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Successful Sweep Jamming Rate Determination of MPSK Modulated RCIED Activation Message Signals

Aleksandar Lebl, Mladen Mileusnić, Predrag Petrović, Branislav Pavić, Verica Marinković-Nedelicki

Radiocommunications department,

IRITEL a.d.

Belgrade, Serbia

lebl@iritel.com, mladenmi@iritel.com, presa@iritel.com, bane@iritel.com, verica@iritel.com

Abstract— This paper presents the development of the method for accurate successful jamming rate calculation when MPSK modulated RCIED activation message is jammed using sweep signal. Opposite to classical methods of error modelling where it is taken that only one bit in a symbol may be altered, it is supposed in this paper that any number of bits in a symbol is the subject of eventual modification. The derived formulas are achieved for QPSK, 8PSK and 16PSK modulated signals jamming. The results calculated by these formulas are verified and obtained by our originally developed simulation method. The results of calculation and simulation agree very well and the maximum difference between calculated and simulated successful jamming rate for any of three analyzed jamming methods and any level ratio between activation message signal and jamming signal does not overcome 1.1%. It is proved that successful jamming rate tends to maximum value 0.5 when jamming signal power increases and that only 20% lower successful jamming rate value is obtained for less than 7dB higher jamming signal level than it is the level of RCIED activation signal. These results point out that it is not necessary to apply too high emission power to achieve acceptable jamming effect. As a consequence, jammer practical implementation is easier and its dimensions are smaller.

Keywords- sweep jamming; successful jamming rate; RCIED activation signal; jamming power; simulation method.

I. INTRODUCTION

Remote controlled improvised explosive devices (RCIEDs) become the great threat nowadays not only in war regions, but also in areas with normal everyday life. It is fascinating how relatively simple devices, realized by simple and cheap modifications of equipment, which may be found in the nearest, free shop, convert to dangerous weapon. Available devices for modifications to RCIEDs and their operation techniques are numerous and they are mutually very different one from the other. That's why the fight against such devices is very complicated and why the implemented jammers against RCIED activation are several times more expensive than the RCIED. As RCIED activation techniques are numerous, there is also a great variety of methods for fight against these hostile activities. Roughly speaking, there are two main types of jamming: active jamming and responsive jamming. The characteristic of the first one is that jamming signal is generated practically constantly, regardless of RCIED activation signal existence. When the second type of jamming is applied, jamming signal is generated only upon RCIED activation signal detection. Although in the first moment it may be concluded that active jamming is more reliable, it is proved

in [2] that responsive jamming may be often more reliable. Among the methods of active jamming, sweep jamming is probably the most popular one. It may be implemented independently or together with other jamming methods [3] - [7]. Application of sweep jamming is wider than just for RCIED activation jamming. It may be used for jamming hostile voice and data communications [8], [9] or for jamming communications over mobile telephony systems [10]-[12]. Although implemented in such great variety of jamming systems, the parameters of sweep jamming are rarely analyzed theoretically [13], [14]. Among these parameters, the authors haven't found the contribution dealing with the exact calculation of Successful Jamming Rate (*SJR*) (or, in other words, Bit Error Rate (*BER*)) for sweep jamming of MPSK modulated RCIED activation message signals. In the contribution [15] it was introduced the variable jamming rate (*JR*) as the relation of time interval when jamming signal generation to the total elapsed time. Here *SJR* is defined in the sense of *BER* [1] to better define this variable according to its real application. The results available in literature, intended to determine *BER* when MPSK signal is transmitted, are obtained for the situations when jamming signal level is lower than MPSK modulated signal level. In such a case the value of *BER* is relatively low. This is not applicable when jamming is realized. For successful jamming realization it is necessary that jamming signal level is (significantly) higher than RCIED activation message signal. We haven't found the analysis for

such signals relation.

II. SJR CALCULATION FOR SWEEP JAMMING OF MPSK MODULATED SIGNAL

The calculation of *BER* for various PSK modulated signal types (MPSK) is based on phasor analysis in the area of constellation diagram, which corresponds to the applied PSK modulation. Vectors in the phasor diagram represent RCIED activation signal and sweep jamming signal at the moment when the frequency of jamming signal is equal (or approximately equal) to the frequency of activation signal.

Fig. 1 is an illustration of the phasor diagram of activation signal (*A*) and sweep jamming signal (*B*). This phasor diagram is presented together with the constellation diagram of MPSK modulated signal. The diagram is shown for $M=16$, i.e. for 16PSK modulation, but the conclusions are general. When jamming of RCIED activation messages is considered, the main interest is focused on the amplitude ratio $B>A$ and such a case is analyzed in this paper and presented in Fig. 1.

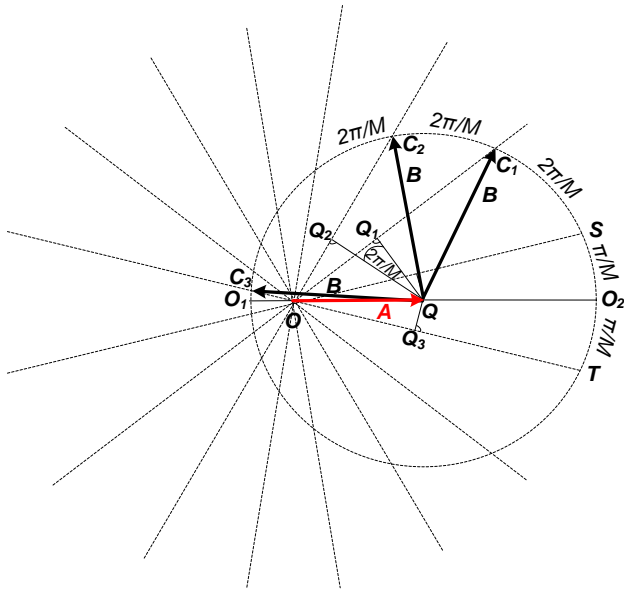


Figure 1. Phasor and constellation diagram for sweep jamming of 16PSK modulated activation message

The activation message vector is placed in the area of angle SOT in the constellation diagram. The value of this angle is $2\pi/M$, which is also equal to the value of all other angles in the constellation diagram corresponding to different coding combinations of MPSK signal. The borders between areas dedicated to different coding combinations are presented by dashed lines in Fig. 1.

The phase ratio between signals *A* and *B* may be arbitrary, meaning that the angle between *A* and *B* in Fig. 1 is anyone between 0 and 2π . As it is $B>A$, the resultant vector may be in any of M areas of the constellation diagram. The calculation for two semicircles from Fig. 1 is equal, so it is enough to perform the calculation for one semicircle, i.e. for the area between 0 and π .

Let us consider the sweep jamming signal phase corresponding to some arbitrary area j ($j=1, \dots, M/2$) between vectors QC_1 and QC_2 . In this case the resultant vector of vectors *A* and *B* is in the area of the angle C_1OC_2 , which is

equal to $2\pi/M$. The lines QQ_1 and QQ_2 are pulled to form rectangular triangles QQ_1C_1 and QQ_2C_2 . As a consequence, the angle Q_1QQ_2 is also equal to $2\pi/M$. The angle C_1QC_2 may be now calculated from

$$\begin{aligned} \angle C_1QC_2 &= \angle C_1QQ_2 - \angle C_2QQ_2 = \\ &= \angle C_1QQ_1 + \angle Q_1QQ_2 - \angle C_2QQ_2 = . \end{aligned} \quad (1)$$

$$= \arccos \frac{QQ_1}{QC_1} + \frac{2\pi}{M} - \arccos \frac{QQ_2}{QC_2}$$

The values of QQ_1 and QQ_2 may be calculated from rectangular triangles OQQ_1 and OQQ_2 . In these triangles the values of angles are

$$\angle Q_1OQ = \frac{(2 \cdot j - 1) \cdot \pi}{M}, \angle Q_2OQ = \frac{(2 \cdot j + 1) \cdot \pi}{M}. \quad (2)$$

Starting from the angles, determined by (2), the angle C_1QC_2 in (1) is

$$\begin{aligned} \angle C_1QC_2 &= \angle C_1QQ_2 - \angle C_2QQ_2 = \\ &= \arccos \frac{A \cdot \sin \frac{(2 \cdot j - 1) \cdot \pi}{M}}{B} + \frac{2\pi}{M} - \\ &\quad - \arccos \frac{A \cdot \sin \frac{(2 \cdot j + 1) \cdot \pi}{M}}{B} \end{aligned} \quad (3)$$

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

$$\begin{aligned} \angle C_3QO &= \angle C_3QQ_3 - \angle OQQ_3 = \\ &= \arccos \frac{A \cdot \sin \left(2\pi - \frac{\pi}{M} \right)}{B} - \left(\frac{\pi}{2} - \frac{\pi}{M} \right), \end{aligned} \quad (4)$$

where the angle OQQ_3 is determined from the rectangular triangle OQQ_3 whose angle QQO_3 is equal to π/M .

The probability P_{arj} that resultant vector end is in some area j of constellation diagram, whose value is determined by (3) or (4), is obtained by dividing this value by π . Now *SJR* may be calculated as:

$$SJR = \sum_{j=1}^{M/2} \frac{f_{mj}}{\log_2 M} \cdot P_{arj}, \quad (5)$$

where f_{mj} is the mean number of faulty bits in a symbol when resultant vector end after sweep jamming is in the area j distant in relation to the activation message signal vector. The value of f_{mj} may be determined as

$$f_{mj} = \sum_{jl=1}^{M/2} \frac{2 \cdot f_{jl}}{M}, \quad (6)$$

where f_{jl} is the number of faulty bits when the activation message signal vector is in some area l and the resultant vector is in the area j distant in relation to the activation message signal vector. For each combination of indices j and l there are two areas at distance j from the area l , one in clockwise direction and the other in counter clockwise direction from the

area 1. Therefore, each f_{ji} value is the mean value of the values determined for these two areas.

III. PARAMETER DETERMINATION FOR VARIOUS MODULATION TECHNIQUES

Our goal is to calculate exact probability of successful sweep jamming in the case that RCIED activation message is transmitted by QPSK, 8PSK and 16PSK modulated signal. The calculation is performed using (5) and (6). The values of P_{arj} in these equations are determined by (3) and (4). The values of M for the derived formulas are 4 for QPSK, 8 for 8PSK and 16 for 16PSK.

A. Analysis for QPSK

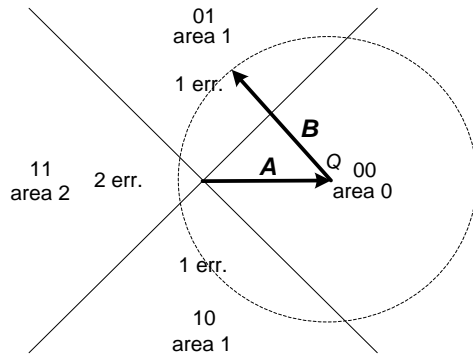


Figure 2. Phasor and constellation diagram for QPSK modulated signal sweep jamming with number of bit errors in each coding area

Fig. 2 presents phasor and constellation diagram for QPSK modulated RCIED activation message sweep jamming. The coded bit combination of QPSK modulated signal is 00 and the vector A of this signal is in the area designated as “area 0”. The coded combinations in areas at distance $j=1$ are 01 (“area 1” in counter clockwise direction) and 10 (“area 1” in clockwise direction). This means that there is one faulty bit (designation “1 err.” in Fig. 2) of total two bits in coded combination if the resultant vector after jamming falls in one of these areas. Therefore, we can write $f_{ji}=1$ in this case. “Area 2” is area at distance $j=2$. As the coded combination in this area is 11, both bits are faulty if the resultant vector falls in this area (“2 err.”). This means that now it is $f_{ji}=2$.

B. Analysis for 8PSK

Fig. 3 presents phasor and constellation diagram for 8PSK modulated RCIED activation message sweep jamming. Coding combination 000 is transmitted in the activation message. As for QPSK signal, the distance j from the “area 0” is presented as the number besides the designation “area”, as well as the number of faulty bits if the resultant vector falls in that area. The number of faulty bits in the areas with the same j in the clockwise and counter clockwise direction is not always the same. In the counter clockwise direction the coded bits combination in the “area 3” is 010, meaning that one of three bits forming the symbol is faulty. The coded bits combination in the “area 3” in clockwise direction is 111. Therefore, now all 3 bits of the symbol are faulty. That’s why designation in this area is “3 err.”. The mean number of faulty bits after the consideration of two available areas at distance $j=3$ is 2.

As for the case of coding bits combination 000 in RCIED activation message, the similar analysis may be performed for all other bits combinations of the activation message. For all these combinations the number of faulty bits in adjacent areas with $j=1$ is $f_{ji}=1$ and for $j>1$ it is $f_{ji}=2$. That’s why the same values are obtained also for f_{mj} . The obtained values of f_{ji} and f_{mj} are summarized in Table I.

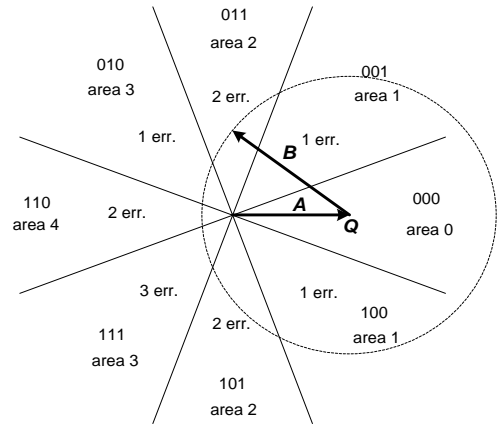


Figure 3. Phasor and constellation diagram for 8PSK modulated signal sweep jamming with number of bit errors in each coding area

TABLE I. THE VALUES OF F_{ji} AND F_{mj} FOR 8PSK MODULATION

code	Area 1	Area 2	Area 3	Area 4
000	1	2	2	2
001	1	2	2	2
011	1	2	2	2
010	1	2	2	2
110	1	2	2	2
111	1	2	2	2
101	1	2	2	2
100	1	2	2	2
f_{mj}	1	2	2	2

C. Analysis for 16PSK

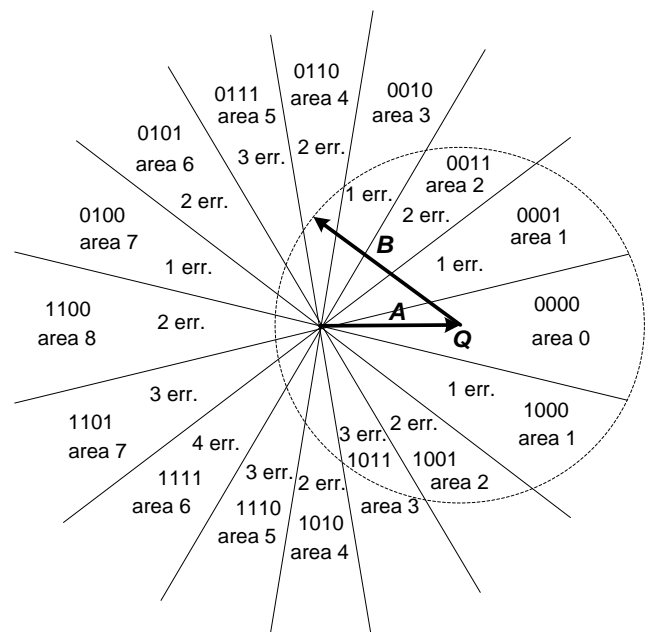


Figure 4. Phasor and constellation diagram for 16PSK modulated signal sweep jamming with number of bit errors in each coding area

Fig. 4 presents phasor and constellation diagram for 16PSK modulated RCIED activation message sweep jamming. Data necessary for the analysis are presented in the relation to the coded bits combination 0000. The values of f_{ji} are not the same for one value of j when analysis is started from different coded bits combinations in the activation message, i.e. from the areas with different l . This is illustrated in Table II.

TABLE II. THE VALUES OF F_{jl} AND F_{mj} FOR 16PSK MODULATION

code	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8
0000	1	2	2	2	3	3	2	2
0001	1	2	2	2	2	3	3	2
0011	1	2	2	2	2	3	3	2
0010	1	2	2	2	3	3	2	2
0110	1	2	2	2	3	3	2	2
0111	1	2	2	2	2	3	3	2
0101	1	2	2	2	2	3	3	2
0100	1	2	2	2	3	3	2	2
1100	1	2	2	2	3	3	2	2
1101	1	2	2	2	2	3	3	2
1111	1	2	2	2	2	3	3	2
1110	1	2	2	2	3	3	2	2
1010	1	2	2	2	3	3	2	2
1011	1	2	2	2	2	3	3	2
1001	1	2	2	2	2	3	3	2
1000	1	2	2	2	3	3	2	2
f_{mj}	1	2	2	2	2.5	3	2.5	2

IV. THE SIMULATION PROGRAM

The main goal in this paper is the calculation of the exact value of the successful sweep jamming probability. The developed calculation method is applicable to the case when only one type of jamming (sweep) signal is generated in one time interval. But, one direction of IRTTEL future development is towards simultaneous generation of two different jamming signals in the same frequency band and even in one of its subbands. It is necessary to predict effects of such jamming before implementing it. In IRTTEL solution of jammer [16] there is a possibility to generate sweep and barrage jamming signal in the same time according to the user's request. This scenario is applicable only for one part of the complete frequency spectrum, but the main intention is to generate these signals in different subbands. For the case of signals generation in the same subband it is difficult to develop an analytical model. There exist the results in literature where system performances are analyzed in the presence of two types of interfering signals [17] [18]. If we would like to implement the results from these references, we may consider that RCIED activation signal is the regular signal and that sinusoidal jamming signal is interference signal. The graphs in [17] [18] are presented also as a function of signal to noise ratio. At a glance it is just what we need. However, the analyzed situation in [17] [18] is quite different than our one. In [17] [18] regular signal is the desired signal and the levels of interference signal and noise are lower than the level of regular signal (the results are limited to the amplitude ratio $A/B \geq 5\text{dB}$, i.e. $A/B \geq 1.8$). When jamming is analyzed, both sweep and barrage jamming signal usually have higher level than RCIED activation signal and the results from these references may not be applied. That's why the results on the base of [17], [18] are only an estimation.

The problems in the development of an analytical model in this case may be overcome by the implementation of simulation program. The program is an original IRTTEL contribution and in the first step presented in this paper the goal was to verify possibility that such a program gives satisfactory results. In other words, the goal was to prove that the results of calculation method and simulation program are mutually comparable in a simpler situation of only sweep jamming application.

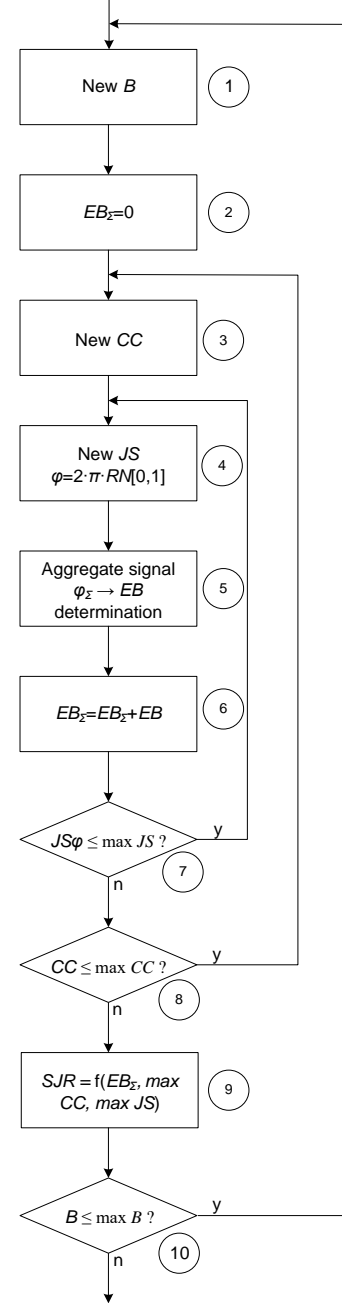


Figure 5. Flow-chart of the simulation program

The flow-chart of the developed simulation program is presented in Fig. 5. The simulation is performed for different values of jamming signal level (B) relative to RCIED activation signal level (block 1 in Fig. 5) and for all predicted code combinations (CC) (block 3). For each such defined combination of B and CC jamming signal starting phase

relative to RCIED activation signal phase is determined on the base of uniformly distributed random number (RN) (block 4).

The next step in simulation program (block 5) is the calculation of the phase of aggregate signal (φ_{Σ}) composed as the vector sum of CC signal (the phase of this signal is φ_{CC}) and jamming signal, whose phase φ is previously determined in the block 4. The calculation is performed applying the equation:

$$\varphi_{\Sigma} = \arctang \frac{\sin \varphi_{CC} + B \cdot \sin \varphi}{\cos \varphi_{CC} + B \cdot \cos \varphi} \quad (7)$$

The value of φ_{Σ} is then used to determine the number of incorrectly received bits (EB) in a MPSK symbol based on the data presented in Tables I or II in dependence on the applied MPSK signal modulation level.

During the whole simulation process the number of incorrectly received bits is accumulated (the register EB_{Σ} initiated in the block 2 is incremented in each program loop pass in the block 6).

The number of repeated program loop passes is determined in blocks 7, 8 and 10. First of all, the simulation is performed for 25 different jamming signal levels. That's why the value max B in the block 10 is 25. Then, the situation is analyzed for every of $M=16$ possible code combinations (CC) as 16PSK modulation is considered. This is the reason why it is max $CC=16$ in the block 8. And, finally, the number of randomly generated jamming signal phases relative to CC signal phase is 1.000.000 leading to the value max $JS = 1.000.000$ in the block 7. The simulation is realized in our originally developed C program using the commercial PC. The simulation for such initial parameters lasts less than 8 minutes.

The values of successful jamming rate (SJR) are determined in the block 9 of the simulation program. This is the output value of the simulation program and it is determined as:

$$SJR = \frac{EB_{\Sigma}}{\log_2 M \cdot \max CC \cdot \max JS} \quad (8)$$

V. THE ANALYSIS RESULTS

Fig. 6 presents SJR values as the function of amplitudes ratio A/B for QPSK modulated activation signal. The graph is designated as $SJR_QPSK_calculation$ in Fig. 6. The results are calculated using formulas (3) to (6), which are intended for $A/B < 1$. As a comparison, the graph with the designation $SJR_QPSK_simulation$ presents the same characteristic obtained by simulation. Simulation is realized according to the flow-chart presented in Fig. 5. The results obtained by calculation and by simulation in this case are nearly completely the same.

Fig. 7 presents SJR values as the function of amplitudes ratio A/B for 8PSK modulated activation signal. The graph is designated as $SJR_8PSK_calculation$ in Fig. 7. As a comparison, the graph with the designation $SJR_8PSK_simulation$ presents the same characteristic obtained by simulation. The results obtained by calculation and by simulation in this case are also nearly completely the same.

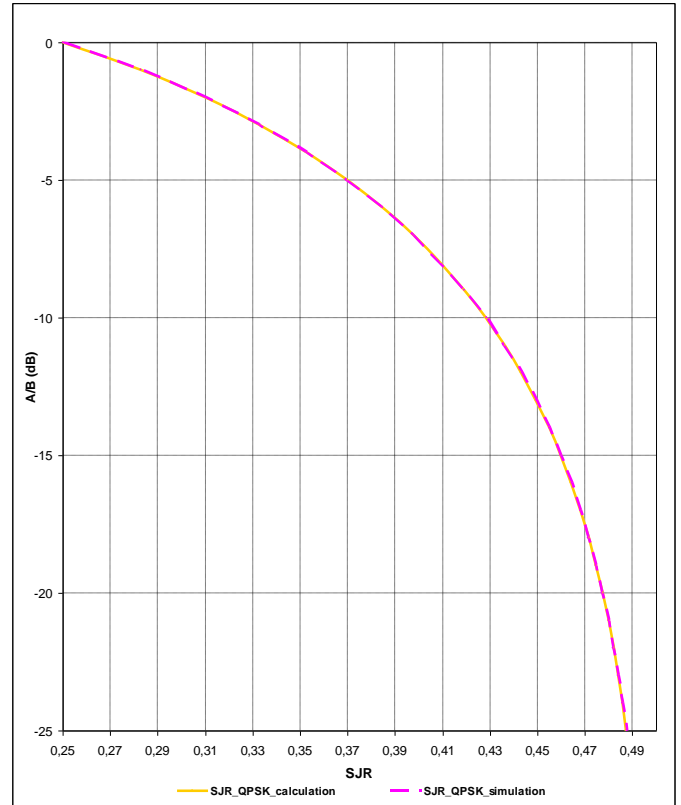


Figure 6. SJR as a function of the relation of amplitudes A/B for QPSK modulated signal determined by calculation and simulation

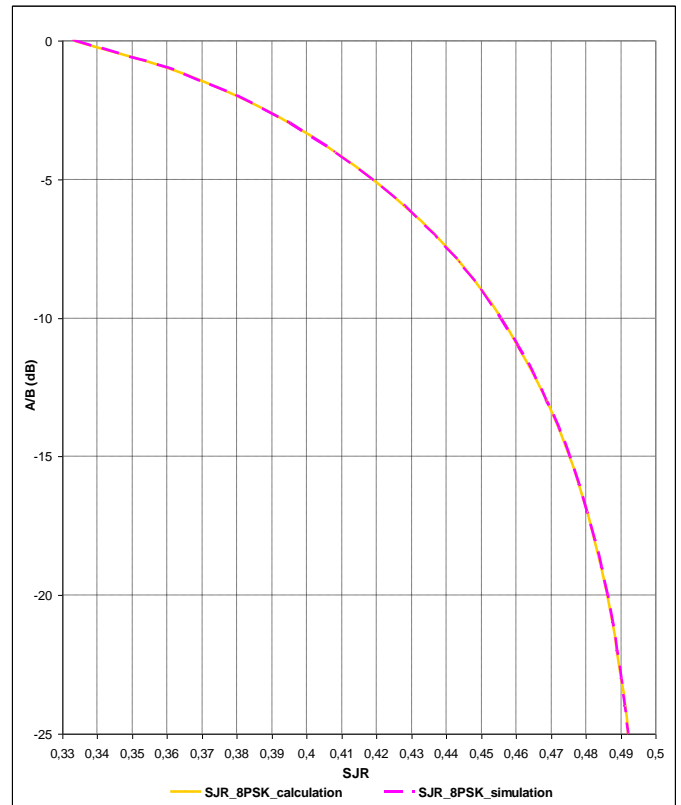


Figure 7. SJR as a function of the relation of amplitudes A/B for 8PSK modulated signal determined by calculation and simulation

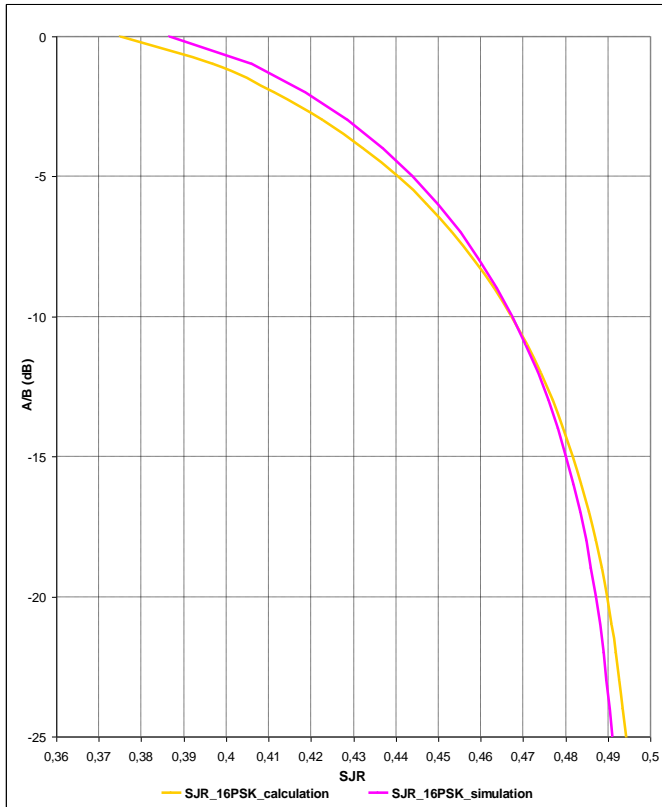


Figure 8. SJR as a function of the relation of amplitudes A/B for 16PSK modulated signal determined by calculation and simulation

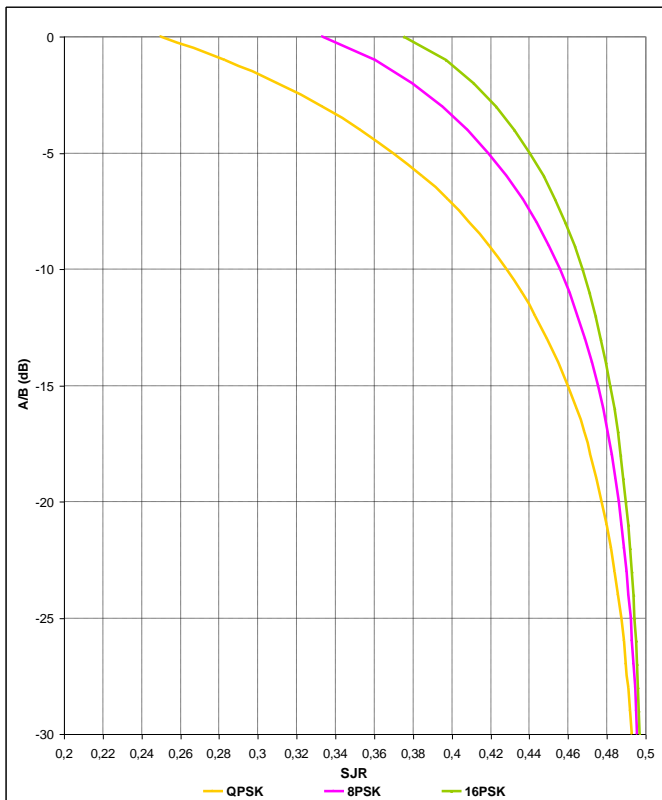


Figure 9. SJR as a function of the relation of amplitudes A/B for QPSK, 8PSK and 16PSK modulated RCIED activation message sweep jamming

Fig. 8 presents comparatively the values of SJR obtained by calculation (the characteristic $SJR_{16PSK_calculation}$) and simulation (the characteristic $SJR_{16PSK_simulation}$) for jamming 16PSK signal. For the range of RCIED activation signal and jamming signal amplitudes between 0dB and -25dB the difference between SJR values obtained by calculation and simulation is maximum 1.1%, thus well approving the reliability of simulation process and nominating it for the analysis of more complicated implementation scenarios.

The results presented in [19] are approximate values of SJR . These approximate values of SJR are always lower than exact values determined in this paper. The emphasized trend in approximation occurs because each symbol error is treated as only one bit in a symbol is erroneous, i.e. that the resultant signal vector is always in the adjacent area to the regular signal area if error happens. The probability that the number of erroneous bits in a symbol is higher than 1 increases when the relative amplitudes ratio A/B decreases (i.e. when jamming signal level increases). This is the reason why the difference between approximate and exact SJR characteristic increases when jamming signal level increases. When considering systems usually analyzed in literature (as, for example, in [17] [18]), we may say that interference, i.e. jamming signal level is significantly lower than regular signal, causing that very rarely more than one bit in a symbol is erroneous. In such a case approximate calculation gives satisfactory results (approximate method is nearly accurate), but for our needs where jamming signal level is higher than RCIED activation signal level, it is much better to implement exact method.

Fig. 9 presents together exact values of SJR for sweep jamming of QPSK, 8PSK and 16PSK modulated activation message signals. This figure shows that for all applied modulation techniques SJR values tend to 0.5 when the ratio of amplitudes A/B decreases. This important conclusion was not possible on the base of the results from [19]. The emphasized result is also implemented in the example in [15], where it is supposed that it is $SJR=0.5$ when jamming of GSM mobile systems is analyzed. The presented graphs in Fig. 9 also show that the higher values of SJR are achieved with the increase of M . This means that it is easier to realize successful jamming of 16PSK modulated RCIED activation message than 8PSK and QPSK modulated messages.

The graphs from Fig. 9 prove that it is not important to increase sweep jamming signal level over some value. The value $SJR=0.4$, which is only 20% lower than the maximum theoretically achievable SJR value, may be reached for the amplitude ratio $A/B=-1$ dB when jamming 16PSK modulated activation message and for $A/B=-7$ dB when jamming QPSK modulated activation message. This analysis enabled us to significantly decrease jamming signal emission power in our new jammer solution [16], [20] comparing to the emission power of the previous solution [21].

VI. CONCLUSIONS

In this paper we developed the method for calculation of the exact values of SJR when sweep jamming of MPSK modulated RCIED activation messages is performed. The method is intended for the analysis in the case when jamming signal amplitude B is higher than activation message amplitude A ($B>A$). The specificity of such an analysis is that more than one bit in a symbol may be incorrectly transmitted. For an

exact *SJR* calculation it is more complicated than if only one bit in a symbol may be erroneous, as it is for $A > B$.

The results from this paper may be used for quantitative estimation of necessary jammer characteristics. Besides the knowledge of these sweep jamming characteristics, it is important to have a good prediction of techniques and devices, which are expected to be implemented for RCIED activation in the region, where jamming is realized [22], [23]. When the techniques of usual attack are well known, it is possible to adjust the level of jamming signal. Possible decrease of jamming signal level without significant degradation of jammer performances leads to emission power saving and lowers the detection probability of our jammer position [24]. In addition, jamming device dimensions could be reduced.

One additional paper contribution is a new simulation method for jamming performance analysis. Simulation method is especially important for the more complicated situations, as for the case when different jamming signal types are implemented in the same time. Such an analysis will be the subject of our future development. In this paper we limited ourselves to the simulation method verification in the case of pure sweep jamming. The calculation and simulation results are nearly quite the same in the case of QPSK and 8PSK modulated RCIED activation signal jamming, while for 16PSK modulated signal there is a low difference (about 1% maximum) in probabilities of *SJR* obtained by calculation and simulation.

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Aleksandar Lebl was born in Zemun, Serbia, in 1957. He received his B.Sc. and M.Sc. from the Faculty of Electrical Engineering in Belgrade, Republic of Serbia, in 1981. and 1986., respectively, and his Ph.D. from the Faculty of Technical Science in Novi Sad, in 2009. He was employed from 1981 in the Switching Department of Institute for Electronics and Telecommunications IRITEL in Belgrade and from 2015 he is in the Radiocommunications Department, also in IRITEL. Dr. Lebl is Senior Research Associate in IRITEL. He is author or coauthor of more than hundred professional and scientific papers. During years he worked on the project of Digital Switching System for Serbian Telecommunication Industry.



Mladen Mileusnić was born in Bjelovar, Croatia, in 1958. He received his B.Sc. and M.Sc. from Faculty of Electrical Engineering in Belgrade, Republic of Serbia, in 1982. and 1999., respectively, and his Ph.D. from the Faculty of Technical Science in Novi Sad, in 2014. From 1986 he is employed in Radiocommunications Department of Institute for Electronics and Telecommunications IRITEL in Belgrade. He worked on many research and development projects in the area of communications systems. Currently, he is the Head of Radiocommunications Department, responsible for services in public mobile communications networks and wireless access networks. Dr. Mileusnić is author or coauthor of more than hundred scientific papers and technical solutions as also three manuals for technical reviews in Regulatory Agency for Electronic Communications and Postal Services (RATEL).



Predrag Petrović is the full member of Serbian Academy of Engineering Sciences. He got The Institute of Electrical and Electronics Engineers (IEEE) Vehicular Technology Society 1982 Runner-Up Paper of the Year Award in Communications Technology for the paper entitled "Digitized speech transmission at VHF using existing FM mobile radios". His doctoral dissertation

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at the Faculty of Electrical Engineering of University in Belgrade was awarded in 1983. In addition, dr Petrović received the Year Award of Elektronska industrija in 1988 for the scientific contribution in the field of real-time automatic radio signals classification. He was the member of the Scientific Council of Serbian Ministry of Education, Science, and Technological Development for Electronics, Telecommunication, and Information Technologies until 2017. He published nearly 140 papers in international and national journals and conference proceedings. His R&D work comprises 80 realized radio, EW, and radar systems and devices as well as 56 projects in telecommunication, mobile radio communications, software defined radio, broadcasting and information security. He was the Vice-President of ETRAN Society of Serbia until 2016. Currently, he is the leader of project TR32051 for Serbian Ministry of Education, Science and Technological Development and the member of TELFOR Scientific Board and INFOTEH Program Board.



Branislav Pavić was born in Belgrade, Serbia, in 1956. He received his B.Sc. from the Faculty of Electrical Engineering in Belgrade, Republic of Serbia, in 1980. He is employed in the Institute for Electronics and Telecommunications IRITEL, now on the position Head of Department for Development and Production in the Radiocommunications Department. Author or coauthor of more than fifty scientific and professional papers from various areas of electronics and winner of several awards for these papers.



Verica Marinković-Nedelicki received her B.Sc. from the Faculty of Electrical Engineering in Belgrade, Republic of Serbia, in 1984. She is employed in the Institute for Electronics and Telecommunications IRITEL from 1984. Now she is on the position Project Manager for the modernization of older generation radars. She has participated in five projects of Serbian Ministry of Education, Science and Technological Development and published more than forty national and international scientific and professional papers.