Anti-jam, Anti-Multipath Spread Spectrum OFDM System

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ABSTRACT

This paper investigates the use of spread spectrum OFDM modulation to provide a variable rate communications link that is tolerant of multipath fading and interference. The system adaptively varies to changing channel conditions in a way that optimizes throughput while maintaining acceptable error rate performance. System performance for a variety of channel conditions including AWGN, static multipath, time-varying frequency selective and frequency non-selective Rayleigh fading shows that a desired BER can be maintained through adjustment of the processing gain. A trade-off analysis between Forward Error Correction (FEC) coding and spreading shows that a coding rate of approximately 1/2 is best, with the remainder of the bandwidth expansion used for spreading. An overall system adaptation strategy in a broad range of channel conditions is presented.

1. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) [1, 2] and Spread Spectrum OFDM (OFDM-SS) [3, 4, 5, 6] have both received considerable attention as methods to efficiently utilize channels with non-flat frequency responses, provide anti-jam properties and enable multiple-access capability. While the use of spreading with OFDM provides both anti-jam capability as well as enabling the use of CDMA it also tends to limit the available throughput due to the bandwidth expansion. A main focus of this paper is the study of the performance of an OFDM system which makes it possible to vary the amount of spreading, and the data throughput, in response to channel conditions. When anti-jam capability is needed, the signaling format is adjusted to increase the spreading while, when the channel is clear, spreading is reduced to increase the throughput. More specifically, in a favorable channel, the system would operate much like the conventional OFDM system where different data bits are transmitted on different carriers yielding high throughput. In a severe interference channel, the system would operate like the OFDM-SS system, sacrificing throughput to provide the needed processing gain to overcome the jamming. In most cases, the system would operate between these two extremes, providing sufficient processing gain to mitigate the channel effects while maximizing throughput. We call this system rate-adaptive OFDM (RA-OFDM).

This paper examines the performance of the RA-OFDM system for an AWGN channel as well as flat and frequency-selective Rayleigh fading channels. In addition to the adjustment of the spreading, the paper considers the trade-off between spreading and Forward Error Correction (FEC) coding in an attempt to determine the best way to allocate the bandwidth resources, i.e. given a fixed channel bandwidth, which combination of processing gain and coding rate will achieve the best performance.

In the following sections, we present the RA-OFDM system and discuss its use in a packet radio network environment. Simulation models are presented and the performance of the system under AWGN, static multipath, frequency selective fading and frequency-nonselective fading channels is illustrated. The trade-off analysis between FEC coding and spreading is performed for AWGN and flat fading channels and the results are further validated by simulation in frequency selective fading conditions. The paper concludes with an overall system adaptation strategy which allows reliable communications in a broad range of channel conditions.

2. RA-OFDM RECEIVER

Variable throughput can be implemented without changing the bandwidth of the signal by adjusting the amount of redundancy in the placement of data bits on the carriers. The highest throughput is obtained by sending different information on each of the carriers as in a conventional OFDM system. The lowest throughput, with the maximum processing gain, occurs when the same information is sent on all the carriers as in an OFDM-SS system. Intermediate throughput values are obtained by sending the same information on some subset of the carriers. Figure 1 shows the RA-OFDM receiver. In the diagram, each summer has M inputs (processing gain is M) and K symbols are sent simultaneously. M and K will vary depending on the processing gain requirements but the product MK will always equal the number of carriers.

The tap weights before the summers in Figure 1 perform channel equalization [6, 7]. It is assumed that a cyclic prefix [8, 9] is used to help mitigate the ISI and ICI, enabling this simple equalizer to be effective. An important aspect of the RA-OFDM technique is that the equalizer coefficients do not need to be re-trained as a result of a change in processing gain, since each complex equalizer coefficient depends only on the *channel* and is independent of the spreading scheme.

3. SIMULATION MODELS

The RA-OFDM scheme is envisioned for use in a packet radio network. The transmitter changes the processing gain of the transmitted signal on a packet-by-packet basis and the receiver learns of these changes through the packet preamble. An example packet structure having a fixed number (1280) of symbols as shown in Figure 2. The preamble section is transmitted using the maximum processing gain

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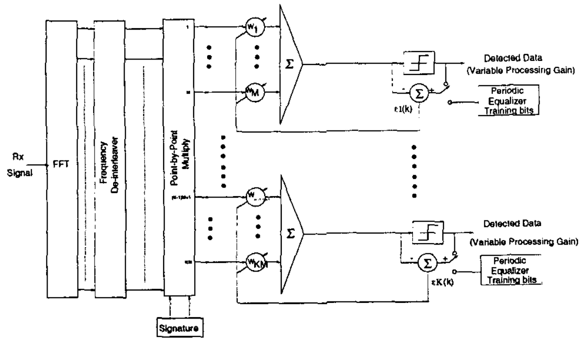

Figure 1. Block Diagram of a RA-OFDM receiver

to ensure maximum error protection and to enable any receiver, including one with a poor channel, to attain packet synchronization. The processing gain for the payload bit stream, however, depends on the actual channel conditions.

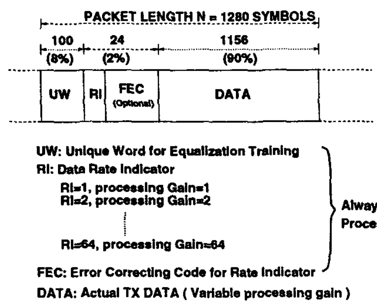

Figure 2. Signal frame format for the RA-OFDM system

The RA-OFDM system will be studied both analytically and through simulation. The analytical model is used primarily to study the performance in AWGN and flat fading channels while the simulation is used to validate the analysis and to obtain performance results for the frequency-selective fading channel. In the simulation, the RA-OFDM modulator with variable processing gain and variable-rate coding, a number of channel models, and the rate adaptive receiver are implemented and used to perform Monte Carlo simulations. The equalizer is adapted using perfect channel information, allowing the performance to be measured without any degradation due to imperfect equalizer tracking of the channel.

A number of different fading channels are considered. The time-invariant multipath channel consists of two equal-power rays with an inter-ray delay of 10 samples. The time-varying frequency-selective fading channel model consists of multiple rays spaced at sample intervals, T_c, and having a flat (uniform) intensity profile. Each ray is independently Rayleigh faded. As in [10], the analysis models the flat Rayleigh fading channel as an M-state Markov chain, where each state corresponds to a range of channel attenuation values.

Unless otherwise specified, the RA-OFDM signal consists of 64 carriers, perfect symbol synchronization is assumed, i.e. the blocks of the data processed by the FFT are time aligned with the symbol intervals of the non-delayed path. Similarly, all processing is performed at baseband, effectively assuming perfect carrier synchronization. Random data is sent by the transmitter and binary signaling is used.

4. RESULTS

4.1. AWGN and Static Multipath Channels

We start by demonstrating the idea of rate adaptation using AWGN and static two-ray channels. The two-ray channel model has inter-ray delay of 10 samples. Theoretical BER results for AWGN and simulation BER results for the two ray channel are shown in Figure 3. This figure illustrates that, as the received SNR varies from -12 dB to 12 dB, a bit error rate of 10^{-3} can be maintained by appropriate control of the processing gain over a 24 dB range. Most of the

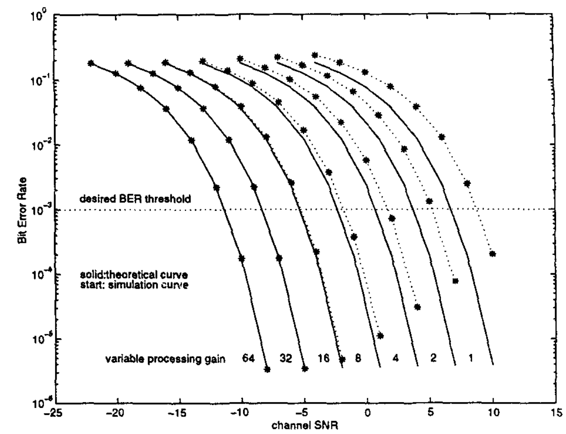

Figure 3. Rate adaptation with cyclic prefix

degradation from the AWGN performance that is evident in the multipath results is due to the fact that some of the channels are faded in the later case. Note that the larger the processing gain, the smaller this degradation due to the averaging effect of the despreading operation.

4.2. Frequency Selective Fading Channel

The frequency-selective fading channel can provide a diversity gain because different portions of the frequency spectrum fade independently. The achievable diversity D depends on the transmission bandwidth B and the coherence bandwidth $(\Delta f)_c$ and can be estimated roughly by [8],

$$D \approx B/(\Delta f)_c \tag{1}$$

The total number of carriers is fixed at 64 and we use a deterministic frequency interleaver which, if possible, separates the redundantly transmitted bits by the coherence bandwidth $(\Delta f)_c$. Thus, the maximum amount of frequency diversity is achieved. Figures 4 and 5 show the simulated BER versus E_b/N_0 for 4-ray and 8-ray channels, respectively. In each case, the processing gain takes the values 1 to 64 in powers of 2 and coding is not used. For a 4-ray channel, the achievable diversity as defined by (1) is 4. This is demonstrated in Figure 4 in which the BER performance improves with increased processing gain until $Pg = 4$, at which point no further gains are evident. The same conclusion holds true for the 8-ray model in Figure 5 in

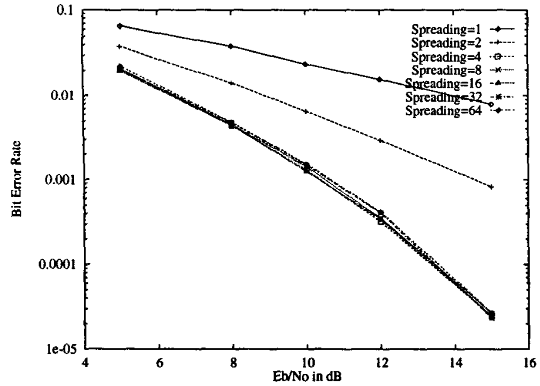

Figure 4. BER performance for a 4-ray selective fading channel, f_D=50Hz

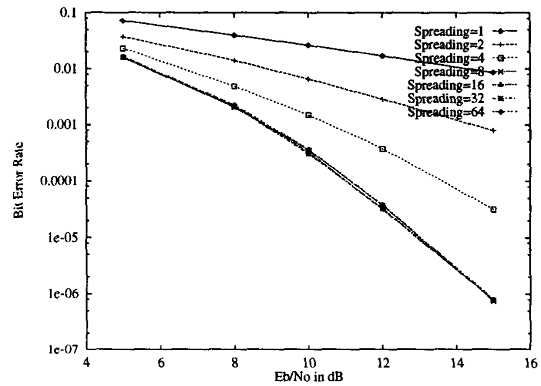

Figure 5. BER performance for a 8-ray selective fading channel, f_D=50Hz

which the performance improves until $Pg = 8$. Therefore, matching the processing gain to the available diversity provides the best performance; spreading further beyond this point does not provide additional *diversity gain* but does still provide additional SNR gain, allowing receiver performance to be further improved at the expense of throughput. This gain is evident if BER is plotted against received SNR rather than E_b/N_0, as was done in Figure 3.

4.3. Frequency Non-selective Fading Channel

With flat Rayleigh fading, the channel frequency response at any given instant is flat across all the subchannels, meaning that diversity gain is not available by simply spreading, interleaving and/or coding across the carriers. Instead, time diversity must be obtained by using these techniques over blocks of data that span many symbol intervals. The slower the fading, the greater the needed time diversity and the less practical this solution becomes.

Figure 6 illustrates the problem with slow fading by showing the performance of a Reed-Solomon (RS) coded OFDM spread spectrum system under Rayleigh fading with various Doppler frequencies. The system has a sampling frequency of 1 MHz, uses a RS(63,32) coder and has a processing gain of 16. The interleaver depth is equal to the size of the RS codeword, 378 bits. As a reference, theoretical curves for flat fading performance with no diversity (L=1) and two-fold diversity (L=2) are also provided. Without using a very long interleaver, the coded OFDM spread spectrum system can perform well in a fast fading channel but not in a slow fading channel.

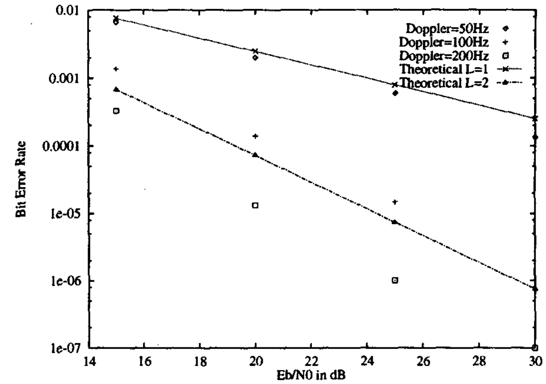

Figure 6. RS coded OFDM spread spectrum system in Rayleigh fading, FFT block size=64, (N,K)=(63,32), Pg=16

The RA-OFDM system approaches the flat fading problem by using coding and interleaving for fast fading channels and rate adaptation to track channel variation in slow fading. In other words, in a fast fading channel, the rate will be adjusted to the *average* channel conditions and coding and interleaving will be used to break up the fades while, in a slow fading channel, the rate adaptation will follow the fluctuations the channel.

To analyze the RA-OFDM system performance, the received signal SNR is partitioned into a finite number of intervals corresponding to the total number of states in the Markov chain model. The thresholds are ordered as $0 < \gamma_1 < \gamma_2 < \cdots < \gamma_M < \infty$ and these thresholds are chosen such that, taking into account the processing gain for each particular state, a desired BER of 10^{-4} is obtained at these thresholds. In the following, the adaptive system adopts 2-state, 3-state and a 4-state adaptation models. The average normalized throughput $\overline{W}$ with the adaptive transmission scheme is given by

$$\overline{W} = \sum_{i=1}^{M} W_i \pi_i, \quad W_i = \frac{(1 - P_{E|i}) R_{c|i}}{P_{g|i}}, \tag{2}$$

where M is the number of adaptation levels, π_i is the probability that the channel is in state i and W_i is the conditional normalized throughput given the state is i, defined as the average number of successfully transmitted information bits per unit time per unit bandwidth. $P_{E|i}$, $R_{c|i}$ and $P_{g|i}$ are the conditional packet error probability, coding rate and processing gain, respectively. Figure 7 shows the throughput of the RA-OFDM system as compared to a fixed rate system. In this case, $R_{c|i}$ is set to 1 for all i, meaning that all the redundancy is from spreading only. It is clear from the figure that partitioning the channel SNR into finite number of discrete states and matching the processing gain of the RA-OFDM system to each of these states yields a huge improvement in the system throughput. One reason for this improvement is that the fixed rate system must be designed to provide the desired BER performance even in the worst-case channel conditions, meaning that it must incorporate a large processing gain. Also, note that the performance of the adaptive rate system gets better when the number of states increases. This improvement is due to the fact that a closer match between processing gain and the channel conditions is achievable.

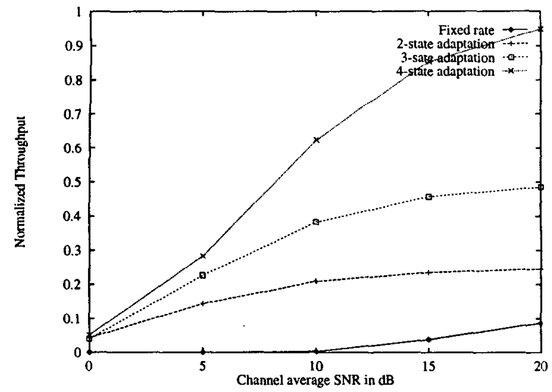

Figure 7. Maximum normalized throughput with fixed rate and RA-OFDM transmission schemes

4.4. Processing Gain vs. Coding Gain

In this section we will continue the rate adaptation analysis by determining the effect of processing gain and coding rate on the total system performance under the constraint of fixed total bandwidth. The trade-off will be based on RS codes, though we have obtained similar results with convolutional codes. Although both error and erasure corrections can be used with RS codes, we will only use error correction decoding in this trade-off analysis.

For a RS(N,K) code, which corrects $t = \lfloor (N-K)/2 \rfloor$ errors, the bit error probability is bounded by [8]

$$P_b < \frac{2^{K-1}}{N(2^K-1)} \sum_{i=t+1}^{N} i \binom{N}{i} P_s^i (1-P_s)^{N-i}, \quad (3)$$

where P_s is the channel symbol error probability. For a binary symmetric channel with transitional probability p, the probability of one or more errors in an m-bit word is

$$P_s = \sum_{e=1}^{m} \binom{m}{e} p^e (1-p)^{m-e} = 1-(1-p)^m. \quad (4)$$

For a coded RA-OFDM system using BPSK signaling, the transitional probability p is given by

$$p = Q\left(\sqrt{2\gamma_b \frac{1}{\frac{N}{K}p_g} p_g}\right) = Q\left(\sqrt{2\gamma_b \frac{K}{N}}\right), \quad (5)$$

where γ_b, p_g and $\frac{K}{N}$ are E_b/N_0, processing gain and coding rate, respectively. $\frac{N}{K}p_g$ is the total bandwidth expansion factor.

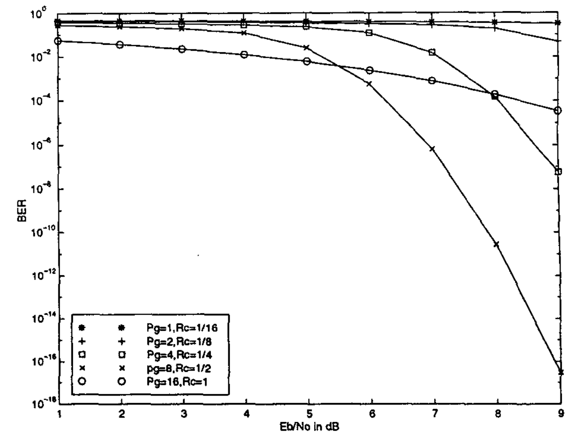

Figure 8. Trade-off between block coding and spreading for AWGN channel, expansion factor =16

System performance when the bandwidth expansion factor is 16 is shown in Figure 8. The coding rates indicated are approximate. Note that the system performs better if more of the available redundancy is used for spreading than for coding. At very low values of E_b/N_0, it is best to use spreading alone while, for moderate to high values of E_b/N_0, the best system uses a rate 1/2 coder. The advantage to allocating more bandwidth to spreading is that the processing gain boosts the SNR seen by the decoder, allowing it to operate effectively. A more powerful (lower rate) code operating without the benefit of the boost in SNR is less effective than the lower rate code with the processing gain. When the same analysis is performed for larger bandwidth expansion factors, the use of a rate 1/2 coder remains the best choice.

Analytical results for a frequency-selective fading channel are much more difficult to obtain, so we will investigate this problem using simulation. The combined RS coded OFDM system is simulated under a 4-ray selective fading channel. We use a FFT size of 1024 which allows the spread code word to fit in one FFT block. BPSK symbols are grouped across frequency to form the RS symbols and the RS codeword is formed across subchannels. Each RS symbol is further repeated by the amount of the processing gain. In this case $N = 15$ and K is varied from 1 to 14 to produce various coding rates. The total bandwidth expansion factor is kept fixed at approximately 30. Figure 9 shows the combined system performance. Once again, the simulation results follow the same trend as the analytical results for the AWGN channel.

To conclude the coding/spreading trade-off analysis, we consider the flat fading channel which does not provide any frequency diversity. However, the processing gain still provides SNR improvement as a result of the coherent combining gain. As the earlier results showed, this SNR improvement can be critical for a coded system to achieve its coding gain. When the fading is slow, the channel attenuation will be roughly constant over the duration of each packet and, therefore, the channel for each packet appears very much like an AWGN channel. Therefore, it is expected that the above coding/spreading trade-off results in AWGN will apply to this case.

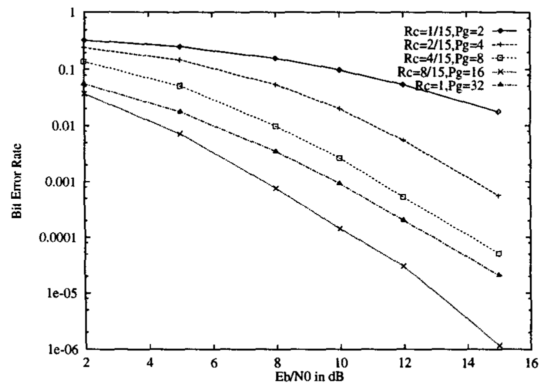

Figure 9. Reed Solomon coded RA-OFDM spread spectrum system in 4-ray selective fading channel, f_D=50Hz, FFT block size=1024

When the fading gets so fast that rate adaptation cannot be used to track the channel variations, coding and interleaving will used to maintain performance at an acceptable level. Using a 4-state Markov model, Figure 10 shows analytical results for the coded RA-OFDM over Rayleigh flat fading. At low E_b/N_0 values, processing gain alone is best,

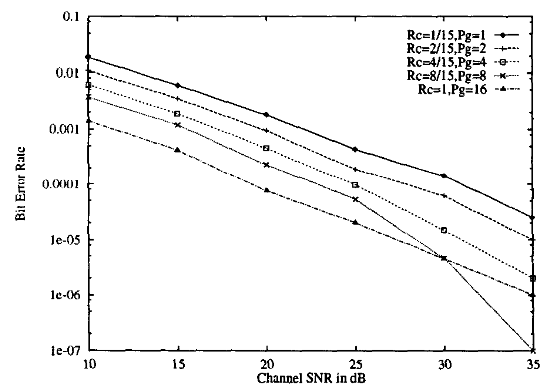

Figure 10. Trade-off between block coding and spreading for Rayleigh fading channel, expansion factor =16

while at higher values of E_b/N_0, using a rate 1/2 coder is best. The cross-over point is somewhat higher in this case than for the earlier results.

5. DISCUSSION

The results that were presented show that, by adjusting the processing gain, it is possible to maintain an acceptable BER over a wide range of channel conditions. In the case of slow flat fading, being able to track channel variations provides a large gain in throughput since the link does not have to be designed for worst-case conditions. Additionally, it is advantageous to use FEC coding along with the processing gain and, under most conditions, a rate 1/2 coder provides the best performance.

The proposed RA-OFDM uses a variable processing gain to deliver the best achievable data rate on a packet by packet basis over AWGN and multipath fading channels. The system uses FEC to supplement the processing gain, frequency domain interleaving to exploit any available frequency diversity, and time domain interleaving to decorrelate any time domain variations which are too rapid to handle through processing gain variation. The overall adaptation strategy is to track variations in the channel whenever possible within the constraints of the access method and the packet length. The best approach is to adjust processing gain on a packet-by-packet basis, but this may not be feasible in some cases. The depth of the time domain interleaving would be determined by the limitations in the system's ability to track channel variations since the main purpose of the interleaving is to "break up" any fades that cannot be tracked. The ability to handle the slow fading case through processing gain adaptation mitigates the need for large interleaver depths, increases the overall throughput of the system and reduces the possibility of a complete loss of signal.

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