A New Technique of Frequency Hopping with Collision Avoidance

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Abstract. *This article proposes a new technique of frequency hopping with collision avoidance (FH/CA). Currently there are well-known systems of frequency hopping which adapt their behavior based on previously measured data (such as PER) for individual channels. The FH/CA system adjusts its behavior based on the current occupancy of several test channels. Using a mathematical model, the performance of the newly proposed FH/CA technique is compared with the currently used techniques FH and AFH. Comparison criteria are the probability of a collision between an FH/CA communication system and a static or dynamic jammer (i.e. other FH or AFH systems).*

Keywords

Frequency hopping, collision avoidance, static jammer, dynamic jammer.

1. Introduction

The technique of frequency hopping [1] (FH) belongs to the group of spread spectrum modulations. The frequency hopping technique is, in principle, a narrow-band transmission at a given moment of time but over a longer period of time it will be spread to the allocated spectrum due to the change in multiple carrier frequencies. The principle of this technique consists in rapid frequency switching of the carrier frequency in a pseudo-random sequence, which is known to both the receiver and the transmitter.

The technique of adaptive frequency hopping [1] (AFH) is based on the FH technique complemented with the ability to recognize statically jammed frequencies and then avoid these frequencies. The parameters used in practice for the detection of static jammed frequencies are e.g. signal strength measurements on individual channels using the RSSI (Received Signal Strength Indication), the packet error rate PLR (Packet Loss Ratio) or the bit error rate BER (Bit Error Ratio). After the evaluation of the measurement, the AFH equipment sorts the frequency channels into good and bad ones. Unjammed channels are identified as good channels while jammed channels are identified as bad channels. In the pseudo-random sequence for channel switching the bad channels are replaced by good channels [2].

The proposed FH/CA (Frequency Hopping with Collision Avoidance) technique is also based on the FH technique. However, the FH/CA station measures signal levels in a number of considered channels before the next jump. Based on the measurements the most appropriate channel is selected.

The advantages of systems with the frequency-hopping technique are, in particular, increased resistance to interference and security. Both advantages follow from the principle of the frequency hopping technique.

To compare the performance of the techniques mentioned, mathematical models are used that were for the FH and AFH techniques taken from [1]. The mathematical model for the FH/CA technique is described in this article. Using this model, the performance of the newly proposed FH/CA technique is compared with currently used FH and AFH techniques. The performance criterion is the probability of collision between the communication system and the static or dynamic jammers in the communication band. As a static jammer we consider a device transmitting continuously at a fixed frequency. As a dynamic jammer we consider device with the FH or AFH technique.

2. State of the Art

Currently the techniques of frequency hopping are described which adapt their behavior based on previously measured data in different channels. Such techniques include, for example, the AFH technology, which is standardized in IEEE 802.15 [1].

The DAFH (Dynamic Adaptive Frequency Hopping) technique [3] dynamically changes a set of employed channels, based on PER (Packet Error Rate). Another technique, EAFH (Enhanced Adaptive Frequency Hopping) [4] based on PER reduces the size of hop set and the length of packets. Channels with a high value of PER are excluded by the EAFH technique.

The UBAFH (Utility Based Adaptive Frequency Hopping) [5] or RAFH (Robust Adaptive Frequency Hopping) [6] techniques derive from PER the mapping of channels. Channels with a lower PER are used more often than channels with a higher PER.

None of the above mentioned techniques is able to reflect the current state of radio channels and is always based on the previously measured data. These techniques often require a redundancy for their activities in the form of a transfer of necessary information relevant to the synchronization of station channel generators.

The newly proposed FH/CA technique reflects the current state of the radio channel before the commencement of data transmission, while minimizing the redundancy required for the synchronization of station channel generators.

3. Description of FH/CA Technique

The proposed FH/CA (Frequency Hopping with Collision Avoidance) technique is based on the FH technique and assumes that it is possible to detect static and dynamic jammers by measuring the signal level (RSSI) for each channel. Before every next jump the FH/CA station measures the signal levels in the G channels considered. Based on the measurements, the most appropriate channel with the lowest value of the signal level measured is selected. So it is more probable that a jump to a channel not occupied by any transmission will occur.

The channels considered are selected using G pseudorandom generators. Before each jump, pseudorandom generators generate a set of considered channel numbers. In one set the channel numbers generated must be different. If some of the numbers generated were identical, new set of numbers would be generated, until all the generated numbers in the set are different.

For FH/CA stations lower rates of hopping are expected, so when using a circuit with a fast phase lock loop it is now realistic to make the necessary measurement of each channel in a time that will be negligible with respect to the system hopping rate.

The advantages can be derived from the nature of FH/CA compared with the existing systems. Compared with the FH system the FH/CA system is capable of potentially avoiding channels that are jammed by static or dynamic jammers. In comparison with the AFH system, the FH/CA system has lower redundancy and is capable of potentially avoiding channels that are jammed by dynamic jammers.

4. Mathematical Model for FH/CA Technique

The mathematical model models the probability of collision between the FH/CA communication system and the static or dynamic jammer in the communication band. The FH/CA system has at its disposal N communication channels, and with every jump it selects one channel from G possible channels. In the band with N communication channels there are in addition to the FH/CA system R static and S dynamic jammers. We consider as dynamic jammers other devices with the FH or AFH technique, which are not synchronized with each other and work independently.

The hopping rate of FH/CA and FH stations can be calculated using the formula

$$V = \frac{1}{T} \quad [\text{hop/s}], \tag{1}$$

where T is the time between two jumps.

For simplicity, it is assumed that the bandwidth of the jammer is the same as the bandwidth of one channel of the FH/CA system. Therefore, one jammer can fully jam one channel. We can assume that the time between two jumps T is for the FH/CA system the same as for the dynamic jammer.

The following formulae (2) to (7) for the FH/CA system are based on a mathematical model for the FH and AFH systems that are published in [1].

If we choose any time t, then the probability that no static jammer transmits on the channel is given by

$$P_{VR} = \left(\frac{N-R}{N}\right). \tag{2}$$

Complementarily we can calculate the probability that a static jammer transmits on the channel by

$$P_{OR} = 1 - P_{VR} = 1 - \left(\frac{N-R}{N}\right) = \left(\frac{R}{N}\right). \tag{3}$$

The hopping of dynamic jammers in the band is random and independent of each other. The probability that at time t the given channel will not be occupied by the dynamic jammer can be calculated by formula (4). And complementarily, the probability that at time t the given channel will be occupied by the dynamic jammer can be calculated by formula (5).

$$P_{VS} = \left(\frac{n-1}{n}\right)^S, \tag{4}$$

$$P_{OS} = 1 - P_{VS} = 1 - \left(\frac{n-1}{n}\right)^S \tag{5}$$

where n is the number of channels used by FH or AFH systems. If the dynamic jammers are of type FH, then the valid formula for n is

$$n = N. \tag{6}$$

If the dynamic jammers are of type AFH, then the valid formula for n is

$$n = \begin{cases} N - R, \; R \le R_{MAX} \\ N - R_{MAX}, \; R > R_{MAX} \end{cases} \tag{7}$$

where parameter R_{MAX} indicates the maximum number of the replaced channels of AFH system [1]. The AFH technique lowers the potential number of channels N by R, maximally by R_{MAX}.

In formula (4) the expression $(n-1)/n$ gives the probability that an individual dynamic jammer has tuned to a different channel than the channel monitored at time t. The exponent S indicates that at time t all S dynamic jammers are located on other channels. Complementarily formula (5) expresses the probability that at least one dynamic jammer operates on the given channel.

Let the time interval between broadcast initiations of dynamic jammers on the given channel be denoted X, where X is a random variable. In a group of S dynamic jammers, an average of z retuning occur in the time interval x according to the formula

$$z = V \cdot S \cdot x . \tag{8}$$

The probability $P(X > x)$ that none of the dynamic jammers retunes to the monitored channel in time x can be calculated by the formula

$$P(X > x) = \left(\frac{n-1}{n}\right)^{V \cdot S \cdot x} . \tag{9}$$

From formula (9) the distribution function $F(X)$ of random variable X can be derived

$$F(X) = P(X \le x) = 1 - P(X > x) = 1 - \left(\frac{n-1}{n}\right)^{V \cdot S \cdot x} . \tag{10}$$

If we use the substitution

$$\lambda = -V \cdot S \cdot \ln\left(\frac{n-1}{n}\right), \tag{11}$$

then for the above distribution function it holds

$$F(X) = 1 - \exp(-\lambda \cdot x) . \tag{12}$$

From this formula it can be deduced that the interval X is a random variable with exponential distribution, where λ is the intensity of transmission channel occupation. For the density probability $f(x)$ the following applies

$$f(x) = \lambda \cdot \exp(-\lambda \cdot x) . \tag{13}$$

As a result of (13), the process of occupying the channels is called the Poisson process, where the average distance between successive occupations of the channel is equal to

$$E(X) = 1/\lambda . \tag{14}$$

The moment of broadcast initiation of a dynamic jammer on the given channel is denoted as t_1. The moment of the following broadcast initiation of another dynamic jammer on the given channel is denoted as t_2. We assume that the FH/CA station is testing channels at the moment $t \in (t_1, t_2)$. During testing the channel, situations A, B, C, D and E may occur (Fig. 1). The time differences $\Delta = t - t_1$ and $\delta = t_2 - t$ are random variables and have, as a result the characteristics of the Poisson distribution, the same distribution as the variable X.

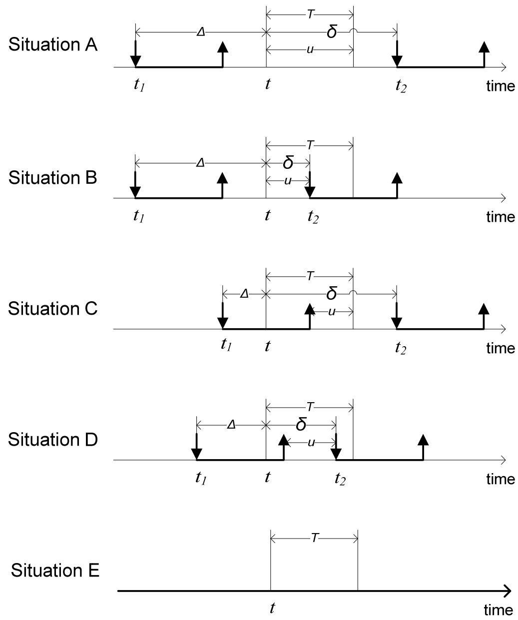

Fig. 1. Possible situations in occupying channels by FH/CA station.

Situation **A** is given by the conditions that there is no static jammer in the channel and that $\Delta \ge T$ and $\delta \ge T$. The described situation occurs with the probability

$$\begin{aligned} P_A &= P_{VR} \cdot P(\Delta \ge T) \cdot P(\delta \ge T) = \\ &= P_{VR} \cdot [1 - F(T)]^2 = P_{VR} \cdot P_{VS}{}^2 . \end{aligned} \tag{15}$$

For the FH/CA station this means that its transmission of length T is not jammed and the time of unjammed transmission is equal to $u = T$. For a mean period of unjammed broadcasts of the FH/CA station, the following formula will be valid for this situation

$$U_A = T . \tag{16}$$

Situation **B** is given by the conditions that there is no static jammer in the channel and that $\Delta \ge T$ and $\delta < T$. For the FH/CA station this means that at the beginning of the transmission the channel will be free but during the transmission it will be occupied by dynamic jammer. The described situation occurs with the probability

$$\begin{aligned} P_B &= P_{VR} \cdot P(\Delta \ge T) \cdot P(\delta < T) = \\ &= P_{VR} \cdot [1 - F(T)] \cdot F(T) = P_{VR} \cdot P_{VS} \cdot P_{OS} . \end{aligned} \tag{17}$$

The period of unjammed broadcasting is in this case equal to $u = \delta$. For a mean period of unjammed broadcasts of the FH/CA station the formula from the general definition of the mean value of random quantity will apply

$$\begin{aligned} U_B &= \frac{1}{P_{OS}} \int_0^T u \cdot f(u) du = \frac{1}{P_{OS}} \int_0^T u \cdot \lambda \cdot \exp(-\lambda \cdot u) du = \\ &= \frac{1}{\lambda} - T \cdot Q, \text{ where } Q = \frac{P_{VS}}{P_{OS}} . \end{aligned} \tag{18}$$

Component $1/P_{OS}$ in the formula serves to normalize the distribution, so that it should hold

$$\int_0^T f(u)du = 1 . \tag{19}$$

Situation **C** is given by the conditions that there is no static jammer in the channel and that $\Delta < T$ and $\delta \geq T$. For the FH/CA station this means that at the beginning of the transmission the channel will be occupied by the dynamic jammer but during the transmission it will be free. The described situation occurs with the probability

$$\begin{aligned} P_C &= P_{VR} \cdot P(\Delta < T) \cdot P(\delta \geq T) = \\ &= P_{VR} \cdot F(T) \cdot [1 - F(T)] = P_{VR} \cdot P_{OS} \cdot P_{VS} . \end{aligned} \tag{20}$$

The period of unjammed broadcasting is equal to $u = \Delta$. For a mean period of unjammed broadcasts of the FH/CA station the formula from the general definition of the mean value of random quantity will apply, which is the same as situation B

$$\begin{aligned} U_C &= \frac{1}{P_{OS}} \int_0^T u \cdot f(u)du = \frac{1}{P_{OS}} \int_0^T u \cdot \lambda \cdot \exp(-\lambda \cdot u)du = \\ &= \frac{1}{\lambda} - T \cdot Q . \end{aligned} \tag{21}$$

Situation **D** is given by the conditions that there is no static jammer in the channel and that $\Delta < T$ and $\delta < T$. For the FH/CA station this means that at the beginning of the transmission the channel will be occupied by the dynamic jammer and during the transmission it will be occupied by another dynamic jammer. The described situation occurs with the probability

$$P_D = P_{VR} \cdot P(\Delta < T) \cdot P(\delta < T) = P_{VR} \cdot F(T)^2 = P_{VR} \cdot P_{OS}{}^2 . \tag{22}$$

The period of unjammed broadcasting is equal to $u = \text{Max}\{0, \Delta+\delta-T\}$. If the FH/CA station did not choose out of $G > 1$ channels, it would mean for a mean period of unjammed broadcasts of FH/CA

$$U = T \cdot P_{VR} \cdot P_{VS} \tag{23}$$

and simultaneously

$$U = \sum_i P_i \cdot U_i \text{, where } i = A, B, C, D, E . \tag{24}$$

From the knowledge of P_A to P_E and U_A to U_E the formula for U_D can be deduced from (23) and (24)

$$U_D = T \cdot Q - 2 \cdot Q \cdot (\frac{1}{\lambda} - T \cdot Q) . \tag{25}$$

Situation **E** is given by the condition that there is static jammer in the channel. For the FH/CA station this means that during the entire transmission, the channel will be occupied by the static jammer. The described situation occurs with the probability

$$P_E = P_{OR} . \tag{26}$$

For the FH/CA station this means that the whole transmission in the given channel is jammed and the period of unjammed broadcasting is equal to $u = 0$. For a mean period of unjammed broadcasts of the FH/CA station the following formula will be valid

$$U_E = 0 . \tag{27}$$

For situation **E** it is necessary to add that in addition to the static jammer in the channel, dynamic jammers may also be present. This does not change the fact that the channel is jammed.

Based on the above formulae, we can calculate the mean period Z of unjammed transmission of the FH/CA station. At the time t of channel measurement the FH/CA station will find with probability P_{TV} that the tested channel is free. This state will be denoted TV and practically includes situations A and B. For P_{TV} it holds

$$P_{TV} = P_A + P_B . \tag{28}$$

At the time t of channel measurement the FH/CA station will find with probability P_{TO} that the tested channel is occupied. This state will be denoted TO and practically includes situations C, D and E. For P_{TO} it holds

$$P_{TO} = P_C + P_D + P_E . \tag{29}$$

The FH/CA station tests G channels. State 1, i.e. at least one of the tested channels is free, comes with a probability P_1.

$$P_1 = 1 - P_{TO}{}^G . \tag{30}$$

State 2, i.e. all tested channels are occupied by jammers, occurs with probability P_2.

$$P_2 = P_{TO}{}^G . \tag{31}$$

First we determinate Z_1, i.e. the mean period of unjammed transmission in state 1. This status occurs in situation A or B and therefore

$$Z_1 = \frac{1}{P_A + P_B} \cdot (P_A \cdot U_A + P_B \cdot U_B) . \tag{32}$$

Variable Z_2 is the mean period of unjammed transmission in state 2 and we calculate it from the mean period of unjammed transmission in situations C, D and E. The mean period of unjammed transmission Z_2 is given by

$$Z_2 = \frac{1}{P_C + P_D + P_E} \cdot (P_C \cdot U_C + P_D \cdot U_D + P_E \cdot U_E) . \tag{33}$$

Based on the knowledge of (27), it is possible to delete from formula (33) the component $P_E.U_E$. Then the mean period of unjammed transmission Z_2 is given by

$$Z_2 = \frac{1}{P_C + P_D + P_E} \cdot (P_C \cdot U_C + P_D \cdot U_D) . \tag{34}$$

The resulting mean period of unjammed transmission Z of the FH/CA system is given by

$$Z = P_1 \cdot Z_1 + P_2 \cdot Z_2 . \quad (35)$$

The probability of unjammed transmission P_{NFHCA} is given by

$$P_{NFHCA} = \frac{Z}{T} . \quad (36)$$

And the complementary probability of jammed transmission (collision) P_{FHCA} for system FH/CA is

$$P_{FHCA} = 1 - P_{NFHCA} . \quad (37)$$

For the case when S = 0, it is possible to calculate the above procedure with a single formula

$$P_{FHCA} = P_{OR}{}^{G}, \text{ for } S = 0 . \quad (38)$$

The described model allows determining the probability of jammed transmission of station FH/CA in conditions of static and dynamic interference. The accuracy of the model was successfully verified on a simulation model.

5. Mathematical Model for FH and AFH Techniques

To compare the FH/CA technique with the FH and AFH techniques it is appropriate to mention models that are used to describe them. These models were taken from [1]. The probability of a collision or a jump of the FH system to the jammed channel is given by formula (39), where N is the number of communication channels, R is the number of channels jammed by static jammers, and S is the number of dynamic jammers. In the case of FH systems they are other FH networks and in the case of AFH systems they are other AFH networks.

$$P_{FH} = 1 - \left(\frac{N-R}{N}\right) \cdot \left(\frac{N-1}{N}\right)^{S} . \quad (39)$$

The probability of a collision or a jump of the AFH system to the jammed channel is given by formula (40), where R_{MAX} is the maximum number of channels replaced by the AFH system.

$$P_{AFH} = 1 - \left(\frac{n-r}{n}\right) \cdot \left(\frac{n-1}{n}\right)^{S}, \text{ where} \quad (40)$$

$$n = \begin{cases} N-R, R \le R_{MAX} \\ N-R_{MAX}, R > R_{MAX} \end{cases}, \quad r = \begin{cases} 0, R \le R_{MAX} \\ R-R_{MAX}, R > R_{MAX} \end{cases} .$$

6. Comparing the Performance of FH/CA and FH Techniques

A comparison of the two systems can be made using formula (41), where we subtract the collision probability of the FH technique from the collision probability of the FH/CA technique, and the result will be related to the collision probability of the FH technique and we will get the resulting gain of the FH/CA technique. A positive result shows the advantage of the FH/CA system while a negative result shows its disadvantage compared to the FH system.

$$A_{FH-FHCA} = \frac{P_{FH} - P_{FHCA}}{P_{FH}}, P_{FH} \ne 0 . \quad (41)$$

For the comparison the settings G = 2, 3 and 4 will be set in the FH/CA technique. The above analyses were calculated for illustration with specific parameters but the following conclusions can be considered general and valid also for different parameters.

First, the analysis of gain in the case of static jammers was made. To illustrate the analysis, the following parameters were used for the calculation: N = 100, G = 2, 3 and 4, R = 1 to 100. According to (40), the calculation of gain $A_{FH\text{-}FHCA}$ was performed, which is represented by the graph in Fig. 2. From Fig. 2, where $A_{FH\text{-}FHCA} = f(R)$, we can see the following characteristics of FH/CA.

The FH/CA technique in a band with static jammers is never worse than the FH technique. The FH/CA technique has a significant gain already when using generators G = 2. Increasing the number of generators G leads to higher gains of the FH/CA technique.

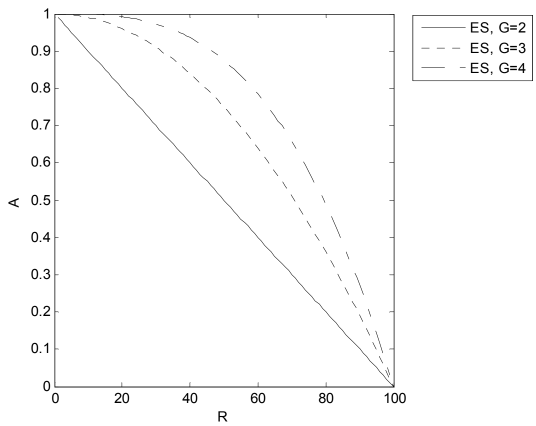

Fig. 2. Comparing the performance of system FH/CA with FH in a band with static jammers (N = 100, G = 2, 3 and 4, R = 1 to 100 and S = 0).

Furthermore, an analysis of gain in the case of dynamic jammers (i.e. other FH systems) was made. To illustrate the analysis, the following parameters were used for the calculation: N = 100, G = 2, 3 and 4, S = 1 to 100. According to (41) the calculation of gain $A_{FH\text{-}FHCA}$ was performed, which is represented by the graph in Fig. 3. From Fig. 3, where $A_{FH\text{-}FHCA} = f(S)$, we can see the following characteristics of FH/CA.

The FH/CA technique in a band with dynamic FH jammers is never worse than the FH technique. The FH/CA technique has a significant gain already when using generators G = 2. Increasing the number of generators G leads to higher gains of the FH/CA technique.

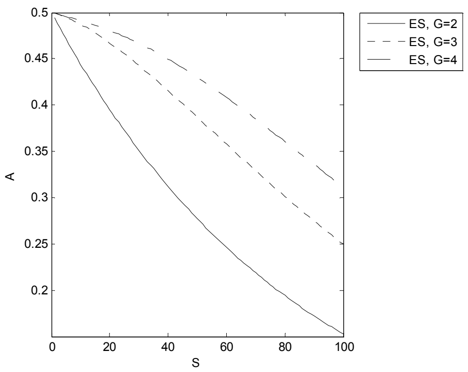

Fig. 3. Comparing the performance of system FH/CA with FH in a band with dynamic jammers (N = 100, G = 2, 3 and 4, R = 0 and S = 1 to 100).

Also, an analysis of gain in the case of static and dynamic jammers was made. To illustrate the analysis, the following parameters were used for the calculation: N = 100, G = 2, R = 1 to 40 and S = 1 to 40. According to (41) the calculation of gain $A_{FH\text{-}FHCA}$ was performed, which is represented by the graph in Fig. 4. From Fig. 4, where $A_{FH\text{-}FHCA} = f(R,S)$, we can see the following characteristics of FH/CA.

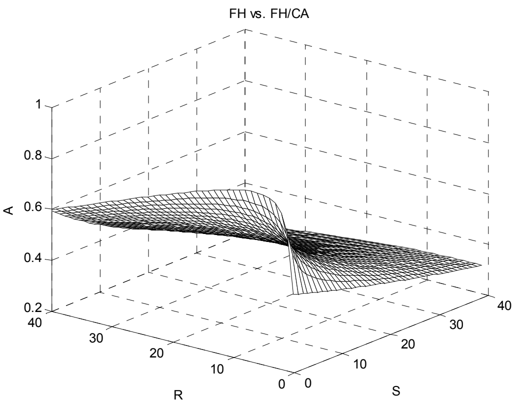

Fig. 4. Comparing the performance of system FH/CA with FH in a band with static and dynamic jammers (N = 100, G = 2, R = 1 to 40 and S = 1 to 40).

The FH/CA technique in a band with static and dynamic jammers is never worse than the FH technique. The FH/CA technique has a significant gain already when using generators G = 2.

7. Comparing the Performance of FH/CA and AFH Techniques

A comparison of the two systems can be made using formula (42), where we subtract the collision probability of the AFH technique from the collision probability of the FH/CA technique, and the result will be related to the collision probability of the AFH technique and we will get the resulting gain of FH/CA technique. A positive result shows the advantage of the FH/CA system and a negative result shows its disadvantage compared to the AFH system.

$$A_{AFH-FHCA} = \frac{P_{AFH} - P_{FHCA}}{P_{AFH}},\ P_{AFH} \neq 0\,. \qquad (42)$$

In the comparison, the setting R_{MAX} = 20 will be chosen for the AFH technique, which corresponds to the value 20% of N [1]. The settings G = 2, 3 and 4 will be set for the FH/CA technique for the comparison. The above analyses were calculated for illustration with specific parameters.

First the analysis of gain in the case of static jammers was made at R_{MAX} = 20. To illustrate the analysis, the following parameters were used for the calculation: N = 100, R_{MAX} = 20, G = 2, 3 and 4, R = 1 to 100. According to (42) the calculation of gain $A_{AFH\text{-}FHCA}$ was performed, which is for $P_{AFH} > 0$ represented by the graph in Fig. 5.

From Fig. 5, where $A_{AFH\text{-}FHCA} = f(R)$, we can see that for $R \leq R_{MAX}$ the FH/CA technique is always worse than AFH. This is because in this case the band is jammed only by static jammers, which the AFH system can completely avoid.

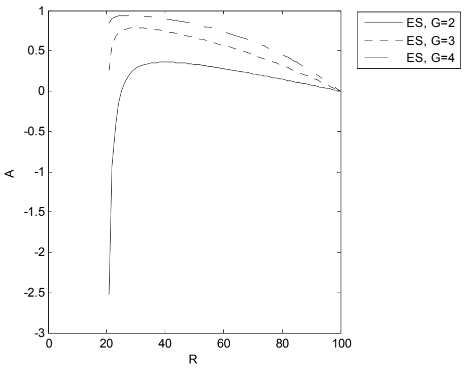

Fig. 5. Comparing the performance of system FH/CA with AFH in a band with static jammers (N = 100, R_{MAX} = 20, G = 2, 3 and 4, R = 1 to 100 and S = 0).

For the case where $R > R_{MAX}$, the situation is more complicated. Based on formulae (38) and (40), condition (43) can be deduced for the threshold value R_0, where the FH/CA technique will be worse than the AFH technique

$$\left(\frac{R_0}{N}\right)^G = \left(\frac{R_0 - R_{MAX}}{N - R_{MAX}}\right). \qquad (43)$$

For G = 2 this condition can be adjusted to the explicit formula

$$R_0 = \frac{N \cdot R_{MAX}}{N - R_{MAX}}\,. \qquad (44)$$

On the whole, it can be said that the FH/CA technique in a band with static jammers is not worse than the AFH technology if $R \geq R_0$. The value R_0 can be obtained by calculation from condition (43).

Next, an analysis of gain in the case of dynamic jammers was made. The parameter R_{MAX} need not be considered in this case, because there are no static jammers in the band. To illustrate the analysis, the following parameters were used for the calculation: N = 100, G = 2, 3 and 4,

$S = 1$ to 100. According to (41), the calculation of gain $A_{FH\text{-}FHCA}$ was performed, which is represented by the graph in Fig. 6. From Fig. 6, where $A_{FH\text{-}FHCA} = f(S)$, we can see the following characteristics of FH/CA.

The FH/CA technique in a band with dynamic jammers is never worse than the AFH technique. The FH/CA technique has a significant gain already when using generators $G = 2$. Increasing the number of generators G leads to higher gains of the FH/CA technique.

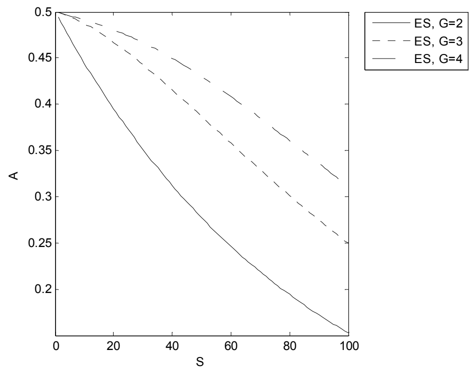

Fig. 6. Comparing the performance of system FH/CA with AFH in a band with dynamic jammers (N = 100, G = 2, 3 and 4, R = 0 and S = 1 to 100).

Further, an analysis of gain in the case of static and dynamic jammers was made. To illustrate the analysis, the following parameters were used for the calculation: N = 100, R_{MAX} = 20, G = 2, R = 1 to 40, and S = 1 to 40. According to (42) the calculation of gain $A_{FH\text{-}FHCA}$ was performed, which is represented by the graph in Fig. 7. From Fig. 7, where $A_{AFH\text{-}FHCA} = f(R,S)$, we can see the following characteristics of FH/CA.

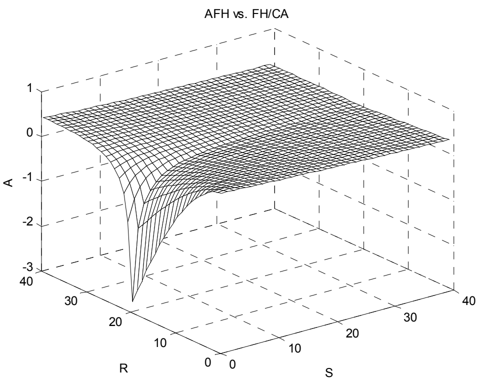

Fig. 7. Comparing the performance of system FH/CA with AFH in a band with static and dynamic jammers (N = 100, R_{MAX} = 20, G = 2, R = 1 to 40 and S = 1 to 40).

The FH/CA technique in a band with static and dynamic jammers usually has better results than the AFH technique. A significant contribution of the FH/CA technique can be seen in the case of dynamic jammers. On the other hand, in the case of static jammers R numbering up to R_{MAX}, the FH/CA technique loses. In the case under investigation, the FH/CA technique has better results than the AFH technique in 95% of cases.

Further, an analysis of gain in the case of static and dynamic jammers was made with parameters similar to the previous case, while increasing G to the value G = 3. To illustrate the analysis, the following parameters were used for the calculation: N = 100, R_{MAX} = 20, G = 3, R = 0 to 40, and S = 1 to 40. According to (42), the calculation of gain $A_{FH\text{-}FHCA}$ was performed, which is represented by the graph in Fig. 8. From Fig. 8, where $A_{FH\text{-}FHCA} = f(R,S)$, we can see the same conclusions as in case where G = 2.

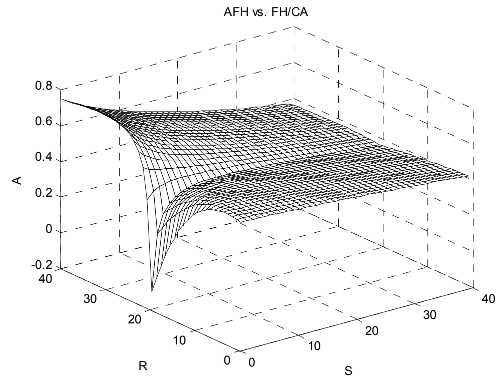

Fig. 8. Comparing the performance of system FH/CA with AFH in a band with static and dynamic jammers (N = 100, R_{MAX} = 20, G = 3, R = 1 to 40 and S = 1 to 40).

By increasing the value G, the performance increased in the case of static jammers in the FH/CA technique. In the case under investigation, the FH/CA technique has better results than the AFH technique in 99.8% of cases.

8. Conclusion

In this article the FH/CA (Frequency Hopping with Collision Avoidance) technique was proposed. The FH/CA station measures signal levels in the considered G channels before every jump. Based on the measurements the most appropriate channel with the lowest value of measured signal level is selected. Therefore, it is more probable that a jump to an unoccupied channel with a transmission will occur.

By comparing the values of the probability of jammed transmission, indisputable theoretical advantages of the new FH/CA technique were found, compared to the currently used FH and AFH techniques. The FH/CA technique always has better or equal results compared with the FH technique in the case of interference by static and dynamic jammers. The FH/CA technique in a band with static and dynamic jammers usually has better results than the AFH technique. A significant contribution of the FH/CA technique can be seen in the case of dynamic jammers. On the other hand, in the case of static jammers the FH/CA technique is in certain situations worse than the AFH technique.

Based on obtained formulae, it is possible to optimize the parameter G of the FH/CA system for the expected number and type of jammers. Based on data obtained from the model, it is also possible to choose an optimum error control code of the FH/CA system for the expected number and type of jammers.

References

[1] PUST, R., BURDA, K. Comparing performance of FH and AFH systems. *International Journal of Computer Science and Network Security*, 2010, vol. 10, no. 2, p. 82-85. ISSN: 1738- 7906.

[2] LAN/MAN Standards Committee of the IEEE Society, IEEE Std 802.15.1-2005, Part 15.1: Wireless MAC and PHY specifications for WPANs. [Online] Cited 2010-09-01. URL: http://standards .ieee.org /getieee802/download/802.15.1-2005.pdf.

[3] POPOVSKI, P., YOMO, H., PRASAD, R. Dynamic adaptive frequency hopping for mutually interfering wireless personal area network. *Mobile Computing, IEEE Transactions*, vol.5, no.8, p. 991-1003, Aug. 2006 doi: 10.1109/TMC.2006.114 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=164474 5&isnumber=34469.

[4] HSU, A.C.-C., WEI, D.S.L., KUO, C.-C.J., SHIRATORI, N., CHUNG-JU CHANG. Enhanced adaptive frequency hopping for wireless personal area networks in a coexistence environment. *Global Telecommunications Conference* GLOBECOM '07. 26-30 Nov. 2007, pp. 668-672. IEEE, doi: 10.1109/GLOCOM .2007.130 URL: http://ieeexplore.ieee.org/-stamp/stamp.jsp ?tp=&arnumber =4411040&isnumber=4410910.

[5] STABELLINI, L., SHI, L., AL RIFAI, A., ESPINO, J., MAGOULA, V. A new probabilistic approach for adaptive frequency hopping. *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, 13-16 Sept. 2009, p. 2147-2151, doi: 10.1109/PIMRC.2009.5450211 URL: http://ieeexplore.ieee.org/-stamp/stamp.jsp?tp=&arnumber= 5450211 &isnumber=5449713.

[6] PARK, K.-J, PARK, T. R., SCHMITZ, C. D., SHA, L. Design of robust adaptive frequency hopping for wireless medical telemetry systems. *Communications, IET*, January 22, 2010, vol.4, no.2, p. 178-191, doi: 10.1049/iet-com.2008.0693 URL: http://ieeexplore .ieee.org/stamp/stamp.jsp?tp=&arnumber=5383645&isnumber=53 83639.

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