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Discrete wavelet transform based unsupervised underdetermined blind source separation methodology for radar pulse deinterleaving using antenna scan pattern

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Abstract: The authors propose a discrete wavelet transform-based unsupervised underdetermined blind source separation methodology for radar pulse deinterleaving using a novel parameter, i.e. the radar antenna scan pattern. Deinterleaving becomes a challenging task in case of dense pulse scenario with parameter agile radars and the authors show that the scan pattern is an excellent parameter for this task. The results also indicate that the methodology is very suitable in case of jittered and staggered pulse repetition interval with reduced missing pulses and false alarm rate. Based on deinterleaved scan pattern information, a preliminary assessment of the number of emitters and their threat levels can be done.

1 Introduction

Electronic warfare (EW) is a specialised mode of modern warfare where military operations are performed in an electromagnetic environment (EME) [1]. The motivation is to gain advantage over the enemy without making physical contact or jeopardising one's own combat capabilities. In such a scenario, the need for developing robust and reliable EW techniques is of utmost importance. Depending upon the nature of military operation, EW can be classified into three broad disciplines: electronic attack (EA), electronic protection (EP) and electronic warfare support measures (ESM). ESM mainly involves actions that supplement EA and EP mechanisms by means of passive and network-centric measures [2] such as threat recognition, target assessment and planning warfare operations.

A radar warning receiver (RWR) system forms an important component of ESM. It is a passive receiver which periodically scans the EME to detect and intercept radio emissions. A number of parameters are then measured from this intercepted emission. For instance, the parameters obtained from a pulsed radar are time of arrival (TOA), pulse repetition interval (PRI), direction of arrival (DOA), pulse width (PW), pulse amplitude (PA), antenna scan pattern and rate (ASP and ASR) [3, 4]. The parameters are then processed to extract information about the nature of emitter responsible for the emissions [5, 6]. This process of analysing, sorting and clustering of the radar pulse parameters is known as deinterleaving.

Radar pulse deinterleaving algorithms can be broadly classified into two main categories: interval-only and multi-parametric [7, 8]. Interval-only algorithms use the TOA information of different pulses to derive techniques based on histogramming [9, 10], statistic association [11] or extended Kalman filter [12–14] which can determine the PRI of the radars. These algorithms have certain limitations owing to their dependency on the histogram bin sizes and high false alarm rates [8]. An algorithm akin to fast Fourier transform to detect the PRIs in the emission called the PRI transform has been proposed in [15]. Many improvements over the original PRI transforms have been proposed in [16–18] to overcome the challenges of parameter agile radars. However, with the increasing use of staggered and jittered PRI [4], the interval-based techniques have become unreliable and obsolete. A state-of-the-art sequential difference (SDIF) histogramming technique based on clustering and PRI transform has been proposed in [19] which shows increased accuracy and robustness to jittered PRI and missing pulses. However many emerging radar systems have shown the capability to alter the PRI [20, 21] and hence detecting the PRI alone cannot guarantee the presence of a specific emitter in all cases.

The multi-parametric analysis, on the other hand, finds a specific emitter by using a combination of mono-pulse parameters [8]. Clustering technique is employed in [6] to sort the mixed signal based on one or more parameters into different bins. The number of emitters can be identified on the basis of a threshold or through joint recognition and identification [7, 22]. Another class of techniques use a number of self-organising neural network algorithms, such as fuzzy adaptive resonance theory, fuzzy clustering and Min–Max clustering [8], to compare if the pulses are from the same emitter using parameters other than TOA such as RF and DOA.

Advanced radar systems pose a limitation to these techniques by constantly modifying the conventional parameters like PRI, carrier frequency and PW to evade detection [23]. In such scenarios, we can no longer rely on the agile parameters for deinterleaving due to high false alarm rate and unsuccessful separation. It can be noted that DOA still remains a reliable parameter for deinterleaving pulses in parameter agile radars. It is not possible for radars systems to change their positions with respect to a receiver in a very short interval to avoid detection. However, the measurement of DOA itself is a challenging task for the RWR as it requires an array of passive sensors to determine the direction of the incoming pulses with high resolution [24]. Also, the state-of-the-art DOA estimation techniques have many limitations in localisation of multiple moving narrowband targets [25]. The techniques are computationally intensive, require extra computations for parameters pairing when multiple sources are emitting and suffer from poor estimation in low signal-to-noise ratio (SNR) when sources are very closely spaced [26].

With the continuously growing complexity of radars, the future trend is towards the development of multi-functional RF systems where radar as well as ESM capabilities are offered on a common platform. This platform can provide functionalities such as surveillance in air, ground and sea in volume and surface search, tracking, reconnaissance with Synthetic Aperture Radar (SAR) spot and real-time data links for network-centric operations [27]. In the development of such applications, the goal is to minimise size, weight, power, cost (SWAP-C) and complexity while simultaneously maximising performance [28, 29]. For such

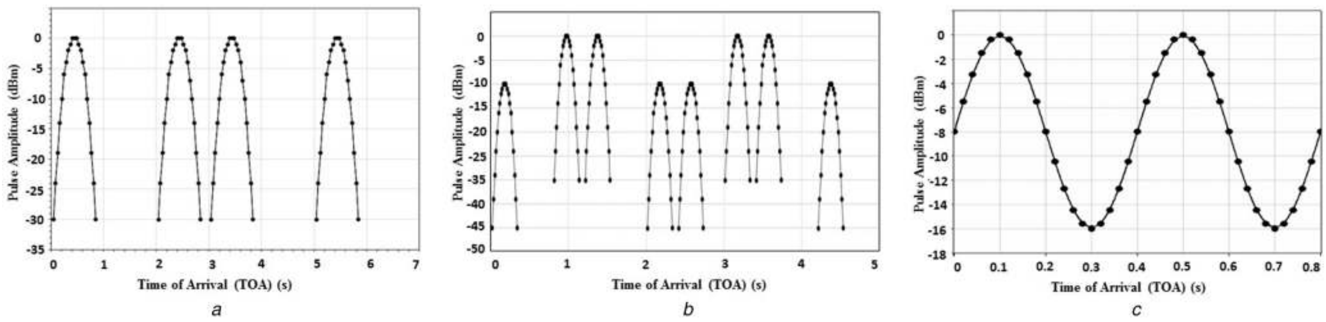

Fig. 1 *Radar ASP*
(a) Circular scan, ***(b)*** Raster scan, ***(c)*** Conical scan. The images have been taken from [30]

resource constraint applications, the state-of-the-art DOA measurement techniques and subsequent deinterleaving are rendered inadmissible. Thus, there arises a need to investigate some other parameters for radar deinterleaving which can be used reliably in agile radar systems and can be captured through a single sensor for such stringent futuristic radar applications.

In this paper, we propose a discrete wavelet transform (DWT)-based unsupervised underdetermined blind source separation (UBSS) methodology for deinterleaving the radar signals using an unexplored yet important parameter in the domain of deinterleaving, i.e. ASP. The importance of radar ASP parameter is explained briefly in Section 2. The proposed methodology identifies three criteria for separating pulses at different levels of separation based on a preliminary DWT analysis. The main contribution of this paper is to propose a methodology for radar deinterleaving in the absence of DOA and PRI information using a reliable parameter measured from a single sensor. Also, deinterleaving in Radar systems is usually followed by estimation of secondary parameters such as PRI, ASP and ASR determination for gaining insight into the nature of the transmission, emitter identification, time-keeping in electronic counter measures and tracking the intercepted targets [19, 30]. Tracking methodologies also require the use of multiple sensors to measure parameters such as Doppler accurately [31, 32]. Thus, deinterleaving and subsequent emitter identification and localisation [33] can be done using the ASP even when the other parameters are available, or they can also be used in conjunction with the ASP to enhance the performance and reliability of the RWR. This can further reduce the computation cost incurred in the RWR [28].

The rest of the paper is organised as follows. In Section 2, we discuss the suitability of radar ASP as a parameter for deinterleaving the radar pulses. In Section 3, we present the proposed methodology for radar ASP deinterleaving in detail using an example of interleaved scan patterns simulated in MATLAB. In Section 4, simulation results are presented and discussed. Finally, in Section 5, we provide a conclusion of the paper.

2 Theoretical background

In an environment where multiple radars are operating and performing similar functions, their parameters tend to overlap. Therefore, a robust parameter is desirable which can resolve the ambiguities usually encountered in carrier frequency, frequency modulation type and time domain modulation parameters such as PW and PRI. Radar ASP is one such parameter which is not influenced by inter and intra-pulse modulation [30].

The type of radar chosen for our study is the conventional pulsed radar which is widely used in ESM for searching, detecting and tracking airborne targets [30, 34]. The pulsed radar ASP is characterised by the envelope of the received signal strength at each time stamp (TOA) as obtained from the PA. The PA is related to the radar signal power, its beam shape and antenna scanning features [34]. Radar ASP is determined by the relative angular position of the RWR with respect to the radar main lobe with the passage of time and proves to be a substitute parameter in the absence of DOA information. It indicates the type of scanning technique being used by a radar transmission system as different radar systems employ different scanning modes [23]. Some examples include conical scan, circular scan, sectoral scan, helical scan, raster scan etc. [35]. A non-exhaustive list of different scan patterns used by various radar transmission systems is shown in Fig. 1. The knowledge of the scan type can also aid in inferring the mission of the radar and ascertaining its threat level in electronic reconnaissance.

Notwithstanding the importance of ASR and ASP, they remain unexplored in the sphere of radar deinterleaving. The literature on radar ASP recognition itself is very limited and the methodology is obscure [36, 37] due to the classified nature of the work. The conventional method to identify a scan pattern in EW is based on manual estimation of scan period where a human operator listens to the received radar tone and guesses the ASR. It can be inferred that the accuracy and reliability of this method is contestable. The determination of ASP becomes a challenging task when multiple emitters are radiating in the same direction and there is distortion due to interference [38]. Methods to automate the process of ASP recognition and classification are proposed in [23, 30, 39].

3 Proposed methodology

Motivated by usefulness of radar ASP, we propose a DWT-based unsupervised UBSS methodology to separate the interleaved radar pulses. This methodology is particularly useful in platforms that use only a single receiver in stringent resource constraint applications. Our approach to the problem is described as follows and is illustrated with the example of a frame in Fig. 2 separated from the mixed data in Fig. 3.

- We first identify and segregate the frames containing interleaved main side lobes of different emitters from the entire mixed data captured via a single passive receiver.
- A moving window is used for this purpose which runs through the entire length of the signal and facilitates frame by frame analysis of the interleaved signal.
- Once the frames are separated, they are transformed to the wavelet domain using Haar wavelet decomposition.
- Three features are observed in the wavelet domain which forms the basis for proposing three criteria for deinterleaving the radar pulses.

The methodology need not take into account how the pulses are interleaved or mixed at the source and hence qualify as an UBSS problem where the number of sensors are less than the number of mixed sources. Also the separation of the pulses is being done without any prior information regarding the number of emitters and pulses belonging to each emitter. The algorithm will adapt to the number of emitters after applying a three level criteria to segregate the pulses. The pulses not belonging to any emitter identified by the preliminary analysis will be segregated to a different bin (say bin-x) and curve fitting will be done on the said bin-x to identify the possibility of another emitter. Thus, the proposed methodology forms an unsupervised deinterleaving technique.

3.1 Frame separation and interpolation

The frame is separated using a rectangular window whose length can be determined from the nature of received EM emissions. In a dense pulse scenario, a small sub-frame is useful so that the number of locally interleaved signals at a selected time frame is not more than five in the present scenario. Fig. 3 shows the mixed radar data captured via a single receiver and Fig. 2 shows a frame separated from the mixed data using a window size of 50 samples. Next, a preprocessing step is required before applying the DWT. Since the time resolution for a small subset of data is very low, the DWT does not detect the localised high frequency components of the signal in the detailed subband (coefficients). A possible solution to retain the temporal resolution is to interpolate the given sub-frame. Difference TOA (ΔTOA) information is used to interpolate the data by finding the minimum TOA difference between two consecutive captured samples in the frame under test. It was noted that during interpolation a number of spurious data points gets inserted between two very closely spaced samples altering the morphology of the signal. Down-sampling of the interpolated signal is done to remove these spurious data points and reduce the number of samples required for subsequent processing, at the same time preserving the original pulses to faithfully reconstruct the deinterleaved signal.

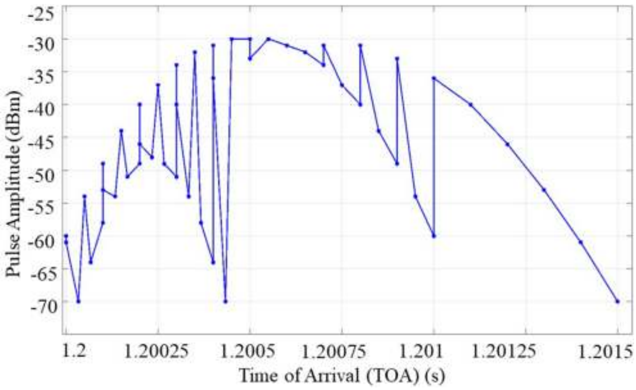

Fig. 2 *Frame separated from the mixed radar data showing the RSP of three interleaved emitters. The frame is captured for a duration of 0.0015 ns*

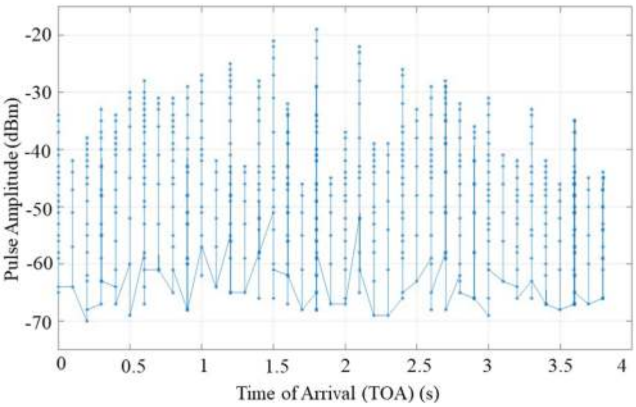

Fig. 3 *Intercepted radar data with interleaved pulses of three emitters*

3.2 Feature detection in the wavelet domain

Discrete Haar wavelet is applied to the preprocessed data and the first level detailed coefficient (CD1) is analysed. It can be noted here that the choice of wavelet is not confined to Haar wavelet only. Since there is no a priori information about the signals to be separated, other classes of wavelets such as Daubechies, Morlet etc. can also be used for the analysis. However, Haar wavelet is chosen as a proof of concept as it has less computational cost compared with other wavelets. The detailed and approximate coefficients can be obtained by simple add/subtract operations. Thus, Haar wavelet can be an excellent choice for the hardware implementation of the proposed methodology. Based on the CD1 analysis, we propose three criteria to separate the interleaved signals as shown in Fig. 4.

3.2.1 Criterion 1 – prominent peak detection: • ***Separating the peaks*** - It was observed that the distinct or prominent peaks in CD1 correspond to the region where interleaving takes place. The magnitude of these coefficients is very large (order of 10) compared with the average value of the remaining coefficients as can be seen in Fig. 4*a*. These peaks are separated using a threshold equal to the chosen decomposition level, i.e. decomposition level-1 in the present case. The peaks separated using the threshold are reconstructed back to the time domain. Since a peak in wavelet domain corresponds to two pulses in time domain, we segregate the consecutive pulses associated with each peak into two bins namely bin-1 and bin-2. In this manner, a preliminary separation of interleaved pulses is done as shown in Fig. 5*a*.

- *Scan pattern morphology identification:* The morphology of the radar ASP as seen in Section 2 plays an important role in the subsequent steps of the proposed methodology. In a practical application like the pulsed radars used in this study, the morphology is inevitably known and cannot be modified very quickly (Fig. 1) [30]. This morphology of the radar ASP can thus be exploited to reconstruct the separated sources by fitting a second- order polynomial to the pulses in bin-1 and bin-2. Curve fitting is a widely used technique in the domain of radar signal processing such as estimation of radar's locations, target recognition and signal sorting etc. [40–42], and here we are introducing it for the first time in the domain of radar deinterleaving.
- *Least square curve fitting of deinterleaved pulses:* A second degree polynomial is used to describe the morphology of the ASP as given in the equation below to denote the transition between two pulses at TOAs TOA_i and TOA_{i+1} as follows:

$$y(t) = C_1 \cdot t^2 + C_2 \cdot t + C_3,$$

where $y(t)$ is the estimated magnitude received by an antenna at a time t and C_1, C_2 and C_3 are constants derived from the PA information. The values of C_1, C_2 and C_3 are determined in the least square sense by using the polyfit function in MATLAB. For obtaining the polynomial regression model, the PA values as detected by prominent peak detection corresponding to their TOA are used. The criteria for selecting the best fitting curve is based on the total fitting error or residual which is minimised from the sum of the squares of the residuals. For a given set of PA and their TOA

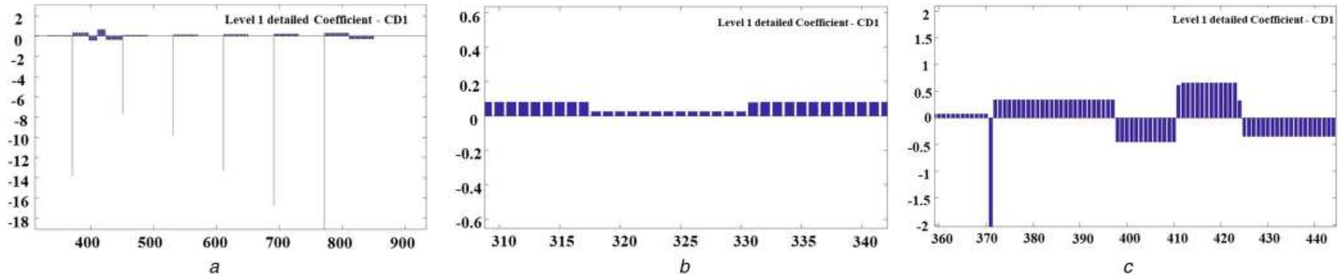

Fig. 4 *Signal Separation Criteria in Detailed Coefficients level-1*
(a) Criterion 1: prominent peak detection, ***(b)*** Criterion 2: amplitude variation, ***(c)*** Criterion 3: zero-crossing detection

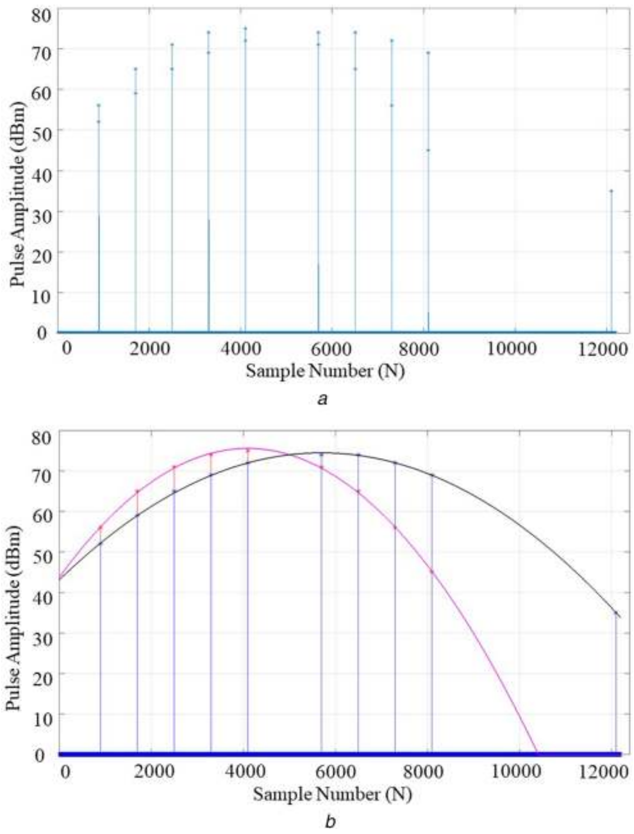

Fig. 5 *Pulse separation based on Criterion 1 - Prominent Peak Detection*
(a) Signal reconstructed from peak detection values, ***(b)*** Curve fitting for the data point separated

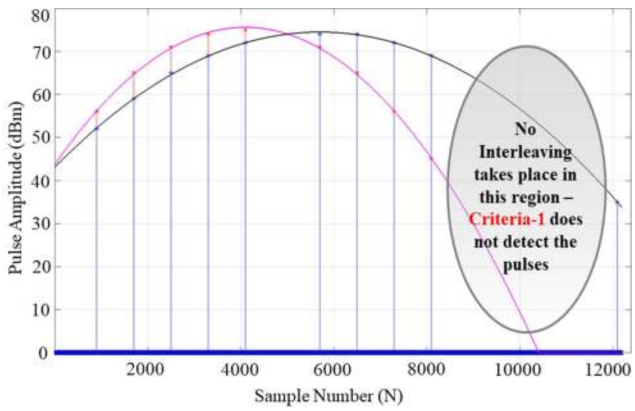

Fig. 6 *Shadow region as obtained in Criterion 1 where the pulses cannot be segregated using prominent peaks*

$[(PA_i,\ TOA_i)]$, where $I = 0,\ 1,\ 2, \dots,\ m$, the sum of squared residuals can be written as

$$E^2 = \sum_{i=1}^{n} (PA_i - y_i)^2 .$$

Such that E^2 is the smallest and gives the least squared method of fitting the curve. Every iteration will have a single instance of curve fitting to fit the missing pulses to the detected emitter.

As seen in Fig. 5*b*, these curves facilitate the identification of the remaining pulses that may belong to the identified emitters and enhance the performance of the methodology by eliminating any spurious pulses not fitting to the curve.

3.2.2 Criterion 2 – detecting the amplitude variation in CD1:

- As can be seen in Fig. 6, a large number of pulses cannot be obtained by solely applying Criterion 1. These missing pulses necessitated the need for further criteria to be obtained from CD1. From the CD1 plot as shown in Fig. 4*b*, it can be found that a series of contiguous coefficients exhibit the same amplitude value which is followed by a change in the amplitude of the following coefficient.
- The amplitude value of each coefficient is compared with that of the preceding coefficient to detect a second activity in the wavelet domain, i.e. amplitude variations. The coefficients having a change in amplitude (greater or lesser) from its preceding coefficients are separated and converted to time domain to obtain the corresponding pulses. It was found that the pulses so obtained belonged to the original emitter. Therefore, detection of amplitude variations in CD1 forms Criterion 2 of the proposed methodology. Fig. 7*a* shows the output of signal reconstruction after detecting the amplitude variations.
- The pulses so obtained are first fitted to the curves belonging to the two bins that were created from Criterion 1. A tolerance of ±20% of the value of PA (as per statistical observation) is taken as a threshold to assign the pulses into bin-1 and bin-2. The remaining signals which do not fit to any of the bins are classified into a third bin namely bin-3, which indicates the presence of more than two emitters in the interleaved frame under observation.
- A second instance of curve fitting is done for the pulses segregated into the three bins namely bin-1, bin-2 and bin-3 as shown in Fig. 7*b*. The curves will be utilised in the next step to detect further pulses belonging to the identified emitters.

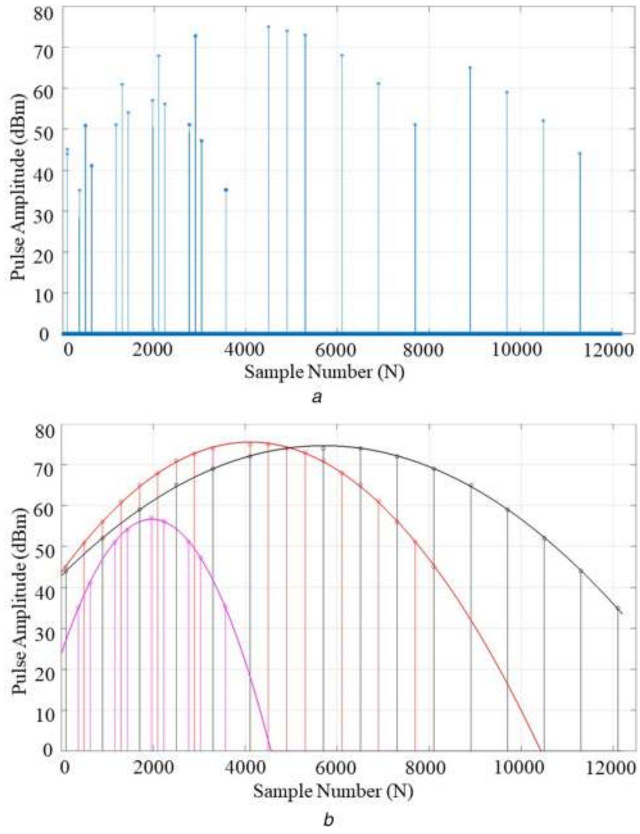

Fig. 7 *Pulse separation based on Criterion 2 - Amplitude Variation in CD1*
(a) Signal reconstructed from amplitude variation, ***(b)*** Curve fitting for Criteria 1 and 2

3.2.3 Criterion 3 – detecting the zero-crossings in CD1:

- After applying criteria 1 and 2, the pulses belonging to different emitters are removed and segregated into their respective bins. Following this, a third activity is detected in CD1 in the wavelet domain. A number of zero crossings are detected, which refers to a transition from a series of positive coefficient values to a series of negative coefficient values and vice versa. These zero crossings occur where there is a high density of interleaved pulses and a large number of peaks and troughs appear.

- The coefficients having a change in polarity from its preceding coefficients (i.e. negative from positive or vice versa) are chosen and converted to time domain to obtain the respective pulses. The pulses so obtained are again found to be belonging to the original mixed signal under consideration. Hence, we proposed a third criterion of zero crossings detection to further detect the missing pulses which were not obtained by criteria 1 and 2.
- Since only the amplitude information is used for deinterleaving the signals in this study, little or no variation in amplitude of the pulses present a challenge in separating the signals. Here, the curves of the signals separated from Criterion 2 as shown in Fig. 7*b* are used for fitting the pulses obtained from Criterion 3. Fig. 8*a* shows the reconstructed signal from zero crossing detection in CD1.
- A third instance of curve fitting is done with the pulses obtained during zero crossing detection. The same tolerance band of ±20% (statistical observation) of the amplitude values was taken as a threshold during curve fitting.
- This step can be seen as a refinement step as those pulses can be obtained which were not observed with the previous criteria and hence could have been reported as missing pulses. The combination of the three criteria separates the three emitter signals into their respective bins as shown in Fig. 8*b*.

3.3 Correlation of consecutive frames

The analysis as shown in Section 3.2 provides the information regarding the number of emitters present during a specific frame of observation. The window is then moved again and the next frame is deinterleaved using the proposed algorithm. Consecutive frames are deinterleaved using the proposed methodology in order to report the total number of emitters in the EM environment. It can also ascertain when these radars stop transmitting. The deinterleaved ASPs can be further correlated for identifying the type of scanning being performed by the emitters by analysing the width of the main lobe and time difference between different lobes of the ASP [30, 36, 37]. This can finally be used to ascertain the threat level of the radar aided by the scan pattern deinterleaving.

We can summarise the proposed radar scan pattern deinterleaving methodology as shown in Algorithm 1 (see Fig. 9).

4 Results and discussion

In order to test and validate the proposed methodology, a simulator was modelled to generate the interleaved radar signal. Naval radars emit EM waves around 9.4 GHz ± 100 MHz [1]. Also airborne weather radar and military radars typically operate in the Xband, in the 8–12 GHz range. As a proof of concept, the simulator has been designed for pulsed radar which are performing circular and conical scan and operating in the naval frequency band, for which we also have the availability of on-field real-time data for further validation of the algorithm. However, this is not a limiting factor for the present analysis and can be extended to the case of helical, raster and sectoral scan. Similar morphology has been obtained for other scan types as reported in the literature [30, 36, 37], and the proposed methodology will be useful in deinterleaving the same. Table 1 shows the parameters for laboratory simulated interleaved radar signals and the field trial data for two interleaved radar signals.

Fig. 10 shows two other interleaved frames separated from the mixed radar data shown in Fig. 3. Fig. 10*a*(i) shows an interleaved frame separated at 1.8 s of the received emission. The frame is captured for a duration of 1.5 ms. The deinterleaved signals after applying the three criteria of the proposed methodology are shown in Fig. 10*a*(ii). The separated frame contains three signals as indicated by different colour codes having scan period of 0.48 ms (blue), 1 ms (red) and 1.5 ms (black). In Fig. 10*b*(i), an interleaved frame is captured at 2.4 s of the emission. Fig. 10*b*(ii) shows the three deinterleaved frames having antenna scan period of 0.48 ms (blue), 1 ms (magenta) and 1.5 ms (black). Correlating the three

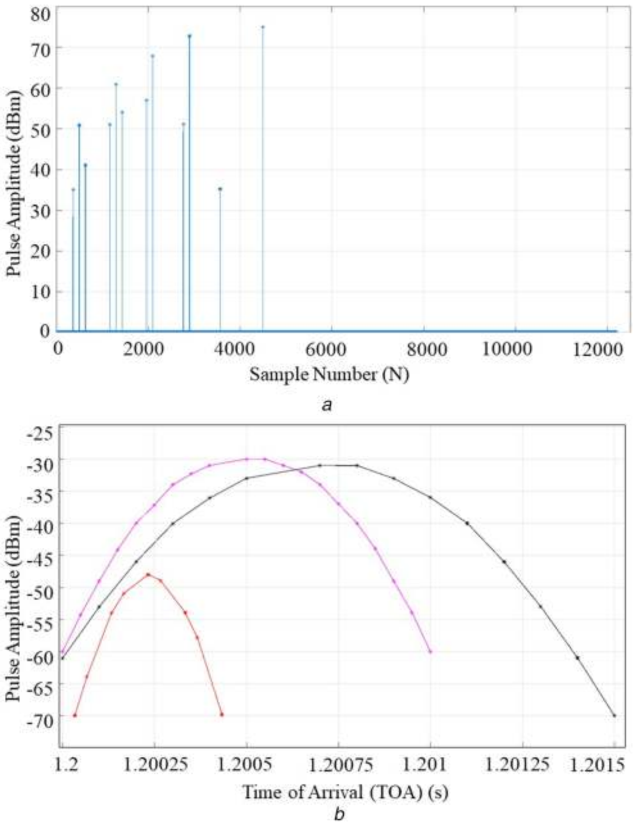

Fig. 8 *Pulse separation based on Criterion 2 - Zero Crossing Detection in CD1*
(a) Signal reconstructed from zero-crossing detection points, ***(b)*** Signals separated from the interleaved frame

1: Separate a frame containing the interleaved main lobes using a moving window.
2: Preprocess the frame by interpolating with the minimum ΔTOA and downsampling.
3: Apply DWT to generate the first level Detailed Coefficients (CD1) of the interleaved frame and apply the following three criteria for deinterleaving.
4: **Criterion 1:** Separate prominent peaks, which exceed a threshold and convert to time domain. Cluster the two data points for every peak into two bins. Fit a 2^{nd} order polynomial to the data points separated into two bins.
5: **Criterion 2:** Detect the amplitude variation occurrences. Fit the data points to the two curves obtained in Criteria 1. Remaining points not fitted to any curve are clustered to a third bin.
6: **Criterion 3:** Detect the Zero-Crossing variations. Fit the data points to the two curves obtained in Criteria 2. The data points not fitted to any of the three bins are separated into a fourth bin.
7: Move the window to separate other frames of the interleaved signal and repeat steps 2 to 6.
8: Correlate the different frames to report the number of emitters present and their scanning mode at different time instances.

Fig. 9 *Algorithm 1: DWT-based radar scan pattern deinterleaving*

Table 1 Radar parameters for proposed methodology

Parameter	Simulated data	Field data
antenna scan period (ASP)	2 ms, 1.5 ms, 1 ms, 0.5 ms	300 ms
radar transmitted power	25 KW	25 KW
dwell time	10 ms	15 ms
RF	9 GHz	2 GHz

frame indicates the presence of three emitters with circular scanning being performed by the radar emission systems.

Another set of radar mixed data was simulated with four emitters having scan periods of 0.5, 1, 1.5 and 2 ms. Fig. 11*a*(i)

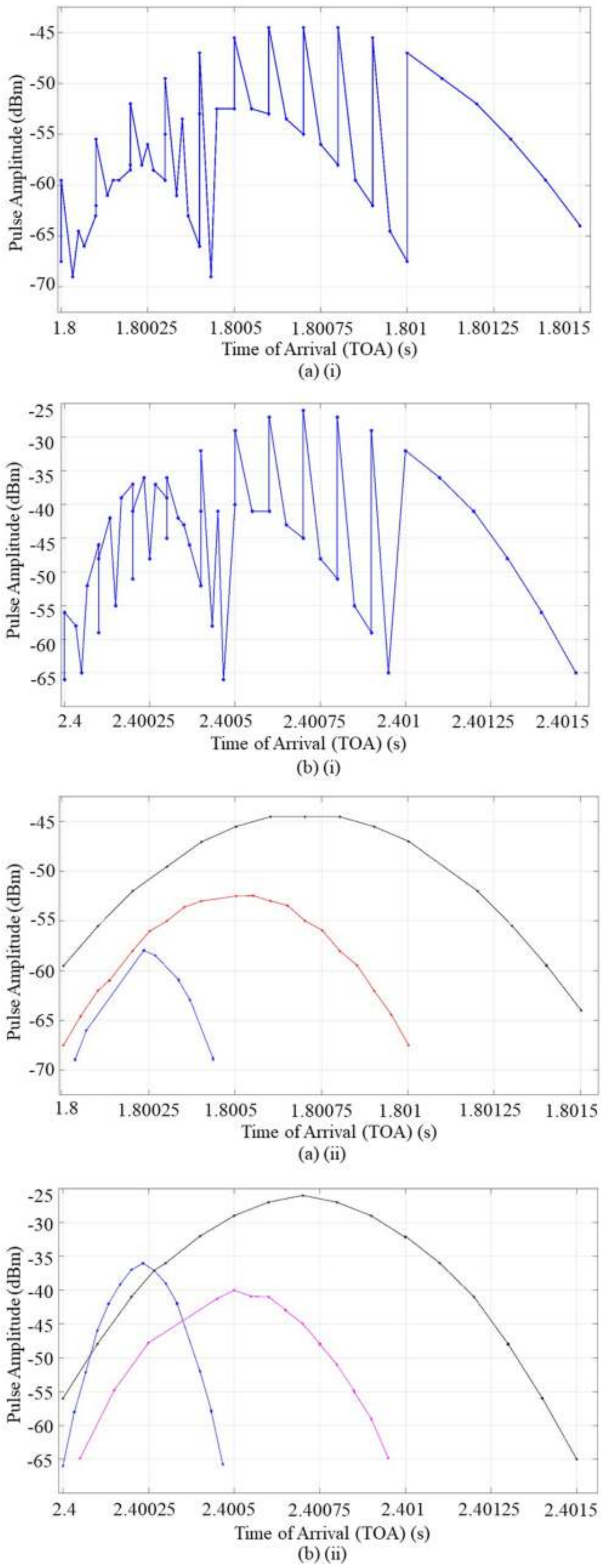

Fig. 10 *Separation of other interleaved frames from the mixed radar data*
(a) Interleaved frame at 2.4 s having 50 pulses, ***(b)*** Interleaved frame at 1.8 s having 50 pulses

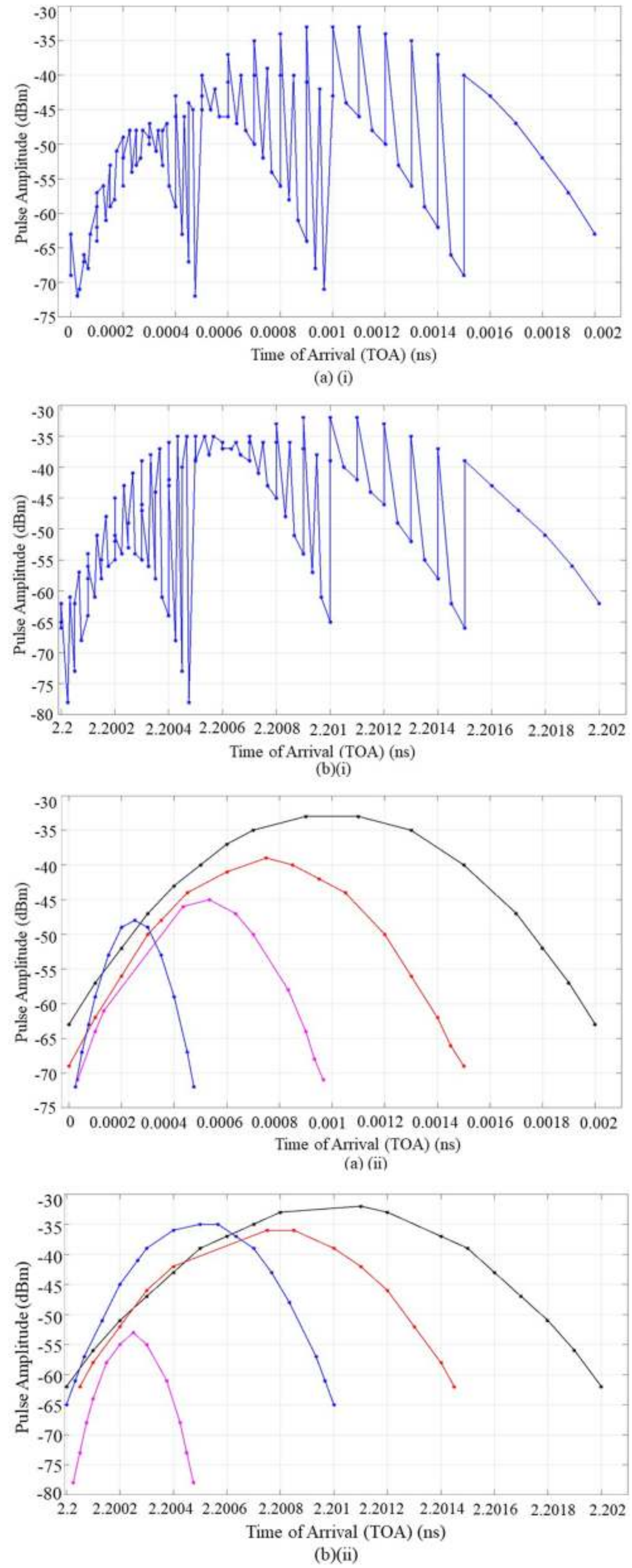

Fig. 11 *Separation of interleaved frames having four signals in the simulated radar data*
(a) The first interleaved frame of duration 2 ms having 90 pulses, ***(b)*** Interleaved frame at 2.2 s having 90 pulses

shows a frame separated at the start of the emission for a duration of 2 ms having 90 samples. Since all the emitters started emitting simultaneously, the first frame is able to capture all the four interleaved emitter pulses in the duration. Fig. 11*a*(ii) shows the deinterleaved frame having four signals using the proposed methodology. The separated signals have a scan period of 0.5 ms (blue), 1 ms (magenta), 1.5 ms (red) and 2 ms (black). A second frame was also captured at the time instance of 2.2 s from the beginning of the emission in Fig. 11*b*(i). The deinterleaved frame is shown in Fig. 11*b*(ii) having four signals with a scan period of 0.5 ms (magenta), 1 ms (blue), 1.5 ms (red) and 2 ms (black). The four-radar emission systems are also shown to have a circular scanning system employed for target detection.

The methodology has also been tested on limited amount of field generated interleaved radar data as shown in Fig. 12*a*. The

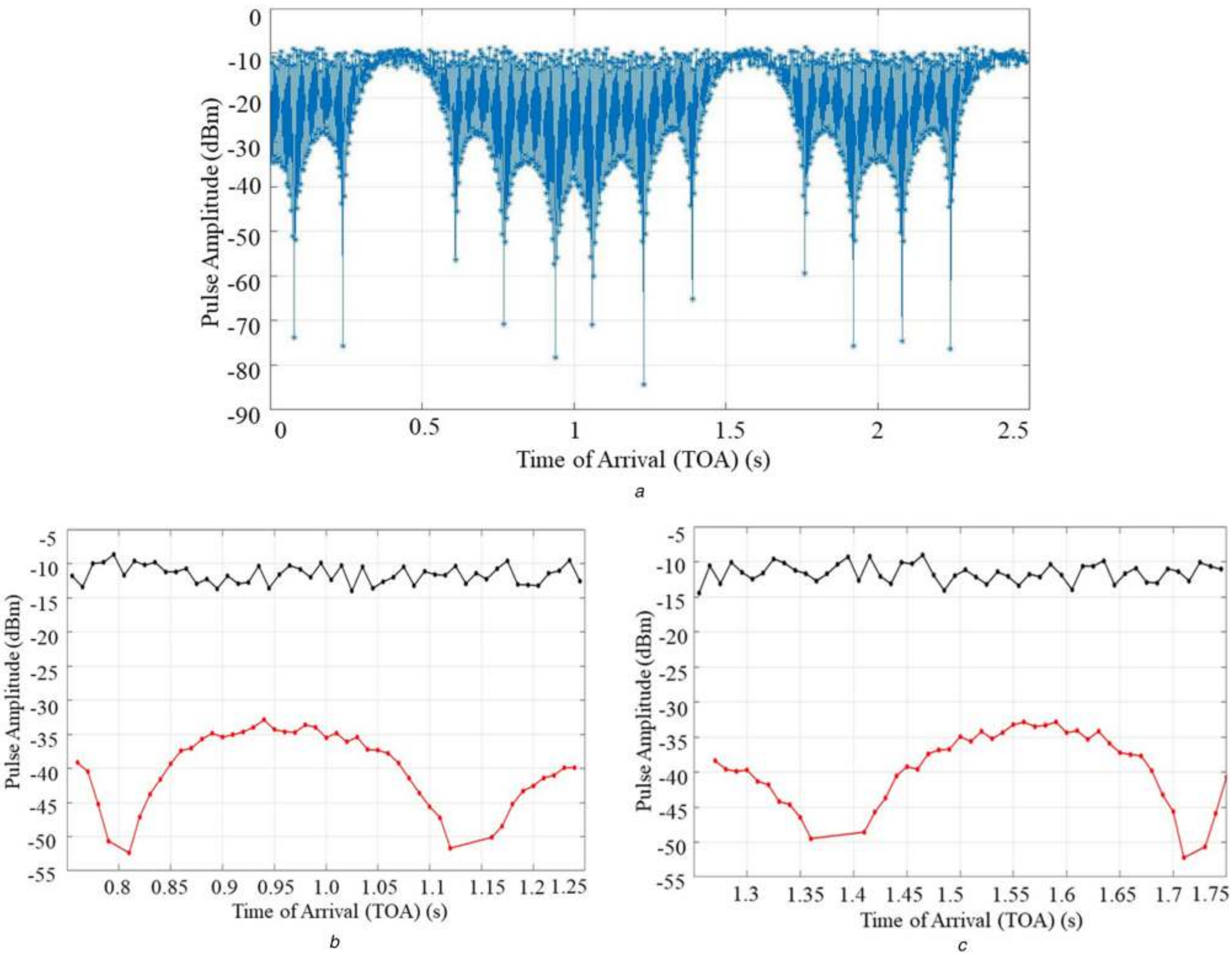

Fig. 12 *Separation of field generated interleaved radar data for two emitters*
(a) Field-generated radar mixed data for two emitters with fixed PRI, ***(b)***, ***(c)*** Separated signals using proposed methodology

Table 2 Comparison of execution time (in seconds)

Jitter bound of PRI, %	Deinterleaving methodologies			
	Improved PRI transform [10], s	Improved SDIF [19], s	Statistical association [11], s	Proposed methodology, s
8	1.59	0.131	7.62	2.304
10	1.61	0.181	7.66	
12	1.65	0.223	9.01	
14	1.653	0.241	13.47	
16	1.74	0.284	15.32	

data set has been generated having two fixed emitters with fixed PRI having missing pulses. The pulse dropout rate is 16–18%. Fig. 12*b* shows a deinterleaved frame separated at 0.8 s from the start of the emission for a duration of 450 ms having 50 pulses. The emitter in black is performing a constant scan with amplitude values in the range of ±3% (c) while the main lobe of the second emitter is separated and shown in red. Another frame is separated as shown in Fig. 12*c* at 1.3 s from the start of the emission for a duration of 450 ms, also having 50 pulses. The frame is deinterleaved and the results show two emitter, the first (black) performing a fixed scan of the environment whereas the second emitter (red) performing a circular scan with a scan period of 300 ms. The execution time for the proposed methodology for each case is 1.89 s.

Table 2 gives the performance analysis in terms of execution time (in seconds) of the proposed methodology and deinterleaving methodologies proposed in [10, 11, 19]. Each algorithm considers four interleaved emitter with a pulse missing rate of 10%. The simulations are performed on a PC with an Intel i5-7500 processor. From Table 2, it can be inferred that the proposed methodology is not in any way limited by the number of missing pulses and pulse jitter. It is able to successfully report the total number of emitters present in all the cases. The number of missing pulses after applying all the three criteria is 2–5% which occur on account of different radar pulses having very little amplitude variation. In comparison, the missing pulse rate of PRI-based techniques is very high at 10–15%, especially in case of staggered and jittered PRIs [10, 11, 19].

The proposed methodology is particularly useful in the case of advanced radar systems as the radar ASP is a reliable parameter. No two radars can physically occupy the same space and hence their scan patterns cannot overlap at all time instances. Also, an emitter gets reported only with a sufficient number of pulses and a distinguishable scan pattern. Therefore, the probability of false alarm is negligible. Finally, the methodology uses low computation units such as Haar wavelet transform, comparisons and thresholding on a small subset of the data. These can be done in a pipelined fashion and hence the proposed methodology is suitable for VLSI implementation on Field Programmable Gate Array (FPGA) and system-on-chip design. Table 3 gives a qualitative

Table 3 Performance comparison for existing methodology and proposed methodology for radar deinterleaving

Parameter	Conventional techniques				Proposed methodology
		PRI-based techniques			
	Clustering [5]	Histogramming [9, 10]	PRI transform [15]	Improved SDIF based on clustering and PRI transform [19]	
parameter agility	not useful	not useful	not useful	not useful	very useful
jittered or staggered PRI	susceptible	susceptible	susceptible	susceptible	not influenced
missing pulses	unreliable	unreliable	reliable	reliable	robust
false alarm rate	very high	very high	high	moderate	negligible
emitter identification	not useful	not useful	not useful	not useful	very useful
computational cost	low	low	high	high	moderate

comparison of the existing and state-of-the-art deinterleaving techniques with the proposed methodology.

5 Conclusion

The paper addresses the problem of radar pulse deinterleaving using a novel and robust parameter, the radar ASP, which has been hitherto unexplored in the domain of pulse deinterleaving. As the EM environment gets more and more complex, advanced radars can change the conventional parameter such as PRI frequently to avoid detection. However, it is extremely difficult to demonstrate scan agility as they cannot change their positions in real time in a very short interval. Therefore, the probability of exhibiting parameter agility (e.g. PRI and PW) in radars is more than scan agility and thus ASP is an excellent choice for pulse deinterleaving. Also, the ASP can be captured using only a single sensor as opposed to another reliable parameter, the DOA which requires multiple sensors to measure the parameter with acceptable accuracy. The use of DWT also makes the system less computationally complex rendering it very useful in a number of resource constraint military and other applications.

The proposed methodology is applied on both synthetic data generated in MATLAB and a limited amount of real data acquired during field trial. The results obtained from the preliminary analysis using the proposed methodology have provided ample scope for further research and refinement of the method. In the present form, the method is best suited to cases where three to four signals are interleaved in a given sub-frame. Our future work involves extending the algorithm to cases where more than four signals of different types of radar scan patterns are interleaved. This can be done by iteratively applying the algorithm after initially categorised pulses are removed. This will further prove to be useful in developing robust and real-time field deployable solutions.

The RWR system is mainly concerned with warning and does not intercept the radars for jamming. However for many electronic intelligence operations the function extends to intercepting radar pulses over scattered lobes. Therefore, another possible direction of research is taking into account the deinterleaving of signals from side lobes in addition to the main lobe. The main difficulty here would be to differentiate the side lobes from the main lobe when only partial data is observed and the methodology needs to consider such cases and should report that a particular scan pattern has X number of side lobes that were received by the RWR.

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