Adaptive Use of Spectrum in Frequency Hopping Multi-Band Transmission

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ABSTRACT

A method to achieve high data rate transmission in a wireless military communications system is proposed. The scheme operates by periodically measuring energy over the span of the transmission band, and identifying spectral areas with low jammer and/or interference energy. A probabilistic algorithm is then used to adaptively define spectral regions in which a frequency-hopped spread-spectrum (FHSS) system can operate. Simulation results have shown that schemes incorporating spectrum measurement and adaptive frequency hopping combined with multi-band transmission, exhibit relatively large gains compared to schemes employing multi-band transmission and considerable gain when compared to a single carrier FHSS transmission scheme.

1.0 INTRODUCTION

Requirements for the next generation of high data-rate tactical ultra high frequency (UHF) communications are to achieve data rates of the order of several Mbps, for which a wideband modulation scheme is required. Additionally, to have sufficient anti-jamming properties, such a waveform would use the spread-spectrum technique of frequency hopping. In the 225-400 MHz tactical band, there are insufficient available frequencies for such a wideband signal to operate and to have sufficient hopping frequencies to provide processing gain against jamming. One proposal has the tactical radio relay bands made available for wideband UHF services, providing 40 MHz, within which a wideband waveform of roughly 5 MHz would hop. This is clearly an insufficient operating band to achieve useful anti-jamming performance.

An alternative approach arises from necessity once it is clear that insufficient contiguous blocks of spectrum are available for wideband frequency hopping waveforms in the military communication bands. An adaptive multi-band modulation scheme utilizing available parts of the spectrum to achieve high data rate communications is proposed. Wideband multi-band modulation is achieved by modulating information onto multiple smaller bandwidth emissions, each of which undergoes frequency hopping, thereby actively avoiding jamming and/or interference, with little or no external supervision. Other schemes where parallel modulation with FHSS are used are for purposes of improving performance using diversity [1], in contrast to the current proposal where the parallel modulation channels carry different data.

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In the jamming environment little is known about the intelligence or the agility of the jammer. Therefore a useful adaptive modulation scheme will respond to changes in the channel environment, searching out spectral regions with low noise or interference for use by the FHSS waveforms, without assuming knowledge of the jammer operation. It will be shown that when such a system is used with a multi-band FHSS modulation, not only is wideband communications enabled, but the fundamental anti-jamming performance of the modulation is improved, as compared with using a single modulated frequency-hopped carrier.

There are three key elements in the proposed adaptive modulation scheme. The first is a periodic measurement of the spectrum energy density over the span of the transmission band (operating band). The operating band is then categorized by energy content, thereby identifying spectral areas with low jammer and/or interference energy. A description is then made of the operating band, with the desirable operating regions assigned a higher likelihood of use than those regions with high levels of noise, interference, or jamming. The desirable regions are then identified as potential candidates for frequency hopping. Finally, a density function governing the spectrum utilization is defined. This governing density function allows the system to automatically adapt, pseudo-randomly but constructively, to the dynamic jamming and interference environment in a way that cannot be predicted by an interceptor. As the jamming or interference environment changes, the spectral density estimation and consequently the governing density function is updated. The latter stage is a key part of the proposed system, as it is the density function that provides the automatic adaptation of the spectrum usage in response to a jammer and/or interference signal. In addition to identifying and ranking desirable spectral regions for communications, the system uses a multi-band frequency hopping scheme to effectively avoid jamming signals and provide high data rate communications in a highly fragmented operating band.

In the following sections, the multi-band FHSS modulation scheme is defined, and a method to adaptively allocate hop frequencies in the jamming environment is presented. This is followed by simulation results showing the performance of the proposed scheme, using multi-band FHSS transmission in the presence of random multi-tone jamming, and is compared to a single carrier FHSS performance. The paper concludes with discussions and conclusions.

2.0 SYSTEM DESCRIPTION

The multi-band FHSS modulation scheme is introduced and defined in detail in [2]. The upconverted transmit signal for Q subbands can be written as:

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

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 $\beta = 0.22$. N_{sb} is the number of symbols in each subband and **s** is a vector of transmit symbols defined as $s_m = \left[s_{0,m}, \ldots, s_{N_s,m} \right]$.

Once the subband data have been formed, it remains to define the specific bands, which vary over time, from which the hopping frequencies are chosen to carry the subband waveforms. However, first, some terminology is defined. The region of the spectrum in which the system can operate is termed the ‘operating band’, see Figure 1. In the case of military UHF communications, for example, this is defined as 225-400 MHz. When this band is subject to jamming, then only a subset of the operating band is deemed as useful to achieve reliable communication and thus chosen to be used at any one time. This subset of the operating band is termed the ‘available hopping frequencies’. The available hopping frequencies therefore, form a subset of the operating band and may consist of a set of non-contiguous frequency ranges. A FHSS radio network will choose the frequencies on which energy is actually emitted, during each hop, pseudo-randomly from the set of available hopping frequencies; in a ‘multi-band FHSS’ scheme, there will be several hop frequencies used concurrently at any time, all of which must lie within the set of available hopping frequencies.

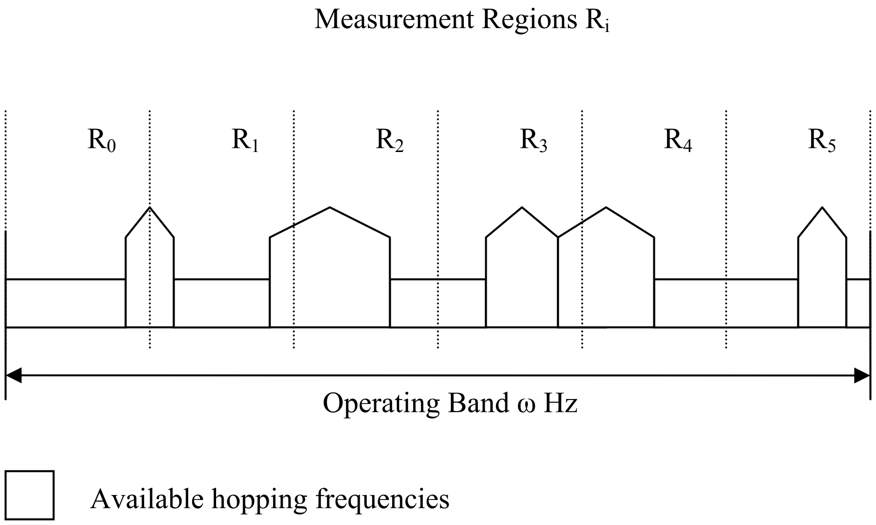

Figure 1 : Example of the transmission spectrum including operating band, available hopping frequencies and measurement regions for the proposed adaptive system.

An integral part of the proposed scheme is the periodic coarse measurement of the spectral energy over the total operating band as seen from the receiver; this is used to assess the occupancy of the operating band by noise, jamming and/or interference. The energy measurements, provided by the coarse measurement, are the basis on which the adaptive system dynamically chooses the available hopping frequencies, although this choice is made randomly so that the jammer can not predict precisely where in the operating band that communications will occur. With regular energy measurements of the operating band, the interference and jamming-free regions are then varied in time. This leads to the set of available hopping frequencies varying in time, in response to a changing external interference or jamming environment. The hop frequencies change after each dwell interval. In effect, the FHSS system is directed to hop into relatively interference-free regions of the operating band adaptively.

An implementation of the scheme involves measurement of the power spectrum density (PSD) magnitude over the operating band. A simplistic but effective measurement scheme is to divide the operating band into a finite number of discrete ‘measurement regions’. An example of the measurement regions $\{R_i\}$ are shown in Figure 1. In this example, the operating band is divided into six regions, whereby the energy is measured within these regions, allowing a discrete approximation to the PSD magnitude to be obtained.

This is a 'coarse' PSD estimate, but it has been found, in simulation, to be a sufficient and acceptable technique to characterize the operating band PSD magnitude as required by the adaptive frequency hopping scheme.

The method can be described by the following steps:

- Divide allocated band ω into N measurement regions with each region $R_i = [f_i, f_{i+1}),\ i = 0,...,N-2$ and $R_{N-1} = [f_{N-1}, f_N]$. The total operating band is then $\omega = R_0 \cup ... \cup R_{N-1}$.

- Measure electromagnetic energy within each region R_i giving E_i. The measurement technique is not specified, although it will generally be performed using signal processing techniques on received signals filtered to within the operating band and sampled using analog-to-digital conversion. The primary constraint on the signal processing is that the energy be measured in the required bandwidths (ie. $[f_{i,} f_{i+1}]$), which can be accomplished using an FFT-based algorithm. The discrete approximation of the operating band PSD is

$$S(f) = \sum_{j=0}^{N-1} \left(\frac{E_j \delta\left(f_j \le f < f_{j+1}\right)}{\left(f_{j+1} - f_j\right)} \right)$$

  where $\delta(\gamma)$ is unity when γ is true, otherwise $\delta(\gamma)$ is zero.

- Define relative weightings W_i for measured energy E_i based on the energy measured in all regions to be

  $W_i = q\left(E_i,...,E_{N-1}\right)$ with $i = 0,...,N-1$.For example, the function $q(\bullet)$ could be the weighted normalization to total energy

$$W_i = \frac{\alpha_i E_i}{\sum_{j=0}^{N-1} \beta_j E_j}.$$

- Define a distribution governing the probability that the FHSS system uses the regions R_i as available hopping frequencies, based on weights W_i, to be $\mathrm{P}_{R_i \dots R_{N-1}}\left(\rho_i,...,\rho_{N-1}\right) = g\left(W_i,...,W_{N-1}\right)$.

The function $g(\bullet)$ is again a design choice and is based on the deployment scenario. Once the probability function has been defined, a decision is taken as whether to use the regions R_i with $i = 0,...,N-1$ for available hopping frequencies within the operating band. This decision is taken randomly with probability $\mathrm{P}_{R_i \dots R_{N-1}}\left(\rho_i,...,\rho_{N-1}\right)$ and thus ensures a degree of uncertainty, in the selection of the hopping frequencies.

To further clarify the idea behind the proposed technique, Figure 2 shows a flow chart depicting the inclusion of the technique in an adaptive frequency hopping system.

Upon link initialization, the hopping sequences are synchronized and the link negotiates transmission scheme parameters such as modulation type, data rate, coding scheme, number of subbands to be used, and probability function $g(\bullet)$. Once initialized, communication across the link may begin. The next step in the flowchart is to monitor the channel quality; which is achieved by measuring the PSD of the operating band and ranking the regions of the spectrum according to their energy content. Once the ranking of the regions is complete, the system determines whether the current hopping frequencies are contained within the set of available hopping frequencies. If they do, and there is no external request to change the hopping frequencies, communication continues. However, if the current hopping frequencies are not a member of the set of available hopping frequencies, a new set of hopping frequencies are generated and used for transmission, and the scheme adaptively changes the transmission parameters to reflect this change.

Figure 2 illustrates the flowchart for a generic adaptation scheme. Thus the channel quality monitoring can be used to either measure the PSD of the channel and identify when a change in hopping frequencies are required; or measure the error rate at the receiver and determine whether a change in transmission system parameters such as the coding rate or scaling back data rate is required. In the latter case, the PSD estimation can be used as an external input to adaptively change the transmission scheme parameters; in this case, the measurement resolution is used as an input to the PSD estimation.

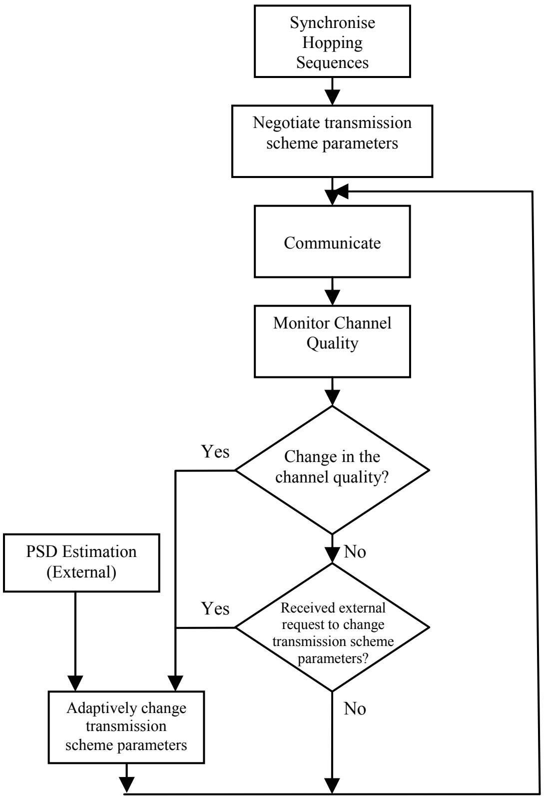

Figure 2 Flowchart depicting how PSD estimation is used in an adaptive system in the presence of signal jamming and/or interference.

There are a number of important points to note when considering the scheme as described above. Firstly, when the regions are ranked and selected as available hopping frequencies, there remains a small probability of the transmission scheme selecting regions containing significant jamming and/or interference. This is a design choice governed by the probability function $g(\bullet)$, and allows the system to avoid situations whereby an intelligent jammer can effectively force the adaptive transmitter into using a specific band by increasing interference energy across other parts of the spectrum. This avoids the situation where then presumably the jammer could monitor this specific band to intercept the message or perform direction finding. The performance degradation from using a jammed band is recovered with error correction. The result is that the proposed scheme selects the available hopping frequencies based on a probability distribution and hence avoids the potential problem where if operating regions were deterministically chosen, that an interceptor could predict or even control the choice of available hopping frequencies.

From this carefully selected set of available hopping frequencies, the FHSS modulation chooses the actual frequencies used for each hop dwell in a conventional pseudorandom manner. The FHSS may use a multi-band or a single band scheme. In other words, the transmission scheme maintains a frequency hopping structure, based on a deterministic pseudo-random hopping code, with the only constraint being that the transmitted hopping frequencies are selected from the set of available hopping frequencies. As the measurement of the PSD in the operating band is updated at a rate equal to or faster than the jammer and/or interference can adapt to the transmission conditions, the scheme then actively avoids the jammer and/or interference.

3.0 SIMULATION RESULTS

Simulations are provided showing the performance of the adaptive scheme in the presence of a multi-tone jamming waveform. Figure 3 shows the BER curves for several signal to jamming ratios (SJR), when the transmitted signal is subject to a jamming waveform consisting of 175 randomly spaced tones (which has been shown to be a worst case scenario) distributed over the entire UHF 225-400MHz operating band. In this simulation, the channel model is assumed to consist of additive noise only and the modulation scheme is QPSK. The transmission system is an uncoded multi-band scheme consisting of one subband with bandwidth of 5MHz (defined as “1x5MHz”). Figure 3 illustrates that as the SJR is decreased, the performance of the scheme deteriorates such that for SJR values of -30dB and less, an irreducible error floor is observed in the receiver performance. Thus, in this scenario, an SJR of -30dB at the receiver is the limiting case on performance.

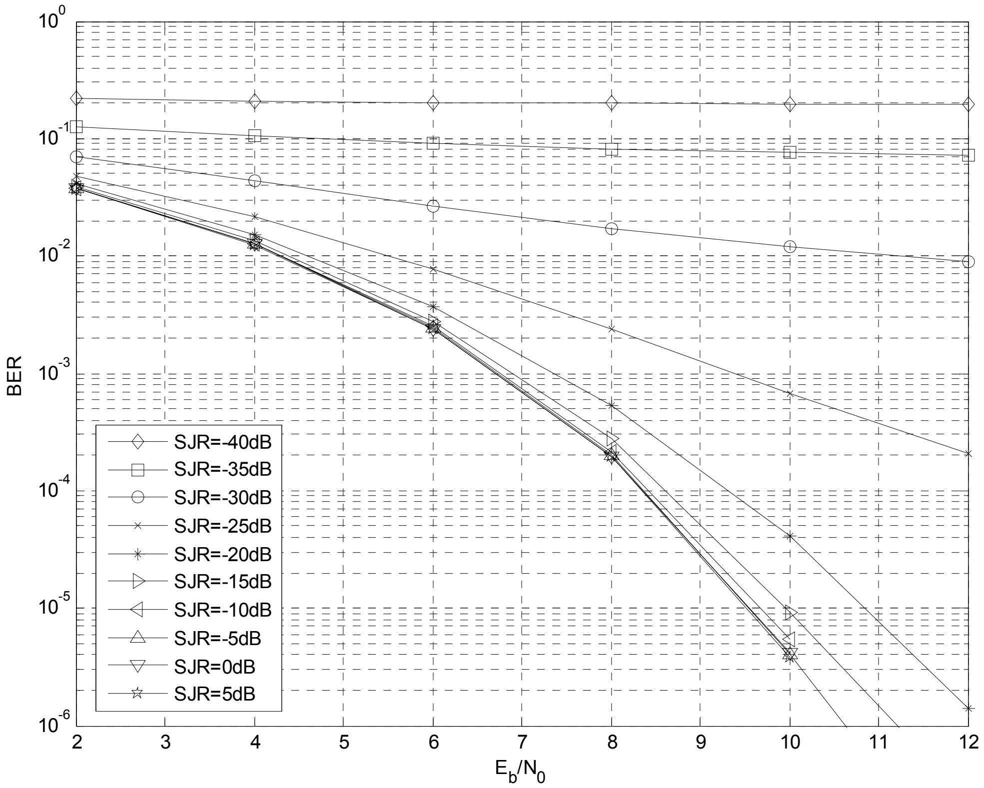

Figure 3 BER performance of CPM in the presence of multi-tone jamming consisting of 175 randomly spaced jamming tones.

To alleviate the limit on the BER performance caused by jamming as shown in Figure 3, an adaptive scheme described by the flowchart in Figure 2 is used to choose parts of the spectrum in which to transmit the multi-band signal containing little or no jammer energy. To demonstrate the obvious advantages of seeking vacant parts of the spectrum for transmission, Figure 4 shows the required Eb/N0 to achieve an error rate of 10^{-3}, as a function of the percentage of the operating band that is rejected. In this case, the percent band rejected refers to regions of the operating band that have been rejected as suitable candidates for the available hopping frequencies due to having high measured levels of interference or jamming. Thus, as the percentage of operating band rejected is increased, the regions of available hopping frequencies selected by the transmission scheme tend toward regions of the spectrum that contain little or no jammer and/or interferer signals, and favour transmission regions with relatively small jammer energy. In addition, Figure 4 shows the attainable gain when multiple hopped subbands are used instead of a single hopped carrier. In this case, all of the multi-band schemes attain a lower Eb/N0 than a single carrier scheme once approximately 20% of the operating band is rejected. Furthermore, transmission with five 1MHz bandwidth (denoted “5x1MHz”) frequency-hopped parallel subbands yields a gain of approximately 7dB compared to a single carrier scheme at the 80% band rejection point. Note that all modulation options shown in Figure 4 use the same total occupied bandwidth and the same total transmitted power, in addition, the resolution of the PSD estimation is set at 1MHz over the 275MHz operating band.

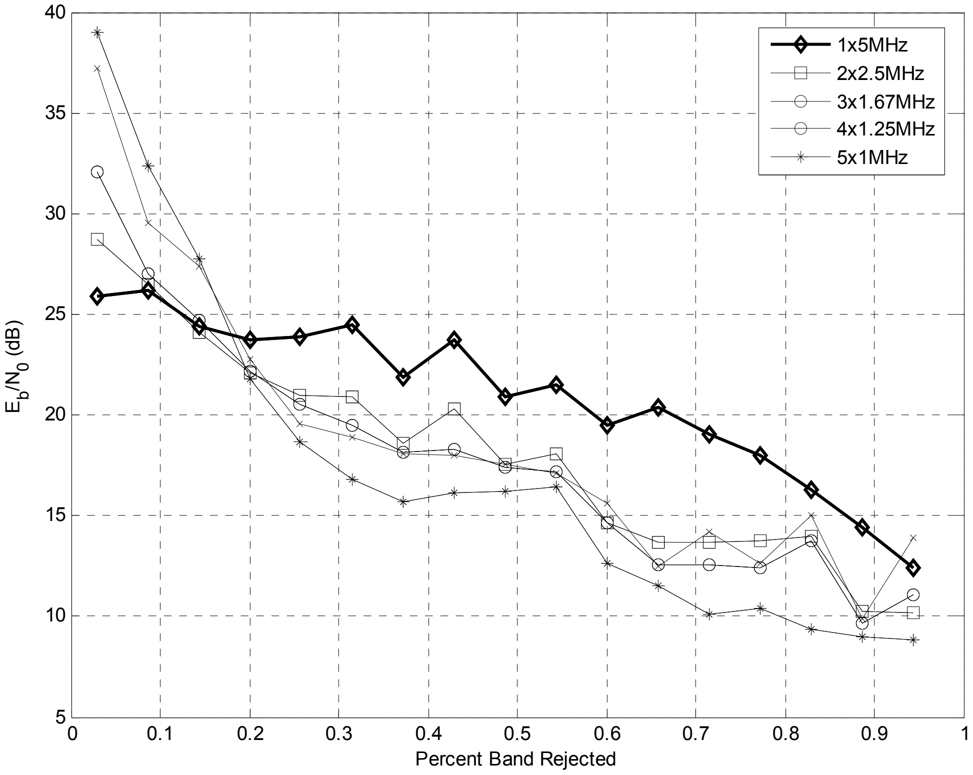

Figure 4 Required EB/N0 to achieve an error rate of 10^{-3} as a function of the percent band rejected.

To further illustrate the achievable gains of using the adaptation algorithm, Figure 5 shows comparative BER performance of the multi-band system with and without the spectrum adaptation for SJR=-30dB. The results show that without adaptation, both the single 5MHz frequency-hopped waveform (denoted “1x5MHz“) and the 5x1MHz waveforms exhibit an error floor. In fact, an error floor will appear irrespective of the number of parallel subbands used, as there is no constraint in place to stop the transmitter selecting frequencies with jamming tones present. In contrast, when the adaptation algorithm is enabled, we observe a considerable gain in BER performance of approximately 3.5dB at an error rate of 10-3 for the multiple band system compared to the single carrier scheme. The relatively poor performance of the single carrier system can be attributed to the fact that the operating band has a relatively large number of high energy jamming tones present, and thus there are relatively few 5MHz contiguous bands free of jamming for the single carrier scheme to select. In contrast, when using a 5x1MHz waveform, the error floor is completely removed, as there are now a relatively large number of 1 MHz jammer-free regions for the transmitter to select. It is important to note, however, that there is a trade-off between the number of subbands used and the BER performance. Increasing the number of subbands to say, ten, enables the transmitter to select a greater number of jammer-free regions, however, the energy per subband is now 1/10th of the single carrier system and thus more sensitive to channel interference

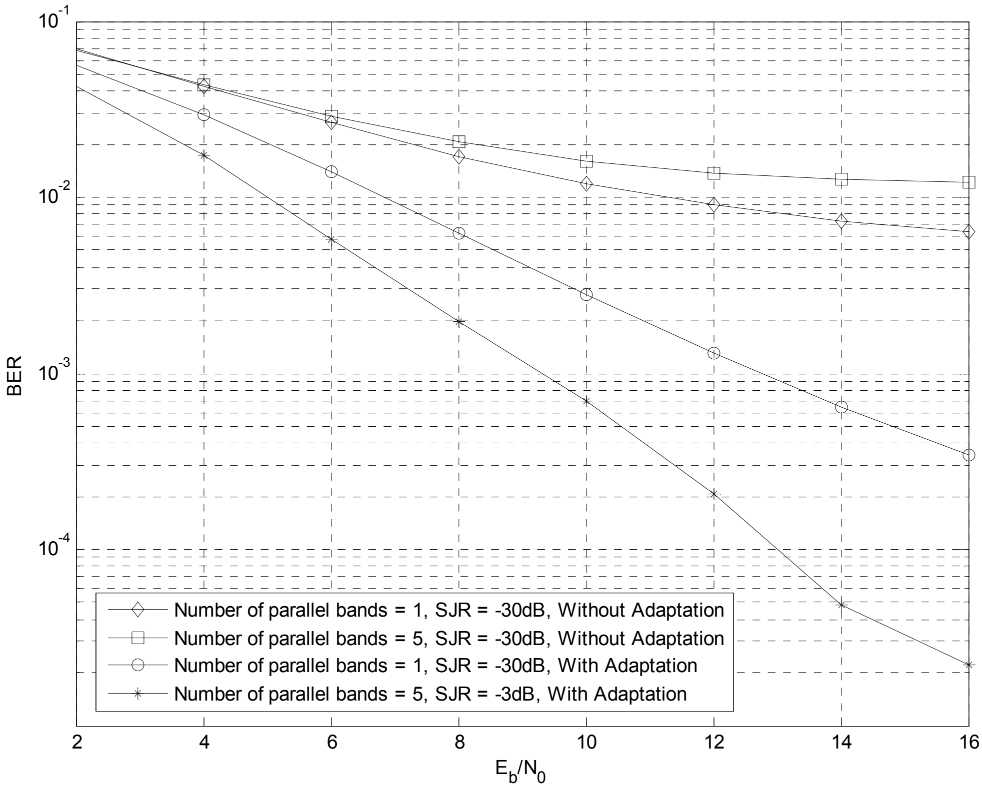

Figure 5 BER performance of the multi-band transmission scheme with and without spectrum adaptation.

The results presented above, demonstrate that for a given jammer waveform, a multi-band solution exists such that the transmission scheme can actively avoid the jamming signal. The selection of the optimal multi-band waveform is a function of the jamming environment and also the resolution of the PSD estimation system, and thus requires optimization for use in a tactical deployment.

4.0 DISCUSSION AND CONCLUSIONS

The adaptive identification of available hopping frequencies has two advantages; first, it provides a method to adaptively reduce the effects of jammer and/or interference; and second, when combined with a multi-band transmission approach, it increases the resilience of the communication system to jammer and/or interference already present within the active spectrum. It is therefore a general spectrum management method that can be combined with other adaptation rules such as modulation, hopping codes, error correction coding etc. to achieve a robust transmission waveform.

Automatic adaptation of the spectrum usage is advantageous for a number of applications, however, in this paper, the adaptation scheme is combined with a multi-band frequency hopping transmission system; thus allowing several parallel subbands to adaptively hop over the entire radio bandwidth whilst actively avoiding jamming and/or interference. For example, in a communication system with a follower jammer signal present, the proposed scheme will automatically change the set of hopping frequencies to portions of the transmission band that contain little or no jamming energy. Thus, under the provision that the periodic measurement of the radio bandwidth is greater than the adaptation rate of the follower jammer, the proposed scheme is effective at actively avoiding jamming and/or interference signals. Furthermore, utilization of bandwidth with this scheme is pseudo-random and so cannot be predicted by jamming systems.

In addition to avoiding jamming and interference, the proposed system has been shown to eliminate error floors in the BER performance. This is particularly important because it allows the transmission system to easily accommodate error correction coding to further increase the waveform robustness. To this end, the proposed scheme offers a neat solution to achieving robust high data rate communications in a highly fragmented operating band.

5.0 REFERENCES

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