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Time-Domain Equalization Technique for Intercarrier Interference Suppression in OFDM Systems

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Abstract: Orthogonal Frequency Division Multiplexing (OFDM) is a modern high data rate modulation technique for wireless communication systems. Due to loss of orthogonality of subcarriers intercarrier interference occurs. In this study the performance of the proposed time-domain equalization technique is compared with the existing frequency domain equalization technique. In frequency domain equalization a correlative polynomial is used in the frequency domain to suppress the ICI. In Time domain equalization technique, a window function is proposed in equivalent to the correlative polynomial used in the frequency domain. MATLAB simulation of the proposed technique shows that the time domain windowing scheme achieves better performance in ICI suppression compared to the correlative coding technique. Time domain windowing technique proposed in this study, offers better Carrier to Interference Ratio (CIR) and BER is reduced compared to the correlative coding method.

Key words: Correlative coding, frequency offset, intercarrier interference (ICI), ICI suppression, carrier to interference ratio, cyclic prefix, serial to parallel converter, parallel to serial converter, orthogonal frequency division multiplexing

INTRODUCTION

OFDM can be seen as either a modulation technique or a multiplexing technique. One of the main reasons to use OFDM is to increase the robustness against frequency selective fading and narrowband interference. It has been accepted for the wireless local area network standards IEEE 802.11a, High Performance LAN type 2 (HIPERLAN/2) and Mobile Multimedia Access Communication (MMAC) Systems (Zhao *et al*., 1998). Also, it is expected to be used for wireless broadband multimedia communications and DVB-T.

In OFDM Multipath interference, was handled in a better way compared to the single carrier modulation systems. The property of spectral overlapping makes the system very sensitive to the frequency offset, which is usually introduced by the mismatch of oscillators at the transmitter and the receiver or the Doppler Effect under the mobile environments. Once the orthogonality of the subcarriers is lost then the ICI occurs which might degrade the system performance significantly.

Without performing frequency offset compensation at the receiver, the conventional ICI self-cancellation schemes (Speth *et al*., 1999; Zhao and Haggman, 2001) is used to mitigate ICI, at the expense of spectral efficiency. Without halving the spectral efficiency the ICI can be suppressed using the Correlative coding scheme (Zhao *et al*., 1998). The performance of the correlative scheme can be increased by using a higher order correlative polynomial (Zhao, 2000).

The ICI on each subcarrier is a function of the channel frequency offset (Cimini, 1985).Windowing can be used to reduce the ICI created as a result of frequency offset (Chin *et al*., 2006). As compared to the existing correlative coding scheme, the proposed windowing technique achieves a better ICI suppression performance. The carrier to interference ratio is improved and a better BER is achieved in this proposed scheme compared to the correlative coding.

ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

In an OFDM system, the whole available bandwidth is divided into N small parts and a block of N data symbols are modulated on N corresponding subcarriers

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which are orthogonal to each other. The spectra of the subcarriers are overlapping; therefore, accurate frequency recovering is needed (Speth *et al*., 1999).

An efficient use of bandwidth can be obtained with a parallel system if the spectra of the individual subchannels are permitted to overlap. The spectra of the individual subchannels are zero at the other subcarrier frequencies The N serial data elements are spaced by $\Delta t = 1/f_s$ where f_s is the symbol rate modulates N subcarrier frequencies, which are then frequency division multiplexed. The signaling interval T has been increased to $N\Delta t$, which makes the system less susceptible to delay spread impairments (Seyedi and Saulnier, 2005).

M-ary digital modulation schemes using OFDM can achieve a bandwidth efficiency, defined as bit rate per unit bandwidth, of $\log_2 M$ bits s^{-1} Hz^{-1}. The subcarriers are spaced by $\Delta f = 1/N\Delta t$ satisfying the orthogonality constraint. The bandwidth efficiency in strictly bandlimited spectra $\beta = \log_2 M$ bits/s/Hz. To obtain the highest bandwidth efficiency in an OFDM system, N must be large (Seyedi and Saulnier, 2005).

Consider the block diagram shown in the Fig. 1, the serial to parallel converter groups the stream of input bits into group of $\log_2 M$ bits, where M is the word size of the digital modulation employed. An IFFT is used to determine the corresponding time domain waveform for the modulated data. The multipath delay spread can be improved by the addition of a guard period between transmitted symbols.

The cyclic prefix is a copy of the last n samples from the IFFT, which are placed at the beginning of the OFDM symbol (Moose, 1994) serves as the guard period. The pilot carriers are included along with the data sub carriers for synchronization. Thus the base band signal for the OFDM transmission is obtained.

Additive White Gaussian Noise (AWGN) channel is introduced between the transmitter and receiver. The receiver does the reverse operation to the transmitter.The guard period is removed from the received signal. The FFT of each symbol is then performed to retrieve the original transmitted spectrum (Cimini, 1985). The demodulation is then performed to retrieve the transmitted input data bits. The equipment complexity can be greatly reduced by eliminating any pulse shaping and by using the IFFT to implement the modulation process. An OFDM signal offers an advantage in a channel that has a frequency selective fading response. Instead of losing the whole symbol, only a small subset of the (1/N) bits is lost in OFDM, which can be recovered with proper coding.

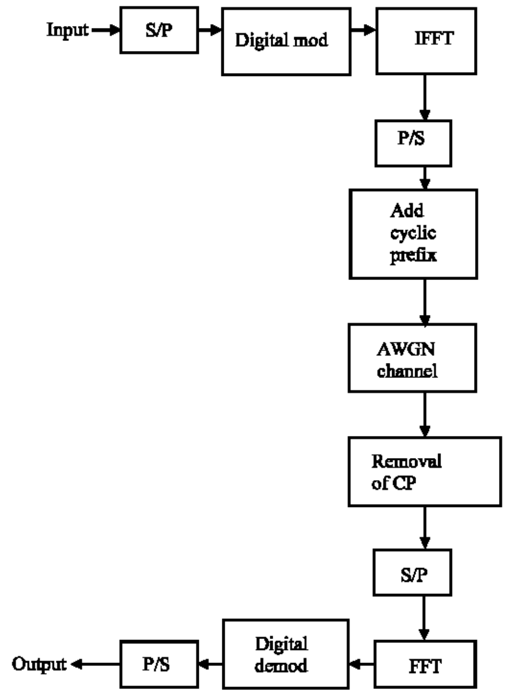

Fig. 1: OFDM system block diagram

ICI SUPPRESSION TECHNIQUES

There are three different approaches for reducing ICI have been developed including frequency-domain equalization, time-domain equalization and the self-cancellation scheme. In the frequency domain equalization technique, the frequency independent sub channels are multiplied by a complex number. In time domain equalization technique, the time domain signals are multiplied by window function. In self cancellation, a symbol is modulated on two different sub carriers with a 180° phase shift between them.

In this study, correlative coding is used in frequency domain equalization scheme for ICI compression, without halving the spectral efficiency. In the proposed scheme, time domain window function is defined in equivalent to the correlation polynomial used in the frequency domain equalization technique. Better ICI suppression performance is achieved in time domain compared to frequency domain scheme.

FREQUENCY DOMAIN EQUALIZATION

Frequency domain correlative coding is a simple solution to IC1 problems and makes OFDM systems less sensitive to frequency errors, thus it reduces the system complexity and increasing bandwidth efficiency (Zhao *et al*., 1998).The correlative coding between signals modulated on subsequent subcarriers is used to compress ICI in OFDM system and the IC1 is measured using subcarrier frequency offset response.

The (1-D) type of correlative coding was chosen and the subcarrier frequency offset response was introduced in terms of Doppler shifts in the channel. For better ICI suppression performance, a higher order correlation polynomial can be used for correlative coding however, the error propagation will come out in the decoding process and degrade the BER performance (Zhao, 2000).

The structure of an OFDM system with correlation coding can be derived from conventional single carrier systems (Fig. 2). By using BPSK modulator, the serial modulated signal, a_k is coded using correlative coding where k is the sub carrier index with k = 0, 1. . .N-1 and N is the total number of subcarriers. Denoting D as the unit delay of the subcarrier index k, the proposed coding with correlation polynomial F(D) = 1-D is performed as:

$$b_k = a_k - a_{k-1} \quad (1)$$

Then the coded symbol b_k, are modulated on N subcarriers. The symbol b_k takes three possible values (-2, 0, 2). Equation 1 introduces the correlation between the adjacent symbols (b_k, b_{k-1}). To avoid the error propagation in the decoding procedure due to correlative coding, precoding is performed before the BPSK modulation.

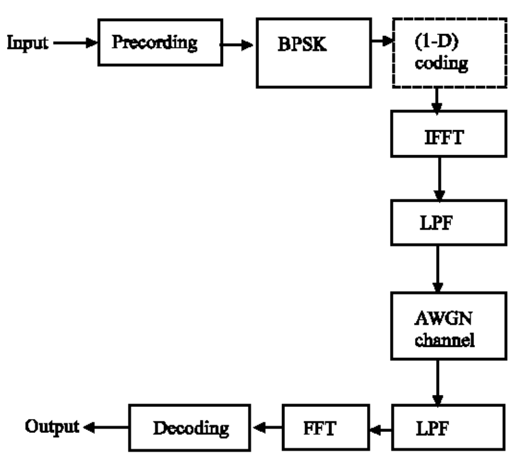

Fig. 2: Simplified block diagram of correlative coding scheme

In OFDM systems, the ICI signal on each subcarrier is a function of the channel frequency offset and the signal values modulated on all subcarriers (Cimini, 1985). For the OFDM, the main sources affecting its BER performances are Additive White Gaussian Noise and Intercarrier Interference. When the frequency error exists, then without considering AWGN, the received signal on each subcarrier can be recognized as a sum of the expected signal and the interference signal.

For an OFDM system with N subcarriers, if the channel frequency offset normalized to the subcarrier separation is denoted by ε, then the received signal on subcarrier k can be derived as:

$$r_k = \frac{1}{N}\sum_{n=0}^{N-1}\sum_{l=0}^{N-1} b_l \exp\left(\frac{j2\pi n(l-k+\varepsilon)}{N}\right) \quad (2a)$$

$$rk = \sum_{l=0}^{N-1} b_l S(l-5) \quad (2b)$$

Where,

$$s(l\text{-}k) = \frac{\sin(\pi\varepsilon)}{N\sin\left(\frac{\pi(\varepsilon+l-k)}{N}\right)}\exp\left(\frac{j\pi((N-1)\varepsilon-(l-k))}{N}\right) \quad (2c)$$

The received signal r_k can be expressed as a sum of the desired signal C_k and the undesired ICI signal I_k:

$$r_k = C_k + I_k \quad (3a)$$

Where,

$$C_k = b_k S(0) \quad (3b)$$

$$I_k = b_l S(l\text{-}k) \quad (3c)$$

The desired signal value Ck depends only on the signal transmitted on subcarrier k, while I_k depends on the signals transmitted on all the other subcarriers. The Carrier to Interference Ratio (CIR) of an OFDM system with (1-D) type correlative coding can be obtained from the following equation:

$$CIR = \frac{\sin^2(\pi\varepsilon)/(\pi\varepsilon)^2}{\sum_{l=0}^{N-1}|S(l)|^2 - \frac{1}{2}\sum_{l=0,l\neq k}^{N-1}\left|S(l)S^*(l-1)+S(l-1)S^*(l)\right|} \quad (4)$$

To analyze ICI level with respect to the frequency error, it is necessary to have a corresponding basic ICI function with respect to the system frequency error. At the transmission side of OFDM systems, signals a_k when k = 0, ... N-1 are modulated onto N subcarriers. It can be done by performing Inverse Fast Fourier Transform to the signal sequence a_k

If the frequency error is sufficiently large, it is possible that $I_k > C_k$ occurs. In such a case, a data decision error can be made even in the absence of AWGN. The BER of an OFDM systems increases rapidly when frequency error increases. The condition $\varepsilon < 0.05$ is necessary to maintain acceptable system performance.

TIME-DOMAIN EQUALIZATION

In Time domain equalization technique, a window function is applied to the data in time domain obtained after performing IFFT operation. For the correlative polynomial (1-D) used in the section 4, the window function proposed to use for ICI suppression is (1-exp (j2πn/N)) (Chin *et al.*, 2006). Time domain equalization technique offers a better performance compared to the frequency.

The application of the windowing function tapers the start and ends of waveform reducing the transients and consequently the spectral spreading. The application can be divided into two groups.

In the first group, windowing is used to reduce the sensitivity to linear distortions. In the second group, windowing is used to reduce the sensitivity to frequency errors. In this study, the second approach is performed. In this case, the window function improves the spectral efficiency and reduces the BER of the OFDM system.

According to the circular convolution property, we can realize the frequency domain circular convolution process by taking an equivalent time-domain windowing operation. For the correlative polynomial used in frequency domain scheme, the window function is proposed in this paper to improve the performance of the OFDM system. For the correlative polynomial (1-D) used in section 4, the window function proposed in this study is expressed as (1-exp (j2πn/N)).

If ICI can be suppressed well by applying the proposed window function, then the remaining task that will affect the BER performance would be decided by the demodulation technique. In the proposed method the decoding process does not need prior information of the transmitted data. For convenience, the proposed window

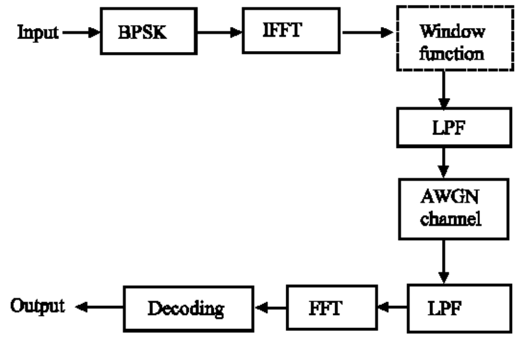

Fig. 3: The equivalent realization form of the proposed correlative coding scheme in time domain

function is applied at the transmitter. The subcarrier spectrum can be observed for the various order of the windowing function.

The Fig. 3 shows that the proposed correlative coding scheme can be realized in the time domain by using a window function. When the time domain window function (1-exp (j2πn/N)) is applied, the data samples transmitted on the k^{th} subcarrier can be expressed as:

$$b_k = a_k(1-\exp(j2\pi n/N)) \qquad (5)$$

The window function used is optimized to obtain a maximized Carrier to Interference Ratio (CIR). So, the order of the window function is optimized to be 1, assuming the modulation system to be BPSK.

$$r_k = C_k + I_k \qquad (6)$$

Where,

$$C_k = b_k S(-\varepsilon) \text{ and} \qquad (6a)$$

$$I_k = \sum_{l=0, l\neq k}^{N-1} b_l S(l-k-\varepsilon) \qquad (6b)$$

The theoretical CIR for the order 1 of the window function is given by:

$$\text{CIR} = \frac{|S(-\varepsilon)|^2}{\sum_{l=0}^{N-1} |S(k-\varepsilon)|^2 - \sum_{l=0, l\neq k}^{N-1} \text{Re}\left(2S^*(k-\varepsilon)S(l-k-\varepsilon)\right)} \qquad (7)$$

The correlative pairs would in average contribute to the smallest ICI only when the weighting magnitudes of

Table 1: OFDM simulation parameters

Parameters	Values
No. of carriers (N)	52
Modulation (M)	BPSK
Frequency offset (ε)	0:0.5
No. of OFDM symbols	100
Bits per OFDM symbol (BPS)	N*log2(M)
E_b/No	1:15
IFFT/FFT size	64-point
Total guard interval	FFT size/4
Channel	AWGN

Table 2: BER performance analysis for E_b/No = 3 dB

	BER		
Frequency offset (ε)	Standard OFDM	Correlative coding	Time domain windowing
ε = 0.15	0.002019	0.000372	0.0000215
ε = 0.16	0.008077	0.001950	0.0001450
ε = 0.17	0.013846	0.004963	0.0004960

the elements of each pair are equal or symmetric, this also agrees with the observation that the distributions of ICI coefficients are circularly symmetric.

When a higher-order correlative polynomial is selected, better ICI suppression performance can be obtained (Zhao, 2000) in equivalent to that if the order of the window function is varied in the proposed window function a stronger main lobe and smaller side lobes in each subcarrier spectrum can be achieved.

SIMULATION RESULTS

In this section, the MATLAB simulations results are provided to evaluate the performance of the proposed ICI suppression scheme. The CIR performance of the proposed scheme is independent of the modulation used, so BPSK modulation is used for convenience. The simulation is performed for various values of ε, in the simulated results performance is shown for the values ε = 0.15, 0.16, 0.17. Other simulation parameters used are shown in Table 1. The same parameters can be used for other modulation techniques such as QPSK, 16 QAM, 64 QAM.

The simulated results for BER performance are shown in Fig. 4-6 and Table 2 for the proposed time domain windowing technique and the correlative coding. In Fig. 4 BER performance curve for the time domain scheme and correlative coding method shows that the BER is reduced considerably compared to the correlative coding scheme. Comparison of the BER performance in the Fig. 4-6 implies that with the increase in the frequency offset value the BER increases and the time domain windowing technique offers a better performance compared to the correlative coding method.

Figure 7 shows the CIR versus normalized frequency offset for the correlative coding and proposed scheme.

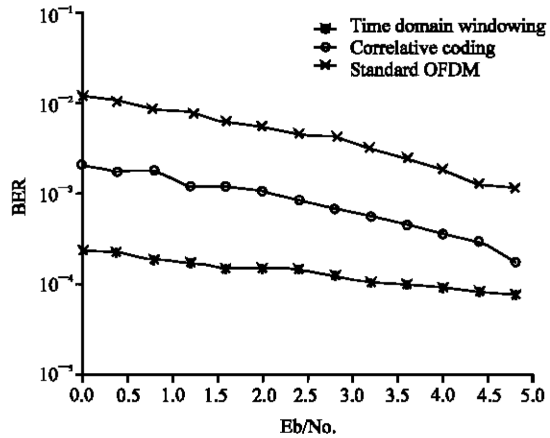

Fig. 4: BER performance of time domain windowing and correlative coding scheme for ε = 0.15

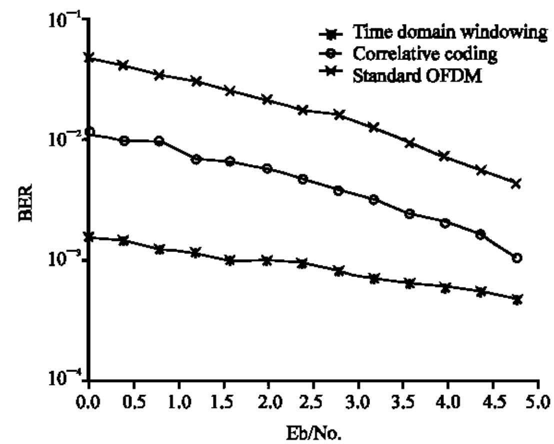

Fig. 5: BER performance of time domain windowing and correlative coding scheme ε = 0.16

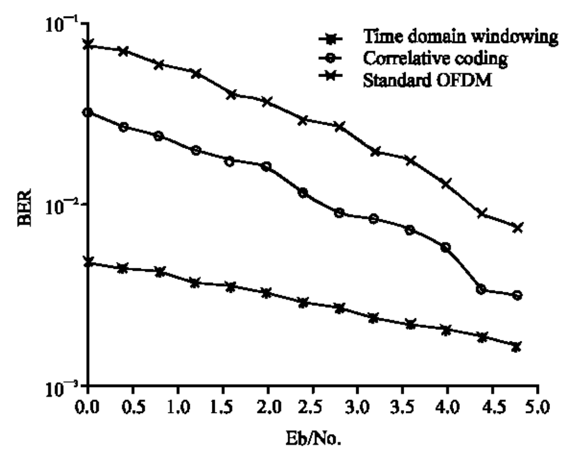

Fig. 6: BER performance of time domain windowing and correlative coding scheme ε = 0.17

From the simulated curves, it can be observed that, when the normalized frequency offset is zero the time domain

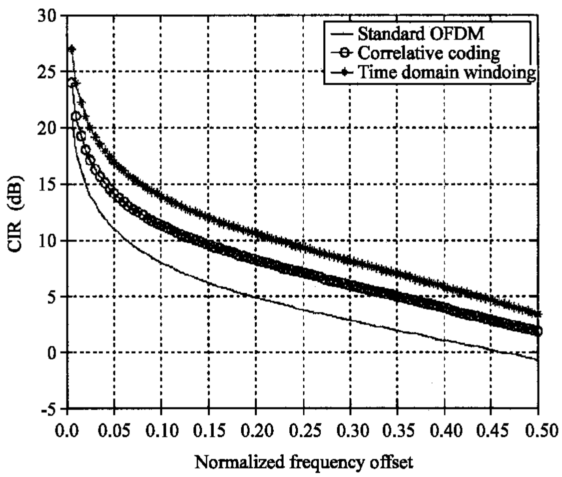

Fig. 7: CIR performance of time domain windowing and correlative coding scheme

Table 3: CIR performance analysis

	CIR (dB)		
Frequency offset (ε)	Standard OFDM	Correlative coding	Time domain windowing
ε =0.1	6.2482	13.4630	24.575
ε =0.2	4.1108	8.9833	15.829
ε =0.3	1.8718	3.8956	6.406

equalization technique behaves same as the standard OFDM without any equalization technique. The effect of the time domain windowing can be explicitly seen from the Table 3, when the frequency offset value increases above 0.1. Thus the proposed scheme outperforms the correlative coding scheme, due to its better capabilities in suppressing ICI and preventing error propagation through OFDM symbols.

CONCLUSION

This proposed ICI suppression scheme using time-domain windowing for OFDM systems, provides a better BER performance compared to the correlative coding. The window function used also avoids the propagation of errors in the demodulation performed. From the Fig. 7 it is inferred that there is a 3dB improvement in CIR in the proposed scheme compared to the existing correlative coding scheme. Further work can be done to improve the BER performance by applying the Maximum Likelihood Sequence Detection (MLSD) and by increasing the order of the window function the CIR can be improved.

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