Pre-Equalised OFDM for Broadband Fixed Wireless Access

C. E. Tan and I. J. Wassell

Laboratory for Communications Engineering
Department of Engineering, University of Cambridge

Abstract: We investigate the performance of a pre-equalised OFDM system compared to that of a conventional OFDM system in a broadband fixed wireless access (BFWA) environment. Issues such as channel estimation requirements, signal power analysis and sub-channel blocking are investigated. Computer simulation results for pre-equalised and conventional systems in a fixed wireless environment (SUI-3 channel) are presented.

1. Introduction

Orthogonal frequency division multiplex (OFDM) systems are known to be capable of high bit rates and robustness against frequency selective fading. However deep fades in the multipath channel cause some OFDM sub-channels to experience very low signal-to-noise ratios (SNR) making the overall bit error rate (BER) performance very poor. The use of higher level QAM makes the situation even worse. For these reasons, there is a need to improve the BER performance for high bit rate applications such as in a Broadband Fixed Wireless Access (BFWA) where coherent OFDM systems are employed. The relatively long channel coherence time experienced in such system allows the use of pre-equalised OFDM, which improves the efficiency and the cost effectiveness of the overall system.

A conventional OFDM system utilises a frequency domain equaliser at the receiver to counteract the effects of the multipath channel. Unfortunately it will give rise to performance limiting noise enhancement since the inverse of the transmission channel is used to perform the correction. In a pre-equalised OFDM system, the inverse of the channel frequency response is used to pre-distort the OFDM signal prior to transmission. In doing so, the channel will act as an equaliser to correct the pre-distorted signal if the transmission is performed within the channel coherence time. The need for an equaliser at the receiver is now not necessary and so the hardware at the receiver can be simplified. Since there is now no noise enhancement at the receiver, a better performance can also be achieved. In this paper, we will investigate the issues that lead to a successful implementation of a pre-equalised OFDM system in a BFWA environment. A pre-equalised OFDM system has also been introduced and discussed in [1] [2] and [3] (where it is known as pre-distortion) and we now discuss its advantages and limitations.

2. The Pre-Equalised OFDM System

A high level block diagram of a typical pre-equalised OFDM system is illustrated in Fig.1. Known training symbols are modulated onto N sub-channels (where N is also the FFT size of the transmitter and receiver) and an inverse Fast Fourier Transform (IFFT) is performed at the OFDM transmitter on the N sub-channels to produce the OFDM symbol. An appropriate length of cyclic prefix is added prior to transmission to avoid inter-symbol interference (ISI) between successive OFDM symbols. At the receiver, the cyclic prefix is removed and Fast Fourier Transform (FFT) is performed to recover the training symbols and so permit an estimation of the channel impulse response (CIR) to be made. The estimated CIR will then be made known to the transmitter via the up-link. With knowledge of the phase and amplitude response on each sub-channel, pre-equalisation or pre-distortion of the QAM-mapped data symbols on each sub-channel at the transmitter can be performed by multiplying each data symbol by the inverse of the channel response at that sub-channel. An ideal pre-equalised system can be written as [4]

$$x_i = d_i \hat{h}_i^{-1} \tag{1}$$

where $\{x_i\}$ denotes the input of the i^{th} sub-channel at IFFT, $\{d_i\}$ denotes data symbols at i^{th} sub-channel, $\{\hat{h}_i\}$ denotes the phase and amplitude of the i^{th} sub-channel estimate.

The pre-equalised data symbols will then go through the same transmission procedure as detailed for the training symbols. When the OFDM data symbols pass through the channel, the multipath channel will equalise the pre-distorted sub-channels and the output of the OFDM receiver (assuming zero noise) will be the original mapped values of the data symbols on each sub-channel. QAM detection then follows. Pre-equalisation will only work if the channel estimation and data transmission processes are performed within the channel coherence time. Owing to this, pre-equalisation is appropriate for BFWA, where the channels are slowly changing.

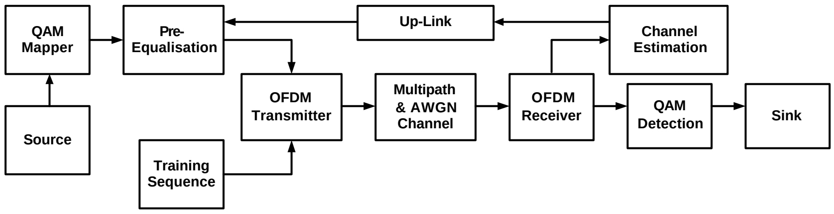

Fig.1: A typical pre-equalised OFDM system

3. Ideal Performance Comparison

Ideal simulation conditions have been assumed to permit a comparison of the best achievable performances for conventional and pre-equalised OFDM with coherent demodulation. Perfect channel estimation has been assumed for both systems. The simulation parameters are shown in Table 1. To enable a fair comparison, appropriate scaling factors have been applied to normalise the results based on signal power at the transmitter output. The simulation BER results are shown in Fig. 2.

	Conventional System	**Pre-Equalised System**
Mean signal power at transmitter output:	2W	12W
Mean signal power at channel output:	2W	2W
Channel inversion:	N/A	Full Channel (All sub-channels)
Modulation schemes:	QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM
Equalisation:	Frequency domain equalisation using the current perfect channel information at the receiver	Pre-equalisation using the current perfect channel information at the transmitter

Table 1: Simulation parameters for ideal performance comparison

From the results presented in Fig. 2, it can be seen that significant improvements in the BER performance are achieved at high SNRs by the use of pre-equalisation. However, the BER results for the pre-equalised system are inferior to the conventional system at low SNRs. To overcome this problem, sub-channel blocking (see section 6) will be employed to improve the performance of the pre-equalised system at low SNR values.

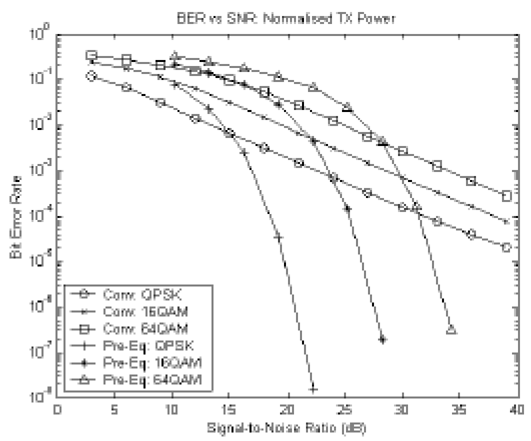

Fig.2: Normalised BER for conventional and pre-equalised OFDM systems

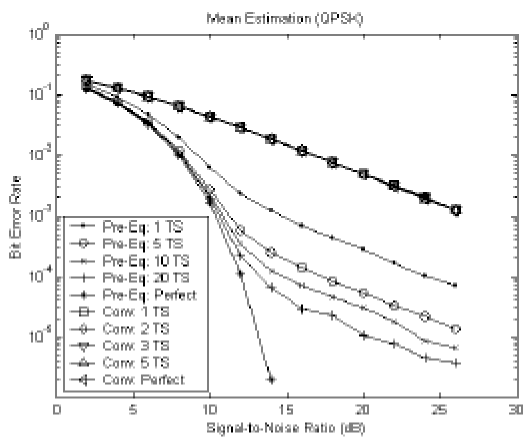

Fig.3: BER performances for different number of training sequences in channel estimate

4. Effects of Imperfect Channel Estimation

For conventional OFDM systems, channel estimation can be performed by sending a number of known training symbols to the receiver and taking a mean of the resulting estimates to yield the final channel estimate (Mean Estimation). In most cases, a simple channel estimation technique such as that mentioned previously using one or two training sequences can give close to ideal performance. However, we will show that the simple channel estimation technique that works well with conventional systems does not appear to perform sufficiently well to achieve close to ideal performance in a pre-equalised system. It turns out that very accurate estimated channel information is required for pre-equalised systems to work properly, otherwise the performance can be very poor especially at high SNR. The BER performances for conventional and pre-equalised OFDM systems using the simple mean estimation technique are shown in Fig. 3. It is possible to increase the number of training symbols (TS) used for channel estimation to improve accuracy, but it will reduce the transmission efficiency for the overall system. Owing to this problem, there is a requirement to adopt an efficient channel estimation algorithm with an estimation accuracy sufficiently high for pre-equalised OFDM systems. Pre-equalisation when applied to systems using high level modulation will require even higher channel estimation accuracy to be achieved.

5. The Transmit Signal Power

The Peak-to-Average Power Ratio (PAPR) problem is always an issue in conventional OFDM systems; this problem is also inherited by the pre-equalised OFDM system. In a pre-equalised system, the presence of low magnitudes in the channel frequency response will cause some sub-channels to experience a very high peak power following the pre-equalisation process. A signal power analysis drawn from the simulations for the two systems transmitting QPSK symbols is shown in Table 2. In the fully inverted channel pre-equalised system it can be seen that the peak power can be as high as 47178W, which is about 1627 times higher than that of the conventional system (in the simulated SUI-3 channel using a 30^{o} antenna beamwidth [5]). For a practical pre-equalised system, sub-channel blocking with threshold limiting for channel inversion is required. Hanzo has previously brought up this issue in [1]. The reasons for using sub-channel blocking (i.e., choosing not to use particular sub-channels) are to avoid the extreme high peak power when a low magnitude sub-channel occurs and also to improve the overall BER performance since it is more difficult to obtain an accurate channel estimate for sub-channels with a low gain.

	Conventional OFDM	**Pre-Equalised OFDM**
Mean PAPR (dB)	6.8	6.6
Mean TX Signal Power (W)	2	12
Highest peak power encountered (W)	29	47178

Table 2: Signal power comparison

In general, there is not much difference between the two systems in terms of PAPR, but the pre-equalised system has a much higher mean power (6 times higher in our simulations for the SUI-3 channel). Since the power allocation at each sub-channel depends on the respective sub-channel magnitude response, this problem cannot be avoided and the measured peak power can be very much higher than that in the conventional system. Owing to this problem, it is not practical to implement a fully inverted channel pre-equalised OFDM system.

6. Sub-channel Blocking

Even though the pre-equalised OFDM system could achieve a BER performance comparable to that of a single carrier system with the same modulation scheme, there are still some practical issues that limit the performance of such a system. We have shown that a more accurate channel estimation algorithm is required for the purpose of acquiring the channel information for pre-equalisation. In fact, a close to ideal channel estimation is required to achieve the optimum performance. Inaccurate channel estimation information, which occurs on sub-channels that experience deep fading will give rise to serious bursts of errors at the receiver. Pre-distorting the transmitted signal based on the channel information, especially those channels experiencing deep frequency selective fades could introduce much higher peak power ratios than in a conventional OFDM system, resulting in linearity and efficiency problems in the transmitter amplifier. Owing to the peak power problems caused by these problematic sub-channels, it is wise to exclude them from the transmission of data. This concept known as sub-channel blocking will improve the overall BER performance as well as reducing the peak power occurring in the system. Simulations performed with various sub-channel blocking enabling threshold levels (based on the channel magnitude response) have been undertaken. The peak transmit signal power and the BER performance as a function of the blocking threshold level are illustrated in Fig. 4 and Fig. 5 respectively.

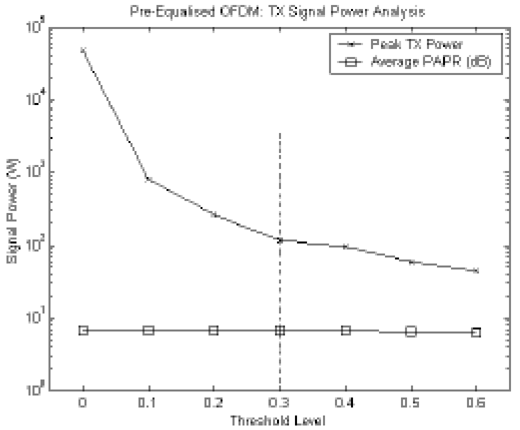

Fig.4: Signal power analysis for sub-channel blocking with different threshold levels

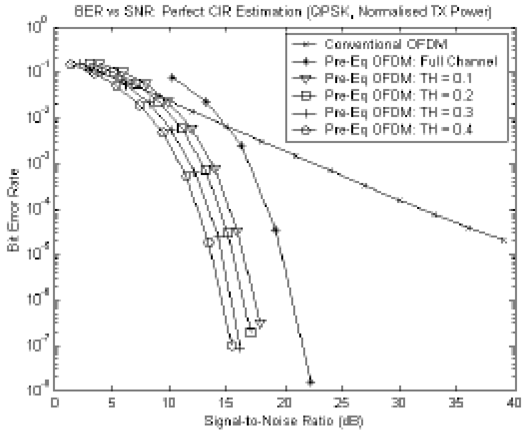

Fig.5: BER performances for different threshold levels of sub-channel blocking

The application of sub-channel blocking will reduce the transmission efficiency since not all sub-channels are used for the transmission of data symbols. The transmission efficiency is defined in terms of the fraction of the total number of sub-channels utilised for data transmission. The transmission efficiency for various threshold levels obtained from the simulations on the SUI-3 channel are shown in Table 3. The transmission efficiency is dependent on the channel conditions for a pre-equalised OFDM system.

Threshold Voltage Levels (V)	0.1	0.2	0.3	0.4	0.5	0.6
Transmission Efficiency (%)	99.7	98.4	96.5	93	88	81.7

Table 3: Transmission efficiency at different threshold levels

We can see that the transmission efficiency reduces as the threshold level increases. Clearly, we need to determine an optimum blocking threshold level to maintain a high transmission efficiency while also achieving a good overall BER performance and a low peak transmit power. From our simulation results obtained for the SUI-3 channel, we conclude that a threshold level of 0.3 offers a good compromise since it achieves a transmission efficiency in excess of 95%; a 5.5dB improvement in performance compared with no sub-channel blocking; a better BER performance than conventional OFDM for a channel SNR in excess of 5dB and a relatively low peak transmit power.

7. Conclusions

We have shown that pre-equalised OFDM is a better solution than conventional OFDM in BFWA applications due to zero noise enhancement and a more simple receiver hardware arrangement. However the introduction of sub-channel blocking is necessary for the practical implementation of such a pre-equalised system.

References

[1] L. Hanzo, W. Webb & T. Keller, *Single- and Multi-carrier Quadrature Amplitude Modulation – Principles and Applications for Personal Communications,* WLANs and Broadcasting, England: John Wiley & Sons, 2000.

[2] M.R.G. Butler, P.N. Fletcher, A.R.Nix & D.R. Bull, "A Constrainst Approach to Pre-Compensation for TDD OFDM Systems," *Proceedings of IEEE VTC'2000,* Rhods, 2000.

[3] F. Tufvesson, M. Faulkner & T. Maseng, "Pre-Compensation for Rayleigh Fading Channels in Time Division Duplex OFDM Systems," *Wireless Personal Communications*, vol.16, no.1; Jan. 2001.

[4] K. Witrisal, Y. –H. Kim, R. Prasad and L. P. Ligthart, "Pre-equalization for the up-link of TDD OFDM systems," *Proceedings of the 12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, PIMRC 2001, vol. 2, pp. 93-98, Sep/Oct 2001.

[5] V. Erceg, K.V.S. Hari, M.S. Smith, D.S. Baum et al., "Channel models for fixed wireless applications," IEEE802.16.3c-01/29r1, 23 Feb. 2001.