400 different signal sequences are generated to test each modulation. All types of modulation have been verified and the result is tabulated. The different modulations are identified at various SNR using the proposed algorithm with moving autocorrelation technique and proposed technique with DIQ technique.

Table 1. Representation of bit-pattern for modulation type (MT) and modulation parameter (MP)

MT code	Bit-pattern for				
	MT	MP			
	B2[3:0]	B1[15:12]	B1[11:8]	B1[7:4]	B1[3:0]
NMCW	0001	0000	0000	0000	0000
FMCW	0010	FMR (KHz)		FD (MHz)	
NMOP	0011	0000	0000	0000	0000
LFMa	0100	0000	0000	ACR (MHz/us)	
LFMad	0101	DCR (MHz/us)		ACR (MHz/us)	
LFMd	0110	DCR (MHz/us)		0000	0000
LFMda	0111	DCR (MHz/us)		ACR (MHz/us)	
NLFMf	1000	0000	0000	0000	0000
NLFMr	1001	0000	0000	0000	0000
SFMa	1010	0000	0000	No. of Steps	
SFMd	1011	0000	0000	No. of Steps	
BPM	1100	BPM Code			

Table 2. Detection performance of modulation identification

Modulation type	Proposed algorithm with moving autocorrelation	Proposed algorithm with DIQ technique	Correct identification
NMCW	-2	5	99
FMCW	-1	7	98
NMOP	-2	6	99
LFM	0	7	98
NLFM	1	8	98
SFM	-2	5	99
BPM	1	8	97

The confusion matrix is extracted from the detection performance at SNR of -2 dB for the proposed algorithm with moving autocorrelation as shown in Table 3. The result shows the detection performance with 99% accuracy at -2 dB SNR for NMCW, NMOP and SFM signals. The probability of correct identification is dropped below respective SNR of all modulations. The different modulations are compared for the SNR required for set modulation and declared modulation.

Minimum SNR required using moving autocorrelation technique and DIQ technique is 1 dB and 8 dB respectively to process all types of modulated signals. Based on this, the sensitivity achieved is -87 dBm and -80 dBm using proposed algorithm with moving autocorrelation technique and DIQ technique, respectively.

Table 3. Confusion matrix of modulation identification at SNR of -2 dB

Declared MT -> Set MT (Below)	NMCW	FMCW	NMOP	LFM	NLFM	SFM	BPM
NMCW	99%	1%	-	-	-	-	-
FMCW	5%	95%	-	-	-	-	-
NMOP	-	-	99%	-	-	-	1%
LFM	-	-	-	94%	4.5%	1.5%	-
NLFM	-	-	-	3.5%	95%	1.5%	-
SFM	-	-	-	0.5%	0.5%	99%	-
BPM	-	-	4%	2.5%	1.5%	1%	91%

The comparison of this work with other similar works is not reasonable because the frequency domain techniques get the inherent processing gain. But they suffer from PW and PRI measurement accuracies. The minimum PW measurement is restricted to the number of FFT points and its percentage of overlapping. Whereas, the proposed time-domain technique measures the minimum PW of the order of 50 ns. The fact of the matter is that lower PW does not have the modulation but still, any processing method should meet all basic system requirements along with critical requirements.

Classification of modulation[27-28] presented are based on the frequency domain processing and they are implemented on DSP processor for ELINT applications. Due to the limitations of the number of MACs in the DSP processor these techniques are not suitable for tactical operations. The proposed decision-tree algorithm is implemented on FPGA hardware which provides real-time performance.

5. IMPLEMENTATION ON FPGA HARDWARE

The proposed algorithm is implemented with a system generator using Xilinx Vivado 2016.4 tool as shown in Fig. 7. The Xilinx device selected is Virtex-7 XC7VX415T FPGA. The synthesis is carried out for netlist generation, mapping for exact mapping of components, place and route is carried out.

The utilisation summary is compared for various FPGA resources with the existing DIQ technique and shown in Table 4. Mainly, DSP resources are utilised very less in the proposed algorithm with moving autocorrelation technique compared to the proposed algorithm with DIQ technique as no filter implementation is required.

The simulation result using the proposed algorithm is shown in Fig. 8 for the LFMad signal. The same input data is used which was used for Matlab simulations. Only two pulses data along with pre and post region is shown to facilitate the simulation. The Mod_Type code can be cross verified as 0x5 (i.e. 0101) with Table 1 for the LFMad signal. This code is generated after 8 clock cycles from the end of the pulse.

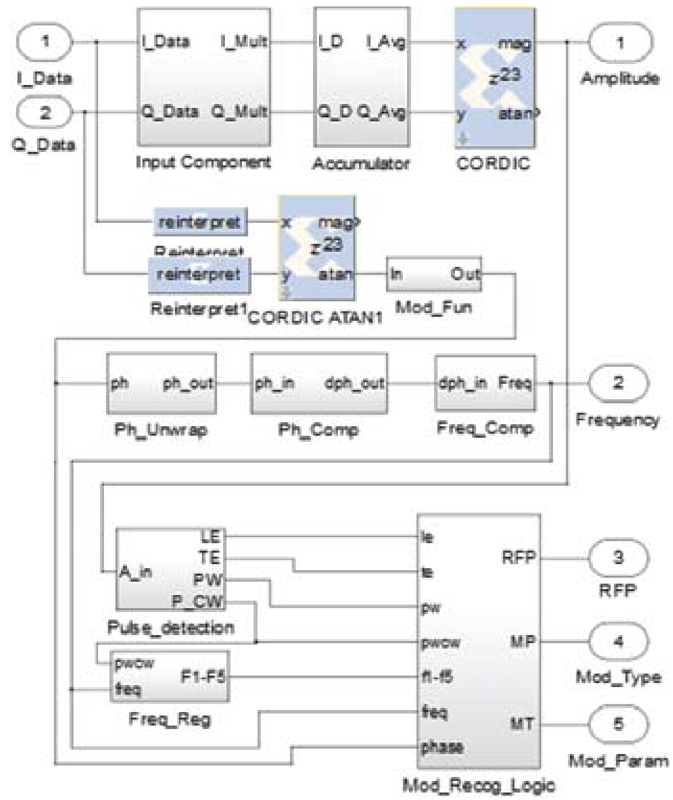

Figure 7. Model generated using system generator.

Table 4. FPGA resource utilisation summary (Device: XC7VX415T)

FPGA resource utilisation	Proposed technique with moving autocorrelation	Proposed technique with DIQ technique	Savings in %
Slice F/Fs	2334	4353	46.38
LUT (4 inputs)	2883	4136	30.29
DSP48E1	12	42	71.43
Block RAM	300	300	-
Total power (mW)	546	782	30.18

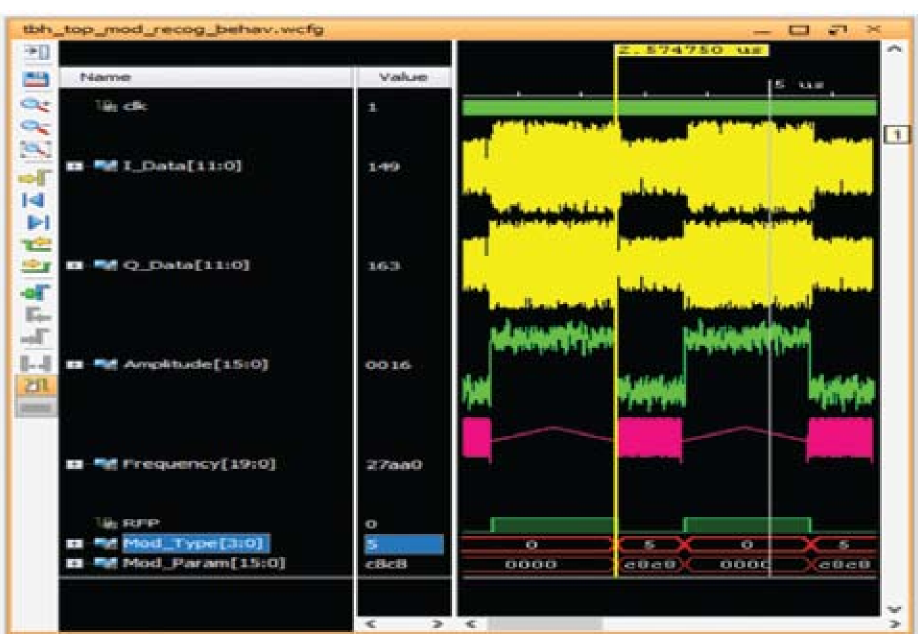

Figure 8. Simulation result for modulation identification feature.

6. CONCLUSIONS

In this work, NMCW, FMCW, NMOP, LFM, NLFM, SFM and BPM modulations have been identified using the decision tree algorithm. This decision tree algorithm used with the moving autocorrelation approach is implemented in FPGA and identified all mentioned modulated signals at 1 dB SNR. Hence, a unique time-domain digital technique for modulation identification has been proposed. The assumptions have been made that at any given point of time one modulation type is present in the input signal. The length of the input signal is assumed constant to generate a particular type of modulated signal in case of the pulsed signal. The advancement in signal processing algorithms, tied with high-performance hardware has enabled to improve the emitter identification and also to achieve a real-time performance. In the future, modulation identification work will be extended for additional signals and a combination of signals.

REFERENCES

1. Conning, M. & Potgieter, F. Analysis of Measured Radar Data for Specific Emitter Identification. *In* Proceedings of the Radar Conference, IEEE, Washington, DC, USA; 2010.
   doi: 10.1109/RADAR.2010.5494658.
2. Gupta, M.; Hareesh, G. & Mahla, A.K. Electronic Warfare: Issues and Challenges for Emitter Classification. *Def. Sci. J.*, 2011, **61**(3), 228-234.
   doi: 10.14429/dsj.61.529
3. Adamy, D.L., EW 101: A First Course in Electronic Warfare. Boston, MA, USA: Artech House, 2001.
4. Adamy, D.L. EW 102: A Second Course in Electronic Warfare. Boston, MA, USA: Artech House, 2004. 2nd Edition.
5. Richard, G.W. ELINT, the Interception and Analysis of Radar Signals. Boston, MA, USA: Artech House, 2006.
6. Niranjan, R.K. & Bhukya, R.N. Approach of Pulse Parameters Measurement Using Digital IQ Method. *IJIEE*, 2014, **4**(1), 31-35.
   doi: 10.7763/IJIEE.2014.V4.403
7. Mahlooji, S. & Mohammadi, K. Very High Resolution Digital Instantaneous Frequency Measurement Receiver, *In* Proceedings of International Conference on Signal Processing and Systems, IEEE, Singapore, 2009.
   doi: 10.1109/ICSPS.2009.43.
8. Niranjan, R.K. & Bhukya, R.N. FPGA based implementation of pulse parameters measurement. *In* Proceedings of Science and Information Conference*,* IEEE, London, 2014, pp. 862-867.
9. Helton, J.; Henry, C.I.; David, M.L. & Tsui, J.B.Y. FPGA-based 1.2 GHz bandwidth digital instantaneous frequency measurement receiver. *In* Proceedings of the ISQED. San Jose, CA, USA, 2008, 265-270.
   doi: 10.1109/ISQED.2008.4479798.
10. Gross, F.B. & Chen, K. Comparison of detectability of traditional pulsed and spread spectrum radar waveforms in classic passive receivers. *IEEE*, 2005, **41**(2), 746-751.
    doi: 10.1109/TAES.2005.1468765
11. Fan, X.; Li, L.; Li, T. & Chen, T. A new method for polyphase pulse compression codes modulation recognition based on IQPF and FRFT. *In* Proceedings of the Advanced Information Technology, Electronic and Automation Control Conference (IAEAC)*,* Chongqing, *IEEE*, 2017*,* 1172-1176.
    doi: 10.1109/IAEAC.2017.8054198
12. Lbpez-Risuefio, G.; Grajal, J.; Yeste-Ojeda, O.A.; Sanz-Osorio, A. & Moreno, J.A. Two digital receivers based on time-frequency analysis for signal interception. *IEEE*, 2003*,* 394-399.
    doi: 10.1109/RADAR.2003.1278774
13. Kawalec, A. & Owczarek, R. Radar emitter recognition using intra-pulse data. *In* Proceedings of the International Conference on Microwaves, 2003.
    doi: 10.1109/MIKON.2004.1357059
14. Nadav, L. & Eli, M. Radar Signals. Wiley–Interscience, New York, 2004.
15. Pace, P.E. Detecting and classifying low probability of intercept radar. 2nd Edition, Artech House, 2009.
16. Tsui, J.B.Y. Digital Techniques for Wideband Receivers. 2nd Ed, Norwood, MA Artech House, 2001, pp. 265-270.
17. Azzouz, E.E. & Nandi, A.K. Automatic Modulation Recognition of Communication Signals. Kluwer Academic Publishers. Boston, MA. 1996.
18. Lin, Yun and Ma, Chunguang. Automatic Modulation Recognition of Communication Signals. *IJFGCN*, 2017*,* **10**(1), 83-96.
    doi: 10.14257/ijfgcn.2017.10.1.08
19. Park, B. & Ahn, J.M. Intra-pulse modulation recognition using pulse description words and complex waveforms. *In* International Conference on Information and Communication Technology Convergence (ICTC), Jeju, 2017, 555-560.
    doi: 10.1109/ICTC.2017.8191039
20. Yar, E.; Kocamis, M.B.; Orduyilmaz, A.; Serin, M. & Efe, M. A Complete Framework of Radar Pulse Detection and Modulation Classification for Cognitive EW. *In* 27th European Signal Processing Conference (EUSIPCO), A Coruna, Spain, 2019, 1-5.
    doi: 10.23919/EUSIPCO.2019.8903045
21. Zhang, J.; Li, Y. & Yin, J. Modulation classification method for frequency modulation signals based on the time–frequency distribution and CNN. *IET Radar, Sonar & Navigation*, 2018, **12**(2), 244-249.
    doi: 10.1049/iet-rsn.2017.0265
22. Azzouz, E.E. & Nandi, AK. Automatic identification of digitally modulated types. *Elsevier, Signal Processing*, 1995, **47**(1), 55-69.
    doi: 10.1016/0165-1684(95)00099-2
23. Nandi, A.K. & Azzouz, E.E. Automatic analogue modulation recognition. *Signal Processing,* 1995, **46**(2), 211-222.
    doi: 10.1016/0165-1684(95)00083-P
24. Nandi, A.K. & Azzouz, E.E. Algorithms for automatic modulation recognition of Communication signals. *IEEE Trans. Commun.,* 1998, **46**(4), 431-436**.**
    doi: 10.1109/26.664294

25. Dubuc, C.; Boudreau D.; Patenaude F. & Inkol R. An automatic modulation recognition algorithm for spectrum monitoring applications. *In* Proceedings of the International Conference on Communications, IEEE, Vancouver, BC., 1999, pp. 570-574.
doi: 10.1109/ICC.1999.768003
26. Chan, Y.T. & Gadbois, L.G. Identification of the modulation type of a signal. *In* Proceedings of the Signal Processing, 1989, **16**(2), 149-154.
doi: 10.1109/ICASSP.1985.1168289
27. You, H. Su. F. & Qu, K. A novel multiple LFM signals detection method. *In* Proceedings of the International Conference on Microwave and Millimeter Wave Technology (ICMMT), 2004, 818-821.
doi: 10.1109/ICMMT.2004.1411655
28. Xu, S.W. & Shui, P.L. Nonparametric Detection of frequency modulated signals using fractional fourier transform. *Electronics Letters,* 2010, **46**(9), 649-650.
doi: 10.1049/el.2010.0569
29. Sung, Stephen & Zhou, Yifeng. Modulation recognition algorithms for Intentional Modulation on Pulse (IMOP) applications, Defence R&D Canada, Patent No. CA020899.
30. Lyons, R.G. Understanding Digital Signal Processing, Boston, Addison Wesley Longman, Inc, 1997. 32-42 p.
31. Niranjan, R.K.; Singh, A.K. & Chunduri, B.R. High accuracy parameter estimation for advanced radar identification of electronic intelligence system. *Def. Sci. J.,* 2020, **70**(3), 278-284.
doi: 10.14429/dsj.70.15105
32. Han, J.; He, M.; Tang, Z. & Hao. Y. A novel method for estimating the SNR of unknown emitter signal. *J. Electron.* (China), 2010, **27**(1), 134-138.
doi: 10.1007/s11767-009-0031-5

ACKNOWLEDGEMENTS

It is immense pleasure to thank Director DLRL, Additional Director and Wing Head for their continuous guidance and support towards this activity. The authors also would like to thanks anonymous reviewers for making various useful suggestions and comments.

CONTRIBUTORS

Mr R.K. Niranjan, received the BE (ECE) from Dr Hari Singh Gour University, Sagar, in 1998 and ME (Systems and Signal Processing) from Osmania University, Hyderabad, in 2012. He is currently pursuing PhD from NIT, Warangal and presently working as Scientist 'F' at DRDO-Defence Electronics Research Laboratory, Hyderabad. He has been working in the area of signal processing for Electronic Warfare systems with specific interests in the area of Data Acquisitions and DSP algorithms implementations in FPGA for real time applications.
Contribution in the current study, he conceived the concept, carried out the literature survey and complete experimental work with interpretation and analysis of result.

Prof. C.B. Rama Rao, did his post-graduation from JNTU, Kakinada and PhD from IIT, Kharagpur. He has been currently working as professor in the Department of Electronics and Communication Engineering, NIT Warangal, India. His research interests primarily include adaptive signal processing, musical instrumental signal processing, speech signal processing and biomedical signal processing. He has published more than 32 papers in reputed Journals and Conferences.
Contribution in the current study, he has given the idea, reviewed the work, validated the results, continuously provided the guidance and given many valuable inputs.

Dr A.K. Singh, did ME in Digital System (ECE) and PhD from Osmania University, in 2003 and 2015, respectively. Currently working as Scientist 'G' at DRDO-Defence Electronics Research Laboratory, he was the instrumental in design and development of digital receiver. His area of interest includes high-speed board design, time-frequency signal processing, and EW Receiver design. Presently he is working for space systems design.
Contribution in the current study, he has supported in making experimental setup, reviewed the incremental work and provided various valuable inputs.