



Vojnotehnicki glasnik/Military Technical Courier
ISSN: 0042-8469
ISSN: 2217-4753
vojnotehnicki.glasnik@mod.gov.rs
University of Defence
Serbia

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Vojnotehnicki glasnik/Military Technical Courier, vol. 70, no. 3, 2022

University of Defence, Serbia

Available in: <https://www.redalyc.org/articulo.oa?id=661772310009>

DOI: <https://doi.org/10.5937/vojtehg70-37535>

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Analysis of repeater jamming of a slow frequency hopping radio

АНАЛИЗ РЕТРАНСЛИРОВАННЫХ ПОМЕХ РАДИОСВЯЗИ С ПЛАВНОЙ ПЕРЕСТРОЙКОЙ ЧАСТОТЫ

Анализа репетитивног ометања радија са спорим фреквенцијским скакањем

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Received: 21 April 2022

Accepted: 24 June 2022

ABSTRACT:

Introduction/purpose: The article presents a model of a slow frequency hopping radio in the case of repeater jamming. The aim is to analyze the effectiveness of repeater jamming to a military tactical slow frequency hopping radio.

Methods: It is assumed that the repeater jammer will be successful in detecting signals with slow frequency hopping at each hop and that it will perform successful partial jamming of the intercepted communication. Under partial jamming, it is considered that a certain part of the transmission time of each hop will be jammed. A theoretical analysis of the impact of a repeater jammer on a frequency hopping radio was performed based on the definition of the total probability of error. Various parameters that affect the segment of hop duration under jamming were considered.

Results: The obtained results show that high effective jamming is achieved even when a short segment of hop duration is jammed. We discuss the conditions for the repeater jammer to detect the signal during each hop and emit the jamming signal with the required strength. It has been shown that increasing the frequency hopping rate can significantly reduce the effectiveness of the repeater jammer.

Conclusion: Repeater jammers are highly effective against slow frequency hopping radio communication systems.

KEYWORDS: spread spectrum, frequency hopping, repeater jamming, error probability.

Р е з ю м е :

Введение/цель: В данной статье представлена модель радиоприемника с плавной перестройкой частоты в случае ретранслированных помех. Цель статьи заключается в проведении анализа эффективности подавления ретранслированных помех в военной тактической радиостанции с плавной скачкообразной перестройкой частоты.

Методы: Предполагается, что устройство подавления ретранслированных помех сможет успешно обнаружить сигналы с плавной перестройкой частоты при каждом переходе и что оно будет успешно выполнять частичное подавление перехваченного сообщения. При частичном подавлении помех считается, что определенная часть времени передачи каждого перехода будет подавлена. На основе определения общей вероятности ошибки был проведен теоретический анализ воздействия ретранслированных помех на радиосвязь со скачками частоты. Были рассмотрены различные параметры, влияющие на продолжительность скачков при помехах.

Результаты: Полученные результаты показывают, что высокая эффективность глушения достигается даже при помехах с короткой длительностью скачка. В статье проанализированы условия, при которых устройство подавления

ретранслированных помех должно обнаруживать сигнал во время каждого скачка и производить сигнал подавления с требуемой силой. В статье доказано, что увеличение скорости скачкообразной перестройки частоты может значительно снизить эффективность ретранслированных помех.

Выводы: Ретранслированные помехи оказывают сильное воздействие на систему радиосвязи с плавными скачками частоты.

К л ю ч е в ы е с л о в а : расширение спектра, скачкообразная перестройка частоты, глушение ретранслятора, вероятность ошибки.

ABSTRACT:

Увод/циљ: У раду је представљен модел радија са спорим фреквенцијским скакањем у случају када је ометан репетитивним ометаčem. Анализирано је ометање војног тактичког радио-уређаја са фреквенцијским скакањем репетитивним ометаčem. Методе: Претпостављено је да ће репетитивни ометач бити ефикасан приликом детекције сигнала са спорим фреквенцијским скакањем код сваког скока и да ће успешно извршити делимично ометање пресретнуте комуникације. Под делимичним ометањем се подразумева да ће одређени временски део трансмисије сваког хопа бити ометан. Спроведена је теоријска анализа утицаја репетитивног ометача на радио са фреквенцијским скакањем на основу дефиниције тоталне вероватноће грешке. Разматрани су и различити параметри који утичу на дужину периода хопа који ће успешно бити ометан.

Резултати: Добијени резултати показују да се ефикасно ометање постиже ако се омета мали део трајања једног скока. У разматраним условима репетитивни ометач детектује сигнал током сваког хопа и емитује ометајући сигнал потребном снагом. Показано је да се са повећањем брзине фреквенцијског скакања може знатно смањити утицај репетитивног ометача. Закључак: Репетитивни ометачи су веома ефикасни у ометању комуникационих радио-система са спорим фреквенцијским скакањем.

KEYWORDS: проширени спектар, фреквенцијско скакање, репетитивно ометање, вероватноћа грешке.

INTRODUCTION

Frequency hopping (FH) radios are designed to avoid narrowband interference or jamming (Scholtz, 1982). That is achieved by frequent changes of the operating frequency in a wide range of the spectrum. The performance of military tactical radio communications is often evaluated by the low probability of intercept and the anti-jamming characteristics (Lee et al, 2006). Frequency hopping belongs to the spread spectrum technology which has a lot of advantages, including but not limited to: anti-jamming, anti-eavesdropping and secrecy (Zhang et al, 2012). Due to these advantages, frequency hopping is a very important part of military communication systems, but also widely used in commercial telecommunication systems.

Frequency hopping is divided into fast and slow. Fast frequency hopping is a technique in which a hop duration is shorter than a bit duration, i.e. one bit is transmitted over several hops. Slow frequency hopping is a technique in which a hop duration is longer than a bit duration, i.e. several bits are transmitted within one hop. Slow frequency hopping is much often used, primarily due to simpler implementation (Torrieri, 1981).

Jammers are malicious radio devices used by attackers to cause intentional interference in radio communications. Jammers are used to completely or at least partially prevent the target from efficient use of the electromagnetic spectrum. Efficient use of the electromagnetic spectrum represents a successful radio communication between two radio devices. Jamming is performed by generating a signal with high strength which is received by the receiver of the jammed device. When a useful signal arrives at the receiver along with a jamming signal, it is not possible to extract useful information.

One of jammers classifications is on continuous wave (CW), pulse and repeater (Todorović, 1994). Based on their bandwidth, jammers can be classified as: wideband, partial-band and narrowband (Lee et al, 2006). Also, some other classifications of jamming techniques focus on noise jamming, tone jamming, sweep jamming and repeater jamming (Zhang et al, 2020). There are many other classifications of jamming techniques (Grover et al, 2014).

In military applications, the ability of the frequency hopping radio to avoid interference is limited by a repeater jammer (also known as a follower jammer). A repeater jammer is a device that intercepts a radio signal, processes it, and then transmits a jamming signal at the same operating frequency. When the transmitter changes the operating frequency, the repeater jammer scans the observed bandwidth and searches for a new frequency to jam again. In the optimal case, the jammer has the transmitter's hopping rate and the sequence of frequencies. To be effective against a frequency hopping system, the jamming energy must reach the target receiver before it hops to the next operating frequency. Thus, the hopping rate is the critical factor in protecting a radio system against a repeater jammer (Torrieri, 2015).

In this article, the effectiveness of a repeater jammer in the case of a radio system with slow frequency hopping is considered. The aim is to determine how the segment of hop duration under jamming affects the performance of the frequency hopping radio.

The second section of the article presents a model of a frequency hopping radio. Section three will present a model of repeater jamming in the case of slow frequency hopping. In Section four, numerical results and their analysis are given, while in the last section the most important conclusions are made.

MODEL OF A FREQUENCY HOPPING RADIO

Frequency hopping is based on operating frequency change in a wide range. During communication, the transmitter and the receiver change their operating frequency in hops, according to a pre-agreed rate and order, which should remain secret for everyone except them. (Todorović, 2021).

A block diagram of the transmitter and the receiver of a frequency hopping radio is given in Figure 1 (Torrieri, 2015). Figure 1 (a) shows a transmitter block diagram. The frequency hopping radio transmitter consists of a modulator, where some of the conventional digital modulations are applied. The modulated signal is further sent to the mixer where it is mixed with the carrier generated in the frequency synthesizer. The rule by which frequency hopping is performed is generated by the pattern generator. The pattern generator actually generates a pseudonoise sequence that defines which next frequency the frequency synthesizer should be set to.

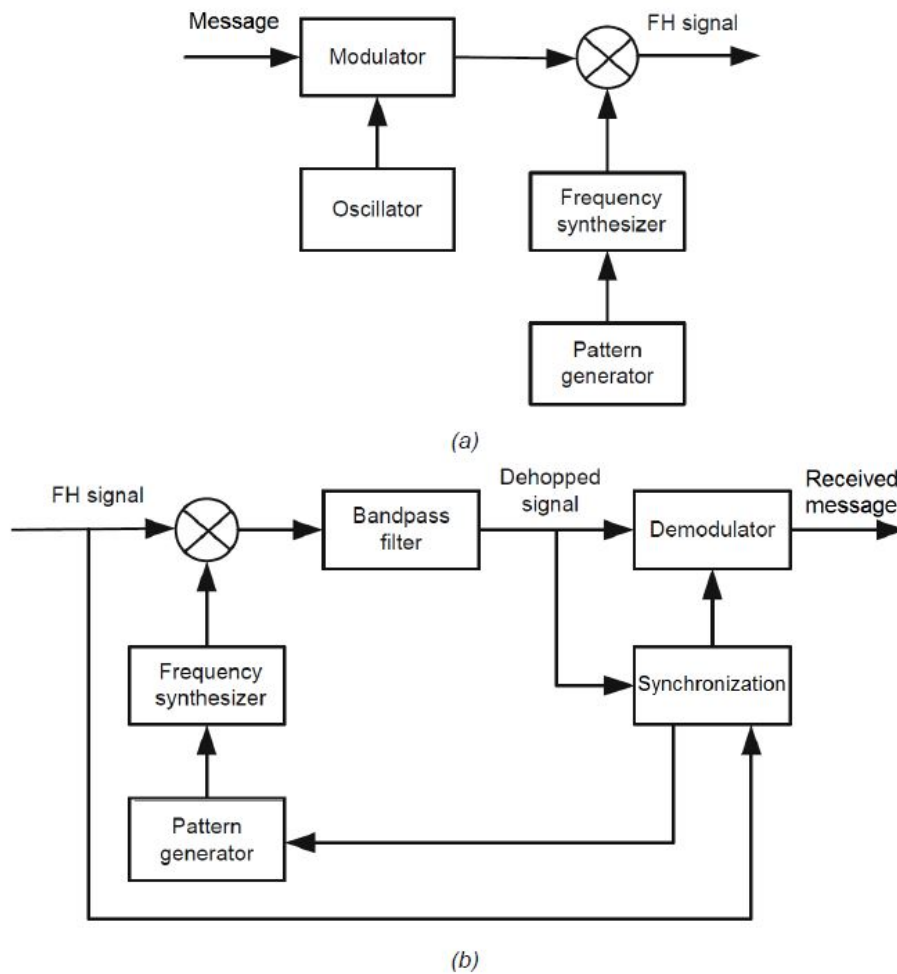


FIGURE 1

General block diagram of a frequency hopping radio: (a) transmitter, (b) receiver

Рис. 1 – Общая блок-схема радиоустройства со скачкообразной перестройкой частоты: (а) передатчик (б) приемник

Слика 1 – Општа блок-шема радио-уређаја са фреквенцијским скакањем:

(а) предајник, (б) пријемник

The general block diagram of the receiver is shown in Figure 1 (b). The pattern generator in the receiver is identical and has to be synchronized with the pattern generator in the transmitter. This ensures that the operating signal frequencies of the transmitter and the receiver change simultaneously. The signal from the output of the mixer is filtered, thus returning to the frequency band of the applied conventional modulation. By demodulating such a signal, an output signal from the receiver is obtained.

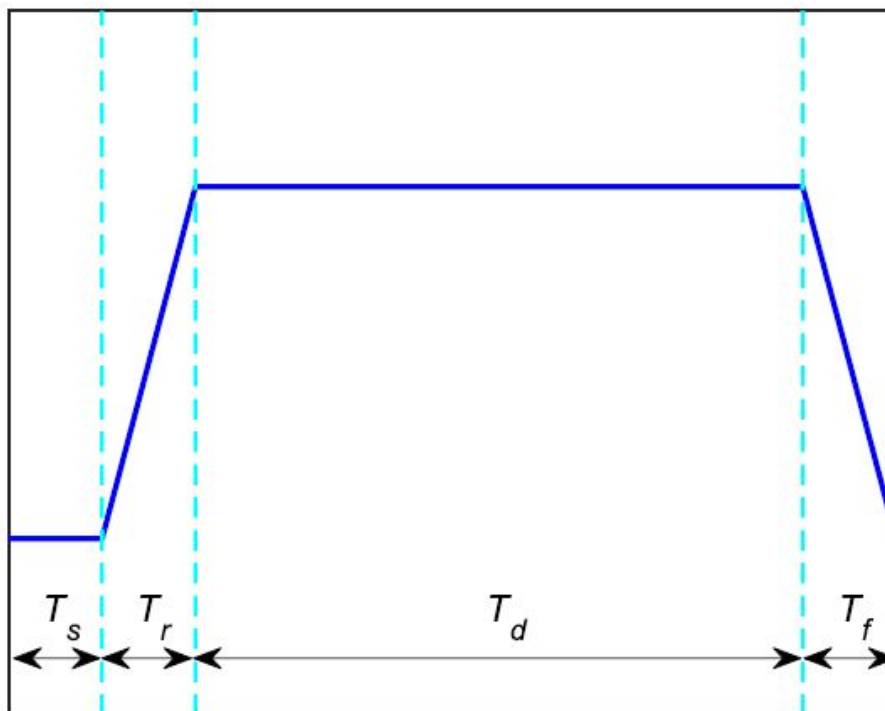


FIGURE 2

Structure of a frequency hop

Рис. 2 – Структура скачка частоты

Слика 2 – Структура једног фреквенцијског скока

The time duration of one hop is called the hop interval and denoted by τ_h (Torrieri, 2015). The structure of the hop interval is presented in Figure 2. The hop duration can be represented as a single pulse consisting of several segments. The most important segment, which also lasts the longest, is called the dwell time and it is marked with τ_d . The rest of the time is the rise time, τ_r , in order to reach the appropriate level before emission, and the fall time, τ_f , in order to level drop after emission. The first segment is the silent time, τ_s , which is used to set up the frequency synthesizer. It is short when hops are within the same subband, and much longer when two neighbouring hops are in different subbands.

JAMMING SCENARIO

Repeater jamming is effective against slow frequency hopping signals. A repeater jammer consists of two parts: a radio signal scanner and a radio signal generator. At first, the jammer performs spectrum scan and detection of received signals (signal intercept) and, based on that information reacts by generating a jamming signal the strength of which has enough power to completely degrade the useful signal on the receiver side (Lichtman & Reed, 2016). The jamming signal must reach the receiver before the jammed communication system moves to the next operating frequency. The repeater jammer has to quickly successively set the frequency synthesizer to different operating frequencies within a wide frequency range (Lee et al, 2006; Hansson et al, 2015).

The FSK (Frequency Shift Keying) modulation technique is the most common in frequency hopping devices. It has been shown that the FSK modulation has additional advantage as the most robust modulation, especially in military applications (Blanchard, 1982). We assume that the repeater jammer cover the entire FSK channel. After detection, the jammer begins to transmit a jamming signal and after a certain time completely jams the useful signal. The error probability would then be defined as follows:

$$P_e = P(\bar{J}) \cdot P(e/\bar{J}) + P(J) \cdot P(e/J), \quad (1)$$

where are:

- $P(\bar{J})$ – the probability that there is no jamming in a certain period of hop duration
- $P(e/\bar{J})$ – the error probability when there is no jamming,
- $P(J)$ – the probability that there is jamming in a certain period of hop duration, and
- $P(e/J)$ – the error probability when there is jamming of the useful signal.

As it is assumed that communication between two radio devices will be certainly jammed in each hop, the key parameter becomes the segment of the dwell time that will be jammed.

Figure 3 shows the geometric arrangement of a transmitter (T_s), a receiver (R_s) and a jammer (Torrieri, 1989). The distances between the elements are indicated. The distance between the transmitter and the receiver is denoted by d_1 , the distance between the transmitter and the jammer with d_2 , and the distance between the jammer and the receiver with d_3 . The directions of signal propagation are represented by arrows. In order to meet the condition for the repeater jammer to be effective in jamming, the following inequation must be met:

$$\frac{d_2}{c} + T_{SJ} + T_{PJ} + T_{RJ} + \frac{d_3}{c} \leq \frac{d_1}{c} + T_d, \quad (2)$$

where the remaining undefined elements of the expression are:

- c – speed of propagation of electromagnetic waves through free space which is $3 \cdot 10^8$ m/s,
- T_{SJ} – time required to scan the frequency band used for signal transmission by the repeater jammer,
- T_{PJ} – time required for the jammer to set the frequency synthesizer to the appropriate operating frequency,
- T_{RJ} – time required for the jammer to reach 90% of the maximum emission strength (rise time), and
- T_d – pulse duration of the useful signal during one hop (dwell time).

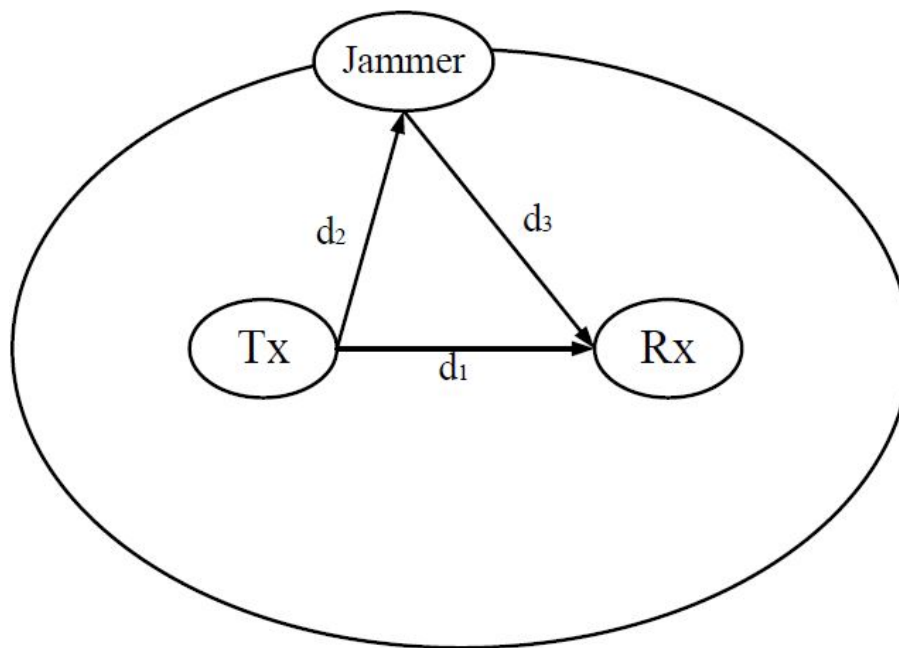


FIGURE 3

Position geometry of the jammer, the transmitter and the receiver

Рис. 3 – Геометрия положения генератора помех, передатчика и приемника

Слика 3 – Геометрија позиција ометача, предајника и пријемника

If expression (2) were to be written as follows:

$$d_2 + d_3 \leq d_1 + (T_d - T_{SJ} - T_{PJ} - T_{RJ}) \cdot c, \quad (3)$$

and if it were assumed that the right side of the inequality is constant, then it would be an expression for an ellipse, where the transmitter and the receiver would be in the foci of the ellipse, and the jammer on the ellipse itself (Torrieri, 1989). If the jammer was outside the ellipse, the jamming would not be effective. Effective jamming could be achieved in cases when the jammer is on the ellipse or inside of the ellipse (Torrieri, 1989).

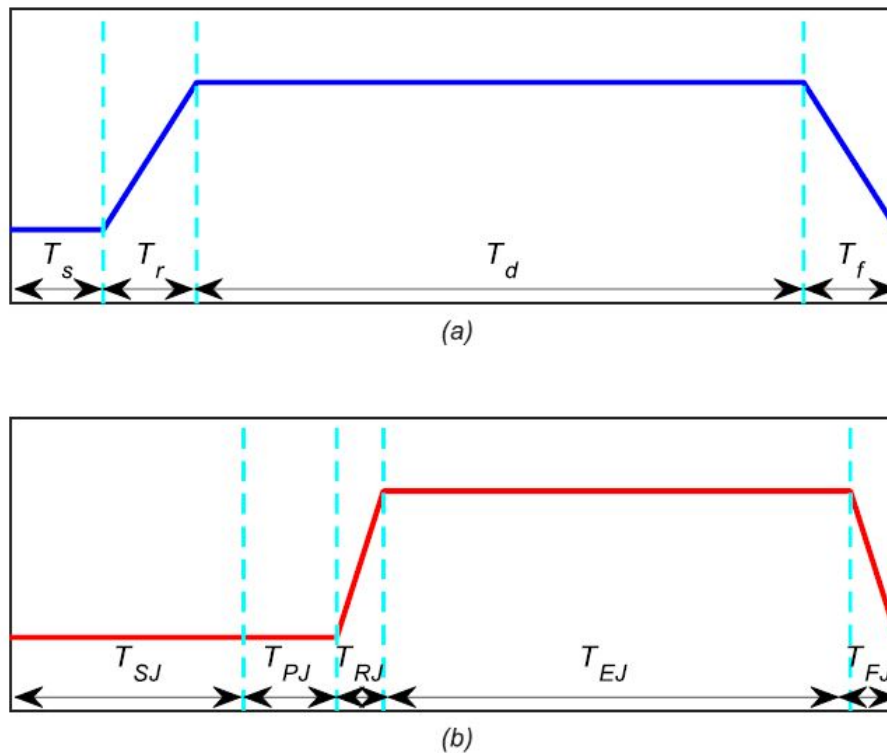


FIGURE 4

Structure of a frequency hop: (a) transmitter, (b) repeater jammer

Рис. 4 – Структура скачка частоты:

(а) передатчика (б) передатчика ответных помех

Слика 4 – Структура једног фреквенцијског скока код:

(а) предајника, (б) репетитивног ометача

Figure 4 shows the segments in hop durations for the transmitter and the jammer. Figure 4 (a) is identical to Figure 2, and it is used for comparative representation. In Figure 4 (b), time segments at the repeater jammer's hop are shown.

The repeater jammer is scanning the spectrum until it detects a communication signal. After detection, during processing, the jammer is setting up a frequency synthesizer on the appropriate operating frequency. The adequate radiated signal strength of the jammer is achieved during the rise time. The effective jamming period is in the segment marked with T_{EJ} (time during which the jammer emits and jams).

The jammer emitted time can be obtained using the following expression:

$$T_{EJ} = T_h - T_{SJ} - T_{PJ} - T_{RJ} - T_{FJ} . \quad (4)$$

After the strength of the communication signal decreases for 3 dB of its maximum, the repeater jammer also decreases its strength in the T_{FJ} interval (fall time). The rise time and the fall time of the repeater jammer are shorter than the rise time and the fall time at the frequency hopping transmitter.

NUMERICAL RESULTS

The analysis of the proposed slow frequency hopping radio and the jammer can be performed based on expression (1). It is assumed in the case of no jamming, the error probability depends only on the noise and multipath fading that can occur in the channel during signal transmission. In this case, the error probability is small enough and communication will be realized successfully. In accordance with the above, two values of $P(e|J)$ were considered: $P(e|J) = 10^{-3}$ and $P(e|J) = 10^{-8}$. Commercial radios require a high quality of service (QoS), so it is necessary that the error probability have very low values. In military radios, functionality has to be provided in hostile environment, so higher values of error probability can be acceptable.

If there is jamming during transmission, one can assume that a signal will be completely degraded. Accordingly, the value of $P(e|J) = 0.5$.

The remaining two parameters from expression (1) are complementary, i.e.:

$$P(\bar{J}) + P(J) = 1. \quad (5)$$

Figure 5 shows the error probability versus the jamming period. Figure 5 (a) shows the entire jamming period for the two cases: $P(e|J) = 10^{-3}$ and $P(e|J) = 10^{-8}$. It can be noticed that two curves almost coincide. This was actually expected because the values of error probability when there is no jamming slightly contribute to the overall error probability. For a more detailed view, Figure 5 (b) shows only 5% of the jamming period. From this Figure, one can see that these two curves are different for only 2% of the jamming period.

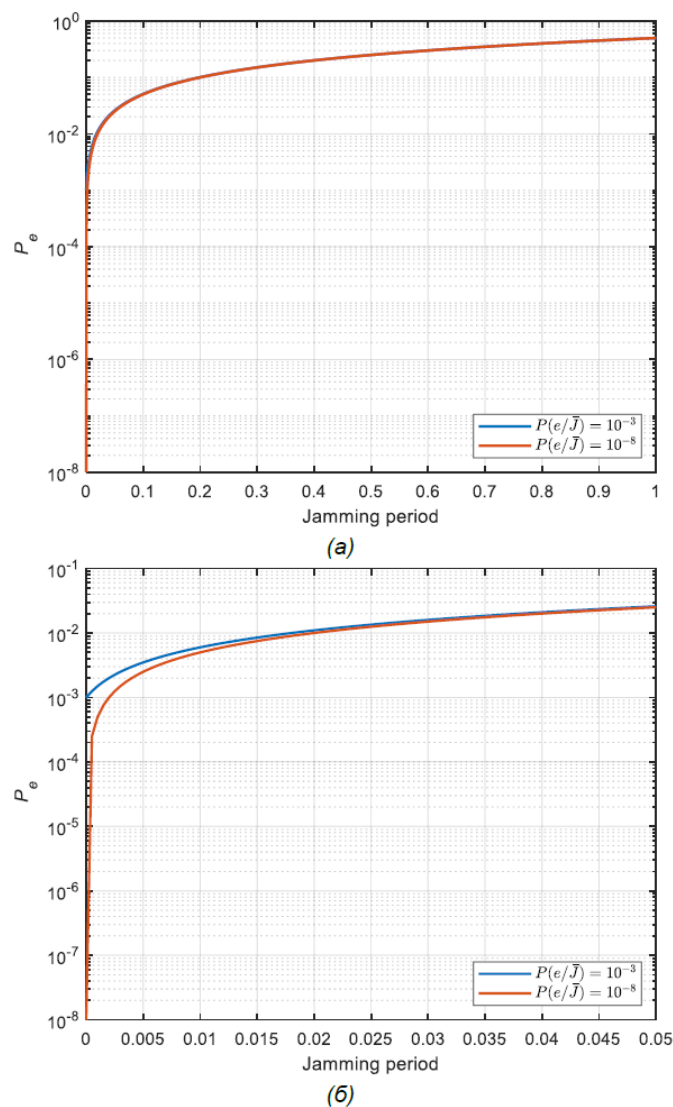


FIGURE 5

Error probability versus jamming period during a hop:
(a) overall diagram, (b) first 5% of the overall diagram

Рис. 5 – Вероятность ошибки в зависимости от периода помех во время перехода: (а) общая диаграмма (б) первые 5% общей диаграммы

Слика 5 – Вероватноћа грешке у односу на период ометања током трајања хопа: (а) комплетан дијаграм, (б) првих 5% временског дела дијаграма

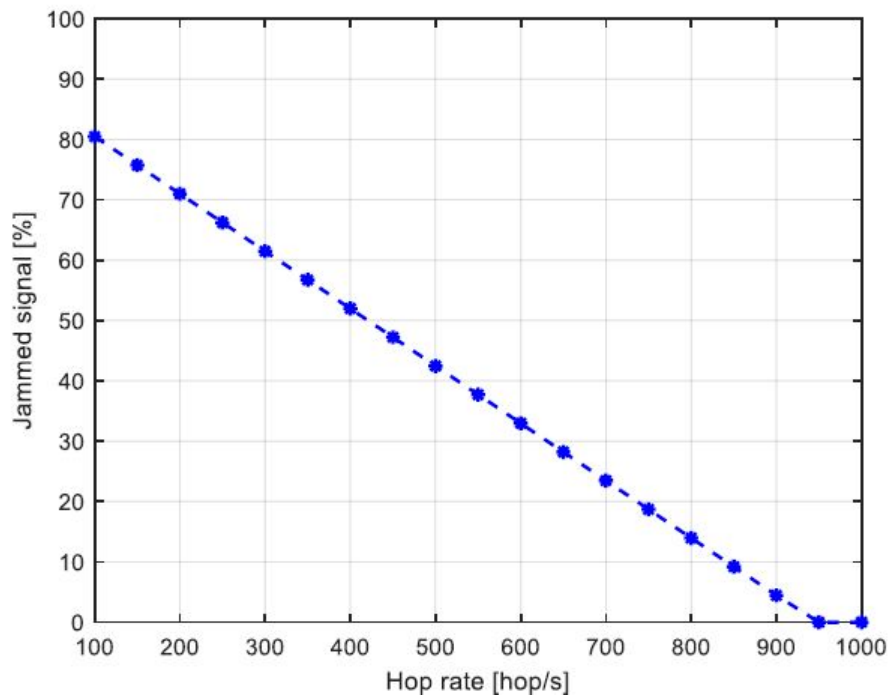


FIGURE 6

Jammed signal in percent against the hop rate of the frequency hopping radio

Рис. 6 – Заглушенный сигнал в процентах по отношению к частоте скачков радиосвязи со скачкообразной перестройкой частоты

Слика 6 – Процент ометаног сигнала у односу на брзину скакања радија са фреквенцијским скакањем

In order to calculate numerical results based on the proposed model, we used realistic data for the repeater jammer: $d_1 = 30$ km, $d_2 = 20$ and $d_3 = 25$ km. The repeater jammer scanning time, the repeater jammer processing time, and the repeater jammer rise time are $T_{SJ} = 150$ μ s, $T_{PJ} = 800$ μ s and $T_{RJ} = 500$ ns, respectively. It is assumed that the FH radio dwell time is 90% of the hop duration and that the silent time is $T_s \approx 0$ s.

The percentage of the jammed signal versus the hop rate is presented in Figure 6. The hop rate varies in a wide range from 100 hops/s to 1000 hops/s. This figure shows a linear decrease in the percentage of jammed signals with the increase of the number of hops per second. It can be seen that the jammer is effective up to a frequency hopping rate of 900 hops/s, at least in a small percentage for higher frequency hopping rates. For frequency hopping rates higher than 900 hops/s, the repeater jammer becomes inefficient.

From Figure 6, it can be seen that over 80% of the hop duration is jammed when the hop rate is 100 hops/s. For higher frequency hopping rates, the percentage of jammed signals is lower. For example, for 900 hops/s, the jammed signal drops to around 4.5%.

Figure 7 once again shows the error probability versus the signal jamming period during a hop. Here, additionally indicated are two values of the error probability for the jamming period which corresponds to the frequency hopping rate of 300 hops/s and 700 hops/s. For 300 hops/s, about 61% of the dwell time is jammed, which causes a high error probability of about $3 \cdot 10^{-1}$. For 700 hops/s, about 23% of the dwell time is jammed, which also causes a high error probability of about 10^{-1} . With the increasing frequency hopping rate, from 300 hops/s to 700 hops/s, the error probability is decreasing for 20%, but still has high values, even for robust military radios.

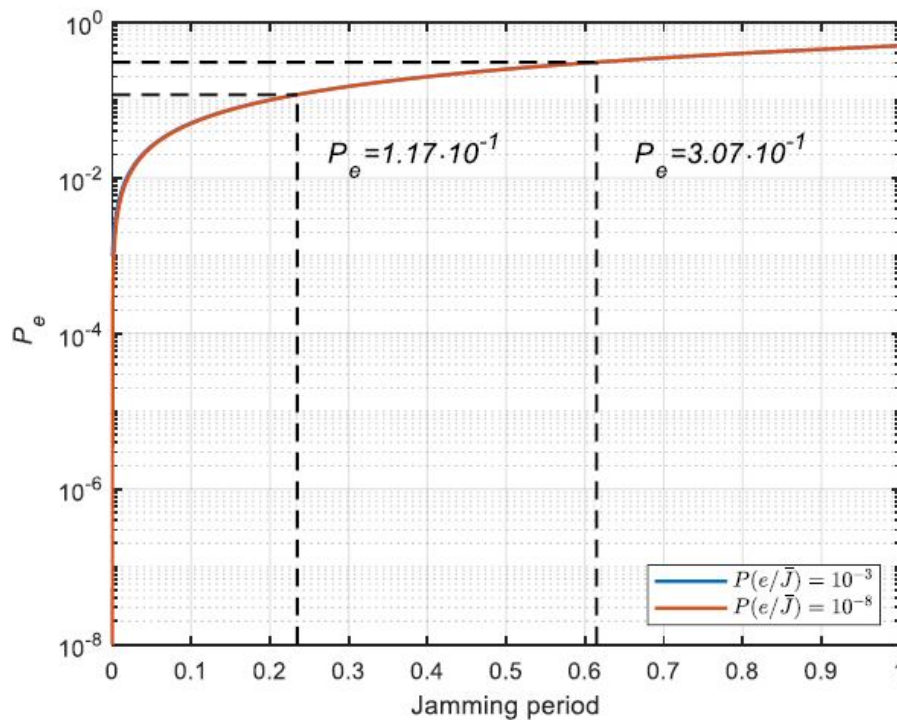


FIGURE 7

Error probability versus the period of jamming during a hop with the specified characteristic values

Рис. 7 – Вероятность ошибки в зависимости от периода помех во время перехода с заданными значениями характеристик

Слика 7 – Вероватноћа грешке у односу на период ометања током трајања хопа са назначеним карактеристичним вредностима

CONCLUSION

Although frequency hopping signal transmission technology was created primarily to avoid jamming signals, it can still be effectively jammed using a repeater jammer. Slow frequency hopping is particularly susceptible to jamming with a repeater jammer. Slow frequency hopping transmits more bits during one hop and the time spent on one operating frequency is longer, so the repeater jamming is facilitated by jamming a certain part of the hop duration.

The considered model of the jamming of the slow frequency hopping radio simply shows the dependence of the error probability on the jammed period of hop duration using the total probability equation. It has been found that the error probability increases significantly after a very short period of hop jamming. It is assumed that the repeater jammer will be successful in detecting and jamming each hop.

The success rate of the hop duration jamming was analyzed depending on the frequency hopping rate. It is shown that the increase of the frequency hopping rate can significantly degrade the efficiency of the repeater jammer.

ACKNOWLEDGMENTS

This research has been a part of Project No. VA-TT/3/20-22 supported by the Ministry of Defence, Republic of Serbia.

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