Deinterleaving of Interfering Radars Signals in Identification Friend or Foe Systems

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***Abstract* — In a dense modern electronic warfare environment, IFF/SSR systems receive a wide range of signals from existing radars. Among the most important tasks of such systems are recognition of signals, extraction of work modes for each of the present objectives, separation of received signals, their classification and identification of friend or foe. Because of the equality of the frequency of interrogation signals, the similarity of pulse width in IFF/SSR Radars, and the lack of accuracy of the pulse amplitude as a proper criterion for classification, it is necessary to use a suitable algorithm for deinterleaving and clustering of such radars. By the present study, after proposing an optimized estimation of MRI mean value and devising a method for extracting interfering radars modes in received frame, the main lobes of the existing radars in considered frame are selected based on choosing a proper threshold. Then, using smoothing method, non-interfered parts of radars are separated. In consequence, by determining MRI modulation type and radars mode pattern from the non-interfered part, deinterleaving of the interfering radars is done.**

***Keywords* — Deinterleaving, IFF, Mode, MRI, SSR.**

I. Introduction

IN telecommunications, ***Identification Friend or Foe*** (***IFF)*** is a cryptographic identification system designed for command and control. It is a system that enables military, and national—civilian-located air traffic control (ATC) —interrogation systems to distinguish friendly aircraft, vehicles, or forces, and to determine their bearing and range from the interrogator. IFF is still in use by both military and civilian aircraft. Modes 1, 2, 3, 4 and 5 are for military use only. Modes 1, 2, 3 are composed of 3 pulses. These modes are identified by the interval of the pulses [1]-[2].Mode 4 is an identification mode with encrypted pulses. It has 4 pulses for synchronization and 32 pulses with encrypted information. As shown in fig. 1, the intervals between all pulses are equal to 2 microseconds and Pulse Width (PW) is 0.5 microsecond, too.

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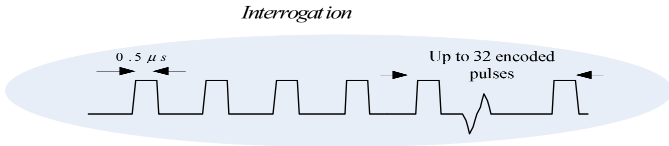

Figure 1. A general view of Mode 4

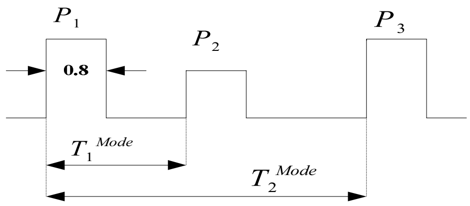

Figure 2. A general view of Modes 1, 2, 3, A, B, C, D

Mode 5 is similar to Mode 4 and it is a crypto-secure Mode but enhanced with an Aircraft Unique PIN. **Secondary surveillance radar** (**SSR**) is a radar system used in ATC, which not only detects and measures the position of aircraft but also requests additional information from the aircraft itself such as its identity and altitude. SSR is based on the military identification friend or foe (IFF) technology, and the two systems are still compatible today. This radar contains five different work Modes (A, B, C, D, S). Fig. 2 and Table. I show a general view of Modes 1, 2, 3, A, B, C, D, and the characteristics of these Modes including radio frequency (RF), PW, and the interval between the pulses, respectively.

In Mode S the interval between P_1 and P_2 is equal to two microseconds and the respective PW is 0.8 microsecond, also the intervals between P_1 and the pulse with information are 18.5 and 22.5 microseconds for short format and long format, respectively (as shown in fig. 3) [3]-[4].It should be noted that the frequencies of interrogation and reply signals in IFF/SSR systems are 1030 and 1090 MHZ, respectively [5]. Regarding the shown values, it is clear that PW and RF cannot be

Table I. the characteristics of Modes 1, 2, 3, A, B, C, D

Mode	$T_2^{Mode}(us)$	$T_1^{Mode}(us)$	PW of P_1, P_2, P_3 (us)	RF (MHZ)
1	3	2	0.8	1030
2	5	2	0.8	1030
3	8	2	0.8	1030

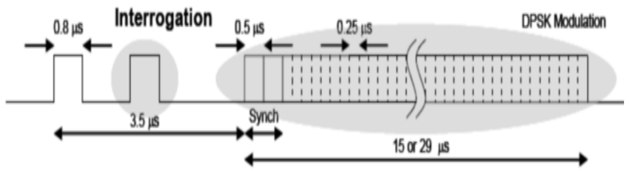

Figure 3. A general view of Mode S[4]

considered as suitable criteria for deinterleaving. Because of the fact that all IFF/SSR radars make use of these Modes and the interfering radars adopt group pulse [6] with similar characteristics, it is a difficult and complex issue to separate radars by use of the interval between the pulses. In this paper, minimum square error estimation of mode repetition interval (MRI) mean value is derived. Then, the method for extracting existing modes in frame and mathematical model for different types of MRI modulation along with their corresponding characteristics are presented. A method for separating non-interfered part of the main lobes of existing radars in one frame and a method for determining MRI modulation type and work mode pattern of any radar are then presented. Finally, the results of testing the proposed algorithm are shown in a simulation scenario presented in table 2.

II. TIME OF ARRIVAL OF MODES

Considering time of arrival (TOA) sequence measured by IFF/SSR system's receiver and in view of TOA of P_1 as representative of each mode, TOA sequence for a mode train in radar with N mode can be written as follows:

$$t_n^{Mode} = t_n^{perfect} + \sigma z_n ; n = 1,2,\ldots, N \tag{1}$$

where $\{z_n\}$ represents samples of zero mean white Gaussian noise with unit variance and σ^2 is additive noise variance. The perfect TOA sequence, $t_n^{perfect}$, of a simple Mode train with Constant modulation can be written as follows:

$$t_n^{perfect} = nD + \varphi ; n = 1,2,\ldots, N \tag{2}$$

D stands for intervals of Mode train and φ is the interval between the first received Mode by IFF/SSR system's receiver and the first Mode of the perfect Mode train. The minimum squared error can be used to estimate the interval. The square error is:

$$MSE(D,\varphi) = \sum_{n=1}^{N} (t_n^{Mode} - t_n^{perfect})^2 \tag{3}$$

By entering (2), into (3), then:

$$MSE(D,\varphi) = \sum_{n=1}^{N} (t_n^{Mode} - (nD + \varphi))^2 \tag{4}$$

Differentiate $MSE(D,\varphi)$ with respect to D and φ, and set the results equal to zero:

$$\begin{cases} \dfrac{\partial MSE(D,\varphi)}{\partial D} = 0 \rightarrow \sum_{n=1}^{N} n(t_n^{Mode} - (nD + \varphi)) = 0 \\ \dfrac{\partial MSE(D,\varphi)}{\partial \varphi} = 0 \rightarrow \sum_{n=1}^{N} (t_n^{Mode} - (nD + \varphi)) = 0 \end{cases} \tag{5}$$

Solving (5), D is obtained and the estimation of Mode Repetition Interval (MRI) is as:

$$\hat{D} = \left[\sum_{n=1}^{N} (n - \frac{(N+1)}{2}) t_n^{Mode}\right] \frac{12}{(N-1)N(N+1)} \tag{6}$$

Conventionally, the mean value of MRI sequence, namely MRI_{ave}, has been estimated using the equation.

$$MRI_{ave} = \frac{t_n^{Mode} - t_1^{Mode}}{N-1} \tag{7}$$

In fig. 4, the minimum square estimation error in (6), is compared with the error of common estimation (MRI_{ave}). As shown in fig. 4, the estimation of (7), is more accurate and the proportion of mean MRI estimation per minimum square estimation errors increases as the number of Modes increases. In the simulations of this figure, noise variance is considered to be 1 and D is assumed to be 100.

In [7] a matrix-based estimation for MRI mean value can be obtained using the following equation:

$$Mean\ \ MRI \approx \frac{N_{TOA}^{Mode}}{|Tr(\Delta TOA^{Mode})^{-1}|} \tag{8}$$

where N_{TOA}^{Mode} shows the number of Modes and Tr denotes the trace of a matrix which is defined as the summation of its diagonal elements. With respect to its $(i,j)^{th}$ element, ΔTOA^{Mode} matrix can be defined as follows:

$$\Delta TOA^{Mode}(i,j) = |t_j^{Mode} - t_i^{Mode}| ; 1 \le (i,j) \le N_{TOA}^{Mode} \tag{9}$$

Equation (6) is a more accurate estimation than (8). It has also low computational complexity comparing with matrix-based estimation.

IFF/SSR radar can change the interval between its modes in terms of different applications. MRI sequence can be expressed as:

$$M_n = t_n^{Mode} - t_{n-1}^{Mode} ; n = 2,3\ldots, N \tag{10}$$

Enter (1), in (8), so:

$$M_n = D_n + \sigma v_n ; n = 1,2\ldots, N \tag{11}$$

Where D_n presents interval between n^{th} mode and $(n-1)^{th}$ mode from the perfect modes train; $\{v_n\}$ is representative of samples of zero mean colored Gaussian noise with variance 2.

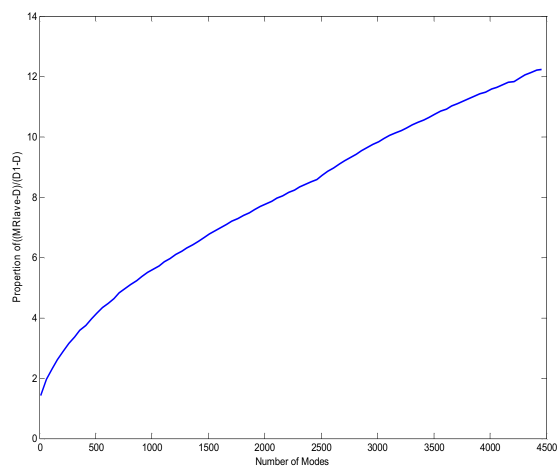

Figure 4. Proportion of mean error per MSE error

IV. Mathematical Model for MRI Modulation

IFF/SSR radars can use different modes repetition patterns with respect to their application. The maximum length of a pattern is equal to the total number of its modes. The patterns are referred to as different types of MRI modulation. Fig. 6 shows different MRI modulations such as Constant, Sliding, Jittered, and Staggered. For separation of radars with different MRI modulations, their mathematical model is first introduced.

As shown in fig. 5, Constant MRI modulation has the simplest modulation in which the modes are repeated with the constant interval, D. In this modulation, TOA sequence and MRI sequence can be expressed as the following:

$$\begin{cases} t_n^{Cons} = nD + \varphi + \sigma z_n ; n = 0,1,2,...,N \\ M_n^{Cons} = D + \sigma v_n ; n = 1,2,...,N \end{cases} \quad (12)$$

Where D is the constant interval and $\{v_n\}$ are samples of zero mean colored Gaussian noise with variance 2. The standard deviation, σ is often less than one percent of D.

In jittered MRI modulation, random TOA variations of modes are limited in a distinct interval.

$$M_n^{Jitt} = D + (J + \sigma) v_n ; n = 1,2,..., N \quad (13)$$

where J is the jitter value which is created in the transmitter radar to avoid the hostile jamming and its maximum value is about 0.25D.

Staggered MRI modulation has M MRI levels, $D_i ; i = 0,1,2,..., M-1$, where common values for M are between two to eight levels. MRI sequence for this modulation is written as the following:

$$M_n^{Stag} = D_{n \bmod M} + \sigma v_n ; n = 1,2,..., N \quad (14)$$

In sliding MRI modulation, MRI levels monotonically change from a level to another one.

$$M_n^{Slid} = D_{start} + D_{step}(n-1) \bmod M + \sigma v_n ; n = 1,2,...,N \quad (15)$$

In this modulation, MRI levels start from D_{start} and Increase D_{step} in each mode.

V. Deinterleaving of Radars

Considering the fact that any radar uses a distinct mode pattern and MRI, extracting these parameters for separating radars is regarded as particularly important. In order to extract these parameters, smoothing method is used so as to separate non-interfered parts in the frame. Based on the extracted parameters of radar, deinterleaving of any typical radar can be done. By the suggested method, pulses of the

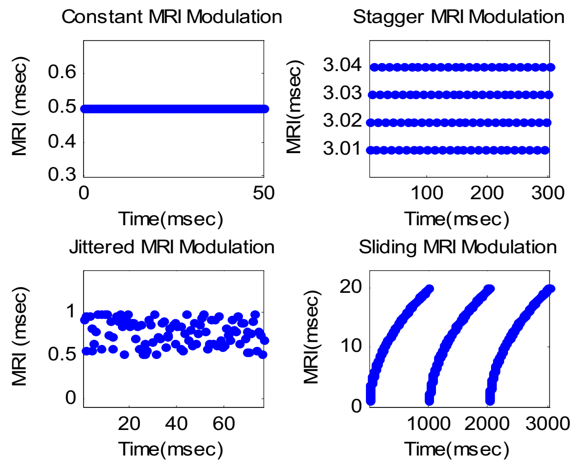

Figure 5. types of MRI modulation

radar received by IFF/SSR receiver with the largest pulse amplitude are first separated (i.e. the radar with the largest pulse amplitude is first separated).

For this end, using (17), a proper threshold from the received signals pulse amplitude is selected and the main lobes of the present radars in the frame are extracted.

$$Amp^{Thr} = \sum_{i=1}^{K} PA_i^{Mode} + \beta \sqrt{\frac{1}{K} \sum_{j=1}^{K} (PA_j^{Mode} - \sum_{i=1}^{K} PA_i^{Mode})^2} \quad (16)$$

where K is the length of PA^{Mode} and $0.5 < \beta < 2$. So, there are L blocks. Each block is a collection of the pulse amplitudes of the main lobes of the existing radars.

It should be, however, noted that there is a possibility of interference in some blocks. Fig. 6 includes a representative example of separated main lobes of two radars which have interference.

Then, using eq. 18 the pulse amplitude for each block can be saved:

$$PA^L = [PA_1^L \quad PA_2^L \quad ... \quad PA_m^L] \quad (17)$$

where m stands for the length of each block. In order to extract interfering signals from non-interfering ones, the three pointed smoothing vector $Coef^L$ is used. With respect to the following equations, this vector can be formed:

$$Coef^L = [coef(1) \quad coef(2) \quad ... \quad coef(m)] \quad (18)$$

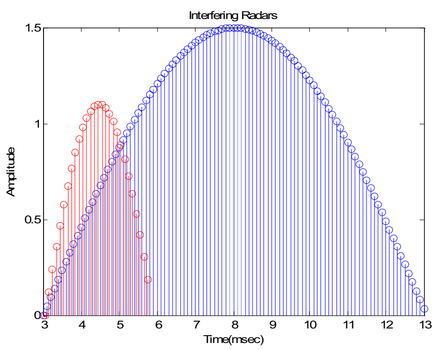

Figure 6. An example of the main lobes of two interfering radars

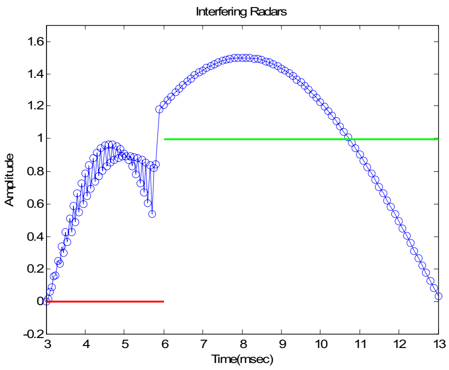

Figure 7. result of three-pointed smoothing

and

$$\begin{cases} coef\,(1) = PA_1^L \\ coef\,(2) = \dfrac{PA_1^L + PA_2^L + PA_3^L}{3} \\ coef\,(3) = \dfrac{PA_2^L + PA_3^L + PA_4^L}{3} \\ \quad\vdots \\ coef\,(m) = PA_m^L \end{cases} \qquad (19)$$

Fig. 7 shows the result of three pointed smoothing mentioned in fig. 6.

Using eq. 21, the subtraction vector can be formed. By calculation of the mean value of this vector, the proper threshold level for separation of the non-interfered part(s) is selected. In fig. 8, the interfered part is underlined by red ink and the non-interfered part is underlined by green ink.

$$diff^{\,vec} = | PA^L - Coef^{\,L} | \qquad (20)$$

$$Thr^{\,level} = \frac{1}{K}\sum_{i=1}^{K} diff_i^{\,vec} \qquad (21)$$

The vector for extracting mode pattern and MRI modulation type can be produced using Thr^{level}, as expressed in the following:

$$pat^{\,vec} = \begin{cases} PA_j^L & ; diff^{\,vec}(j) \le Thr^{\,level} \\ 0 & ; diff^{\,vec}(j) > Thr^{\,level} \end{cases} \qquad (22)$$

Equation (23) represents a vector of the modes owned by radar of which interfered parts are omitted.

Fig. 9 shows a vector used for extracting mode pattern and MRI modulation type. By use of the above-mentioned vector (pat^{vec}), MRI modulation type and mode pattern can be simply obtained. It should be noted that the type of MRI modulation can also be determined using auto-correlation function method [8].

VI. Deinterleaving Results

Regarding the simulations and the proposed algorithm for separating the interfering radars, deinterleaving results are shown in fig. 9. As this figure shows, the suggested algorithm has little sensitivity towards

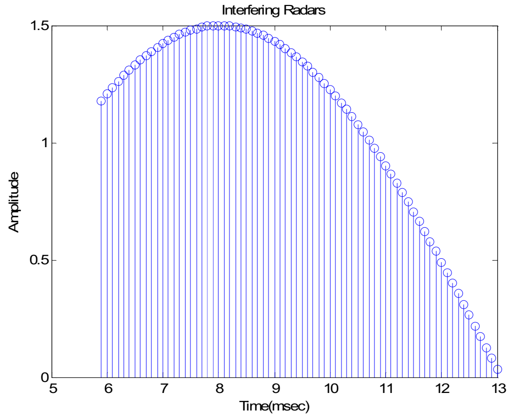

Figure 8. contents of $pat^{\,vec}$ for fig. 7

spurious pulses. It can be accounted for by the fact that the suggested mode extraction algorithm is very suitable which can omit noises during mode extraction. In the scenario presented in table 2, the second column shows the mode pattern of radar and the third column is for type of MRI modulation. The fourth column of this table shows the number of modes owned by typical radar, the fifth column represents the percentage of lost pulses, and the sixth column shows spurious pulses. Also, the next two columns respectively show MRI levels and the number of pulses which are owned by radars. The last column contains the percentage of deinterleaving of radar pulses with the mean value of 91 percent. It show be noted that for deinterleaving, the value of α is assumed to be 0.005.

VII. Conclusions

With regard to the importance of identification of friend and foe in modern electrical war environments, a need for developing and employing an effective method for separation of interfering received signals, extraction of MRI modulation type and determination of mode pattern can be perceived and stressed. This

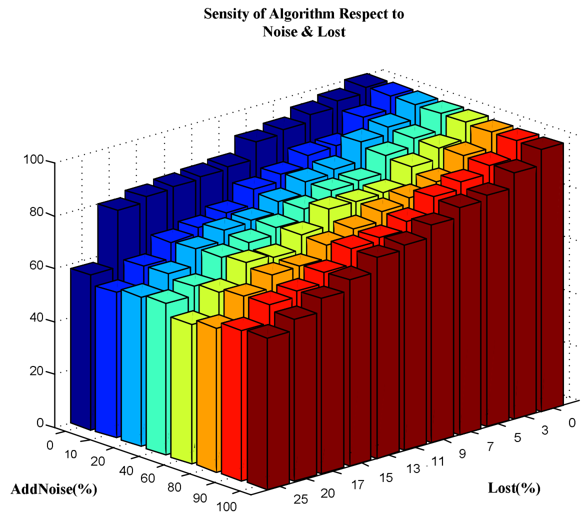

Figure 9. accuracy of proposed algorithm in relation to Lost Pulses & Spurious Pulses

Table 2. The radar parameters of simulation scenario

Source Number	Mode Type	MRI Modulation	Mode Number	Lost Pulses (%)	Spurious Pulses (%)	MRI Level (msec)	Pulse Number	Deinterleaving Results (%)
1	123C	Constant	1400	10	82	5	6880	89.32
2	AC	Stag4	1600	12	90	3.1 3.7 4.2 4.8	8025	80.13
3	SA3C	Jit-20%	1550	8	85	3.5	7914	92
4	1C3A4S	Constant	2300	9	95	4	12244	91.05
5	C23	Stag3	1350	11	80	3.5 4.5 5.5	6488	83.79
6	123ACS	Stag-6	2250	7	75	3.3 3.6 3.8 4.2 4.9 5.5	10985	97
7	13	Constant	1200	10	87	5.5	6058	91.93
8	1423	Constant	2450	9	93	4.5	12908	92.94
9	3241	Stag4	1100	8	92	4.6 4.95 5.45 5.93	5829	85.38
10	1A3S	Jit-15%	1150	6	80	4.6	5837	96.08
11	123S	Sliding	1450	11	87	2.5 3.5 4.5 5.5	7239	86.95
12	CSA4	Jit-25%	1300	7	75	3.75	6347	94.58

paper has proposed a model for times of arrival and MRI sequences and their noise. A comparison of MSE estimation and average estimation of MRI level has been made. Moreover, a method for extracting modes has been developed. Considering the lack of accuracy in the application of radio frequency parameters and pulse width, the proposed method of the present study for deinterleaving of radars is highly effective owing to its simultaneous use of two parameters of radar work pattern and MRI modulation type.As a result of using this method, processing of signals of such radars is facilitated and the considered targets can be achieved. Simulation results show that the suggested method is very useful for radar signal processing and identification of friend and foe in IFF/SSR systems.

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