Performances of RCIED Activation Signal Multisweep Jamming

Aleksandar Lebl, Vladimir Kosjer, Jovan Radivojević and Mladen Mileusnić

***Abstract*— In this paper we present the characteristics of RCIED activation message signal multisweep jamming. Mathematical analysis is developed for MPSK modulated signals jamming. The first contribution of the paper is that analytical expressions for *BER* calculation are developed for the whole set of amplitude ratios of RCIED activation signal to the jamming signal. The characteristics of multisweep jamming are compared to the characteristics of pure sweep jamming. The second important paper contribution is the proof that multisweep jamming implementation increases jamming reliability while in the same time decreases necessary jamming power comparing to pure sweep jamming.**

***Index Terms*— RCIED - remote controlled improvised explosive devices; MPSK modulated signal; pure sweep jamming; multisweep jamming; jamming signal power.**

I. INTRODUCTION

Security threats related to different explosive devices activating prevention constantly grow in importance. Among these threats remote controlled improvised explosive devices (RCIEDs) have the special place. Such threats are not important only in war regions, but also in the peacetime [1], [2]. The wide scope of literature related to RCIED activation prevention is presented in References [3]-[13]. The dominant technique for prevention of remote activation of improvised explosive devices is sweep jamming and it is applied to practically all available jammer solutions, like in [14]-[18]. Sweep jamming is also used in IRITEL jammer solutions [19]-[20]. Sweep jamming is popular because of its reduced emission power comparing to its alternative – barrage (or noise) jamming [21]. The problem may arise when sweep jamming is applied to the case of short RCIED activation message duration. In such a case sweep jamming rate may not be sufficient to assure coincidence of sweep signal and activation message frequencies at least once during a short time interval [22], [23]. Combined jamming (sweep and barrage in the same time) is one way to mitigate this problem, but the most important benefit of combined over pure sweep jamming is to increase jamming possibility for several dBs when RCIED activation message signal level is comparable to jamming signal level [24]. One possible method to overcome the problem of unsufficiently high sweep rate is the use of multisweep jamming [25]. Multisweep jamming implies to cover a number of narrower frequency bands in one sweep cycle at a time in comparison to pure sweep jamming where only one wider frequency band is covered in one moment. In the Section II we present the elements for a method to calculate Bit Error Rate (*BER*) when sweep jamming is applied. The mean number of incorrectly transmitted bits in a symbol is determined as described in the Section III. Section IV presents modifications in the method for *BER* calculation when multisweep jamming is implemented instead of pure sweep jamming. The *BER* graphs for different phase modulated (PSK) signals are presented in the Section V. Implementation of multisweep jamming leads to jamming signal power save and this is illustrated by two examples also in the Section V. At the end, paper conclusions are in the Section VI.

II. METHOD FOR *BER* CALCULATION WHEN PURE SWEEP JAMMING IS USED

The *BER* calculation in this paper is performed for MPSK modulated RCIED activation signal. Specifically, the results are obtained for the cases when QPSK, 8PSK and 16PSK are applied. This means that each symbol in MPSK signal represents 2, 3 or 4 bits, respectively. The starting point in our analysis is the algorithm developed in [26], [27] and this algorithm is completed to cover all possible values of RCIED activation signal amplitude (A) to the jamming signal amplitude (B) ratio. The analysis in [26] and [27] covered only the ratio range $A/B\leq 1$ and now we consider also the range $A/B>1$.

A. *Analysis for A/B>1*

Let us suppose that RCIED activation signal is sinusoidal. It may be represented by a phasor whose intensity is A in Figure 1. The pure sweep jamming signal is also sinusoid with intensity B and it is represented in the Figure 1 at the moment when its frequency during sweeping is approximately the same as the frequency of RCIED activation signal. The end of the phasor B is on the circle with the centre in the point Q with radius B depending on the phase ratio between RCIED activation signal and jamming signal. Phasor diagram with vectors A and B is presented together with the constellation diagram for M-ary PSK (the corresponding value in Figure 1 is M=16).

The analysis according to Figure 1 is valid for $A/B>1$. The *BER* value calculation depends on the values of A/B ratio within this area $A/B>1$.

Let us start from the highest value of A/B ratio, i.e. from the lowest jamming signal levels. If the jamming signal amplitude

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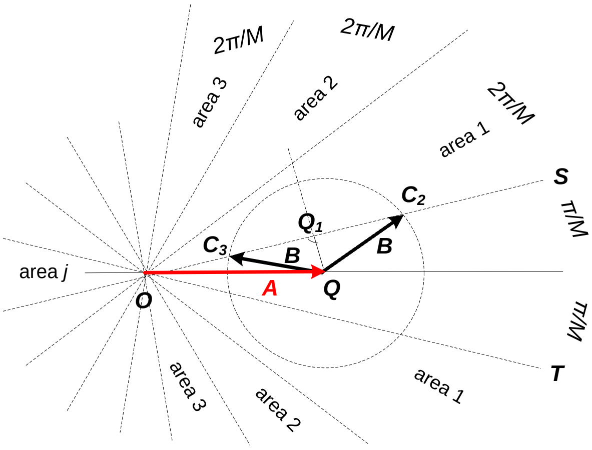
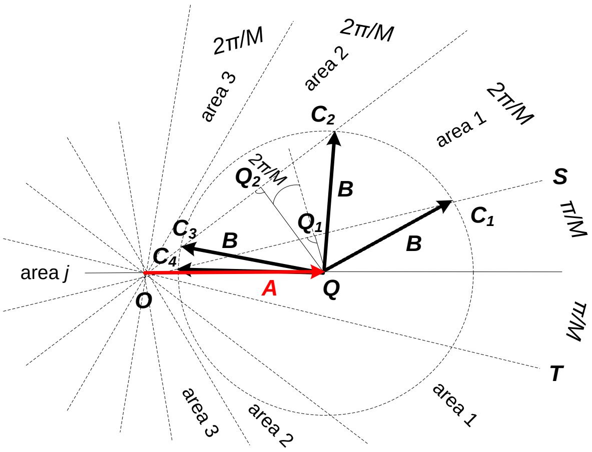
is $B<QQ1$, i.e. $B<A\cdot\sin(\pi/M)$, the end of phasor B is in any case within the angle SOT, meaning that there is no bit errors ($BER=0$). In this case jamming is never successful.

The following possibility is that the jamming signal amplitude satisfies the condition $A\cdot\sin(\pi/M)<B<A\cdot\sin(3\cdot\pi/M)$ where it is $QQ_1=A\cdot\sin(\pi/M)$ (Figure 1a)). In the case that the end of B phasor is in the angle SOT, jamming is unsuccessful (no bit errors). When the B phasor end is in the adjacent area to the SOT angle (on the arc C_2C_3 in area 1), jamming becomes successful. Supposing that phase angle (<) between RCIED activation signal and jamming signal is uniformly distributed in the area $(0,\ 2\cdot\pi)$, the probability that the B phasor end is in this area equals:

$$P_{C_2C_3} = \frac{<C_2QC_3}{\pi} = \frac{2}{\pi}\cdot\arccos\frac{QQ_1}{QC_2} = \frac{2}{\pi}\cdot\arccos\frac{A\cdot\sin\frac{\pi}{M}}{B} \qquad (1)$$



a)



b)

Figure 1 – Phasor and constellation diagram for MPSK signal jamming when signal amplitude ratio is $A/B>1$: a) for $A\cdot\sin(\pi/M)<B<A\cdot\sin(3\cdot\pi/M)$; b) for $A\cdot\sin(3\cdot\pi/M)<B<A\cdot\sin(5\cdot\pi/M)$

If the jamming signal amplitude is further increased ($A\cdot\sin(3\cdot\pi/M)<B<A\cdot\sin(5\cdot\pi/M)$), the B phasor end may be also in the next one to the adjacent area (area 2 in the Figure 1b)). Jamming signal B phasor end is in the adjacent area when it is on the arc C_1C_2 or on the arc C_3C_4 (in the area 1). The probability that B phasor end is on the arc C_1C_2 is

$$\begin{aligned} P_{C_1C_2} &= \frac{<C_1QC_2}{\pi} = \frac{<C_1QQ_2-<C_2QQ_2}{\pi} = \\ &= \frac{<C_1QQ_1+<Q_1QQ_2-<C_2QQ_2}{\pi} = \\ &= \frac{1}{\pi}\cdot\left(\arccos\frac{QQ_1}{QC_1}+\frac{2\cdot\pi}{M}-\arccos\frac{QQ_2}{QC_2}\right) = \\ &= \frac{1}{\pi}\cdot\left(\arccos\frac{A\cdot\sin\frac{\pi}{M}}{B}-\arccos\frac{A\cdot\sin\frac{3\cdot\pi}{M}}{B}\right)+\frac{2}{M} \end{aligned} \qquad (2)$$

and the probability that it is on the arc C_3C_4 is

$$\begin{aligned} P_{C_3C_4} &= \frac{<C_3QC_4}{\pi} = \frac{<C_4QQ_1-<C_3QQ_1}{\pi} = \\ &= \frac{<C_4QQ_1-(<C_3QQ_2+<Q_2QQ_1)}{\pi} = \\ &= \frac{1}{\pi}\cdot\left(\arccos\frac{QQ_1}{QC_4}-\arccos\frac{QQ_2}{QC_3}-\frac{2\cdot\pi}{M}\right) = \\ &= \frac{1}{\pi}\cdot\left(\arccos\frac{A\cdot\sin\frac{\pi}{M}}{B}-\arccos\frac{A\cdot\sin\frac{3\cdot\pi}{M}}{B}\right)-\frac{2}{M} \end{aligned} \qquad (3)$$

Total probability that phasor B end is in the adjacent area (area 1) is the sum of probabilities that it is on the arc C_1C_2 and on the arc C_3C_4, i.e.:

$$\begin{aligned} P_1 &= P_{C_1C_2}+P_{C_3C_4} = \\ &= \frac{2}{\pi}\cdot\left(\arccos\frac{A\cdot\sin\frac{\pi}{M}}{B}-\arccos\frac{A\cdot\sin\frac{3\cdot\pi}{M}}{B}\right) \end{aligned} \qquad (4)$$

Phasor B end is in the area 2 when it is on the arc C_2C_3. The probability of this event is calculated as:

$$P_{C_2C_3} = \frac{<C_2QC_3}{\pi} = \frac{2}{\pi}\cdot\arccos\frac{QQ_2}{QC_2} = \frac{2}{\pi}\cdot\arccos\frac{A\cdot\sin\frac{3\cdot\pi}{M}}{B} \qquad (5)$$

For a general case, let us suppose that area j is the most distant area of the vector B end in relation to vector A area and that 1 is the adjacent area. The probability that vector B end is in the area j may be expressed as:

$$P_j = \frac{2}{\pi}\cdot\arccos\frac{A\cdot\sin\frac{(2\cdot j-1)\cdot\pi}{M}}{B} \qquad (6)$$

The probability that *B* vector end is in some other less distant area *k* (where $1 \le k < j$) from vector *A* area is:

$$P_k = \frac{2}{\pi}\cdot\left(\begin{array}{l}\arccos\dfrac{A\cdot\sin\dfrac{(2\cdot k-1)\cdot\pi}{M}}{B}-\\ -\arccos\dfrac{A\cdot\sin\dfrac{(2\cdot k+1)\cdot\pi}{M}}{B}\end{array}\right) \qquad (7)$$

It is important to emphasize that jamming signal end may be in maximum $(M/2)+1$ areas when $A/B>1$.

B. Analysis for A/B<1

Figure 2 presents together phasor and constellation diagram for MPSK signal jamming in the case when amplitude of the jamming signal is greater than the RCIED activation signal amplitude ($A/B<1$) [26], [27]. In this case jamming signal end may be in all *M* areas. The probability that *B* phasor end is on some arc (for example C_1C_2) in the area *k* distant from the area of vector *A* may be determined in the same way as this probability is expressed by (2):

$$P_k = \frac{1}{\pi}\cdot\left(\begin{array}{l}\arccos\dfrac{A\cdot\sin\dfrac{(2\cdot k-1)\cdot\pi}{M}}{B}-\\ -\arccos\dfrac{A\cdot\sin\dfrac{(2\cdot k+1)\cdot\pi}{M}}{B}\end{array}\right)+\frac{2}{M} \qquad (8)$$

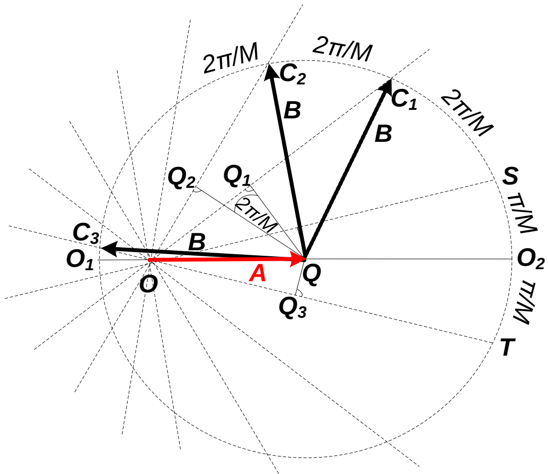


Figure 2 – Phasor and constellation diagram for MPSK signal jamming when signal amplitude ratio is *A*/*B*<1

This calculation procedure may be implemented for all coding areas except the last one (area *j*) which corresponds to the angle C_3QO_1. For this area, it is

$$P_j = \frac{\angle C_3QO}{\pi} = \frac{\angle C_3QQ_3 - \angle OQQ_3}{\pi} = \qquad (9)$$

$$= \frac{1}{\pi}\arccos\frac{A\cdot\sin\left(2\cdot\pi-\dfrac{\pi}{M}\right)}{B}-\left(\frac{1}{2}-\frac{1}{M}\right)$$

where the angle OQQ_3 is determined from the rectangular triangle OQQ_3 whose angle QOQ_3 is equal to π/M.

III. THE NUMBER OF ERRONEOUS BITS IN A SYMBOL

The following important element for our analysis is the mean number of incorrectly transmitted bits in a symbol for different surrounding coding areas (E_{mk}). It depends on the position of jamming signal vector end (i.e. how many areas it is distant from the position of RCIED activation signal vector). The values of this parameter are presented in the Table I for QPSK, 8PSK and 16PSK modulation according to the results from [26], [27]. In this table adjacent area to the area of RCIED activation signal position is designated as area 1 ($k=1$). The most distant area for QPSK signal is area 2 for QPSK modulated RCIED activation signal, area 4 for 8PSK and 8 for 16PSK.

TABLE I

Mean number of bit errors in a symbol (E_{mk}) when jamming is implemented for various RCIED activation signal modulation types

Modulation	Bits in symbol	Areas (*k*)							
		1	2	3	4	5	6	7	8
QPSK	2	1	2						
8PSK	3	1	2	2	2				
16PSK	4	1	2	2	2	2.5	3	2.5	2

The total number of incorrectly transmitted bits in a symbol of RCIED activation message is now determined considering probability that resultant vector is in each of surrounding coding areas (P_k) and the mean number of incorrectly transmitted bits (E_{mk}) for the considered area:

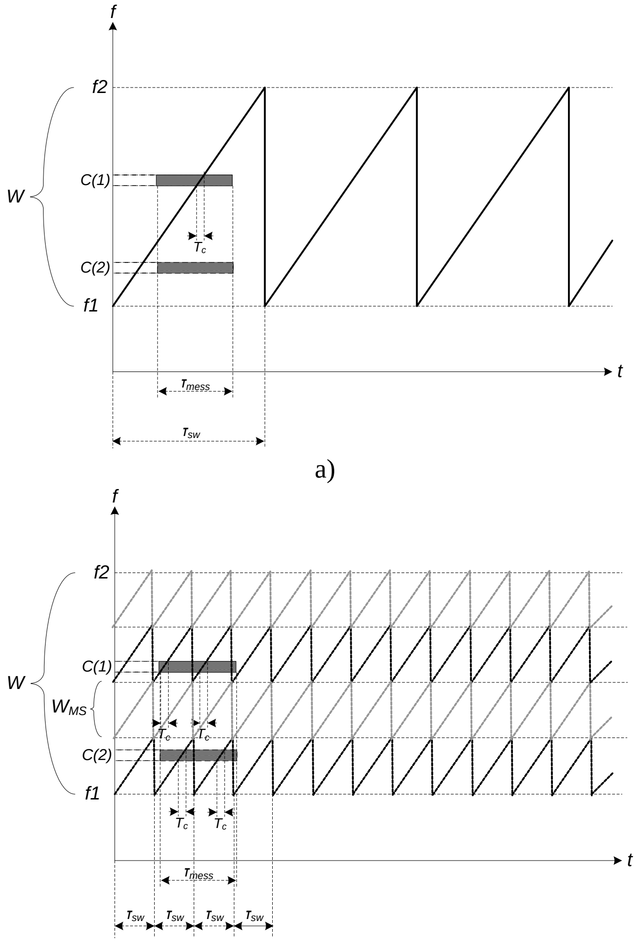
$$N_{EB} = \sum_{k=1}^{j} P_k \cdot E_{mk} \qquad (10)$$

Here *j* is the most distant coding area from the position of RCIED activation message signal vector as already stated. The value of *BER* for our further analysis is now calculated dividing the value in (10) by the number of bits forming a symbol or $\log_2 M$.

IV. INFLUENCE OF MULTISWEEP JAMMING ON *BER* CALCULATION

Figure 3 presents example of RCIED activation message signal jamming by pure sweep signal (Figure 3a)) and by multisweep signal (Figure 3b)). The presentation is in the field signal frequency as a function of time. The complete jamming frequency band is $f2-f1=W$. RCIED activation signal is in the frequency band *C(1)* and in *C(2)*. Message duration is T_{mess} and in the case of pure sweep jamming this duration is lower than the sweep period T_{sw}. As a consequence the message in the band *C(1)* may be successfully jammed (according to Figure 1a)), but the message in the band *C(2)* will not be jammed.

Multisweep jamming is realized in such way that frequency range *W* is divided into four equally wide parts (W_{MS}). Jamming is performed simultaneously in all four parts. In this case both RCIED activation message signals are successfully jammed during time intervals designated by T_c. Jamming is more reliable, because in this example both message signal frequencies coincide with the jamming signal frequency two times.



a)

b)

Figure 3 – RCIED activation message signal jamming by: a) pure sweep jamming; b) multisweep jamming

Let us suppose that K_{MS} is the number of different simultaneous sweep signals in a multisweep signal (K_{MS}=4 in the Figure 3b)). The frequency band which is swept equals

$$W_{MS} = \frac{W}{K_{MS}} \qquad (11)$$

for each one of sweep components in multisweep signal. On the base of (11) the sweeping period of multisweep signal (Figure 3b)) may be expressed as

$$T_{sw} = \frac{W_{MS}}{v_{sw}} = \frac{W}{v_{sw} \cdot K_{MS}} \qquad (12)$$

where v_{sw} is the speed of sweeping. Then the number of coincidences between frequency of RCIED activation message signal and the jamming signal frequency is

$$n = \left\lfloor \frac{T_{mess}}{T_{sw}} \right\rfloor = \left\lfloor \frac{T_{mess} \cdot v_{sw} \cdot K_{MS}}{W} \right\rfloor \qquad (13)$$

where $\lfloor \ \rfloor$ means rounding to lower integer value.

It is considered that a symbol in RCIED activation message may be incorrectly transmitted when there is coincidence between two signal frequencies. In such case the real *BER* is determined by the method explained by equations (1)-(9). To simplify our analysis, we suppose that only one symbol is altered during each coincidence event. This approximation is „on the safe side“, because alterations on more symbols lead to higher successful jamming probabilities. The total number of incorrectly transmitted bits may be determined as

$$N_{EBMS} = N_{EB} \cdot n \qquad (14)$$

V. *BER* RESULTS FOR VARIOUS MPSK SIGNALS

Figure 4 presents *BER* as a function of the RCIED activation message signal amplitude to the jamming signal amplitude ratio (*A*/*B*). The results are related to three modulation types of RCIED activation signal: QPSK, 8PSK and 16PSK. For the amplitudes ratio $A/B \leq 1$ ($A/B \leq 0$ in dB) the derived formulas are (8) and (9) and for the amplitudes ratio $A/B > 1$ ($A/B > 0$ in dB) the obtained formulas are (1) - (7). The breakpoint (which is at *A*/*B*=0.7dB for 8PSK modulated RCIED activation signal and at *A*/*B*=5.1dB for 16PSK signal), is the consequence of the fact that at these signal levels the mean number of erroneous bits in a symbol changes from one to two (or vice versa). In other words, at *A*/*B* ratios higher than the emphasized ones only one bit in a symbol may be in error and for lower ratios it is possible to have more than one erroneous bit in a symbol.

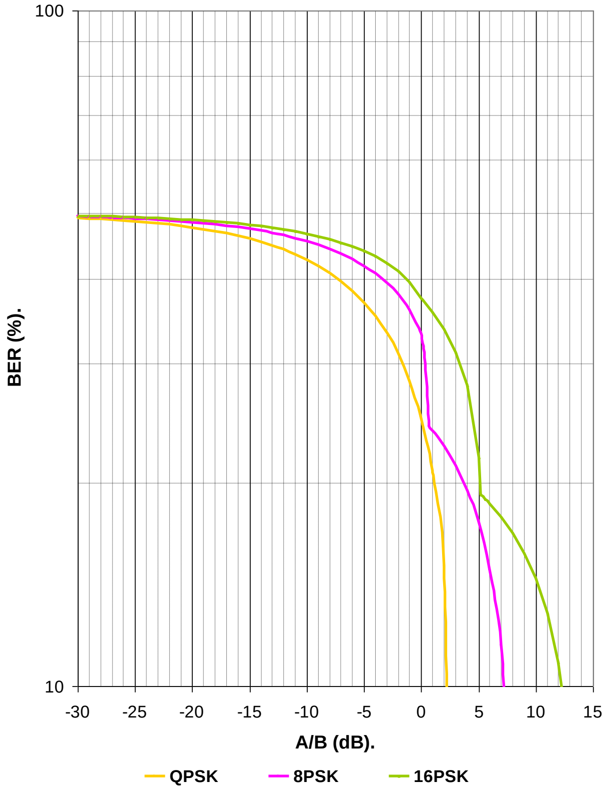


Figure 4 – *BER* as a function of amplitude ratio RCIED activation to the jamming signal for QPSK, 8PSK and 16PSK modulated RCIED activation message signals

Two practical examples related to the calculation applications and solutions will be given in further text.

Example 1: RCIED activation message is transmitted as 16PSK signal of T_{mess}=6ms duration. Jamming of this message is considered to be successful (RCIED is not activated) when at least 4 bits in its content are received incorrectly. What speed of sweeping and what jamming signal power are necessary to be applied to achieve such a result with pure sweep signal? In which way will jamming signal power be changed if pure sweep signal is replaced by multisweep signal with four simultaneous sweep signals at the same sweep speed?

Solution: Let us first suppose that it is necessary to achieve signal frequencies coincidence two times during the RCIED activation message lifecycle. In this way 2 symbols (or 8 bits as 16PSK is implemented) would be hit by jamming. As 4 bits have to be altered, *BER* value should be at least 0.5. This value of *BER* may not be achieved by limited jamming power according to the graph in the Figure 4. Two frequencies should be equal at least 3 times during the activation message, or sweep period should be 2ms or less according to (13). It means that the number of incorrectly transmitted bits per symbol should be 4/3=1.333 or *BER*=1.333/4=0.333. This value of *BER* is achieved when power ratio between RCIED activation signal and jamming signal is A/B=2dB according to the graph in Figure 4 for 16PSK signal.

When multisweep signal with 4 simultaneous sweep signals is implemented, frequencies of RCIED activation signal and sweep signal coincide 12 times as a consequence of (13) (48bits total are hit by jamming). The corresponding value of *BER*=4/48=0.0833. The value A/B=12.5dB may be determined again from the Figure 4. As there are 4 simultaneous signals of equal power in multisweep signal, the total power ratio is decreased for 6dB comparing to A/B (A/B_t=6.5dB). It means that multisweep signal implementation in this case caused power saving of 4.5dB.

Example 2: RCIED activation message is transmitted as 16PSK signal of T_{mess}=1ms duration. The sweep signal period is T_{sw}=2ms. Jamming of the activation message is considered to be successful (RCIED is not activated) when at least 3 bits in its content are received incorrectly. What jamming signal power is necessary to be applied to achieve such a result with pure sweep signal? How will jamming signal power change if pure sweep signal is replaced by multisweep signal with four simultaneous sweep signals at the same sweep speed?

Solution: In this case the possibility to realize jamming for pure sweep jamming is 0.5 because T_{mess}/T_{sw}=0.5. The goal to change the content of 3 bits may be only considered for 50% cases when frequencies coincidence exists. This coincidence happens only once during the message lifecycle. According to the graph in the Figure 4, *BER* values are always less than 0.5, so maximum 2 of 4 bits in 16PSK signal may be altered. The conclusion of this complete analysis is that the request to achieve 3 erroneous bits is never reached. On the contrary, the request may be always satisfied by multisweep jamming. According to (13), frequencies coincidence exists two times during the message lifecycle. It means that total 8 bits are hit by jamming and it should be *BER*=0.375 (3 of 8 erroneous bits). The defined goal is achieved when A/B=0dB according to the Figure 4. The total power for 4 simultaneous signals in multisweep signal is increased for 6dB meaning that A/B_t=-6dB. The conclusion of this example is that the goal, which couldn't be satisfied by pure sweep jamming, is realized by multisweep jamming with not so high jamming signal power.

VI. CONCLUSIONS

In this paper the characteristics of multisweep signal jamming are presented comparing to pure sweep jamming. The *BER* values are determined for the complete set of amplitude ratios RCIED activation signal level to the jamming signal level. Multisweep jamming implementation is specially justified in the case when RCIED activation message duration is comparable or lower than the pure sweep signal period. Multisweep jamming increases jamming reliability and decreases necessary jamming power for such signals timing relations. The conclusions are practically illustrated by two examples with the emphasis on the example 2 where jamming requests even may not be satisfied in any case by pure sweep jamming. It may be satisfied using multisweep jammig with not high signal power.

There are two different strategies for multisweep signal generation: linear frequency change from its minimum till maximum value which is analyzed in this paper and random frequency change while sweeping. Both these strategies are implemented in IRITEL jammer [19], [20]. This second strategy based on the earlier experience related to already implemented RCIED activation devices [7] may contribute to more reliable jamming. The subject of our future work will be analysis of random multisweep jamming and selection of optimum strategy for jamming frequency change. The special topic of interest could be application of multisweep jamming in the case of RCIED activation message signals transmission over mobile operators networks.

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