IT'S A COMPLEX WORLD 'RADAR DEINTERLEAVING'

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Abstract

In this paper, we will look at how digital radar streams of pulse descriptor words are sorted by deinterleaving techniques to identify unique emitters. The paper will cover:

1. What is a radar pulse and how it is characterised?
2. The complexity of real world real world data captures
3. How radar pulses are deinterleaved

Introduction

The goal of deinterleaving is to classify radar signals by their unique characteristics and use this data to:

1. Identify radar emitters operating in the environment,
2. Determine the emitter location or direction,
3. Determine the emitter characteristics.

Receiving and processing of radar pulses to determine information on another radar emitter is often used for friend and foe identification in a defence environment. It can also be used in applications of radar transponders that transmit back synchronised responses and messages to the emitting radar.

For the purpose of detecting and identifying radars in the environment, the pulse sequences received from radars are used. The problem of determining the presence of a specific emitter in the environment is a problem of detecting a consistent pulse sequence in the incoming stream of interleaved pulses. Pulses arrive at the receiver of the system in natural time order and so become interleaved as shown in Figure 1. Challenges exist when two or more emitters' pulses overlap in time and cannot be easily detected or are simply not received. This further increases the challenge of deinterleaving the pulses into identified emitters.

Conditions that have an impact on pulse train deinterleaving are [4]:

- Pulse overlap,
- Dropped pulses,
- Extraneous pulses (multipath),
- Intermittent pulse trains (effect of radar's scan characteristic),
- Pulse shadowing,
- Receiver blanking.

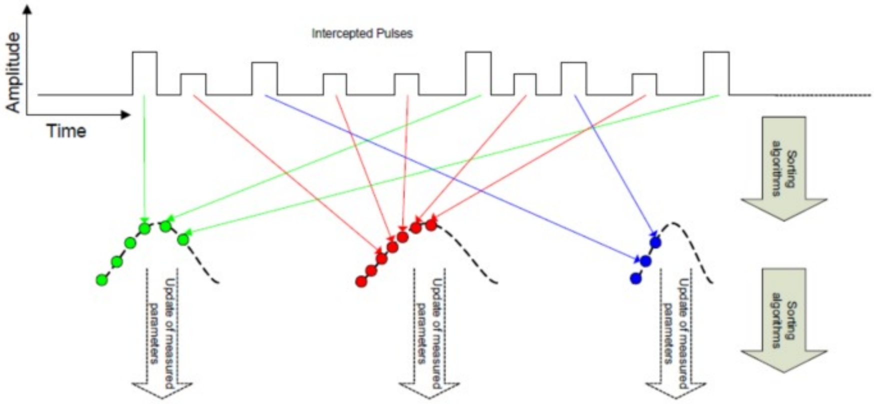

Figure 1 Interleaved Pulses [3]

Emitters can be classified in two ways:

1. Fixed stable: Identifies emitters with parameters that are constant with time
2. Discrete agile: Emitters with a recognisable distribution of values such as regular stagger, switch, dwell and pseudo random emitters.

This paper will focus on deinterleaving of fixed stable emitters.

The Radar Pulse

A radar pulse is characterised by its RF Start Frequency (SF), End Frequency (EF), Pulse Duration (PD) and Pulse Amplitude (PA). Additionally, the Modulation On the Pulse (MOP) and Angle of Arrival may be available. A typical radar pulse is shown in Figure 2.

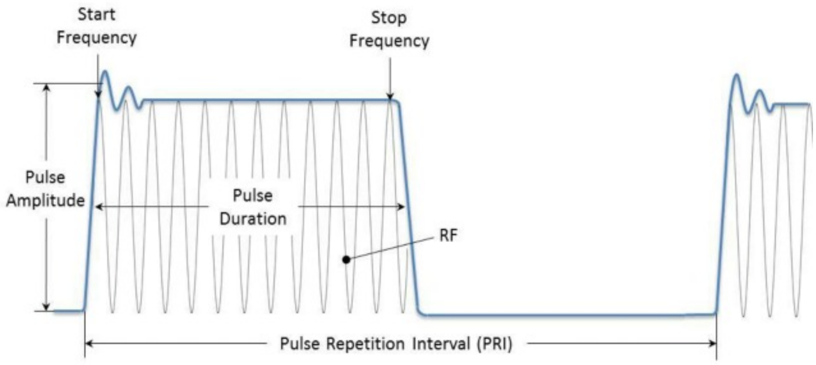

Figure 2 Radar Pulse

Digital capture of the received radar pulse is achieved using Analogue to Digital Converters (ADC) and a FPGA to process and convert the RF pulse into a digital representation. Typically, the receiver will convert the received RF signal into a video amplitude and a voltage representing the frequency of the RF carrier. See Figure 3.

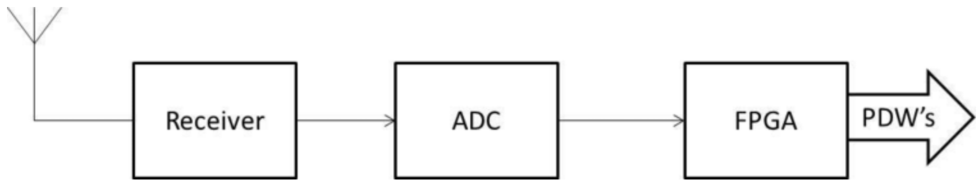

Figure 3 Digital Capture system of Radar Pulse

The digital signal processing in the FPGA converts the received analogue pulse into a digital stream of pulse descriptor words (PDW). The pulse descriptor word includes the characterised pulse information with an applied time stamp (TS) of when the pulse arrived (TOA) in the system. Each one of the parameters will be in the region of 16 to 31 data bits. These parameters are typically converted into compensated and normalised parameters in their respective units, e.g frequency in MHz, Pulse Duration in us. Figure 4 shows a five parameter PDW.

Start Freq (SF)	End Freq (EF)	Duration (PD)	Amplitude (PA)	Time Stamp (TOA)

Figure 4 Pulse Descriptor Word (PDW)

The deinterleaver may reside in either the FPGA, embedded system or industrial computer depending on system requirements.

The transfer speed and volume of PDW's between each of the systems on the data link requires careful consideration. By way of an example, a system with a PDW of 160 bits in length, transferring on a serial link with a pulse duration of 50ns at 80% duty cycle requires 2.5Gbps, see Figure 5. The pressure on the link will further increase with denser environments and multiple frequency band inputs.

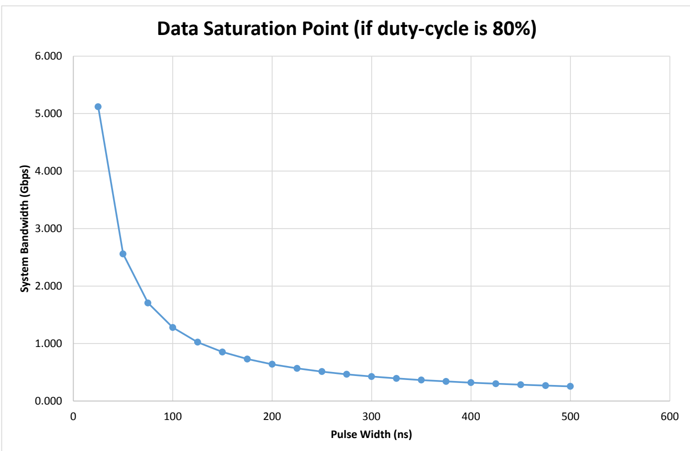

Figure 5 Data Saturation Point of Link

Clustering

Clustering is the technique of grouping together radar pulses into unique sets of emitter characteristics using captured radar pulses and derived pulse characteristics such as Pulse Repetition Interval (PRI). Clustering algorithms need to take into account known schemes applied to the pulse train by radar emitters such as:

1. Fixed stable – identifies emitters with values that are constant,
2. Discrete agile – identifies emitters with a recognisable distribution of values such as regular stagger, switch, dwell, wobulated (varying parameters in a wobble like fashion) and pseudo random emitters.

It is important to consider the requirements of the overall system in terms of processing time and the type of radar schemes that are expected to be present in the operational environment. For example, radar pulse deinterleaving of commercial marine ship radar's characteristics may predominately be expected to be constant, as opposed to a system required to cluster military radar's which apply more complex agile schemes.

Not all parameters are useful in the initial deinterleaving and clustering of emitters. For example, pulse amplitude would not be used due to its varying nature. Frequency, pulse duration and modulation of the pulse are the dominant parameters that can be used in the clustering process.

Clustering algorithm

The success of clustering is a balance between system performance requirements and cost. Some techniques for clustering algorithms are described below in Table 1 for comparison. The remainder of this paper will be concerned with an improved version of the chain algorithm.

Technique	Overview	
Chain Algorithm	The algorithm calculates the difference between a sample pulse and an existing cluster center of pulses. The cluster that yields the smallest difference to the sample pulse and meets a required threshold level is the closest match and the sample pulse is added to the cluster. If the distance between the sample pulse and cluster is large a new cluster center is created.	Quick processing for fixed stable emitters
Sequence Search Method	By assuming a starting PRI estimation, the algorithm starts from the the first pulse in the buffer and then searches for the next pulse, using the TOA the PRI can be derived from the two pulses.	Quick processing for fixed stable emitters

	The algorithm then searches through the remaining PDW data set searching for the next pulse with that PRI. The algorithm is designed to manage missing pulses though the search. On completion or detection of a large gap in the PDW data the algorithm will stop and if enough pulses exist for the PRI, mark and remove them from the data block. On completion of this, the algorithm resets to the first pulse and continues to look for the next valid pulse and its PRI, the algorithm continues until all data is processed.	
Histogram based	Generally uses DTOA (Difference Time Of Arrival) to determine PRI histograms. As new emitters appear, peaks appear in the PRI histogram identifying emitters. PDW's would usually be processed in blocks. Time gaps in pulse streams can lead to increased differences, causing uncertainty. Various approaches can be used such as: • All difference Histogram • Difference Histogram • Sequential Difference Histogram • Cumulative Difference Histogram	Better performance on agile emitters.
Wavelet detector Method	Using a wavelet transform [1][2] uses TOA of the pulse. The approach is to detect if a signal with a period (T) at a given time (t). If the detector exceeds a threshold a pulse train at a period (T) is found. Complexity can arise when multiple points exceed the threshold, this is handled using decision making algorithms and merging techniques.	Good for agile emitters

Table 1 Clustering Techniques

Chain Clustering Algorithm

In order to cluster radar pulses, a distance clustering algorithm is required. This scheme determines the *distance metric* between two points (pulses) in a plane. The Euclidian distance function is used and is given by:

$$d(\bar{x}_i, \bar{x}_j) = \sqrt{\sum_{k=1}^{N} |x_{ik-}x_{jk}|^2}$$

Equation 1 Euclidian distance function

where $\bar{x}_i$ and $\bar{x}_j$ are the distance of the pulses being measured and x_{ik}, x_{jk} are the K^{th} feature of $\bar{x}_i$ and $\bar{x}_j$.

Modified Distance Function Applied to Radar Pulse

The main objective is to determine if two pulses are similar to each other. This can be achieved by expanding on the Euclidian to include PDW parameters of the radar pulse, Start Frequency (SF), End Frequency (EF) and Pulse Duration (PD), see Equation 2. If further parameters are available, such as angle of arrival (AOA) and pulse modulation, these may be included in the algorithm. A weighting parameter is further added to the function that allows a weight for each of the pulse parameters.

$$d(\bar{x}_{Pulse'}, \bar{x}_{Pulse}) = \sqrt{\left(\sum_{K=1}^{N} \frac{|x_{SF'k-}x_{SFk}|^2}{{w_k}^2}\right) + \left(\sum_{K=1}^{N} \frac{|x_{EF'k-}x_{EFk}|^2}{{w_k}^2}\right) + \left(\sum_{K=1}^{N} \frac{|x_{PD'k-}x_{PDk}|^2}{{w_k}^2}\right)}$$

Equation 2 Expanded Distance Function

Where $\bar{x}_{Pulse'}$ is the first pulse or mean value of an accumulated clustered pulse set and $\bar{x}_{Pulse}$ is the pulse to be used to measure the distance with.

The Cluster

The objective of the cluster is to hold received pulse descriptor words that are statistically similar and as such have a high probability of being from the same emitter type. The cluster may contain many unique emitters of the same type of radar system. At a later stage, unique emitters can be identified using TOA, PRI, Amplitude, beam shapes and widths.

To determine how close a new measured pulse is to a cluster set, the mean and standard deviation is calculated based on the PDW's present in the cluster. This is updated for each new pulse added into the cluster.

Figure 6 gives an overview of the process as could be implemented in a system.

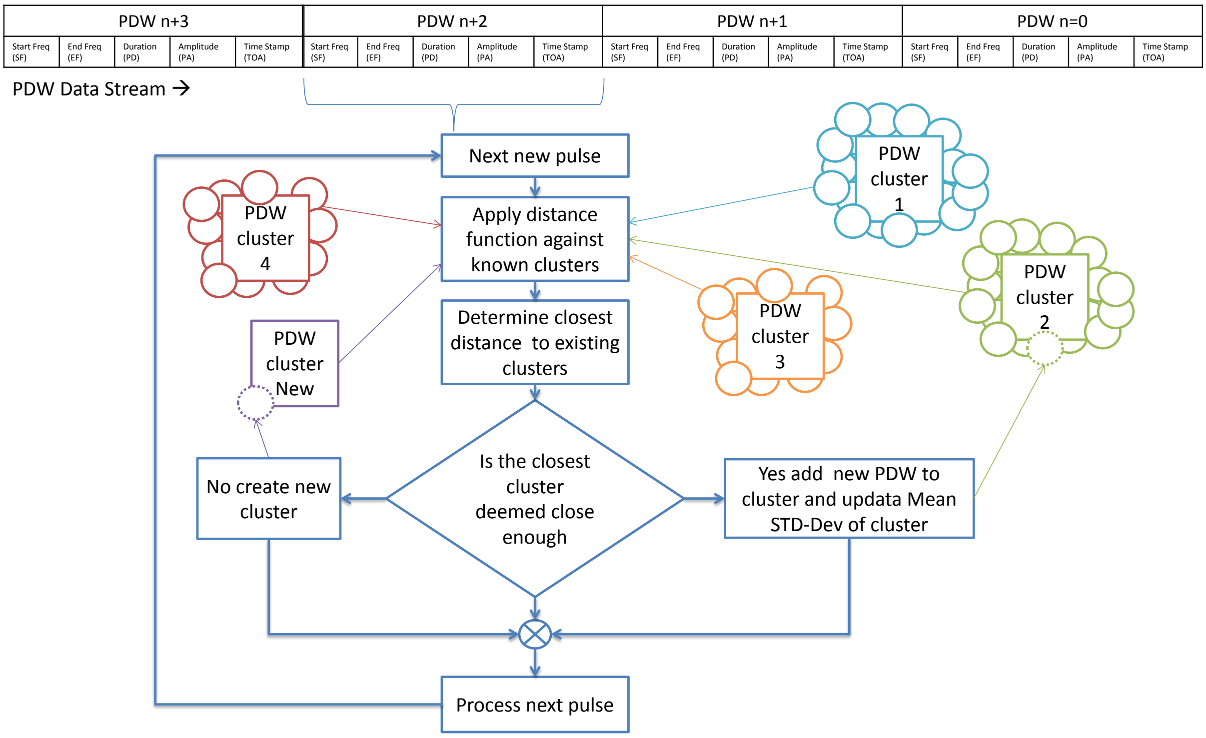

Figure 6 Clustering flow diagram

Figure 7 gives an overview of the system design which starts from the pulse analysis, leading to signal processing of the PDW data stream and then deinterleaving. The PDW data set snippet in Figure 7 shows the PDW data passed into the deinterleaver algorithm, with the results in this example indicating a 100% correct clustering of emitters.

In reality, it is very difficult to achieve a 100% success rate. The deinterleaver is a statistical balance based on hardware performance and knowledge of emitter characteristics. This practical understanding is key to the system performance as it allows the configuration of the deinterleaver parameters that set weighting and distance values. In a real environment, it is very likely that emitting radar pulses are far from perfect due to system design, tolerance and often degradation of Traveling Wave Tubes (TWT) in the field.

The varying parameters of an emitter will likely lead to multiple clusters being generated for the same emitter during the deinterleaving process. In a dense and complex environment, this can quickly consume all of the system memory. It is favourable to including a second stage of deinterleaving to merge clusters together that are deemed to be statistically close to each other.

This approach allows system memory reuse and single emitters types to be merged together in a more efficient manner.

On completion of the deinterleaving process, the next stage would be to carry out emitter identification within each of the cluster sets, using TDOA, sweep rates and beam width techniques to further extract emitters. Depending on the system, identified emitters can be placed in a cluster database to improve system performance over time.

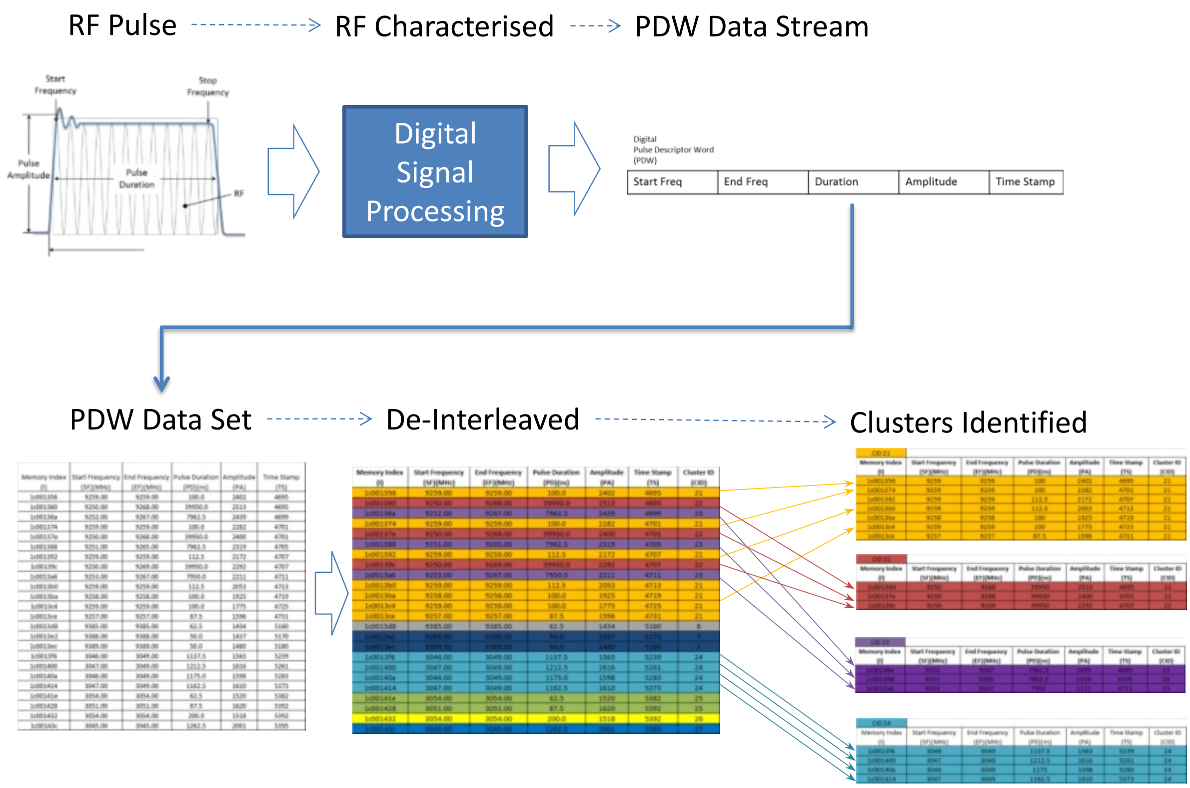

Figure 7 Clustering system

Real World Data

The radar environment can quickly become complex when there are a number of emitters present. Figure 8 presents a 2 second data capture. It is the deinterleavers task to make sense of this complex environment and present it in a usable format.

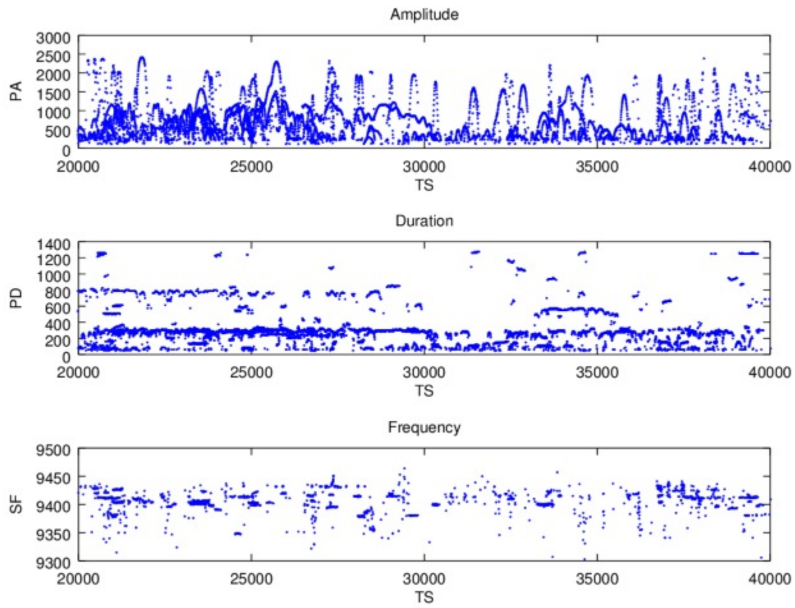

Figure 8 Example radar data captures

Figure **9** shows the pulse descriptor word and the allocated cluster ID plotted against frequency and pulse duration. These results were obtained from the clustering algorithm described earlier running on a small embedded system. (Red markers = SF, Blue markers = EF)

The successful clustering of emitters can clearly be seen with around 120 clusters generated for this dataset.

In Figure **9**, marker 'A' effectively shows a pulse cluster with different start and stop frequencies, and marker 'B' shows a cluster with very few pulses.

Figure 10 is the same data but looking at 10 emitters in more detail. It can be observed that good grouping of the cluster parameters is achieved for these clusters.

Figure 11 shows the complexity of 120 emitters in the environment. This indicates a large number of emitters operating at around 50-100ns pulse duration.

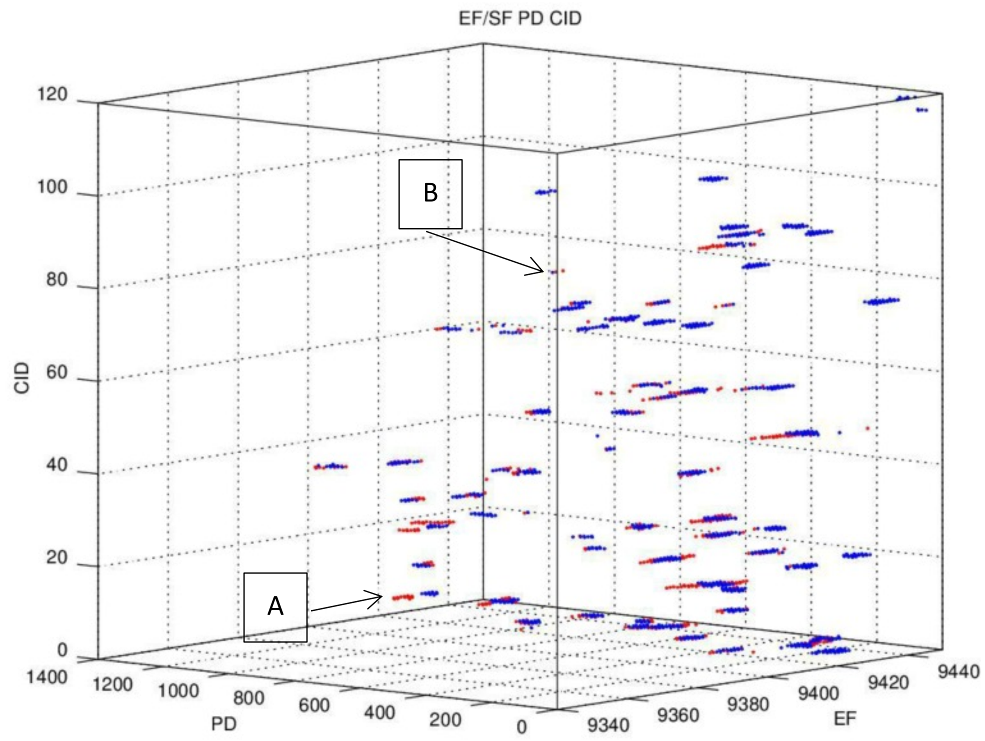

Figure 9 **Example Clustering of Emitters**

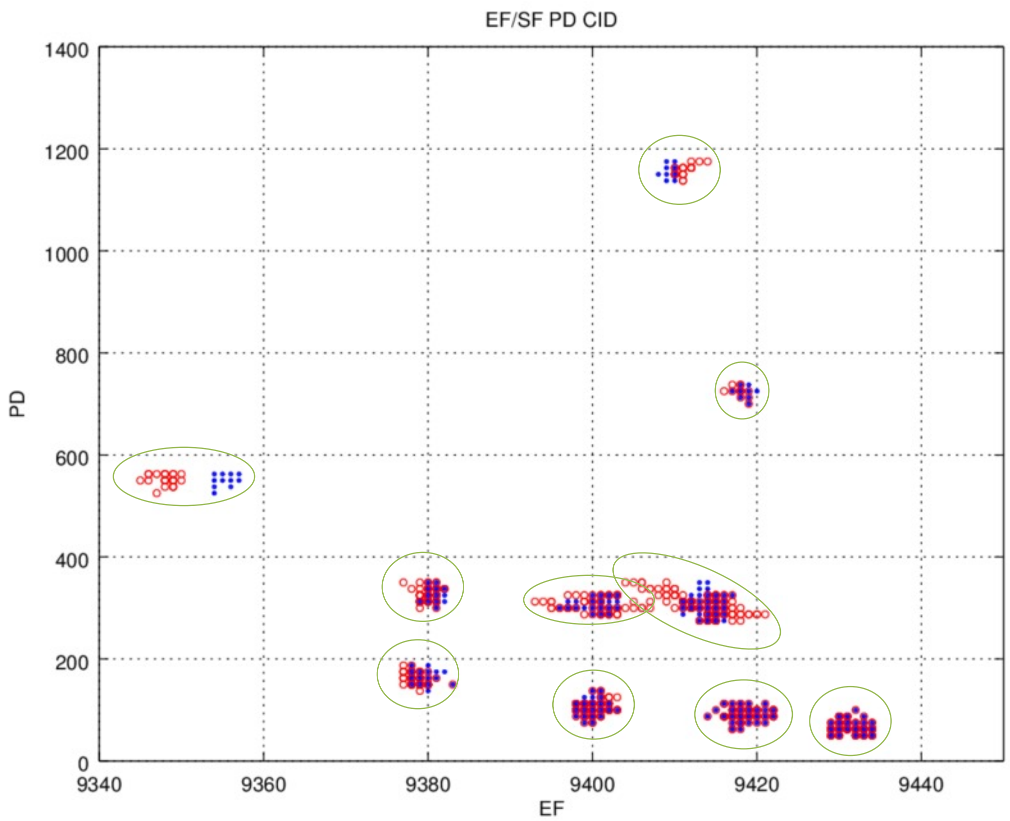

Figure 10 Clustered 10 Emitters Plotted against PD and Frequency

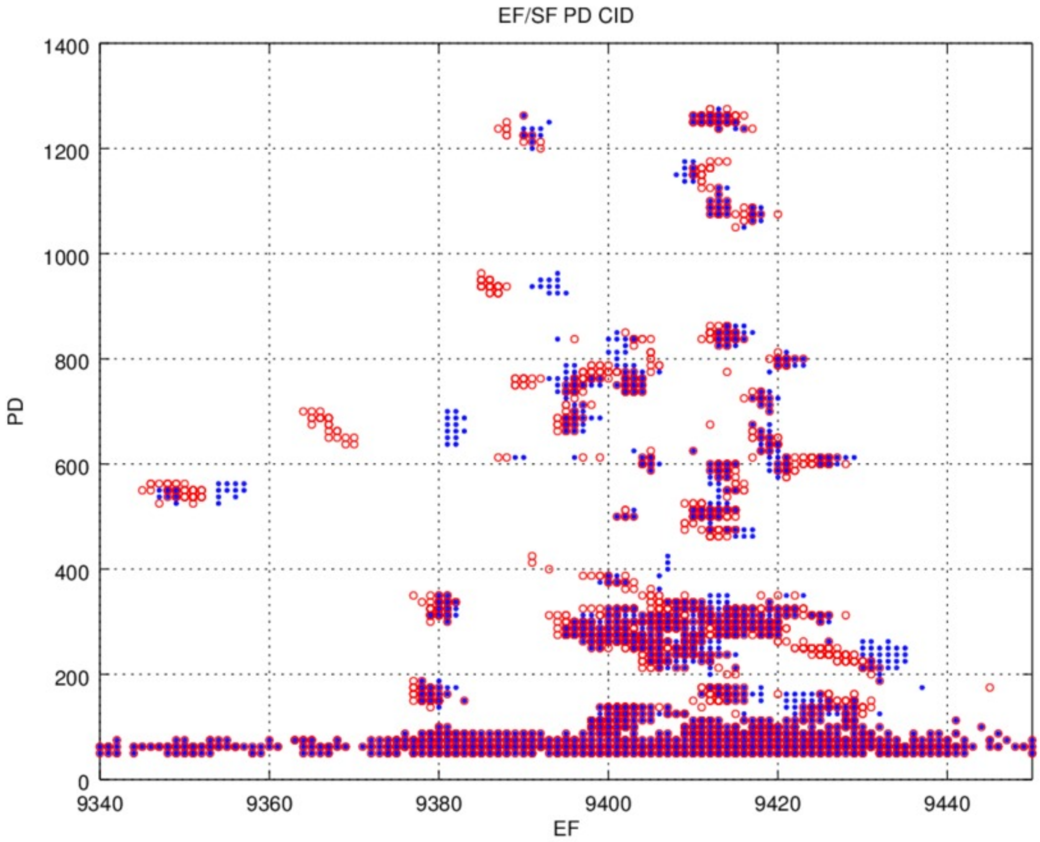

Figure 11 Clustered 120 Emitters Plotted against PD and Frequency

Conclusion

Given that the real world environment of radar pulses is very complex and taking into account millions of radar pulses and multipath effects, the improved chain sequence example explained in the paper can be a good choice for systems deinterleaving fixed static emitters. The radar emitter environment soon get very complex in dense emitter environments and as such, a successful pulse deinterleaver has a tough job.

Document References

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2 Douglas E. Driscoll & Stephen D. Howard, "THE DETECTION OF RADAR PULSE SEQUENCES BY MEANS OF A CONTINUOUS WAVELET TRANSFORM", Electronic Warfare Division Defence Science and Technology Organisation PO Box 1500, Salisbury, SA 5108, Australia

3 Pushparaj Silva, "Analyzing Tool for Radar Data", ISSN-1653-5715

4 Rogers, J. A. V, "ESM Processor System for High Pulse Density Radar Environments", IEE Proceedings