Impact of Adjacent Channel Interference on the Performance of OFDM Systems over Frequency Selective Channels

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ABSTRACT

This paper deals with the problem of modelling of adjacent channel interference in OFDM systems, and the impact it may have on the bit error rate performance of such systems subject to a number of system variables and a number of channel conditions which may be encountered when such systems are deployed for certain applications such as high speed wireless LANs and DTTB.

1.INTRODUCTION

Interest in high speed data transmission over radio channels has been growing over the past few years. For transmission rates in the range 25 Mb/s, wireless channels appear to be highly frequency selective, a fact which leads to severe ISI on the receiving end of single-carrier transmission systems. One of the techniques that can be used to combat ISI is Orthogonal Frequency Division Multiplex Modulation (OFDM) where the high speed data is essentially transmitted over a large number of carriers. OFDM has been recently used or proposed for various applications including digital audio broadcasting [1,2], high bit rate digital subscriber lines [3] and digital TV broadcasting [4]. OFDM techniques use overlapped orthogonal signals to divide a frequency selective channel into a number of narrowband flat subchannels. The data are sent in parallel over the narrowband ISI-free subchannels. When applied to a multipath fading channel, the data are coded jointly to mitigate fading problems and extract the inherent diversity of the channel.

Although a number of studies have been published regarding the performance of OFDM-type signals in interference dominated environments such as the ADSL channels, not much has been published for its performance over wireless channels. In particular, [5] presents an analytical treatment as to how to calculate the adjacent channel interference power subject to certain constraints, as a function of time and doppler spreads for a particular time varying impulse response.

[3] presents a number of points related to the sensitivity of OFDM to co-channel analog TV interference which is known to be non-flat in the frequency domain. Methods for dealing with the nonflat spectrum include variable bit-allocation, power allocation depending on present interference conditions and the use of forward error control and interleaving to recover the data transmitted on the affected carriers.

Reference [6] gives the derivation of the theoretical channel capacity for a system with co-channel interference. An OFDM system with the pulse shaping optimized for minimum out-of-band energy (low sidelobes) is designed, and an allocation algorithm is devised to assign different power levels and different symbol constellation size to different OFDM carriers. The allocation algorithm considers the goal of achieving a target BER at a given signal to interference ratio by transmitting as many bits per second as possible. Those OFDM carriers that have a poor SIR are assigned low level constellations (4-QAM), while those with small interference use larger constellation sizes (M-QAM). Power is allocated in such a manner that all carriers would yield about the same error rate.

This paper presents some findings related to OFDM adjacent channel interference into an OFDM desired signal. The adjacent channel interference is affected by the transmitter power amplifier nonlinearity and nonlinearity of the receiver front-end. The PA nonlinearity is modelled using the measured transfer characteristics of some commercially available devices. Another type of nonlinearity, an amplitude clipper, is also investigated in this paper. The paper discusses the relationship between the adjacent channel spectral characteristics, the receiver front end analog filtering, and the MSE of the received QAM symbols for various levels of output back-off, and frequency guard intervals. Models for the OFDM system under consideration are described in some details, with emphasis on certain elements such as the nonlinearities, channel estimation, models for the interfering signal,..etc.

Computer simulation is used to treat the problem over channels with arbitrary multipath profiles, and also to investigate the impact of interference on channel estimation and channel equalization. The simulation model is quite flexible in that it allows the user to identify the system parameters such as sampling frequency, OFDM frame length, amount of output back-off, type of nonlinearity in addition to the size of the signal constellation. Mean-square error results and bit error rate results will be presented for 16QAM-OFDM.

SYSTEM MODEL

Figure 1 presents the block diagram of the simulated system. In the following details of the implemented model are given.

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DESIRED SIGNAL TRANSMITTER

The data source provides uniformly distributed random binary symbols which are first applied to a QAM baseband modulator which maps binary data into QAM constellation points.

The OFDM Modulator is based on an IFFT for baseband processing of the desired signal, with an arbitrary number of subcarriers, and a cyclic prefix of adjustable length so as to have support for various channel impulse responses and various receive filters. The generated signal is oversampled, by padding the input to the modulator with an adequate number of zeros, and thus performing a larger IFFT.

The IF modulator is an IQ modulator which is used to translate the signal frequency components to an appropriate RF frequency. It should however be noted that actual simulation is implemented using complex envelope representations for signals, and the lowpass equivalents of other system related functions such as analog filtering.

Power amplifier nonlinearity is accounted for in one of two ways; an amplitude clipper is used to represent a worst case scenario. A measured nonlinearity of a solid stae PA is also incorporated. In both cases the output back-off is used as a parameter. The output back-off is measured in dB relative to the 1 dB compression point in case of the SSA, and relative to the corner point in case of the amplitude clipper.

ADJACENT CHANNEL INTERFERENCE

The interference employs the same type of modulation as the desired OFDM signal, with some differences as outlined below.

OFDM modulator: The baseband processing of the signal complex envelope is implemented as a sum of complex exponentials with phases and amplitudes dependent on the relevant QAM symbols. This approach is used to allow for a possible mismatch in symbol rates between the desired and interfering signals. A sample timing mismatch is also allowed for. **The IF modulator** shifts the spectrum of the adjacent channel allowing for an adjustable guard band between the two signals.

The Power amplifier nonlinearity is based on a measured characterisic of a SS amplifier, in addition to a simple amplitude clipper. It should be noted that this block does not account for an amplifier gain; only the AM/AM and AM/PM distortion.

The desired signal and the adjacent channel are combined, and the resulting signal is then frequency translated in order to place the DC component at the middle of the desired OFDM spectrum.

As for the physical channel, any impulse response is supported, with the condition that the cyclic prefix attached to the OFDM frame be chosen accordingly. The noise is additive white gaussian with zero mean, and variance chosen to satisfy the chosen signal to noise ratio.

RECEIVER

The receive (analog) filter separates the desired OFDM signal from the adjacent channel. An 8th order Butterwoth filter response with a 3-dB bandwidth equal to the Nyquist bandwidth of the desired signal is used. It will be demonstrated that the frequency response of this filter plays an important role in determining the nature of interference that the desired signal is subjected to.

The sampler performs data rate sampling of the received signal and generally requires an OFDM symbol timing reference. After the acquisition of an OFDM frame, the cyclic prefix is removed (and this requires a frame timing reference). The OFDM baseband demodulation is implemented using the Fast Fourier Transform. The output of this block represents the received QAM symbols multiplied by the discrete frequency response of the overall system, including the physical channel.

The Equalizer is a zero forcing frequency domain equalizer. The channel estimate (required for equalization) is obtained by a channel estimation algorithm that relies on a number of pilots. The number of channel estimation pilots is dependent on the length of the effective impulse response of the system (including the physical channel) as seen by the receiver.

The essential Simulation parameters include the QAM constellation size, OFDM frame length, length of the cyclic prefix,: width of the frequency guard between the desired and interfering signals, symbol rate mismatch, sample timing mismatch, the power amplifier back-off, the impulse response of the physical channel, and the receiver analog filter response.

RESULTS

In order to gain a qualitative understanding of the effect of ACI on the desired OFDM signal, a number of simulation runs were carried out .

Figures 2shows a set of graphs indicating the mean square error of the received signal constellation as a function of the FFT frequency bin index. This MSE variable is obtained as the average of the square difference between the receiver output and the transmitted QAM points after proper normalization. Investigation of figure 2a, obtained for a flat channel and linear amplifiers for both the desired and interfering signals, reveals that the mean square error varies in a wide range and also seem to have a general trend in that it reaches a minimum in the middle of the frame, and tend to increase towards the frame edges. It is also evident that the MSE tend to peak at an FFT bin with an index that is equal to the frequency guard interval between the desired and interfering signal. This can be concluded from

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a comparison of figures 2a and 2b.

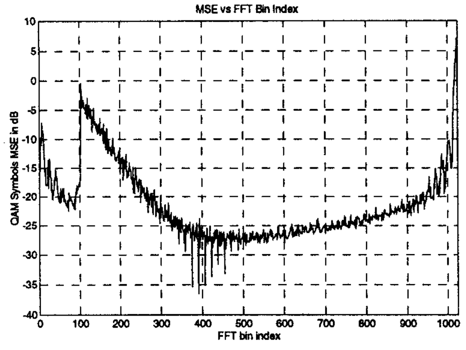

Figure 2a: For a flat channel, 10% guard, linear Amp

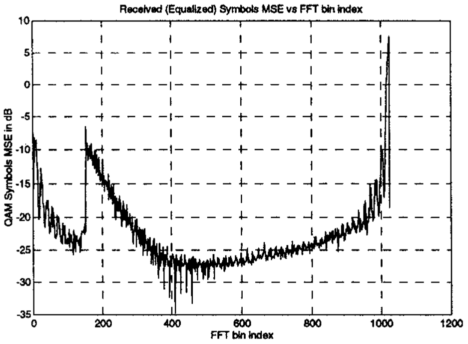

Figure 2b: for a flat channel, linear Amp and 15% guard

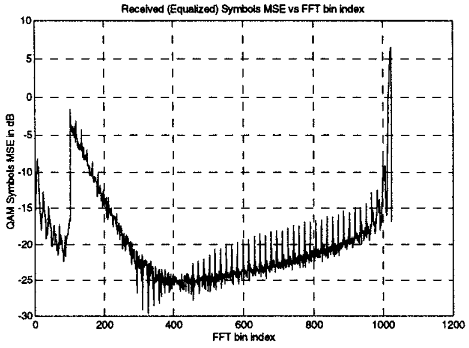

Figure 3a: flat channel, BO= 10 dB, 10% guard

Figures 3a and 3b show the impact of transmitter nonlinearity on the MSE of the received QAM symbols. A comparison of figure 3a and figure 2a shows that the amplifier nonlinearity affects the MSE in two ways; the overall average (over all FFT bins) tends to increase, and also intermodulation products that are related to the channel estimation pilots begin to affect several equally spaced FFT bins. The MSE peak at bin # 102 and the adjacent bins remains unchanged. Figure 3b is quite similar to figure 3a except that the overall average is now about two dB higher. Figure 4 is similar to figure 3b except that the channel frequency response is frequency selective (based on a two ray model for the physical channel, with a second ray delay equal to 1/512 of the OFDM symbol period). Apart from a slight increase in terms of overall average, the distribution of the MSE remains about the same as that of figure 3b.

Figure 5a shows the MSE when the PA nonlinearity exists in both the desired and interfering signal paths and the channel is frequency selective; it is evident that the MSE shows less non-uniformity for various FFT bins, although the effect of intermodulation products in both the desired signal and the interferer is still apparent.

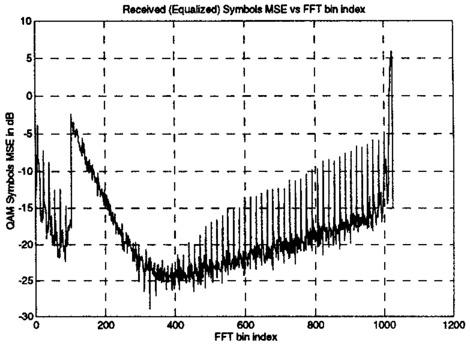

Figure 3b: flat channel, BO= 7dB, 10% guard

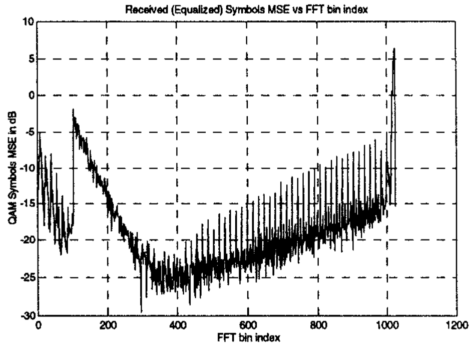

Figure 4: frequency selective channel, BO= 7 dB, 10% guard

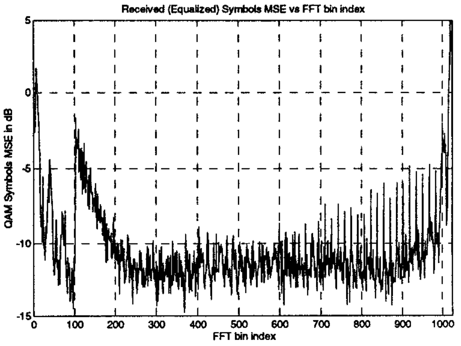

Figure 5a: MSE for a frequency selective channel in the presence of amplifier nonlinearity for both the desired and interfering signals. BO= 7 dB for both PA's

The constellation of the received signal under those same conditions is depicted in figure 5b. It is to be noted here that part of the distortion seen in figure 5b is due to channel estimation errors, which are brought about by the nonlinearity of the desired signal path.

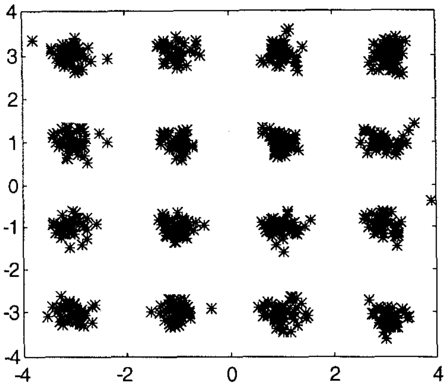

Figure 5b: Received signal constellations under same conditions as figure 5a. In both cases, the output BO is set at 7 dB.

The preceding discussion leads to the conclusion that the effect of ACI on OFDM signals is far from even for different frequency bins; the carriers closer to the centre of the desired signal band are most protected. Carriers spaced from the edge of the desired signal band by an amount equal to the frequency guard are more vulnerable than others. This general picture seem to hold even when amplifier nonlinearity and the frequency selectivity of the channel are accounted for. To investigate these points further a number of bit-error-rate simulation experiments have been conducted. Figure 6 shows the number of bit errors per subcarrier as a function of frequency. These results represent error counts obtained by transmitting 100 OFDM frames each consiting of 1024 symbols (16QAM) at an SNR of 10 dB. We notice the obvious dependence on the distribution of the adjacent channel interference as depicted in figure 3a. Symbols transmitted in the vicinity of FFT bin # 102 have suffered more errors than most. BER results under different conditions showed similar trends to those of figure 6.

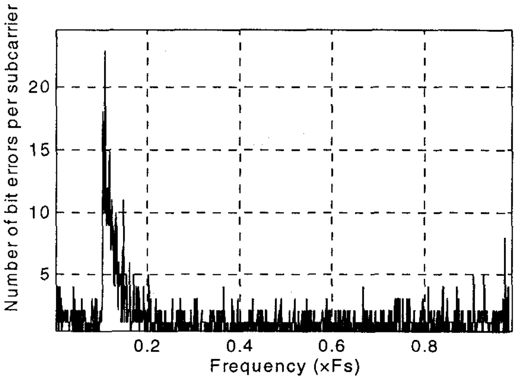

Figure 6: Bit error counts, vs frequency, for an interferer with a SSA output backoff of 7 dB, and SNR of 10 dB

SUMMARY

This paper has presented a qualitative picture of OFDM interference into an OFDM signal under various conditions. The results presented herein suggest that the effect of ACI can best be thought of as consisting of two components; an in-band component which is caused by the spectral side-lobes of the interfering channel and which fall within the passband of the desired signal receiver. The second component, out-of-band, is caused by the spectral components of the interferer which fall outside the 3-dB passband of the receiver. The in-band component gets enhanced by the interferer PA nonlinearity. The out-of-band component is created as a result of undersampling, and is largely independent of the PA nonlinearity. For guard intervals less than 15% of the occupied bandwidth, the out-of-band component seem to be dominant. This component can in principle be reduced by increasing the frequency guard, or by increasing the complexity of the analog receive filter even further.

As far as the physical channel frequency response is concerned, we found that the distribution of the ACI power did not seem to vary noticeably with the channel response; this can be explained on the basis that the in-band component of interference passes through the frequency domain equalizer, which is intended to comensate for the nonflatness of the overall channel. As a result, the in-band component seen by the receiver would remain mostly unchanged by the channel response. Minor changes in the out-of-band component have been noticed with the channel response.

Intermodulation products related to the channel estimation pilots appear to increase rapidly as the PA back-off ratio is decreased below 10 dB. It should however be pointed out that no-attempt has been made in designing the pilots in terms of their locations, phases and their magnitudes.

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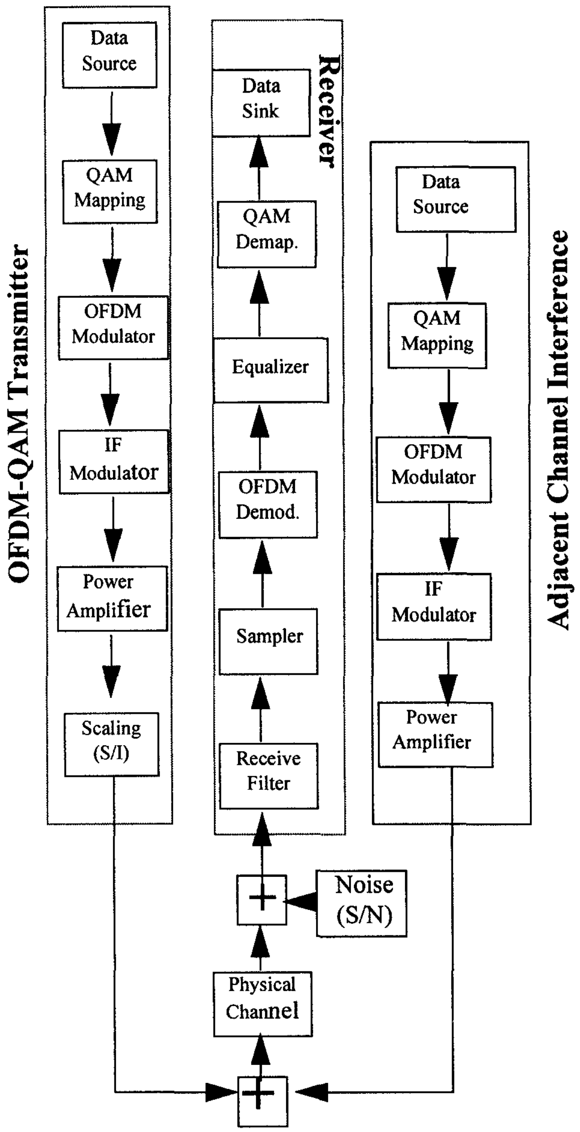

Figure 1: Block diagram of the simulated system