Mutual Interference of Frequency Hopping with Collision Avoidance Systems

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Abstract. *The aim of this article is to quantify and analyze mutual interference of Frequency Hopping with Collision Avoidance (FH/CA) systems. The FH/CA system is a frequency hopping system where stations select the least jammed channel from several possible before the next jump. The article describes a mathematical model that allows determining the upper limit of the probability of collision of multiple FH/CA systems operated in a common band. The dependence obtained for mutual interference of FH/CA systems is compared with the dependence for mutual interference of conventional FH systems. The result of the comparison is a conclusion that, in terms of mutual interference, it is more advantageous to operate the FH/CA systems than the conventional FH systems.*

Keywords

frequency hopping, frequency hopping with collision avoidance, dynamic jammer, FH, FH/CA.

1. Introduction

The technique of frequency hopping (FH) belongs to the group of spread spectrum modulations [1],[2]. The FH technique is, in principle, a narrow-band transmission at a given moment of time but over a longer period of time the signal energy will be spread to the whole 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 advantages of systems with the frequency-hopping technique are, in particular, increased resistance to interference and higher security. Both advantages follow from the principle of the FH technique.

The FH/CA technique [3] (Frequency Hopping with Collision Avoidance) is based on the FH technique. Before the next jump however, the FH/CA station measures the signal levels in several considered channels. Based on the measurements the least jammed channel is selected. The FH/CA technique is a new technique, which has been published only recently. Thus, apart from paper [3], there is no other paper dealing with this topic. The FH/CA technique potentially produces a higher robustness with respect to jamming than hither to known techniques such as classical frequency hopping or adaptive frequency hopping. Therefore, this technique is much promising in military applications, where we can expect mass deployment of FH stations. But, mass deployment of FH stations implies a high level of mutual jamming of these devices. It is exactly this problem that is the topic of this paper.

For a practical deployment of the FH/CA system and for the selection of optimal parameter values it is useful to know how multiple independent FH/CA systems will mutually interfere in the common frequency band. The model for determining the intensity of mutual interference is as yet known only for conventional FH systems [4]. A mathematical model required for the FH/CA technique is described in this article. Using the above model the intensity of the mutual interference of FH/CA and FH systems is compared, intensity of mutual interference being the probability of collision between the communication system and the dynamic jammer in the frequency band. As a dynamic jammer we consider other systems operating in the band.

2. Mathematical Model

The FH/CA system has at its disposal N communication channels, and with every jump it selects one channel from G possible channels [3]. In the band with N communication channels there are in addition to the FH/CA system S dynamic jammers. We regard as dynamic jammers other FH/CA systems that operate in the band. It is assumed that these systems have the same parameters (e.g. tuning speed) and are not synchronized with each other and work independently. For the purposes of mathematical model the monitored FH/CA system will be the $(S+1)^{\text{th}}$ FH/CA system in the band.

The median number of occupied channels in the communication band is dependent on the number of active FH/CA systems and is therefore denoted as a function $O(s)$, where s is the number of active FH/CA systems in the communication band. If in the communication band another

FH/CA system is activated i.e. the $(s+1)^{\text{th}}$ system, the probability $P_O(s)$ that at the time of measurement any channel from the G channels under test will be occupied is:

$$P_O(s) = \frac{O(s)}{N} \ . \tag{1}$$

The probability $P_{OG}(s)$ that all from G possible channels will be occupied:

$$P_{OG}(s) = P_O(s)^G \ . \tag{2}$$

The activated $(s+1)^{\text{th}}$ system will be tuned to the already occupied channel and therefore will not increase the number of occupied channels, with probability $P_{OG}(s)$. Complementarily we can calculate the probability $P_{VG}(s)$ that at least one of G possible channels will be free:

$$P_{VG}(s) = 1 - P_O(s)^G \ . \tag{3}$$

The activated $(s+1)^{\text{th}}$ system will be tuned to an unoccupied channel and therefore increase the number of occupied channels by one, with probability $P_{VG}(s)$.

For the mean number of occupied channels $O(s+1)$ in the case of $(s+1)$ active FH/CA systems the following recurrent formula is then valid:

$$\begin{aligned} O(s+1) &= O(s) + 0 \cdot P_{OG}(s) + 1 \cdot P_{VG}(s) = \\ &= O(s) + \left[1 - \left(\frac{O(s)}{N}\right)^G\right] \end{aligned} \tag{4}$$

and $O(0) = 0$.

For simplicity, it is pessimistically assumed that the probability of the monitored FH/CA system colliding with some jammer P_{FHCAX} is equal to the value of the probability of tuning to an already occupied channel $P_{OG}(S)$ after the activation of all $s = S$ jammers (i.e. the other FH/CA systems).

$$P_{FHCAX} = P_{OG}(S) \ . \tag{5}$$

Simulation experiments showed that in reality the value of P_{FHCAX}, i.e. the probability of the monitored FH/CA system colliding with a jammer (i.e. another FH/CA system) is lower. The aforementioned formula for the mean number of occupied channels (4) is valid for a gradual insertion of FH/CA systems into the communication band. After inserting all of the FH/CA systems into the communication band it happens that some FH/CA system which is transmitting on an unjammed channel must tune to a jammed channel. As a result of this occurrence the mean number of occupied channels in the stabilized state is less than formula (4) provides.

The aforementioned mathematical model inaccuracy increases with the number of generators G and with the increasing value of the ratio of dynamic jammers to the number of channels S/N. For practical use, the mathematical model according to equation (5) can be considered sufficient. The reason is that the inaccuracy described above has a pessimistic character (i.e. the calculated collision probability is higher than the real one) and this inaccuracy shows up markedly only under extreme conditions, when the number of dynamic jammers approaches the number of channels. This conclusion is corroborated in Fig. 1, which shows the collision probability dependence on the number of FH/CA systems given by (5), and the same dependence obtained from the simulation model. Four simulation runs were performed for each point in Fig. 1, and one thousand hops were performed in each simulation run. Simulations were done using Matlab. From the figure it is clear that for same value of P_{FHCAX} the values of jammer numbers are a bit different. For example, when $P_{FHCAX} = 0.1$, this error is approximately 2 systems, i.e. the relative error is 4.1 %. Such an error is acceptable for practical system design.

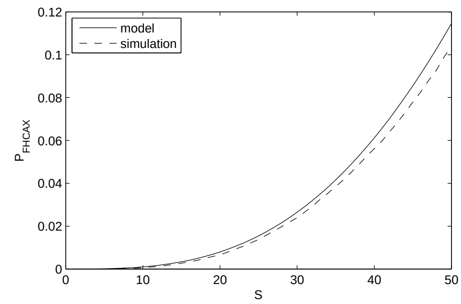

Fig. 1. Collision probability dependence on the number of FH/CA systems ($N = 100$, $G = 3$, $S = 1$ to 50).

3. Comparing the Performance

To compare the FH/CA technique with the conventional FH technique it is appropriate to introduce a model for the description of mutual interference of FH systems. This model has been taken over from [4] and modified. The probability of a collision or a jump of the FH system to the jammed channel is given by formula (6), where N is the number of communication channels and S is the number of dynamic jammers (i.e. the other FH systems).

$$P_{FH} = 1 - \left(\frac{N-1}{N}\right)^S \ . \tag{6}$$

A comparison of the two systems can be made using (7), where we subtract the collision probability of the FH/CA technique from the collision probability of the FH 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.

$$A_{FH-FHCAX} = \frac{P_{FH} - P_{FHCAX}}{P_{FH}}, P_{FH} \neq 0 \ . \tag{7}$$

The above analyses were calculated for specific parameters but the following conclusions can be considered general and valid also for different parameters.

For the comparison of mutual interference of FH/CA and FH systems, the following parameters were used in the calculation: $N = 100$, $G = 2,3$ and $S = 0$ to 100. Using (6) and (5), the calculation of collision probabilities P_{FH} and P_{FHCAX} were performed, with the results represented by the graphs in Fig. 2. Fig. 2 shows that the FH/CA technique significantly increases the number of FH/CA system which can simultaneously operate in the common band. For example, for the probability of collision $P_{FH} = P_{FHCAX} = 0.1$ 10 FH systems can operate simultaneously in the band, but in the case of FH/CA systems with $G = 3$ it can be up to 47 systems which is approximately five times more, that can operate in the same band with the same intensity of jamming. This is a significant benefit.

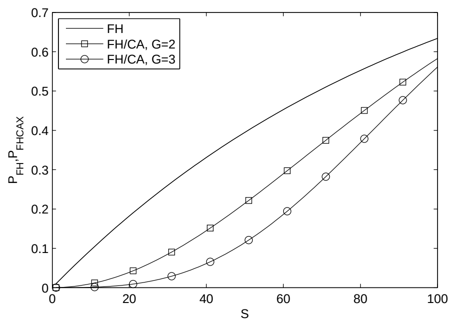

Fig. 2. Collision probability of FH/CA and FH systems in a band with dynamic jammers ($N = 100$, $G = 2$ and 3, $S = 0$ to 100).

Using (7), the calculation of gain $A_{FH-FHCAX}$ was performed, which is for $P_{FH} > 0$ represented by the graph in Fig. 3. From Fig. 3, where $A_{FH-FHCAX}$ =f(S), we can see the following characteristics of the FH/CA system.

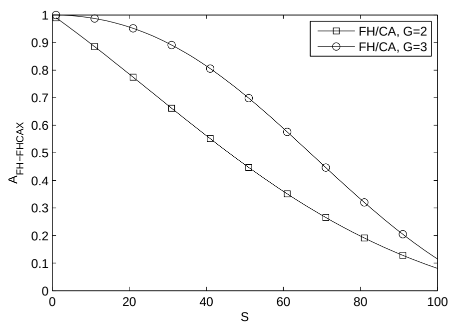

Fig. 3. Gain of FH/CA system in comparison to FH system in a band with dynamic jammers ($N = 100$, $G = 2$ and 3, $S = 1$ to 100).

The FH/CA technique in terms of mutual interference is never worse than the FH technique, because for the mentioned values of S it always holds $A_{FH-FHCAX} > 0$. The FH/CA technique has a significant gain already when using $G = 2$ generators. For example, for $S = 20$ and $G = 2$, the probability of collision with FH jammer is for FH technique $P_{FH} = 0.18$ while for the FH/CA technique it is $P_{FHCAX} = 0.0390$.

The probability of collision is almost five times lower when using the FH/CA technique than with the FH technique. Increasing the number of generators G leads to higher gains of the FH/CA technique. In this context, we have to bear in mind that increasing the value of parameter G leads to increased system redundancy and also to increased probability of desynchronization of stations. In the case of different jamming intensity conditions (i.e. in the case of very different values obtained by measuring the signal levels of stations) each station may select a different channel for a given time interval.

4. Conclusion

The described model of mutual interference of FH/CA systems allows assessing the possibility of simultaneous operation of multiple FH/CA systems in the common band. This possibility is simultaneously compared to a variant with simultaneous operation of multiple conventional FH systems. It turned out that the mutual interference of FH/CA systems compared with FH systems is significantly smaller, which allows operating much more multiple independent FH/CA systems than it is possible in the case of conventional FH systems in the same band. The FH/CA technique has a significant gain already when using $G = 2$ generators. Based on the formulae obtained, it is possible to optimize the parameter G and the error control code of the FH/CA system for the expected number of FH/CA systems operating in the common band.

References

[1] TORRIERI, D. *Principles of Spread-Spectrum Communication Systems*. New York: Springer, 2005.

[2] SIMON, M., OMURA, J., SCHOLTZ, R., LEVITT, B. *Spread Spectrum Communications Handbook*. McGraw-Hill, 2001.

[3] PUST, R., BURDA, K. A new technique of frequency hopping with collision avoidance. *Radioengineering*, 2010, vol. 19, no. 4, p. 499 - 506.

[4] 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.

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