FACTA UNIVERSITATIS
Series: **Electronics and Energetics** Vol. 33, N° 3, September 2020, pp. 459-476
https://doi.org/10.2298/FUEE2003459M

RELIABILITY ANALYSIS OF DIFFERENT RCIED ACTIVATION SIGNAL RESPONSIVE JAMMING TECHNIQUES AND THEIR COMPARISON TO ACTIVE JAMMING *

Mladen Mileusnić, Predrag Petrović, Vladimir Kosjer, Aleksandar Lebl, Branislav Pavić

IRITEL a.d., Belgrade, Serbia

Abstract. *In this paper we compared the time required for the successful jamming of remote controlled improvised explosive devices activation using active and responsive jamming methods. As a representative of active jamming method we analyzed jamming signal generation using frequency sweep. For the analysis of the possible activating signal presence based on responsive jamming procedures we first supposed Fast Fourier Transform (FFT) implementation and compared its analysis rate to the rate of sweep jamming. Taking into account the current technology state, it is proved that the time required to achieve the successful jamming relied on FFT analysis may be less than in the case of active sweep jamming. After that we considered pros and cons for energy detector and matched filter detector implementation in responsive jamming. For these two detector types it is shown how to determine the number of analysis blocks to achieve approximately the same number of collected samples as in the case of FFT implementation, starting from the probabilities of false detection and miss of detection.*

Key words: *Active and Responsive jamming, RCIED - remote controlled improvised explosive devices, Frequency sweep, Fast Fourier Transform, Energy Detector, Matched Filter, Jamming Reliability*

1. INTRODUCTION

The common characteristic of all remote controlled improvised explosive devices (RCIED) is that they are activated by wirelessly transmitted messages. The results of RCIED activation message could be disastrous regarding people lives (VIP persons) and the equipments damages. All elements related to activation signal characteristics (signal power, frequency, implemented modulation method, message duration) are completely unknown. This fact produces great problems in the realization of RCIED activation jammers.

Received February 4, 2020; received in revised form March 3, 2020
Corresponding author: Aleksandar Lebl
IRITEL a.d., 11080 Belgrade, Batajnički put 23, Serbia
E-mail: lebl@iritel.com
* The earlier version of this paper is awarded as the best one in the section Telecommunications at the 6th IcETRAN Conference, Silver Lake, 3-6 June 2019, [1].

Contributions [2] and [3] provide a general overview of jammers types, communications jamming requirements and their efficiency analysis. Modern communications jamming principles and techniques may be found in [4].

There are two basic approaches to the jammer implementation. The first one is active jamming, which consisted of continuous predefined jamming signals sending independently of the RCIED activating message characteristics. In this concept there are no „look through“ phases to detect the activation message existence and the jamming signal characteristics are selected in general using previous experience and expectations. The most important freely selected jamming signal parameter is the RF signal level. This level has to be as high as possible to successfully prevent activating message reception. Two key features which are not optimally chosen relate to continuous jamming regardless of RCIED activation message existence and the RF jamming signal level necessary for jamming successfulness due to the fact that the activation signal level is unknown.

The alternative approach to jammer implementation is responsive jamming concept. In this case the jamming signal characteristics can be optimized using look through intervals to detect the activation message existence and its level. That's why it is possible to send the jamming signal only during activation message presence and jamming signal level can be adjusted to the activation message level in order to successfully deny the threat. A wide range of active and responsive jammers may be found in [5]-[14].

It may be concluded from this short presentation of active and responsive jamming characteristics that active jamming is always successful, while responsive jamming efficiency depends on activation message detection reliability. The question is whether responsive jamming reliability may be higher than for active jamming. In this paper we compare the reliability of mostly implemented active jamming method – frequency sweep [15]-[19] to the reliability of a representative method for activating signal eventual presence detection in order to generate jamming signal according to the activation signal characteristics by implementation of Fast Fourier Transform (FFT) in the analysis [14].

A brief principle schematic of RCIED activation signal detection is explained in Section 2. After that the method for RCIED activation signal frequency spectrum estimation based on FFT analysis is presented in Section 3 with the emphasis on the required time for calculation. Sections 4 and 5 deal with the specificities of energy detector and matched filter detector implementation for RCIED activation message detection. The emphasis is on the determination of collected samples number. Section 6 is devoted to frequency sweep jamming and to determination of required time to realize one complete jamming cycle. In Section 7 jamming reliability on the basis of FFT analysis is compared to the frequency sweep jamming reliability, whereby two special purpose processors are considered for FFT calculation. Reliability estimation is based on the required time to allow successful jamming. Section 8 is focused on the presentation how to determine the necessary number of analysis blocks in energy detection or matched filter detection to achieve the comparable sample collection rate of these two detectors to FFT based detector. At the end, the paper conclusion is given in Section 9.

2. PRINCIPLES OF DETECTION PROCESS

Main principles of RCIED activation signal detection may be explained using simplified block-schema presented in Fig. 1.

The first phase in detector function is signal samples collecting (block SCOL). After that follows processing of these samples (block PROC). The final step is making a decision about (eventual) presence of RCIED activation signal on the base of a set of comparison rules (block DECISION). These comparison rules are adjusted to the applied method of signal samples processing.

This paper is mainly devoted to the block PROC. The analyzed methods are FFT, energy detector and matched filter. When the second or the third of these three methods is implemented, digital filter precedes the phase of processing.

According to the available literature, there are also other methods which are less often applied for spectrum sensing, but they are possible candidates for RCIED activation signal detection. Some of them are waveform based detection, eigen-value based detection, wavelet based edge detection, ciclostationary feature detection [20] and so on. These methods, as generally less often applied ones, are beyond the scope of this paper.

Fig. 1 Block schema of RCIED activation signal detector

3. SIGNAL SPECTRUM ESTIMATION ON THE FFT BASE

FFT is the calculation procedure, which allows relatively fast estimation of discretized signal frequency spectrum. Starting from n time samples of analyzed signal, this procedure gives a snapshot of signal frequency spectrum also in n points, i.e. n spectrum lines are obtained. FFT is the optimum method taking into account the required number of mathematical operations for signal spectrum determination. There are $(n/2)\cdot\log_2(n)$ complex multiplications and $n\cdot\log_2(n)$ complex additions [21]. The limitation for n is that the condition $n=2^a$ must be satisfied, where a is the positive integer number. This is a significant saving in the number of mathematical operations and in the required calculation time comparing to the classical method of frequency spectrum estimation by Discrete Fourier Transform (DFT). Namely, it is necessary to perform n^2 complex multiplications and $n^2–n$ complex additions to obtain n frequency spectrum components by DFT on the base of n time samples.

Let us suppose that f_s is the frequency of analyzed signal sampling. The sample acquisition time is then:

$$t = \frac{n}{f_s} \tag{1}$$

The frequency resolution on the base of sample acquisition time may be determined as:

$$df = \frac{1}{T} = \frac{f_s}{n} \tag{2}$$

Therefore, frequency resolution is improved when acquisition time is increased, i.e. the space between frequency spectral components of the analyzed signal is lower.

Constant advancements in processor realization technology and mathematical algorithm improvements are visible in two aspects of FFT calculation progress. On the one side the number of points in which frequency spectrum is determined is constantly increased, and on the other side the required FFT calculation time for some exactly determined number of frequency spectrum components is constantly decreased, chronologically, successively according to presentations in [22], [23], [21], [24]. We selected two approaches referenced in [21] and [24] due to very fast processing algorithms.

Data presented in [24] is related to the FFT calculation time as a function of the number of signal time samples implemented for FFT calculation, i.e. as a function of the obtained frequency components number in the analyzed spectrum. The presented data is for processor clock of 1GHz. It is further emphasized in [24] that improvement may be achieved by processor clock speed increase to 1.25GHz. Besides, it is stated in [25] that maximum processor clock frequency may be even 1.4GHz. On the base of these data, the FFT calculation time (T_{cal} in ms) is presented in Table 1 as a function of the number of points used in a calculation, for a processor clock of 1.25GHz and for 8 processor cores. The value of the constant K is 1024 in the first column of the Table 1.

The time of FFT calculation (T_{cal} in μs) according to the data emphasized in [21] is presented in the Table 2. The processor clock in this case may be in the range between 60MHz and 150MHz [26]. That's why data are presented for the mean processor frequency of 100MHz. FFT hardware accelerator (HWAFFT) is one of the parts in the processor implemented according to [21]. HWAFFT is intended for faster FFT calculation. Data in Table 2 are related to the case when HWAFFT is implemented. The number of points is relatively small (till 1024) where FFT is calculated comparing to the number of points, where FFT results are presented in Table 1.

In accordance to Fig. 1, the total time, which is needed for signal analysis in a jammer (T_{an}) before (eventually) starting RCIED activation jamming signal emission, consists of three components: sample acquisition time (T), FFT calculation time (T_{cal}) and the time, which is necessary to compare obtained signal frequency components after FFT calculation (T_{comp}) in order to determine whether it is necessary to start jamming. When considering the last component (T_{comp}), there is not such a data in a literature, because calculation is very specific. For our analysis, we supposed that taking equal values of T_{cal} and T_{comp} is a quite good approximation, i.e.

$$T_{an} = T + T_{cal} + T_{comp} = \frac{n}{f_s} + 2 \cdot T_{cal} \tag{3}$$

Table 1 The time of FFT calculation as a function of the number of calculation points for the processor presented in [24]

Number of points for FFT calculation	Calculation time T_{cal} [ms] (8 cores, 1.25GHz)
16K	0.1051
32K	0.1584
64K	0.2517
128K	0.5128
256K	0.9488
512K	2.4824
1024K	5.1226

Table 2 The time of FFT calculation as a function of the number of calculation points for the processor presented in [21]

Number of points for FFT calculation	Calculation time T_{cal} [μs] (with HWAFFT, 100 MHz)
8	1.3
16	1.7
32	3.21
64	4.36
128	9.12
256	16.68
512	37.4
1024	73.15

4. RCIED Activation Signal Detection by Energy Detector

Energy detector is the simplest techniques for signal detection [27]. In the same time it is a very often applied technique. It is necessary first to measure signal energy in the pre-defined frequency band. The measured signal energy is then compared to the energy threshold according to the equation

$$E(x) = \sum_{n=1}^{N} (x(n))^2 > \gamma \tag{4}$$

where N is the number of samples implemented for signal energy estimation, $x(n)$ is the amplitude of n^{th} sample and γ is the threshold power.

Although simple for implementation, energy detector performances are degraded due to noise uncertainty (noise level is variable during time) and background interference [28]. Noise uncertainty may be bounded or unbounded [29]. As a consequence of noise uncertainty, the detection by energy detector may become even impossible under relatively low value of signal to noise ratio (*SNR*) [30]. In other words, there exists a *SNR* wall: detection is possible only when signal power is higher than noise power uncertainty.

For the analysis in this paper and for the comparison of energy detector characteristics with the characteristics of other methods for reactive jamming the most important parameter is the number of samples (N) to achieve necessary detection reliability. Our analysis is based on the formula for N from [27] [31]:

$$N = 2 \cdot \frac{(Q^{-1}(P_f) - \sqrt{1+2\cdot SNR}\cdot Q^{-1}(P_d))^2}{SNR^2} \tag{5}$$

where P_f is probability of false detection (detector announces signal presence although there is no signal), P_d is probability of successful detection and Q^{-1} is inverse Gaussian-Q function. In other words, Q^{-1} is the inverse of

$$Q(x) = \frac{1}{2\cdot\pi}\cdot\int_x^{\infty} e^{-\frac{u^2}{2}1}\cdot du \tag{6}$$

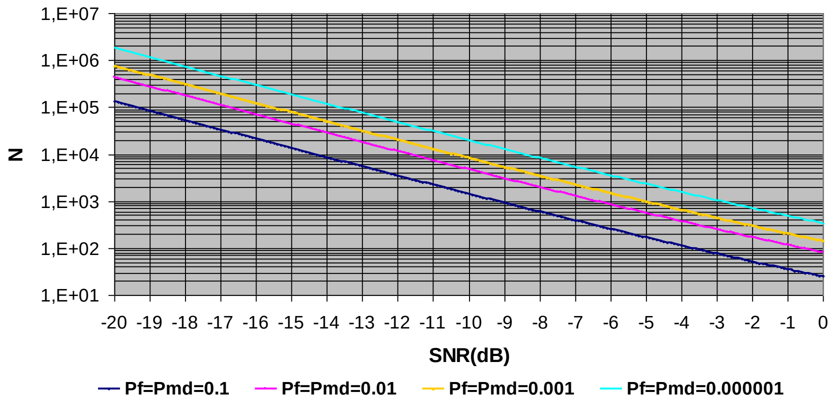

Fig. 2 The necessary number of samples (N) when energy detector is applied as a function of signal-to-noise (SNR) ratio without noise uncertainty for different values $P_{md}=P_f$.

One additional important parameter in energy detection systems analysis is miss in detection P_{md} (detector does not detect a signal although it exists). Probabilities P_d and P_{md} are connected by the equation

$$P_{md} = 1 - P_d \tag{7}$$

Fig. 2 presents the necessary number of samples (N) as a function of signal-to-noise ratio (SNR). The results are presented for equal values of P_f and P_{md}. There is no noise uncertainty which means that optimum detector threshold value exists independently of SNR. For small SNR signal detection is always possible, but the value of N significantly increases.

In our concrete implementation it is more important to achieve low value of P_{md} than to achieve low value of P_f. In other words, consequences of miss in detection are more severe (RCIED is activated because there is no jamming) than if the detection is false (only jamming signal is waste generated). That's why the results for probability values satisfying the condition $P_{md}<P_f$ are presented in Fig. 3.

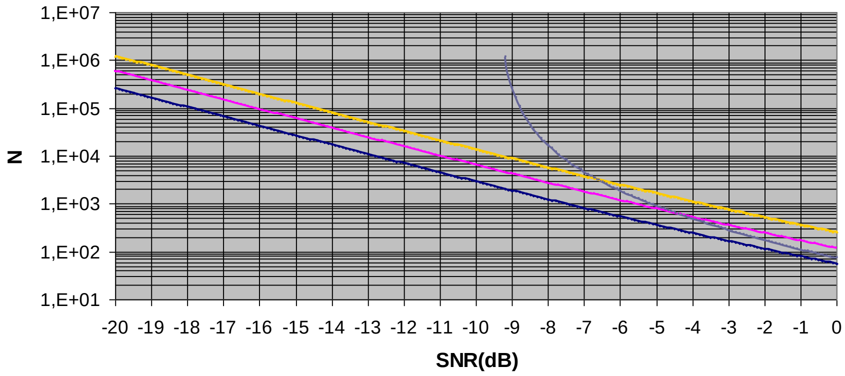

Fig. 3 The necessary number of samples (N) when energy detector is applied as a function of signal-to-noise (SNR) ratio without noise uncertainty for different values $P_{md}<P_f$.

Noise uncertainty is modelled in such a way that the value ρ-(1/ρ), where it is $\rho>1$, is subtracted from the value *SNR* in the denominator of equation (5). This means that noise power, instead of having power equal to σ^2 when noise is completely defined, now has the value of power between $(1/\rho)\cdot\sigma^2$ and $\rho\cdot\sigma^2$. *SNR*-wall is presented by the fourth graph in Fig. 3. Even for a very small noise uncertainty value ρ=0.25dB or ρ=1.059 when it is P_f=0.1 and P_{md}=0.01 the value of *N* tends to infinity for *SNR*~-9.3dB and below this value -9.3dB it is not possible to detect a signal. As a conclusion it may be said that it is very important to constantly monitor the noise level and to adjust threshold value according to instantaneous noise level and in this way to avoid *SNR*-wall appearance.

5. RCIED Activation Signal Detection by Matched Filter

The second often implemented technique of spectrum analysis is based on the method of matched filters. The main property of such filters is that they are optimum linear filters applied for signal detection in white Gaussian noise, meaning that maximum *SNR* is achieved by their implementation [32]. Although this property contributes to easier and faster signal detection, the drawback of matched filter implementation is that it is necessary to precisely know time characteristics of the signal which has to be detected. Such knowledge is possible in some implementation areas, as for example, in cognitive radio [32], [33]. But, if considering RCIED activation signal jamming, there is a great variety of possible and, in the same time, unpredictable activation techniques. They usually depend on the devices which may be easily purchased in some country (region) and easily adapted for its malicious function. The number of applied solution types is not great in the analysis presented in [34] with the dominant implementation of one type, thus simplifying and limiting the necessary number of different matched filters. Nevertheless, application of matched filters is not quite suitable for RCIED activation signal detection and the analysis of this method has more theoretical than practical significance.

Similarly to the analysis of energy detector, the necessary number of samples to achieve the desired probability of false alarm and probability of successful signal detection may be determined on the base of equation from [27]:

$$N = \frac{(Q^{-1}(P_f) - Q^{-1}(P_d))^2}{SNR} \tag{8}$$

Fig. 4 presents the necessary number of samples (*N*) as a function of signal-to-noise ratio (*SNR*) when matched filter is implemented. The results are obtained by equation (8) and are presented for equal values of P_f and P_{md}. After that, Fig. 5 presents the corresponding results if $P_{md}<P_f$. It is necessary to collect and analyze lower number of samples to achieve the same values P_f and P_{md} as when energy detector is implemented. This is noticeable if graphs from Figs. 2 and 4, as well as graphs from Figs. 3 and 5 are mutually compared.

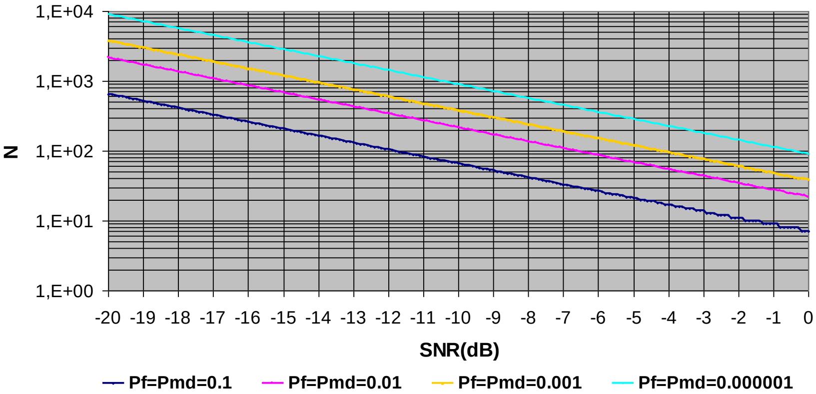

Fig. 4 The necessary number of samples (*N*) when matched filter is applied as a function of signal-to-noise (*SNR*) ratio for different values $P_{md} = P_f$.

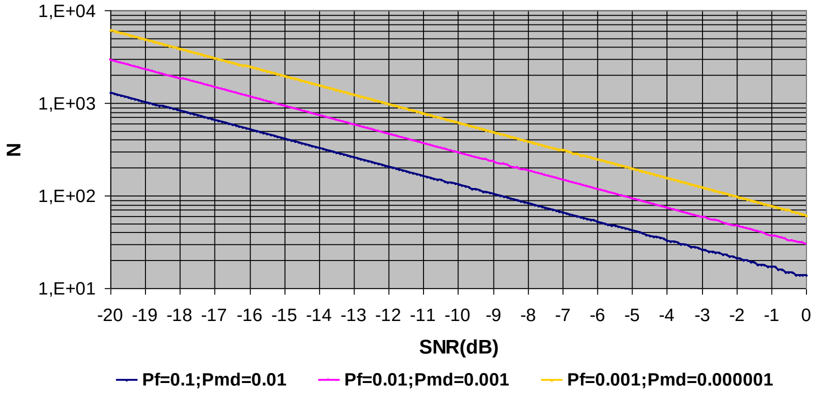

Fig. 5 The necessary number of samples (*N*) when matched filter is applied as a function of signal-to-noise (*SNR*) for different values $P_{md} < P_f$.

6. Active Jamming Using Frequency Sweep

Frequency sweep is often used method of active jamming. It is necessary to linearly change signal frequency step by step from its minimum value (*f1*) to the maximum one (*f2*) in order to realize a sweep. It is a readily implemented jamming method, because a significantly smaller power is necessary in relation to wideband jamming based on Additive White Gaussian Noise (*AWGN*) [17] - [19]. Linear frequency change of jamming signal frequency is practically approximated by a stepwise change, as it is presented in Fig. 6. There are two parameters, besides outmost sweep signal frequencies *f1* and *f2*, which model signal frequency change: frequency change step (f_Δ) and each step time interval duration while the same signal frequency is generated (T_Δ).

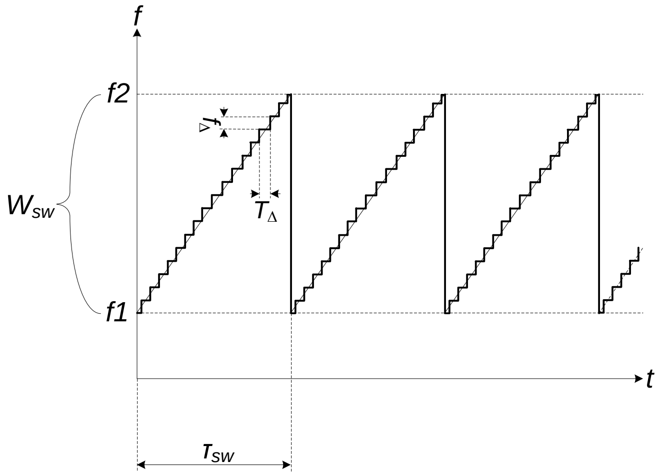

Fig. 6 Practical implementation of frequency sweep in the RCIED activation message active jamming.

The total step number in jamming realization may be represented by an equation:

$$N = \frac{f2 - f1}{f_\Delta} \tag{9}$$

while the duration of one total sweep cycle may be represented as:

$$T_{sw} = N \cdot T_\Delta = \frac{f2 - f1}{f_\Delta} \cdot T_\Delta \tag{10}$$

7. Comparison of the Active and Responsive FFT Jamming Reliability

The starting data in our analysis will be the required time to realize sweep jamming of RCIED activation signal under the condition that at least once jamming signal frequency and RCIED activation message frequency are approximately equal. After that we shall determine the total time from the beginning of the analyzed signal sample acquisition including FFT calculation time until the start of jamming signal emission on the detected RCIED activation signal frequency. In order to achieve comparison requirements of these two results, we shall suppose that the number of steps in sweep procedure (*N*) is equal to the number of points where the analyzed signal spectrum is estimated (*n*).

There is a number of D/A converters, which may be implemented for jamming signal generation. One typical example may be found in [35]. This D/A converter is used in our jammer solution [16]. It generates analog signal from the samples, whose maximum frequency is pretty high (f_s=3.5GHz), thus enabling maximum generated signal frequency f_g=1.4GHz.

Let us suppose that RCIED activation jamming is realized by jamming signal generation in a frequency band between *f1*=20MHz and *f2*≈1.33GHz. We shall further define the frequency change step f_{Δ}=20kHz, and the frequency sweep step duration T_{Δ}=200ns (very short time, a greater time is used in a practical realization - T_{Δ}=1μs or more [16]). On the base of (9) we obtain the number of steps in a sweep procedure realization *N*=65536=64K, and on the base of (10) sweep procedure duration is T_{sw}≈13.1ms.

Let us now have a device for responsive jamming, which collects the analyzed signal samples (performs A/D conversion) at the same frequency f_s=3.5GHz as the frequency of samples for D/A converter [36]. Number of samples that need to be collected, and consequently obtained number of the analyzed signal discrete frequency components is the same as the number of sweep steps (*n*=65536=64K). In this way it is achieved that the accuracy of jamming signal frequency *df* according to (2) is the same as the step of sweep signal frequency change f_{Δ} according to (9). In the case of responsive jamming, the signal sample acquisition time from (1) will be *T*≈18.7μs, while on the basis of Table 1 the FFT calculation time is T_{cal}=251.7μs. According to our adopted approximation it is also T_{comp}=251.7μs. Taking into account these three values, the total analysis time on the basis of (3) is T_{an}=522.1μs.

Comparing two time intervals which are the main indicators of active and responsive jamming reliability (T_{sw} and T_{an}), it is concluded that responsive jamming on the basis of FFT implementation is significantly more reliable (in our example ≈25 times) than active jamming by frequency sweep. One additional element which is an advantage of responsive jamming is the fact that after the analysis process (T_{an}) jamming may be performed only on the detected activation signal frequency with no time limit. In the case of active jamming, signal frequency is only during a short time period T_{Δ} approximately equal to the activation signal frequency. Therefore, due to greater jamming time it is also higher the probability that jamming is successful when responsive jamming is implemented.

Fig. 7 presents the results of reliability comparison of responsive jamming based on FFT analysis according to data from [24] in relation to active jamming based on frequency sweep. When active jamming is considered, jamming time on each frequency is adopted to be 200ns. Two extreme cases are chosen for responsive jamming: a) the first one, which allows maximum analysis speed (maximum specified processor clock

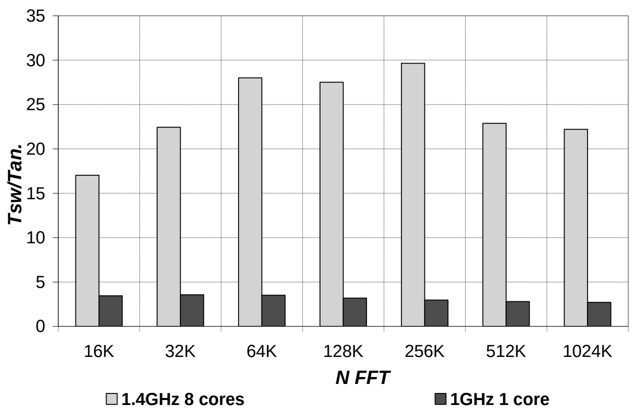

Fig. 7 The reliability of responsive jamming on the FFT basis according to [24] in relation to active frequency sweep jamming.

frequency 1.4GHz and maximum number of processor cores – 8) and b) the second one, which corresponds to the minimum analysis speed (minimum processor clock frequency 1GHz and minimum number of processor cores – 1). The required number of processor cycles for FFT calculation as a function of the number of FFT points is taken according to Table 1 from [24]. After that, it is determined the necessary time for FFT analysis in some cases. The graph in Fig. 7 indicates higher reliability of responsive jamming on the base of FFT in relation to active jamming using frequency sweep in all jamming conditions, because the calculated relation of jamming reliability is always between two extreme cases presented in Fig. 7 (i.e. this relation is always greater than 1).

Fig. 8 presents the results of reliability comparison of responsive jamming based on FFT analysis according to data from [21] in relation to active jamming based on frequency sweep. The processor implemented for FFT calculation operates on lower frequencies (between 60MHz and 150MHz) [26] than in the example from Fig. 7. That's why it is adopted that analyzed signal sampling is realized on a significantly lower frequency (800MHz) than in the example in Fig. 7. This further means that jamming is realized in this case for lower frequencies (till 320MHz).

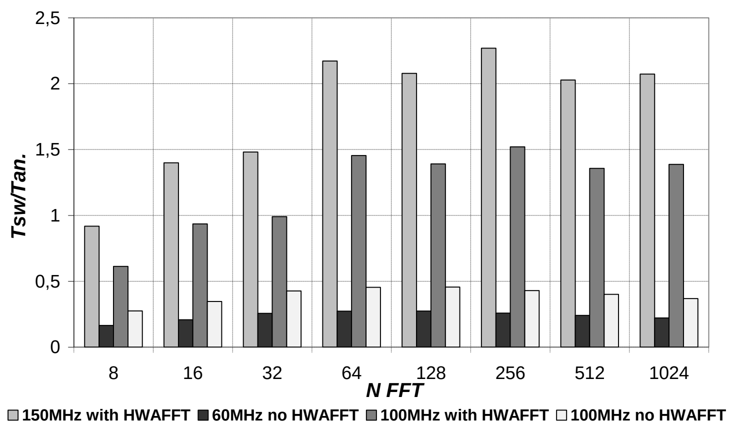

Fig. 8 The reliability of responsive jamming on the FFT basis according to [21] in relation to active frequency sweep jamming.

The results in Fig. 8 are presented separately in the case that HWAFFT is used for an analysis and when it is avoided. The maximum processing rate in this case is achieved if HWAFFT is used together with maximum processor clock frequency (150MHz), while the minimum processing rate is if HWAFFT is not used and the processor clock frequency is minimum (60MHz). These results are presented by first two vertical graphs for each number of frequencies in FFT analysis. Besides these two graphs, the results for mean processor clock frequency (100MHz) are presented when HWAFFT is used and when it is not used. The required number of processor cycles to calculate FFT for some number of points in FFT analysis is determined on the base of Table 3, i.e. Table 4 from [21].

Using the analysis the results in Fig. 8 it can be concluded that the application of HWAFFT allows also in this case that responsive jamming using FFT may be more reliable than the active jamming by frequency sweep (except for the smallest number of analyzed frequencies – 8, which is unlikely to occur in practice). On the contrary, if HWAFFT is not used, responsive jamming reliability using FFT becomes lower than the reliability of frequency sweep jamming (because the relation $T_{sw}/T_{an}<1$). For the mean processor clock frequency (100MHz) and with the HWAFFT implementation for the smaller number of points in the analysis, frequency sweep implementation is more reliable, while for the greater number of points the analysis on the base of FFT is better.

8. PERFORMANCES OF ENERGY DETECTOR AND MATCHED FILTER DETECTOR ON THE BASE OF MAIN FFT PARAMETERS

In our further analysis we are going to investigate achievable performances of energy detector and matched filter detector on the base of 64K collected (analyzed) signal samples, as in the case of FFT analysis. In this way analysis procedure duration is comparable for these two methods. The time of sample collection is exactly the same as we suppose the same sampling rate in two presented cases.

Fig. 9 presents the simplified timing diagram of a jammer realized on the base of energy detector. The value *SNR* is relatively low when the whole available frequency bandwidth is analyzed at once, such that the necessary number of samples (*N*) for the analysis is higher than 64K. That's why the complete frequency bandwidth of the analyzed system is separated into *n* distinguished blocks, meaning that bandpass filtering (BPF) is the first step at each of *n* executed block inputs for energy detection (ED). At the output of each block is comparator (COMP) and after that (in the block DECISION) is determined whether RCIED activation signal is present. The principle structure is the same if energy detector is replaced by matched filter (MF), except that designations ED1...EDn in Fig. 9 have to be replaced by MF1...MFn. There are two algorithm execution possibilities: 1. sequential processing in each of *n* blocks (Fig. 9a)); 2. parallel processing in *n* blocks when considering the elapsed time (Fig. 9b)). Of course, the combination of these two structures is also possible, but this time scenario is beyond the scope of our analysis. If the white noise power in the whole available frequency bandwidth is designated by σ_v^2, the power at the output of each of *n* bandpass filters is σ_v^2/n, because white noise frequency spectrum is considered to be uniform and it is split into *n* equal frequency portions. It means that *SN*R in the energy detector where RCIED activation signal appears is *n* times higher than without spectrum separation.

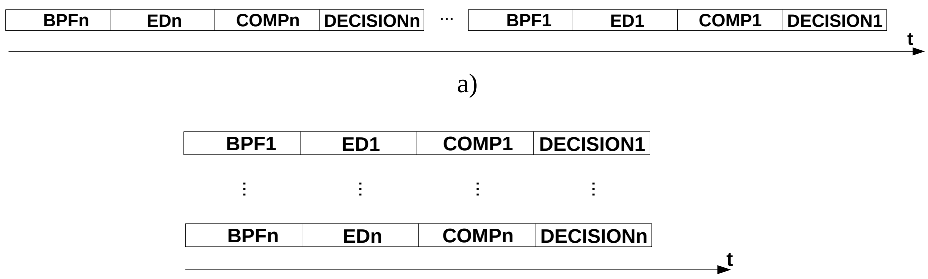

Fig. 9 The timing diagram of the energy detector based jammer: a) sequential processing; b) parallel processing

Fig. 10 presents the total number of analyzed samples (*N*) to successively perform energy detection as a function of the number of blocks (frequency spectrum parts) *n* when *SNR*=-20dB for the whole frequency bandwidth in the case that sequential processing is applied as in Fig. 9a). The total number of collected samples is determined as a product of the number of sequentially realized blocks and the necessary number of samples for each block to achieve the noise power σ_v^2/n. The results are presented for three pairs of values P_f and P_{md} when there is no noise power uncertainty and for one of these parameter pairs when the value of noise power uncertainty is ρ=0.25dB. We want to have 64K analyzed samples as in the case of FFT based detection and we may determine the necessary number of sequential blocks for different P_f and P_{md}. For example, when it is P_f=0.1 and P_{md}=0.01, it is enough to have *n*=5 sequential blocks when there is no noise power uncertainty. This value increases to even *n*=24 when noise power uncertainty is only ρ=0.25dB. It is expected that such a low ρ is very rare, because there are usually a lot of different signals besides white noise in the wireless system surrounding.

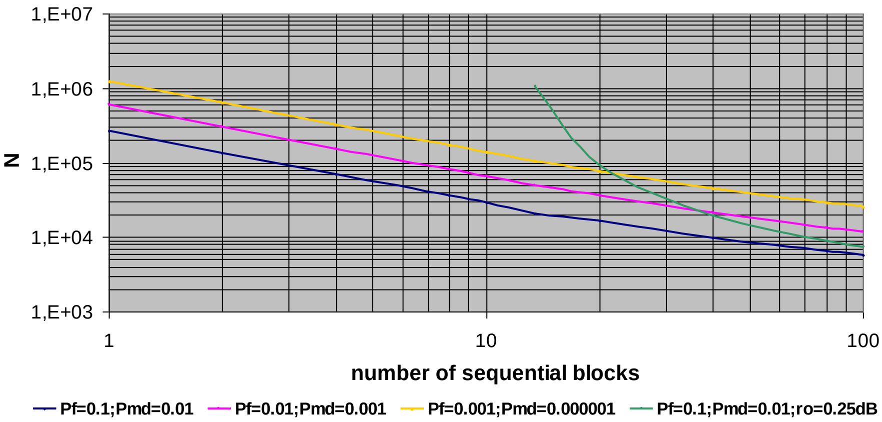

Fig. 10 The necessary number of analyzed samples (*N*) as a function of the number of analysis blocks in the case of energy detector implementation when *SNR*=-20dB for the whole frequency bandwidth when sequential processing is used.

Fig. 11 presents the total number of analyzed samples (*N*) to perform energy detection as a function of the number of blocks (frequency spectrum parts) *n* when *SNR*=-20dB for the whole frequency bandwidth in the case that parallel processing is applied as in Fig. 9b). The parameters on this figure are the same as for Fig. 10. If there is no noise power uncertainty, it is enough to have only 2 parallel blocks and to collect about 64K samples when it is P_f=0.1 and P_{md}=0.01. With the noise power uncertainty we ought to have 14 blocks.

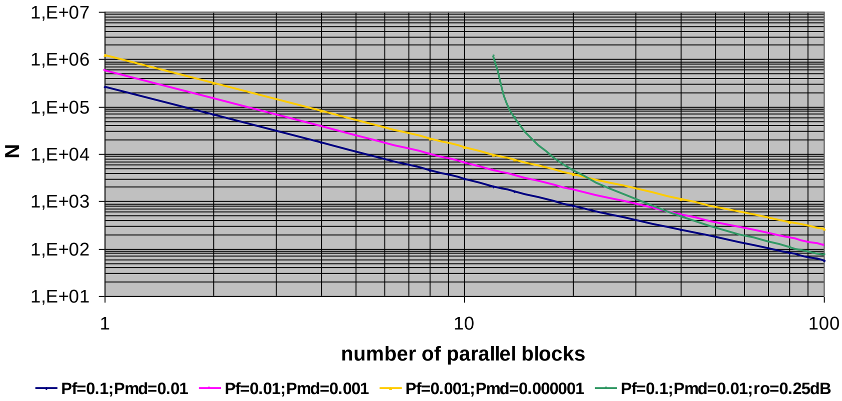

Fig. 11 The necessary number of analyzed samples (*N*) as a function of the number of analysis blocks in the case of energy detector implementation when *SNR*=-20dB for the whole frequency bandwidth when parallel processing is used.

Fig. 12 presents the total number of analyzed samples (*N*) to perform matched filter detection as a function of the number of blocks (frequency spectrum parts) *n* when *SNR*=-40dB for the whole frequency bandwidth in the case that sequential processing is applied as in Fig. 9a). The conditions for the graphical presentation are the same as in Fig. 10. In this case the number of necessary points for the analysis is independent of the number of applied sequential blocks. Such behaviour is the consequence of the fact that *SNR* is linear factor in the denominator of equation (8). It means that algorithm characteristics may not be improved by sequential processing for matched filter implementation. Opposite to this, *SNR* appears as the quadratic factor in the denominator of equation (5) for energy detector. Also *SNR* appears under the square root of the numerator in the same equation. Such complex dependence causes decreasing of the number of necessary samples when the number of analysis blocks increase in the case of energy detector implementation.

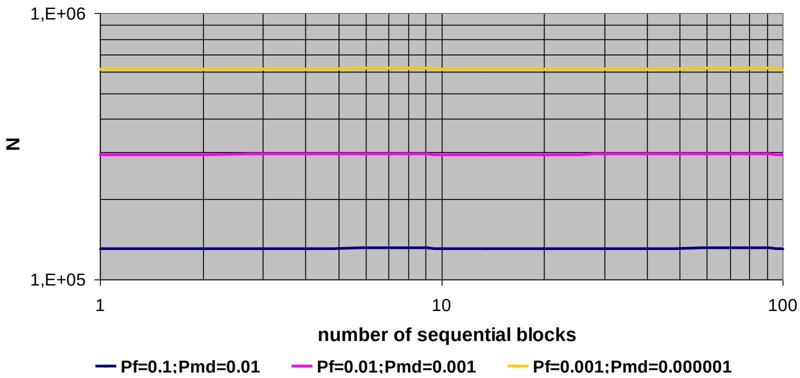

Fig. 12 The necessary number of analyzed samples (*N*) as a function of the number of analysis blocks in the case of matched filter detector implementation when *SNR*= -40dB for the whole frequency bandwidth when sequential processing is used.

Fig. 13 presents the total number of analyzed samples (*N*) to perform matched filter detection as a function of the number of blocks (frequency spectrum parts) *n* when *SNR*=-40dB for the whole frequency bandwidth in the case that parallel processing is applied as in Fig. 9b). The results are presented for hundred times worse value of *SNR* than in the case of energy detector consideration. This is one more proof of the better matched filter performances comparing to energy detector.

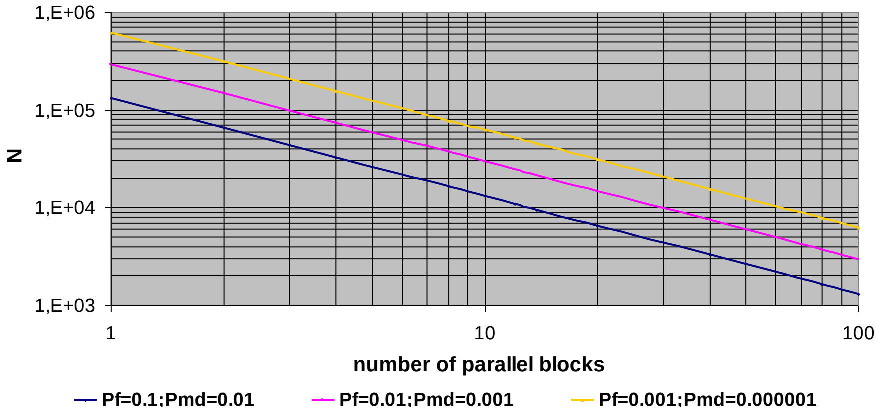

Fig. 13 The necessary number of analyzed samples (*N*) as a function of the number of analysis blocks in the case of matched filter detector implementation when *SNR*= -40dB for the whole frequency bandwidth when parallel processing is used.

Energy detector or matched filter detector as the base of RCIED activation jammer are more suitable in the case when there is necessary to intercept only a frequency spectrum part. In such a case the number of sequential or parallel blocks on the block-schema from Fig. 9 is decreased as a consequence of increased *SNR*, making a solution practically realisable. This situation is presented in [34], where it is demonstrated that even in the area of significant military war activities, there is not too high number of implemented RCIED activation solution types. Therefore, if energy detector or matched filter detector supervises the wideband signal, the number of spectrum parts to which the whole frequency bandwidth is separated is relatively low (not more than 100 according to figures 10-13). As a consequence, each frequency part for detection is relatively wide and it may be efficiently jammed only by frequency limited noise (barrage) jamming. Opposite, FFT gives a lot of points where frequency spectrum is estimated (64K in the example in Section 7). That’s why jamming may be realized on one or more precisely defined frequencies implementing pure sinusoid (spot) jamming.

The pipeline processing is one possibility to several times increase the analysis rate without significantly increasing hardware size. This possibility may be considered first of all when FFT method is applied, but also when energy detector or matched filter detector are considered. The principle details about pipeline processing in RCIED detection are found in [1], [37].

8. Conclusions

The results of the calculation presented in this paper have proved that responsive jamming may be more reliable than active jamming. This is the first paper contribution. The required time for secure jamming signal generation on the frequency of RCIED activation message is analyzed as a criterion of jamming reliability. As the result of complete analysis based on FFT, the frequency of RCIED activation signal is obtained, and jamming on the exactly determined frequency may be initiated. The results are compared for two processors, which are specialized for FFT calculation. One of these two processors provide that responsive jamming based on FFT implementation is more reliable than active jamming using frequency sweep. In this case analysis rate is several times, and even up to several tens of times higher when FFT is implemented in the analysis in relation to the frequency sweep rate. For the second analyzed processor reliability of responsive jamming depends on processor hardware characteristics such as the processor clock frequency and whether hardware accelerator (HWAFFT) is applied. If HWAFFT is included in the analysis with the higher processor clock frequency, jamming based on FFT analysis is certainly more reliable. On the contrary, if HWAFFT is not used with the lower processor clock frequency, the speed of FFT analysis may not approach jamming speed realized by frequency sweep.

The second paper contribution is related to the possibilities of energy detector and matched filter detector implementation for RCIED activation responsive jamming. It is proved that these jamming types are more suitable for jamming of narrower frequency bands, because frequency spectrum is estimated in significantly lower number of points than it is the case with FFT analysis. The additional problem for energy detector and matched filter detector implementation is a priori unknown shape of RCIED activation signal and noise power level. To overcome these problems, these two detectors require collecting relatively high number of signal samples. It is explained how this number of samples may be reduced while considering the desired probabilities of false detection and miss of detection, as well as analysis rate (number of collected samples).

It can be summarized that the results of comparative analysis presented in this paper prove that at up-to-date technological development level, RCIED activation responsive jamming may be very reliable and very often even more reliable than active jamming, especially when FFT analysis is considered.

This paper is the extended and enhanced version of the contribution [1]. Comparing to [1], completely new sections are 2, 4, 5 and 8. Section 2 presents the principle block-schema of the analyzed solutions to simplify readers following the text as two new methods are described in the paper. These two new methods are introduced in Sections 4 and 5. The priority in the analysis is given to the determination of necessary number of samples to achieve comparable timing performances to the RCIED activation signal detector realized by FFT. The main new results for practical jammer realization are in the Section 8, where it is analyzed how to choose the most important jammer specification parameters: the necessary number of collected samples and the number of sequential or parallel blocks to achieve the desired jammer characteristics.

Acknowledgement: *The paper is realized in the framework of the project TR32051, which is cofinanced by Ministry of Education, Science and Technological Development of the Republic of Serbia, 2011-2019.*

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