Performance Analyses of Fast Frequency Hopping Spread Spectrum and Jamming Systems

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Abstract: *As technology becomes increasingly able to meet the requirements, interest in faster, noncoherent, frequency hopping rates to reduce the jamming of communication has heightened. The focus of this paper is on the performance of the fast frequency hopping spread spectrum system operating in the presence of partial band noise jamming. In this paper we consider a communication system that transmits binary data sequence or M frequency shift keying over a channel. With non-coherent detection, the MFSK tones on a given hop must be separated in frequency by an integer multiple of chip rate to provide orthogonality. The worst case partial-band noise jammer chooses fraction (r) to maximize the bit error probability (P_b) for a given M and signal to noise ratio. It has been observed from the simulation results that increases with K, illustrating the effectiveness of worst-case jamming (r_{wc}) against FH/MFSK signals at typical operating points. It may be noted that r_{wc} decreases as E_b/N_J gets larger.*

1. Introduction

There is considerable current interest in the application of frequency-hopping spread-spectrum techniques for combating jamming in radio communication systems [6, 5, 11, 4].

In 1993, Hussain and Barton [3] analyzed the communication performance of the noncoherent FSK system with the phase noise of oscillator in the Additive White Gaussian Noise (AWGN) channel using the phase noise analysis method. In 1999, Tsao *et al.* [8] analyzed the performance of the optical heterodyne FSK satellite communication system with phase noise. In the above [3] and [8], these were not on the fast FH system analysis, but only on the performance of the basic FSK system. In 1998, Teh *et al.* [9] addressed the multitone jamming rejection of FFH/Binary Phase-Shift Keying (BFSK) linear-combining receiver over Rayleigh-fading channels. In 2001, Shin and Lee [7] analyzed the performance of an FFH system with diversity combining in Rayleigh, partial-band, and multitone jamming environments. In the work described above [9] and [7], the performance of an FFH/FSK system with diversity combining more analyzed in detail.

Some of issues that have an impact on the relative applicability of frequency hopping Anti-Jamming (AJ) techniques are the jamming threat, in terms of type, sophistication, and number of jammers the acceptable quality of communications performance, the interface with other system elements, and the available bandwidth. The claim of reduced processing gain vulnerability for frequency hopping is a real threat to a frequency hop system. A follower jammer is a jammer that attempts to defeat the pseudorandomness of an antijam system by listening to the alternative being used by the communicator and then allocating all his resources to jamming that alternative. The degree of success enjoyed by the follower jammer is strictly a function of the percentage of the chip time that can jam. This in turn is a function of the communicators dwell time on each chip and by both the delay experienced by the follower jammer in determining the alternative being used by the communicator and by the delay associated with path geometry. It is the communicators dwell time that is the key factor in making the follower jammer a significant threat to the frequency hop system.

2. Non-Coherent FH/MFSK Approach for Anti-Jamming System

Another terminological ambiguity is the widespread use of the word "chip" to refer to an individual FH/MFSK tone of shortest duration, which should not be confused with the PN chips that drive the frequency synthesizer. In FFH system where there are multiple hops per *M*-ary symbol, each hop is a chip, whereas, in an SFH system a chip denotes an *M*-ary symbol. The chip rate $R_c = \max(R_h, R_s)$ is the highest FH system clock rate and the energy detectors, as shown in Figure 1 generate outputs at this rate. In the FFH mode, the *M*-ary symbol metrics are usually formed

by linearly combining the R_h/R_s detected chip energies for each symbol, resulting in a non-coherent combining loss.
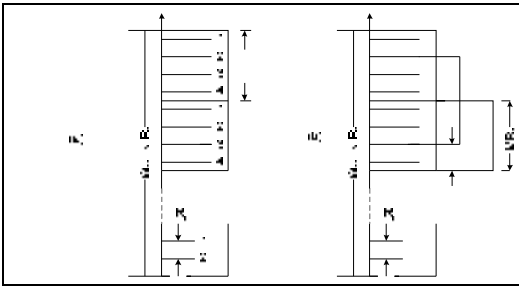

Figure 1. Frequency structures for FH/MFSK systems with N_t tones separated by R_c in (a) *M*-ary bands are contiguous and non-overlapping, (b) bands are shifted by R_c. Here $M = 4$.

With non-coherent detection, the MFSK tones on a given hop must be separated in frequency by an integer multiple of R_c to provide orthogonality. This implies that a transmitted symbol will not produce any cross talk in the other *M-1* energy detectors, and if the *M-ary* band contains Additive White Gaussian Noise (AWGN), the components of that noise in each detector output will be uncorrelated. Figure 1(a) depicts a common implementation in which the entire SS band is partitioned into $N_t = W_{ss}/R_c$ equally spaced FH tones [2]; these are then grouped into $N_b = N_t/M$ adjacent, non-overlapping *M*-ary bands, each with bandwidth MR_c. Under this arrangement, the PN binary *k*-tuples direct the frequency synthesizer to any of $N_b = 2^k$ carrier frequencies, and each FH tone is assigned to a specific, hop-invariant *M*-ary symbol. It is conceivable that a sophisticated jammer could exploit this assignment scheme. One method of scrambling the FH tone *M*-ary symbol mapping from hop to hop is to allow the synthesizer to hop the carrier over all but *M-1* of the N_t available frequencies so that adjacent *M*-ary bands are only shifted by R_c, as shown in Figure 1(b). A more jam-resistant and more expensive approach is to use *M* distinct frequency synthesizers to individually hop the *M*-ary symbols, destroying the contiguous nature of an *M*-ary band.

There are situations in which it is desirable to avoid certain regions of the Radio Frequency (*RF*) band (e.g., fading or narrowband jamming), and here FH enjoys a distinct advantage over Direct Sequence (DS) systems.

In addition to its AJ capability, an SS signal is generally difficult to detect and even harder to decipher by an unauthorized receiver. This characteristic is usually referred to as Low Probability of Intercept (LPI). Most interceptors operate as energy detectors and they have to monitor the received signal long enough to achieve a sufficiently high Signal to Noise Ratio (SNR) for reliable detection in the presence of background noise. The LPI advantage of an SS signal is that its power is spread over a bandwidth considerably larger than conventional transmissions, significantly increasing the noise in a receiver that is not privy to the despreading sequence.

3. Performance Analyses

In FH systems, the available channel bandwidth is subdivided into a large number of contiguous frequency slots. Spread-spectrum techniques have extensively been used for combat radio systems due to the favorable LPI and Low Probability of Detection (LPD) capabilities. Channel coding, interleaving, diversity, and their combinations effectively counter the severe degradation due to a jamming and thus, reduce the detectability of signals by an intercept receiver. Jammers are usually defined as a group of hostile communicators or intentional interferers that attempt to disrupt the communications of targeted users by transmitting an interfering signal over the same communication range. Partial-Band Noise Jamming (PBNJ) is one of the most effective jamming strategies against FH systems.

3.1 Partial Band Noise Jammer

A PBNJ where the jammer transmits noise over a fraction of the total spread spectrum signal band spreads noise of total power *J* evenly over some frequency range of bandwidth W_J, which is a subset of the total spread bandwidth W_{ss}. We define fraction (r) [1] as the ratio

$$r = \frac{w_j}{w_{ss}} \tag{1}$$

where r is (0, 1) which is the fraction of the total spread spectrum band that has noise of power spectral density [1]

$$\frac{J}{W_J} = \frac{J}{W_{SS}} \cdot \frac{W_{ss}}{W_J} = N_J / r \tag{2}$$

$$N_J = N_J / r \tag{3}$$

Suppose a gaussian noise jammer chooses to restrict its total power *J* (referenced to the FH receiver input) to a fraction r of the full *SS* bandwidth W_{ss}, as shown in Figure 2. A corresponding degraded SNR level

$$\frac{E_b}{N_t} = \frac{r \, E_b}{N_t} \tag{4}$$

It is assumed in Figure 2 that the jammer hops the jammed band over W_{ss}, relative to the FH dwell time $1/R_h$, but often enough to deny the FH system the opportunity to detect that it is being jammed in a specific portion of W_{ss} and take remedial action.
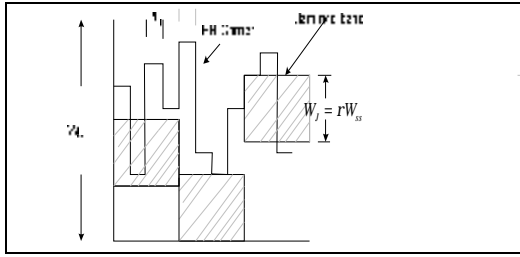
Figure 2. Partial-band noise jamming of FH system illustrating that jammer concentrates power in fraction r of SS bandwidth, and hops noise band to prevent FH band avoidance countermeasure.

Also to simplify the analysis, we will assume the shifts in the jammed band coincide with carrier hop transitions, so that the channel is stationary over each hop. Furthermore, we will assume that on a given hop, each M-ary band lies entirely inside or outside W_J. As Viterbi [10] has noted on a given M-ary symbol transmission, if only part of the M-ary band is jammed, and /or if it is only jammed over part of the symbol band, less noise is intercepted by the energy detectors, thereby reducing the probability of error.

Because of the pseudorandom hopping, it is reasonable to model the FH/MFSK system in partial-band noise as a two state channel, independent from hop to hop. With probability r, an M-ary transmission is jammed and the conditional P_b is determined by the SNR ratio of equation 4; but, since we are neglecting thermal noise, with probability $(1-r)$, the transmission is noiseless and an error-free decision is made then the average error rate is simply [1].

$$P_b = \frac{1}{2(M-1)}\sum_{i=2}^{M}(-1)^i\binom{M}{i}e-(KrE_b/N_J)(1-1/i) \quad (5)$$

$$P_b = r\,P_b\,\frac{r\,E_b}{N_J} \quad (6)$$

From equations 4 and 5 the resulting average performance can be expressed as

$$P_b =$$

$$max_{0<r\leq 1}\left[\frac{r}{2(M-1)}\sum_{i=2}^{M}(-1)^i\binom{M}{i}e^{-(KrE_b/N_J)(1-1/i)}\right] \quad (7)$$

For $M=2$, this maximation is a simple mathematical calculation; for larger values of M, it must be evaluated numerically.

$$P_b = \begin{cases}\frac{1}{2(M-1)}\sum_{i=2}^{M}(-1)^i\binom{M}{i}e-(KrE_b/N_J)(1-1/i),\\ and\ r_{wc}=1;\ \frac{E_b}{N_J}\leq g\\ \frac{b}{E_b/N_J},and\ r_{wc}=\frac{g}{E_b/N_J};\frac{E_b}{NJ}\geq g\end{cases} \quad (8)$$

4. Results and Discussion

As mentioned in Equation 4 that if r is reduced, the probability that an M-ary transmission is jammed is decreased, but jammed signals suffer a higher conditional error rate, resulting a degradation in the performance of FH/MFSK, depending on the values of M and E_b/N_J. Figure 3 illustrates the utility of jamming only part of the RF band for $M=2$. Taking $r=1/2$, over the same noise power then only half of the transmission are jammed, Reducing r to ½ degrades the performance more than an order of magnitude because of the steepness of the P_b curves in the selected region for different values of r, as shown in Figure 3.

The results indicated that the worst performance for these parameters occurs when the values of E_b/N_J gets smaller. Figure 3 depicts the performance of an FH/BFSK system in partial band noise for several partial-band jamming factors r. For small enough E_b/N_J, it is evident that broadband noise jamming ($r=1$) is the most effective. The performance in the worst case partial-band noise r_{wc} (maximum P_b) is the upper envelope (or supremum) of the family of P_b curve for different values of r, as shown in the Figure 3, when E_b/N_J exceeds a threshold level, $r_{wc}<1$ indicating a partial-band jamming advantage. The worst case partial-band noise jammer chooses r to maximize the P_b for a given M and E_b/N_J. It may be noted that r_{wc} decreases as E_b/N_J gets larger. Different values of r as a function of P_b, as shown in Table 1.
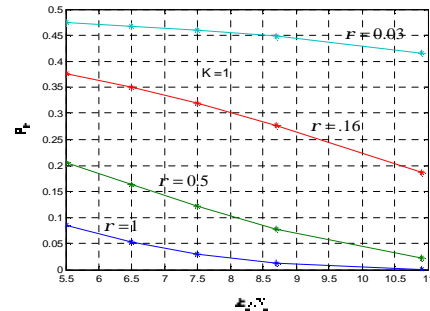

Figure 3. Performance of FH/BFSK system in partial-band noise for several fixed values of r.

Table 1. Variation of P_b with different values of r.

E_b/N_J (dB)	P_b			
	$r=1$	$r=0.5$	$r=0.16$	$r=0.03$
5.5	0.0848	0.2059	0.3764	0.4741
6.5	0.0536	0.1637	0.3498	0.4676
7.5	0.0301	0.1226	0.3189	0.4596
8.7	0.0123	0.0784	0.2763	0.4474
10.9	0.0011	0.0231	0.1869	0.4157

Equation 6 illustrates that so long as E_b/N_J is not unusually small, worst case partial-band jamming converts the exponential relationship between P_b and E_b/N_J in equation 4 into an inverse linear dependence. As shown in Figures 4 to 7, the resulting degradation can be severe for small P_b's: and increases with K, illustrating the effectiveness of worst-case jamming against FH/MFSK signals at typical operating points.

Equation 3 indicates that r_{wc} becomes very small for large E_b/N_J; that is, a worst case noise jammer concentrates its power in a small portion of W_{ss} at low P_b's. The signals do not get jammed most of the time, but those that do are likely to result in errors. This an indication that some form of coding redundancy that causes data decisions to depend on multiple symbols transmissions can reduce the effectiveness of partial-band jamming. Different values of P_b have been derived, as shown in Tables 2 to 5, by using $K = 1, 2, 3,$ and 4.

Table 2. Variation of P_b with different values of r keeping K=1.

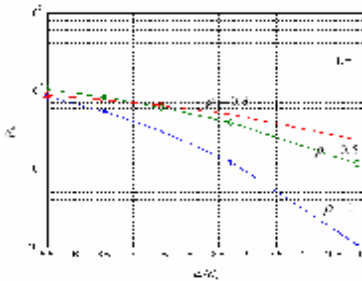| E_b/N_J(dB)	P_b		
	$r = 1$	$r = 0.5$	$r = 0.3$
5.5	0.0848	0.1030	0.0881
6.5	0.0536	0.0818	0.0768
7.5	0.0301	0.0613	0.0645
8.7	0.0123	0.0392	0.0493
10.9	0.0011	0.0115	0.0237

Figure 4. Degradation in FH/MFSK performance due to worst case, PBNJ with $M = 2$.

Table 3. Variation of P_b with different values of r keeping K=2.

E_b/N_J(dB)	P_b		
	$r = 1$	$r = 0.5$	$r = 0.3$
5.5	0.5180	1.5268	1.8626
6.5	0.2067	0.9645	1.4139
7.5	0.0650	0.5409	0.9994
8.7	0.0109	0.2211	0.5842
10.9	0.0001	0.0192	0.1347

Table 4. Variation of P_b with different values of r keeping K=3.

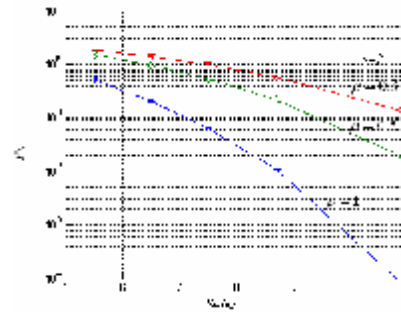| E_b/N_J(dB)	P_b		
	$r = 1$	$r = 0.5$	$r = 0.3$
5.5	0.3445	2.4651	4.288
6.5	0.0868	1.2376	2.8361
7.5	0.0153	0.5198	1.6853
8.7	0.001	0.1358	0.7532
10.9	0	0.0035	0.0834

Figure 5. Degradation in FH/MFSK performance due to worst case, PBNJ with $M = 4$.
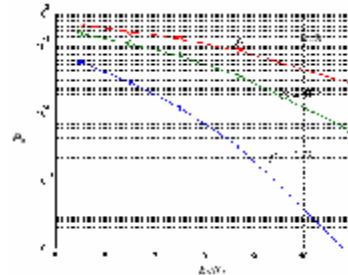

Figure 6. Degradation in FH/MFSK performance due to worst case, PBNJ with $M = 8$.

Table 5. Variation of P_b with different values of r keeping K=4.

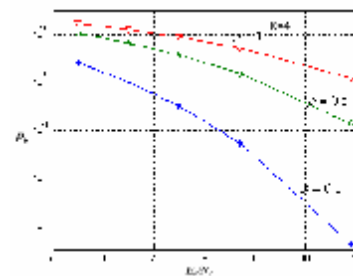| E_b/N_J(dB)	P_b		
	$r = 1$	$r = 0.5$	$r = 0.3$
5.5	0.0650	1.1290	2.8003
6.5	0.0103	0.4505	1.6137
7.5	0.0010	0.1417	0.8062
8.7	0.0000	0.0237	0.2755
10.9	0.0000	0.0002	0.0147

Figure 7. Degradation in FH/MFSK performance due to worst case, PBNJ with $M = 16$.

5. Conclusion

This paper provides an analytical framework for evaluating the performance of fast frequency hopping spread spectrum operating in the presence of partial band noise jamming. Numerical results have been presented for several cases and can be easily obtained from the available formulas for all the remaining cases for which they were not presented.

The availability and use of side information improves the system performance in all cases. In particular, it increases the value of r more drastically than it decreases the value of E_b/N_J. By contrast,

increasing the values of M decreases the value of E_b/N_J more drastically than it increases the value of r. Similarly, lowering the code rate improves r more drastically than it improves E_b/N_J.

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Othman Sidek obtained BSc in electronics in 1982 at University Sains Malaysia (USM), MSc in communication engineering from University Manchester Institute of Science and Technology, Manchester, United Kingdom in 1984. Since then served as a lecturer at USM for nearly four years pursuing PhD at Bradford and completed in 1993. His topic for PhD was using AI in CAD for VLSI. However, after a year of return, he turned to hardware design using FPGA, later exploring and introducing HDL into teaching and research. His research interest includes advanced FPGA design, IC design and MEMS. Currently, he is the director of Collaborative Microelectronic Design Excellence Centre, an initiative he started with the support of the Malaysian government in order to create more IC designers among Malaysian universities. Also, actively involves with research supervision and publications.

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