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A Novel Hybrid Scheme using MLE with Pulse Shaping for ICI Cancellation in OFDM Systems

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Abstract— **Carrier frequency offset (CFO) in orthogonal frequency division multiplexing systems results in heavy degradation to the system performance. Pulse shaping and Maximum likelihood estimation (MLE) are two of the several techniques available in the literature for reducing the undesired effects caused by CFO using inter carrier interference (ICI) cancellation and CFO correction respectively. In this paper, we combine these two techniques to cancel ICI further, thereby achieving a better bit error rate (BER) performance than the BER achieved by either of the two above mentioned schemes. It has been shown that around 1.7 dB BER performance improvement could be achieved using the new hybrid scheme as compared to MLE technique with low pass filtering. Further, the hybrid scheme adopted in this work is less sensitive to CFO compared to pulse shaping scheme.**

Keywords- **AWGN channel; Bit error rate, Carrier frequency offset; Convolutional code; Maximum likelihood estimation; Orthogonal frequency division multiplexing; Pulse shaping.**

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is a popular modulation scheme in high-speed communication systems. But it is very much sensitive to the carrier frequency offset (CFO) which may be caused due to difference in the carrier frequencies of transmitter and receiver. So, care has to be taken to have highly accurate oscillators which may be costlier. Self-cancellation schemes [1], frequency domain equalization [2], windowing at the receiver [3], Maximum likelihood estimation (MLE) technique [4] and pulse shaping are some techniques for ICI cancellation caused by CFO. Pulse shaping in OFDM system with improved sinc power (ISP) pulse results in lower side lobes, improved power and spectral efficiency [5]. MLE technique estimates the CFO accurately [4]. In this paper, we attempt to combine pulse shaping with the MLE technique to achieve better system performance.

The paper is organized as follows. Section II presents a brief introduction to OFDM system, with its advantages and disadvantages. It further describes the need for pulse shaping and some of the pulse shaping functions available in the literature. Section III outlines the MLE technique proposed in [4]. The OFDM system combining the pulse shaping with the MLE technique is developed in Section IV. Simulation results are provided in Section V, and Section VI summarizes our conclusions.

II. OFDM WITH PULSE SHAPING

OFDM

For a linearly modulated system with data rate R and pass band bandwidth B, the basic principle of OFDM is to break this wideband system into N linearly modulated subsystems in parallel, each with sub channel bandwidth $B_N = B/N$ and data rate $R_N \approx R/N$. For sufficiently large N, the subchannel bandwidth B_N is much less than coherence bandwidth, ensuring relatively flat fading on each subchannel. As OFDM makes use of computationally efficient FFT algorithm, it has low computational complexity. OFDM with forward error correction (FEC) method is most suitable scheme to transmit the information wirelessly - quickly and accurately.

Some advantages of the OFDM system are Robustness against delay spread and inter symbol interference, computational efficiency, and immunity to timing jitter. But, there is a stringent requirement that the subcarriers in OFDM system must be orthogonal to each other. If the frequency separation of the OFDM subcarriers is imperfect, i.e. subcarrier separation is not exactly equal to $1/T$, where T is the OFDM symbol time; the received samples of the FFT will contain interference from adjacent subchannels, degrading the system performance. Generally, a cyclic prefix is used in OFDM to eliminate the inter symbol interference (ISI) and inter carrier interference (ICI), which are caused by the errors in the sampling time or channel disturbances [6-8].

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Pulse Shaping Functions

Base band pulse shaping filters help to achieve better spectral occupancy. In RF communication, pulse shaping is essential for making the signal fit in its frequency band. Recently, pulse shaping filters are also being used for ICI cancellation caused by CFO in OFDM systems. The ideal band-limited ISI-free pulses are inherently of infinite length. For practical systems, the ideal pulses are truncated, which introduces side lobes in the PSD. In a good pulse function design, care must be taken to minimize the amplitude of side lobes.

Rectangular filter (sinc filter) has long been known, but it has poor performance due to slowly decaying tails. A popular variant of the Rectangular filter is the Raised cosine filter. In this, the first part is the sinc function which ensures transitions at integer multiples of symbol time. The second term, which is_the cosine correction part, helps to reduce excursions in between sampling instants. Time response of raised cosine filter falls off much faster than the rectangular pulse. The roll-off factor *α*, relates the achieved bandwidth to the ideal band width. It indicates how much more band width is used over the ideal band width. Smaller value of *α* is required for band width efficiency. Frank's pulse is discontinuous for *α ≠ 1*, hence leads to larger out of band emissions at larger band widths [9]. The side lobes of sinc power (SP) pulse have lower amplitude than Better than raised cosine (BTRC) pulse, providing better SIR performance than that of BTRC pulse [10,11]. A modified version of SP pulse, which is the ISP pulse, provides a good performance improvement against ICI as compared to the above mentioned pulse shapes. The exponential term of the ISP pulse provides faster decay rate than the SP pulse and reduces the side lobes. This results in reduction of the ICI power. The parameter *a*, is used to set the amplitude, time spread and frequency spread as per requirement. Rectangular pulse has highest amplitude side lobes while that of ISP pulse is almost zero. The amplitude of the ISP pulse is the lowest at all frequencies [5]. Mathematical representation of these Pulse shaping functions is given below. In (1- 8), *P* represents the pulse function, *T* is the OFDM symbol time, *n* is an integer, *N* is the FFT size, *k* and *m* are variables which take integer values in the range *0,1 ,……,N-1.*

Rectangular pulse:

$$P_R = \sin c(fT)$$

Raised cosine pulse:

$$P_{RCOS} = \sin c(fT)\frac{\cos(\pi\alpha fT)}{1-(2\alpha fT)^2}$$

Better than raised cosine pulse:

$$P_{BTRC} = \sin c(fT)\frac{2\beta fT\sin(\pi\alpha fT)+2\cos(\pi\alpha fT)-1}{1+(\beta fT)^2}$$

$$where\ \ \beta = \frac{\pi\alpha}{\ln(2)}$$

Frank's pulse [8]:

$$P_{FRANK} = \sin c(fT)\big((1-\alpha)\cos(\pi\alpha fT)+\alpha(\sin c(\alpha fT))\big)$$

Sinc power pulse [9]:

$$P_{SP} = \sin c^n(fT)$$

Improved sinc power pulse [5]:

$$P_{ISP} = \exp\left(-a(fT)^2\right)\sin c^n(fT)$$

Pulse shaping function is one of the governing factors for two important system performance specifications - Signal to ICI power ratio (SIR) and normalized out of band power (γ). SIR depends on the symbol location, total number of subcarriers and the pulse shaping function while γ depends on available band width and pulse shaping function. An optimum pulse function provides good SIR and minimum out of band power.

SIR, which is the ratio of desired signal to ICI power, is computed as follows:The average ICI [11]:

$$\overline{\sigma^2_{ICI}} = E[\sigma^2_{ICI\,m}] = \sum_{\substack{k=0\\k\neq m}}^{N-1}\left|P\left(\frac{k-m}{T}+\Delta f\right)\right|^2$$

Signal to interference ratio [11]:

$$SIR = \frac{|P(\Delta f)|^2}{\sum_{\substack{k=0\\k\neq m}}^{N-1}\left|P\left(\frac{k-m}{T}+\Delta f\right)\right|^2}$$

III. MLE TECHNIQUE

As proposed by Moose, The MLE technique considers repeating of an OFDM symbol per frame and comparing the phases of each of the subcarriers between the successive symbols. As the modulation phase values are not changed, the phase shift of each of the carriers between successive repeated symbols is due to the frequency offset. The frequency offset is estimated using MLE algorithm. All the *N* sub carriers of OFDM system are considered to be data subcarriers in the following description. If an OFDM transmission symbol is repeated, in the absence of noise, the received sequence is a *2N* point sequence as given in (9). If X_k is the k^{th} subcarrier data of an OFDM symbol, H_k is the transfer function of the channel at the k^{th} subcarrier frequency, then the sequence is as given below [4]:

$$r_n = \frac{1}{N}\sum_{k=0}^{N-1}X_kH_k\exp\left(\frac{j2\pi n(k+\varepsilon)}{N}\right)$$

$$where\qquad n = 0,1,\ldots\ldots,2N-1$$

Let R_{1k} and R_{2k} represent the k^{th} element of the *N* point FFT of the first *N* points and next *N* points of (9) respectively.

$$R_{1k} = \sum_{n=0}^{N-1} r_n \exp\left(-\frac{j2\pi nk}{N}\right)$$

$$R_{2k} = \sum_{n=N}^{2N-1} r_n \exp\left(-\frac{j2\pi nk}{N}\right)$$

$$= \sum_{n=0}^{N-1} \left(r_n \exp\left(j2\pi\varepsilon\right)\right)\exp\left(-\frac{j2\pi nk}{N}\right)_{\tilde{1}}$$

where *k=0,1 ,……,N-1* and ε is the normalized CFO, which is ratio of the actual frequency offset to the inter carrier spacing. As stated in [4], If AWGN of *W* is combined, we get the above two components respectively as:

$$Y_{1k} = R_{1k} + W_{1k}$$

$$Y_{2k} = R_{1k}\exp(j2\pi\varepsilon) + W_{2k} \quad 11$$

Both the ICI and signal are changed in the same manner for R_{1k} and R_{2k}, which is proportional to the frequency offset. The MLE of the offset can be computed using MLE algorithm [4].

$$\hat{\varepsilon} = \frac{1}{2\pi}\tan^{-1}\left(\frac{\sum_{k=0}^{N-1}\operatorname{Im}\left(Y_{2k}Y_{1k}^{*}\right)}{\sum_{k=0}^{N-1}\operatorname{Re}\left(Y_{2k}Y_{1k}^{*}\right)}\right) \quad 1$$

This offset value is subtracted from the phase of each of the subcarrier data of the OFDM symbol, resulting in the cancellation of the offset and thus improving the performance of the OFDM system experiencing CFO.

IV. SYSTEM MODEL

System block diagram is shown in Fig. 1. Input Binary data stream is converted to frames and error control coded using convolutional coding with a rate ½ encoder having generator matrix of [7, 5]8. This data is modulated with quadrature phase shift keying (QPSK) modulation and converted into 52 parallel streams using serial-to-parallel block (S/P in Fig. 1). Resulting signal is applied to inverse fast Fourier transform (IFFT) block. OFDM system parameters are chosen as per 802.11a standard with an FFT size of 64, 52 data subcarriers (pilot subcarriers are also considered as data subcarriers), and a carrier frequency of 2.4 GHz. Cyclic prefix of length 16 is chosen to safe guard data against ISI. The first OFDM symbol of each frame is repeated for MLE technique. It is assumed that the CFO is constant within a given frame. This parallel data is converted to serial form (P/S block in Fig. 1), then to the analog representation and passed through a pulse shaping filter. This filter serves dual purpose of making compact the required spectrum and providing immunity to the CFO noise. Each pulse shaped frame is up-converted to the desired band with a carrier frequency fc to provide the output of the transmitter s(t), which is passed through the additive white Gaussian noise (AWGN) channel. Over sampling factor of 5 is considered in the simulation. At the receiver, the received signal r(t) is band pass filtered and down converted to the base band signal. It is assumed that there is a CFO of Δf, introduced during down conversion. The resulting signal is passed through a matched filter and digitized. The offset is computed using first and the second OFDM symbols of each frame, after scraping their cyclic prefix, as per the MLE technique suggested by Moose in [4]. The offset correction is applied to all the OFDM symbols, after discarding the repeated symbol. The cyclic prefix is removed and OFDM demodulation is carried out. After QPSK de-modulation, 3 bit soft decision Viterbi decoding is performed to recover the estimated data.

The performance of the convolutional coded QPSK system is observed under three different cases - using ISP pulse shaping alone, low pass filtering with MLE technique, and ISP pulse shaping with MLE technique. For the first case, OFDM symbol repeat block at the transmitter and CFO estimation block at the receiver are removed. In case of low pass filtering with MLE technique, the pulse shaping filter at the transmitter is replaced by 5th order low pass Butterworth filter and the pulse shaping filter at the receiver is replaced with length 6 linear phase FIR low pass filter.

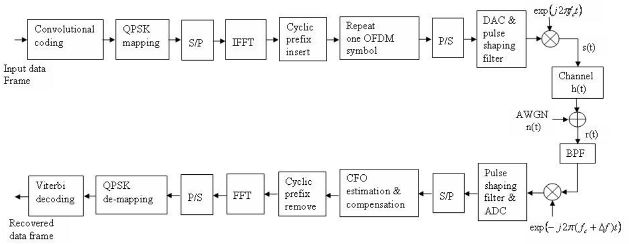

Fig.1 System block diagram

Performance Evaluation

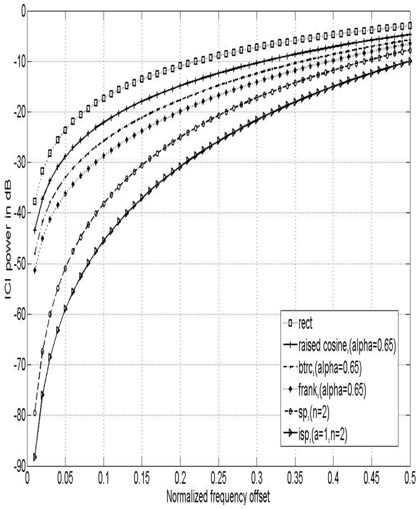

Figure 1. ICI with different Pulse shaping functions

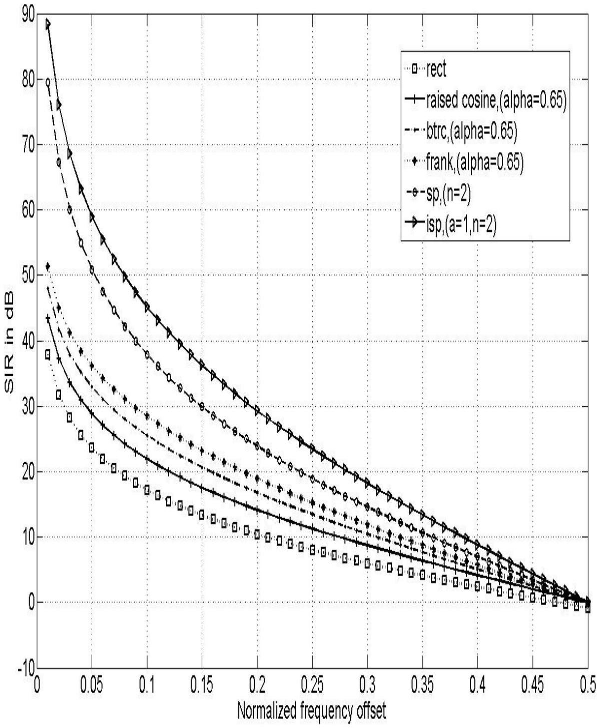

Figure 2. SIR with different Pulse shaping functions

Mat lab tool was used and Monte-Carlo simulations were carried out. Pulse functions were simulated as given in (1-6). ICI and SIR were computed as in (7) and (8) respectively for NCFOs in the range 0 to 0.5, with a step size of 0.01. For the convolutional coded OFDM system, a data set of 1040000 bits was used, which was further split into frames of 520 bits each.

V. PULSE SHAPING

Fig. 2 gives a plot of ICI power for different pulse functions. At a normalized CFO (NCFO) of 0.05, ICI power of ISP pulse function was around 35.45 dB less than that of rectangular function. SP pulse had very close performance with around 8.15 dB higher ICI power than the ISP pulse. ICI power increased with the NCFO and the response for all pulse functions came closer at a NCFO of 0.5.

Fig. 3 shows the response of SIR v/s NCFO. At a NCFO of 0.3, SIR of all the pulse functions was below 20 dB which indicates that the pulse shaping seizes to achieve ICI cancellation beyond a NCFO of 0.3. A comparison of ICI power, and SIR revealed the domination of the good features of the ISP pulse over the other pulses considered for the analysis, making the ISP pulse to be the best choice for the next part of our analysis.

ICI Cancellation in Coded OFDM System

Once the pulse function was chosen, the performance of convolutional coded QPSK system was simulated for different cases.

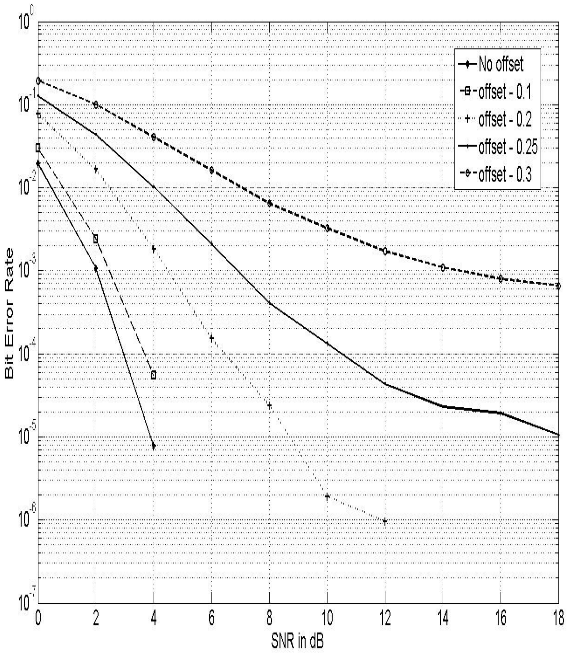

Figure 3. BER plot of convolutional coded QPSK OFDM system with ISP pulse shaping for different CFOs

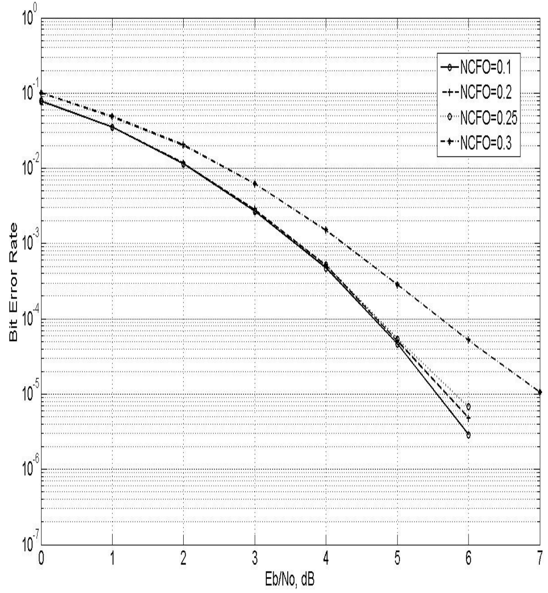

Figure 4. BER performance of convolutional coded OFDM system using MLE technique, with low pass filtering.

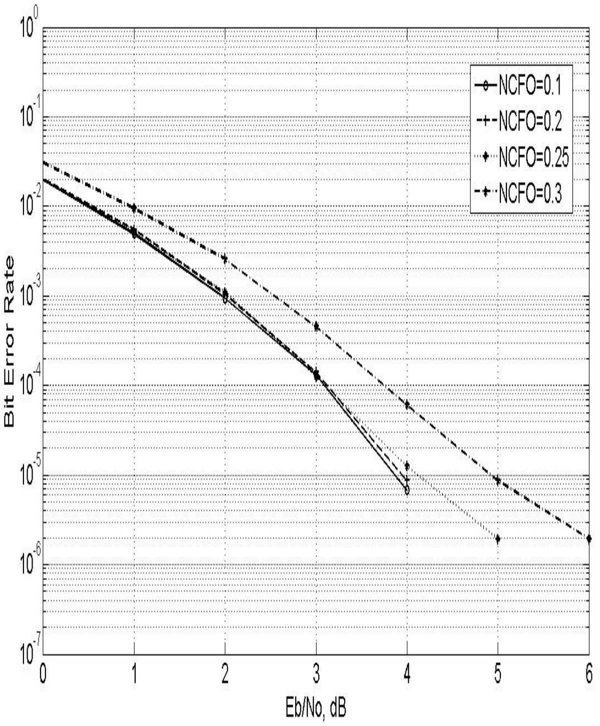

Figure 5. BER performance of the convolutional coded OFDM system using MLE technique combined with pulse shaping

BER performance of the system with pulse shaping alone is shown in Fig.4. It is clear from the plot that the system is immune to NCFOs of up to 0.1. For higher offsets, it was possible to overcome the effect of CFO by sacrificing the SNR. But the system response saturated to a BER of around $6x10^{-4}$ for a NCFO of 0.3. To achieve a BER of 10^{-5} with a NCFO of 0.25, the system required around 14.1 dB more of SNR compared to system without offset, which was quite high. The results indicate that pulse shaping method is suitable for lower offsets, up to NCFOs of around 0.15 in a QPSK system using convolutional coding.

Fig.5 shows the BER performance of the convolutional coded OFDM system using MLE technique with low pass filtering as described in section IV. The response was much better than that of pulse shaping method. The system was almost immune to the offsets up to a NCFO of 0.25. To achieve a BER of 10^{-5} with a NCFO of 0.25, the system required 1.85 dB more of SNR compared to the system with pulse shaping and without offset, which was a good improvement compared to the first case. For a NCFO of 0.3, there was a higher SNR requirement by 3.1 dB, as compared to the case of pulse shaping without offset, to achieve a BER of 10^{-5}.

In Fig.6, we show the improved results by combining MLE technique and pulse shaping. The system was immune to the offsets up to a NCFO of 0.25. To achieve a BER of 10^{-5} with a NCFO of 0.25, the system required only 0.3 dB more of SNR compared to system without experiencing offset, which was quite a good response compared to the other two cases. For a NCFO of 0.25 and BER of 10^{-5}, as compared to the first case of pulse shaping alone, there was 9.85 dB improvement in the BER performance and compared to the case of MLE technique with low pass filtering, it gave 1.65 dB improvement.

Conclusion

Pulse shaping is a method of ICI cancellation while MLE technique provides good CFO correction factor for the OFDM system suffering from CFO. In this paper, we have combined these two techniques to get the best BER performance of the OFDM system. A comparison with ISP pulse shaping alone and low pass filtering with MLE technique justifies the same. At a NCFO of 0.25, the new scheme provided a BER performance improvement of 1.65 dB as compared to MLE technique with low pass filtering, while the same was 9.85 dB as compared to pulse shaping alone for a BER of 10^{-5}. It was further seen that this modified scheme is much immune to CFO than the other two schemes considered, naturally making it the best choice for ICI cancellation in OFDM systems experiencing CFO.

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