Robust Frequency Hopping for High Data Rate Tactical Communications

Colin Brown, Philip J. Vigneron
Communications Research Centre[1]
3701 Carling Avenue
PO Box 11490, Station H
Ottawa, Ontario K2H 8S2
CANADA

colin.brown@crc.ca, philip.vigneron@crc.ca

ABSTRACT

An adaptive frequency hopping spread-spectrum (FHSS) modulation scheme is proposed which efficiently utilizes available transmission bandwidth, whilst providing robustness to jamming techniques in wireless tactical communication systems. The proposed technique operates by transmitting multiple, single-carrier, parallel transmission subbands, which may occupy non-contiguous frequency regions. Simulation results demonstrate that the proposed scheme exhibits significant gain in error rate performance, as compared to a single subband system, in the presence of signal jamming and/or interference without a reduction in either the transmission data rate or an increase in transmitter power. In addition, the proposed scheme can adapt to use the available bandwidth for communicating, thus increasing the overall bandwidth utilization of the system.

1.0 INTRODUCTION

Frequency hopping can be used to limit performance degradation due to interference in a communications system and to reduce the likelihood of interception. For military applications, frequency hopping is particularly important as interference can take the form of signal jamming, multi-path interference or multi-user interference. In general, the latter two forms of interference are mitigated by including some form of channel equalisation in the receiver or by adequately controlling the number of users in a given transmission area. In terms of signal jamming, however, conventional systems use either a combination of frequency hopping techniques, interleaving, error correction coding and adaptive hopping sequences or they must resort to scaling back the expected data rates in response to certain jamming waveforms.

Schemes that mitigate the effects of adaptive jamming waveforms, such as follower jammers, rely on the transmitter hopping rate being greater than the tracking rate of the jammer. In partial or full band jamming, however, it may be difficult to avoid performance degradation while communicating, irrespective of the frequency hopping rate. In addition to the problems associated with providing anti-jamming capabilities, modern communication systems do not possess the ability to use the entire radio bandwidth in an adaptive and flexible manner, reflecting the highly-structured nature of legacy radio waveforms and of spectral allocation previously seen in military and civilian communications. This means that spectrum usage is often very fragmented and inefficient, with potentially large portions of the spectrum, though allocated, practically going unused.

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The technique presented herein provides an adaptive multi-band frequency hopping scheme that efficiently uses the available transmission bandwidth, which may be available only as disjoint subbands, whilst providing robustness to signal jamming and interference in wireless military communications. Conventionally, communication in a wireless system is achieved using a suitable access scheme transmitting in one contiguous block of frequency spectrum. In the presence of signal jamming, current frequency hopping techniques are designed so that a modulated carrier hops over the entire allocated radio bandwidth and actively avoids the signal jamming waveforms. In other words, a single contiguous block of frequency is hopped multiple times per second over the entire allocated frequency spectrum. For certain types of jamming, however, such as full or partial band jamming, the degradation in error rate performance or required transmit power is still observed irrespective of the hopping rate of the transmitted signal.

In some jamming scenarios, it is more effective to modulate data onto multiple parallel hopping waveforms. Most generally, the proposed scheme adaptively change the multi-band structure of the transmitted waveform by dividing the single contiguous block of transmitted data over multiple, variable width, parallel subbands. This scheme differs from the system proposed by Lance et al [1] as the latter scheme considers only attaining frequency diversity by transmitting replicas of the data signal. The main advantages of dividing the single contiguous block of data into parallel subbands are: firstly, it extends the transmitted symbol period and thus provides an initial performance gain in terms of robustness to multi-path interference; secondly, it provides frequency diversity allowing an increased performance gain when used with interleaving and forward error correction; and finally, it increases the inherent resilience to certain types of signal jamming e.g. continuous wave jamming. It will be demonstrated that in certain jamming scenarios there is an optimum number of subbands, with the optimum being, in general, greater than a single subband system.

The following sections detail the scheme proposed herein. Section 2.0 provides a more detailed description of the multi-band scheme compared to conventional anti-jamming and/or interference suppression schemes. This is followed in section 3.0 with simulation results showing the performance of the scheme for various types of jamming. Section 4.0 then concludes with a short discussion and the main conclusions embodied by this paper.

2.0 SYSTEM DESCRIPTION

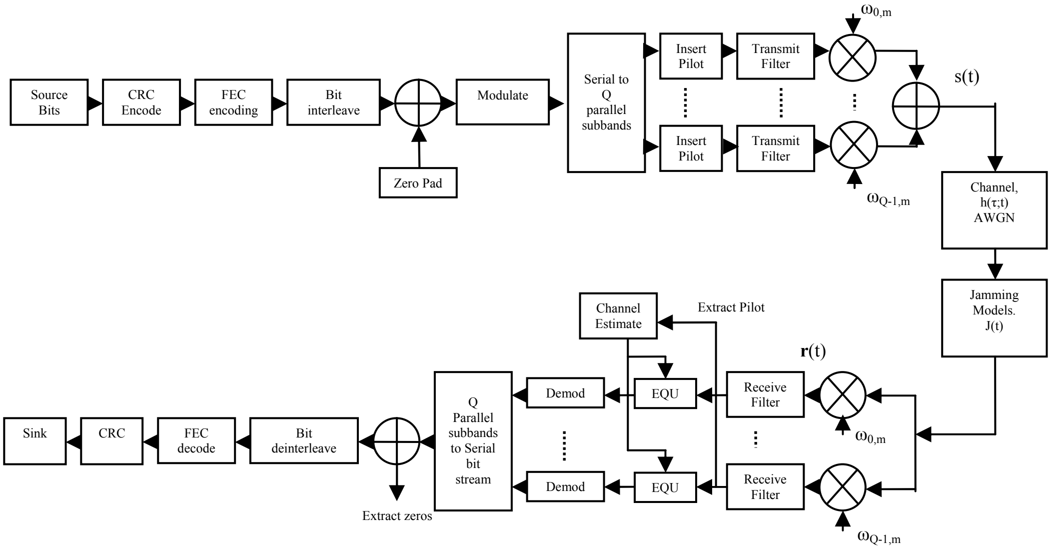

Figure 1 : Block diagram of the transmitter and receiver chain for a multi-band frequency hopping scheme.

Figure 1 shows a block diagram of the proposed multi-band frequency hopping system. In the system, the source generates N_b information bits which are appended by a cyclic redundancy check code, c, prior to encoding by a forward error correction code, producing code words of length n/k. The encoded bit stream is then interleaved to avoid bursts of errors in the receiver and mapped onto a linear modulation scheme of N_s symbols, where $N_s = ((N_b + c)\,n/k)/\log_2(M)$, k/n represents the coding rate and M represents the modulation order. For convenience, the sequence of complex symbols can be written as a vector $s_m = \left[s_{0,m},\ldots,s_{N_s,m}\right]$, where N_s represents the number of symbols in a coding block. At the serial to parallel converter, the block of N_s symbols is divided into Q subbands, each with $N_{sb} = N_s/Q$ symbols per subband. A pilot sequence is then inserted and each subband is band-limited and frequency translated to the user defined pseudo-random hopping frequencies. Thus, the signal at the output of the transmitter can be written as [2][3]:

$$s(t) = \sum_{m=-\infty}^{\infty}\sum_{q=0}^{Q-1}\mathrm{Re}\left\{s_{q,m}(t)e^{j\omega_{q,m}t}\right\} \qquad (0.1)$$

where $\mathrm{Re}\{\bullet\}$ represents the real part of $\{\bullet\}$, $\omega_{q,m}$ are the hopping frequencies for each subband, selected to ensure negligible adjacent carrier interference and which vary for each hop interval and $s_{q,m}(t)$ are the transmitted symbols in mth hop defined as:

$$s_{q,m}(t) = \sum_{j} s_{qNsb+j}\,g(t - mT_h - jTs), \quad \text{for } q = 0,1,\ldots Q-1 \qquad (0.2)$$

where T_s is the symbol period, T_h is the hopping interval and $g(t)$ is the impulse response of the pulse shaping filter. For the results provided, the filter $g(t)$ is a root raised cosine filter with a roll-off factor of $\beta = 0.22$.

Assuming the receiver is synchronized to the transmitter and the pseudo-random hopping frequencies $\{\omega_{q,m}\}$ are known, the equivalent low pass signal at the input to the receiver filters can be written as:

$$r_{q,m}(t) = \sum_{m=-\infty}^{\infty} \sum_{l} s_{q,m}(t - \tau_l(t)) h_{q,m}(\tau_l(t)) + w_{q,m}(t) + J_{q,m}(t) \qquad (0.3)$$

where $h_{q,m}(\tau_l(t))$ represents the time variant complex channel gain delay τ_l, $w_{q,m}(t)$ is the additive white Gaussian noise with a two-sided spectral density of $N_0/2$ and $J_{q,m}(t)$ is the additive jamming and/or interference waveform present in the qth subband and the mth hop.

The received signal is then filtered by the pulse matched filters and sampled at the symbol rate T_s, such that the input to the bank of channel equalizers in the mth hop is given as:

$$y_{q,m}(nTs) = y_{q,m}(n) = \sum_{l=0}^{L-1} s_{q,m}(n-l) f_{q,m}(l_n) + I_{q,m}(n), \qquad mN_{sb} < n \le (m+1)N_{sb} \qquad (0.4)$$

where $f_{q,m}(l_n)$ represents the equivalent complex baseband representation for the transmit filter, channel and receiver matched filters $g*(-t)$, respectively, in the qth subband and the mth hop, $I(n)$ represents the sampled additive combination of the interference terms $J(n)$ and $w(n)$ filtered by the receiver matched filter and L represents a finite set of channel coefficients.

Equation (0.4) shows the worst case interference present in the received signal, including intersymbol interference (ISI), jamming and additive noise terms. However, one advantage of a multi-band scheme compared to a single carrier system is that for a given wideband data signal, the multi-band scheme transmits using multiple narrowband signals and thus the fading experienced in each subband is frequency flat. As a result, the equivalent low pass channel $\{f_{q,m}(l_n)\}$ in equation (0.4) reduces to:

$$f_{q,m}(0) = \alpha_{q,m} e^{-j\theta_{q,m}}$$

$$y_{q,m}(n) = s_{q,m}(n) \alpha_{q,m} e^{-j\theta_{q,m}} + I_{q,m}(n), \qquad mN_{sb} < n \le (m+1)N_{sb} \qquad (0.5)$$

where $\alpha_{q,m} e^{-j\theta_{q,m}}$ represents a complex channel gain which is constant over the hop interval. It is assumed that the sequence of hop frequencies are chosen such that $f_{q,m}(0)$ and $f_{u,v}(0)$ are uncorrelated for $q \ne u$ and $m \ne v$.

The term $f_{q,m}(0)$ in the received signal can be effectively estimated by extracting channel information from the pilot symbols and then averaging over all pilot symbols, in a hop, to produce an estimate $\hat{f}_{q,m}(0)$. In a frequency flat slow fading channel, the averaging of pilot information will reduce the noise of the channel estimate. However, the received signal remains corrupted by the interference term $I(n)$, of which the jamming signal is the dominant effect in the degradation of the BER performance. In [4] an adaptive scheme is discussed to select areas of the spectrum with little or no jammer energy for transmission of a multi-band system, thus actively avoiding areas of the spectrum with relatively large jammer and/or interference signals $I(n)$. However, even without adaptive spectrum selection techniques, a considerable gain in the BER performance is still achieved using a multi-band transmission approach compared to a single carrier system, due primarily to the frequency hopping nature of the transmission scheme and the inherent time diversity achieved by interleaving over multiple parallel subbands.

In the following section, simulation results are presented comparing the performance of a single subband scheme with multiple subbands in a variety of jamming scenarios.

3.0 SIMULATION RESULTS

The following results compare the performance of a single subband scheme with various multi-band systems in a variety of jamming scenarios. The modulation scheme under consideration is QPSK and the channel model is additive white Gaussian noise. Except where indicated, the results show BER performance for uncoded waveforms, thus the effects of jamming can be more readily quantified. Further, the performance trends exhibited can be equally extended to higher order linear modulation schemes and also to non-linear modulation schemes, such as continuous phase modulation (CPM).

Figures 2 and 3 show the performance of a single subband consisting of a 5MHZ bandwidth (denoted ‘1x5MHz’) and multiple subbands consisting of five 1MHz bands (denoted ‘5x1MHz’) respectively, subject to partial band noise jamming. The total UHF operating bandwidth is 175MHz, and the frequency hopping rate for the simulations is 1000 hops per second. Partial band noise (PBN) jamming consists of adding a white Gaussian noise jamming signal, over the band of interest, for an SJR = -30dB and a residual Eb/N0 = 10dB. The BER curves in the figures represent the performance when a percentage of the operating band is subject to jamming; thus 100% PBN (equivalent to full band noise (FBN) jamming) means that the entire operating band is subject to jamming, and hence, for this case, the BER performance will be equivalent for all multi-band transmission schemes. To illustrate the potential gains fully when using multiple subbands, Figures 2 and 3 show the performance for QPSK modulation with a rate ½ convolutional code. In this case, Figure 2 shows that the gain in performance compared to Figure 3, as the percent PBN is decreased, can be attributed to interleaving over the multiple subbands. Moreover, as the percentage of the operating band that is subject to jamming is decreased, the 5x1MHz parallel transmission scheme is able to recover bursts of errors when a hopping frequency that is subject to PBN jamming is selected. Indeed, by increasing the interleaving duration to cover multiple subbands and frequency dwells, a further diversity gain is achievable.

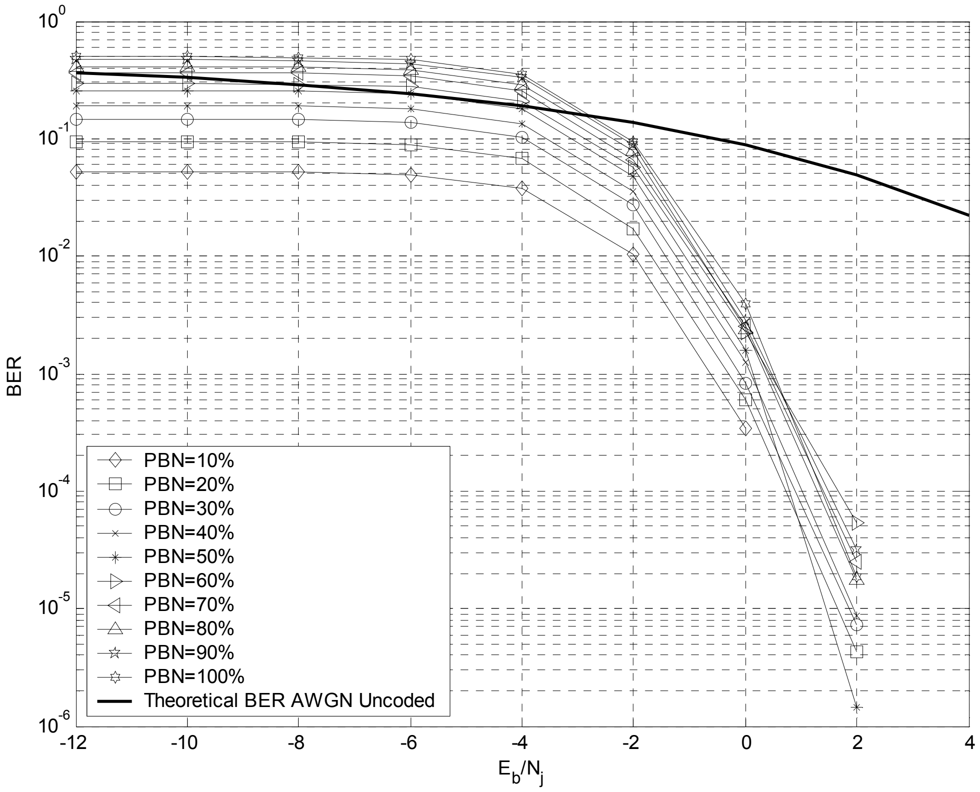

Figure 2: BER performance for rate ½ QPSK in PBN jamming, for a 1x5MHz system, with a residual E_b/N_0=10dB.

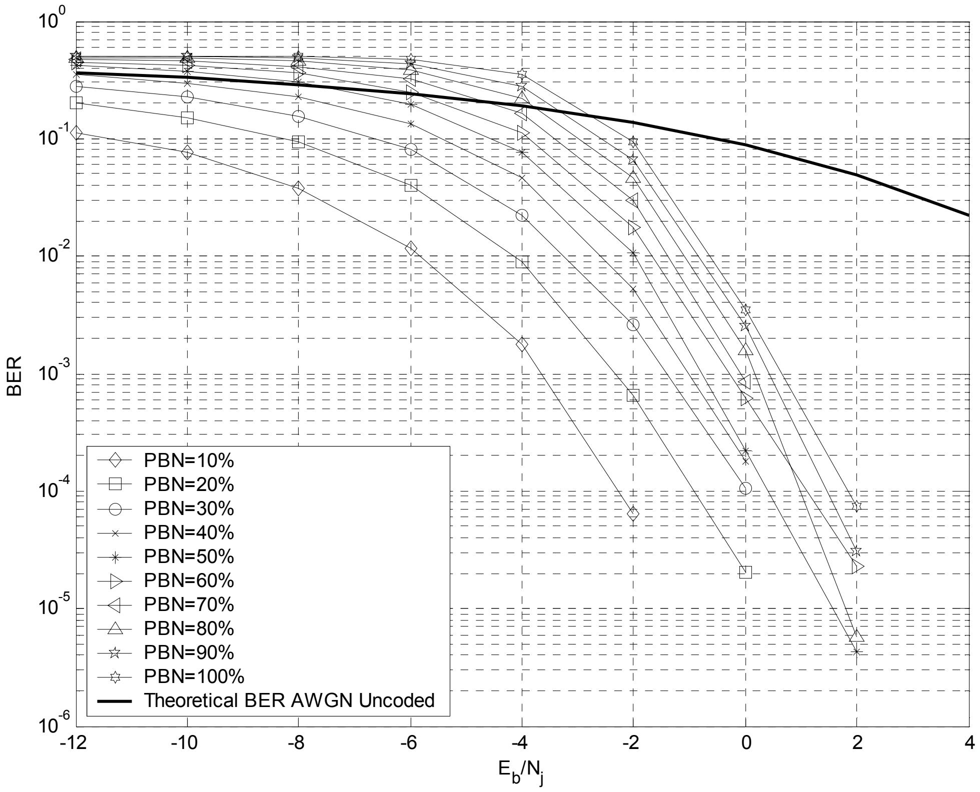

Figure 3 : BER performance for rate ½ QPSK in PBN jamming, for a 5x1MHz system, with a residual E_b/N_0=10dB.

In Figures 4 and 5, the BER performance is shown for a 1x5MHz system and a 5x1MHz system, respectively, subject to multi-tone (MT) jamming. The jammer waveform consists of 175 jamming tones evenly distributed over the UHF operating band. It is clear that as the signal to jammer ratio (SJR) is decreased, the 5x1MHz scheme in Figure 5 is more robust to this particular form of jamming compared to the 1x5MHz scheme, with the limiting case on performance for the latter scheme being for SJR=-30dB. In other words, the multiple subband system demonstrates a considerable gain in BER performance compared to the single subband scheme in jamming scenarios with relatively high SJRs.

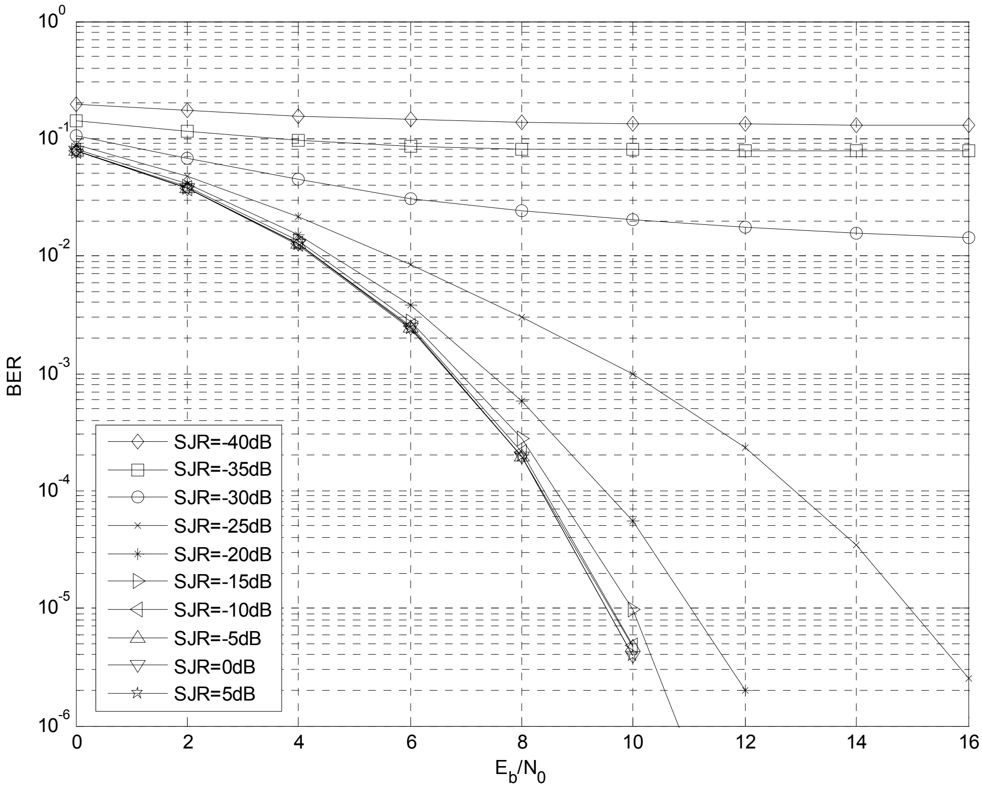

Figure 4: BER performance for uncoded QPSK in MT jamming, for a 1x5MHz system, subject to 175 evenly distributed jamming tones.

To demonstrate further the obvious advantage in using multiple subbands, Figure 6 shows the BER performance in multi-tone jamming as a function of the number of subbands used. Note, the total transmission bandwidth for the simulation results remains fixed at 5MHz, such that the subband bandwidths are defined as $Q\text{x}(5MHz/Q)$; this ensures that the data rate of the system is approximately equal for all subbands tested. It is interesting to note, from Figure 6, that as the number of subbands is increased, a corresponding increase in the BER performance does not exist for all combinations of subbands. This result can be explained as follows: for a given total emitter energy, the energy per subband is a function of the number of subbands used in transmission. Thus, as the number of subbands increases, the bandwidth and energy per subband decreases, resulting in a transmission waveform that is less likely to be detected, due to the smaller bandwidths, but is now more sensitive to jamming waveforms when the hopping frequencies coincide with jammed regions of the spectrum. This means that an optimum number of subbands will exist, dependent on the jamming environment encountered. For the multi-tone jamming waveform set at SJR=-30dB, Figure 6 shows that the optimum number is four subbands each of 1.25MHz bandwidth (4x1.25MHz).

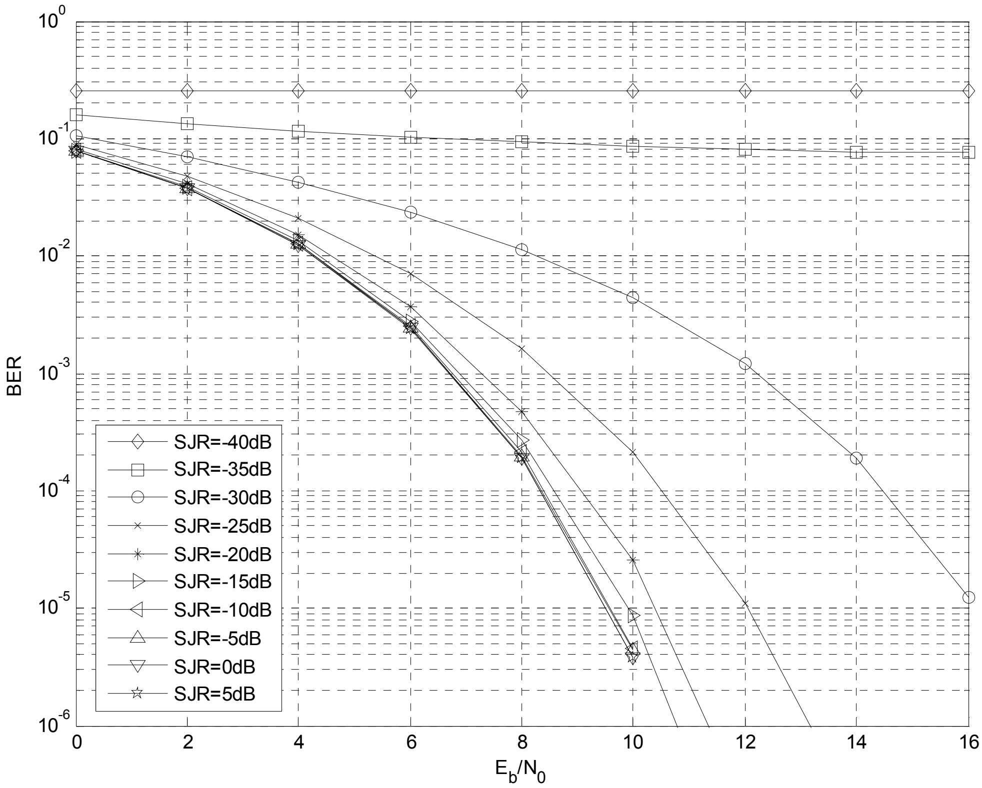

Figure 5: BER performance for uncoded QPSK in MT jamming, for a 5x1MHz system, subject to 175 evenly distributed jamming tones.

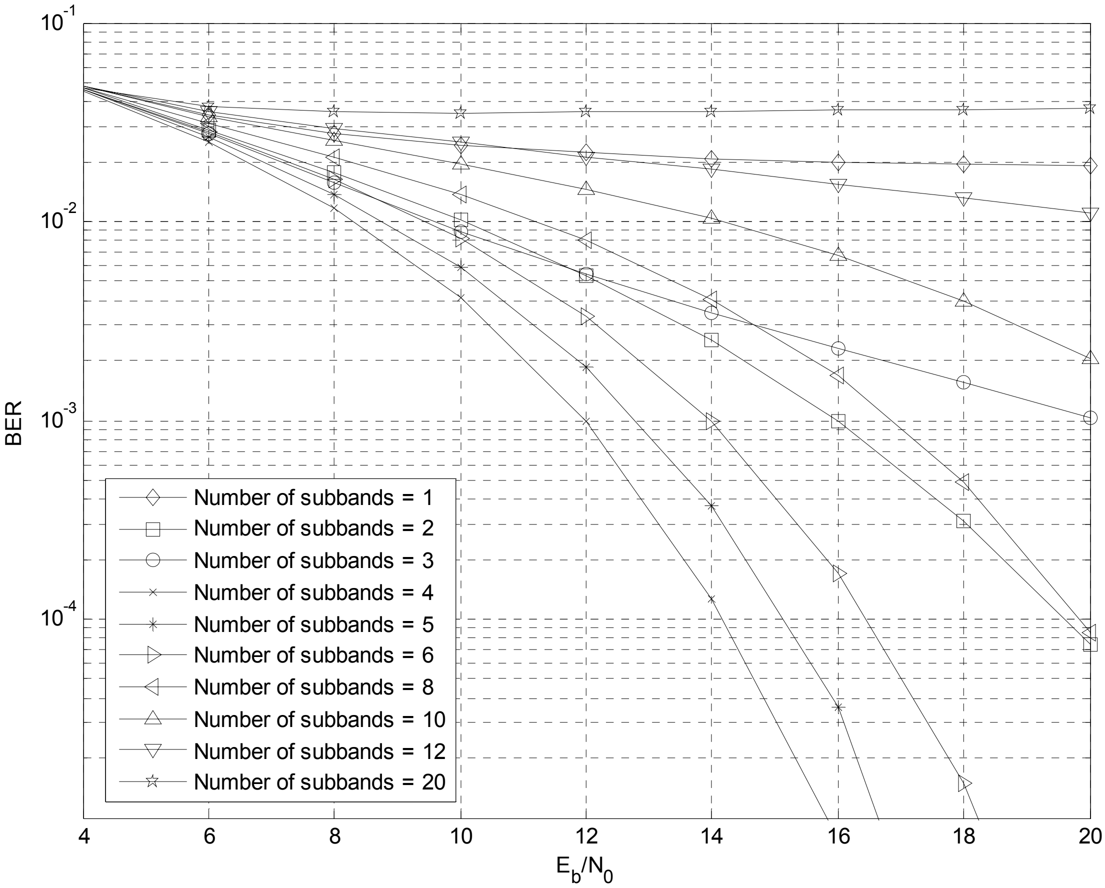

Figure 6: BER performance for uncoded QPSK in MT jamming, for various subbands, subject to 175 evenly distributed jamming tones of SJR=-30dB.

4.0 CONCLUSIONS

An adaptive frequency hopping spread-spectrum (FHSS) modulation scheme which efficiently utilizes available transmission bandwidth, whilst providing robustness to jamming techniques has been proposed. Simulation results have shown that in PBN, the multi-band scheme exhibits a diversity gain compared to a single subband solution, due to interleaving over multiple parallel subbands. In addition, when comparing the performance in multi-tone jamming, the proposed technique exhibits a considerable gain over single subband system for various SJRs. It is important to note, however, that the proposed multi-band scheme requires no extra power or bandwidth to realize the performance gains, compared to a conventional single subband solution.

Additionally, there are no requirements for jammer information to be known in order to obtain performance benefits. If jammer information is available, the proposed system can make adaptive adjustments to improve performance further, for example, by careful choice of subband frequencies.

5.0 REFERENCES

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