AN ICI REDUCTION SCHEME FOR OFDM WITH PHASE NOISE OVER FADING CHANNELS

Lokesh C.,
Assistant Professor,
Department of E & E E,
VVCE,Mysore, India.
lokesh.c@vvce.ac.in.

Prof. Dr. Rekha K R
Professor,
Department of E & C E,
SJBIT, Bangalore, India.
krrekha@sjbit.edu.in

Prof. Dr. Nataraj K R
Professor,
Department of E & C E,
SJBIT, Bangalore, India.
nataraj.sjbit@gmail.com

Supritha M R
Assistant Professor,
Department of E & E E
JNNCE, Shimoga, India.
Supritha_prakash09@jnnce.ac.in

Abstract: Orthogonal Frequency Division Multiplexing has become a key element of todays wireless communication systems. However, its sensitivity to oscillator phase noise is responsible for Common Phase Error (CPE) and Inter-Carrier Interference (ICI) which greatly degrades the overall system performance. In this contribution, we address the problem of reducing the effects of phase noise in an OFDM system operating over a frequency selective fading channel. We propose a method for jointly estimating the channel and CPE in a first step and removing ICI in a second step. The algorithm is simulated on both coded and uncoded systems with phase noise over a fading channel.

Index Terms: Common Phase Error (CPE), Inter-Carrier Interference (ICI), Inter Symbol Interference (ISI).

I. INTRODUCTION

The principles of multicarrier modulation have been in existence for several decades. However, in recent years these techniques have quickly moved out of textbooks and into practice in modern communications systems in the form of Orthogonal Frequency Division Multiplexing (OFDM). OFDM is a special form of multicarrier modulation technique which is used to generate waveforms that are mutually orthogonal and then distributes the data over a large number of carriers that are spaced apart at precise frequencies. This spacing provides the "orthogonality" in this technique which prevents the demodulators from seeing frequencies other than their own. In an OFDM scheme, a large number of orthogonal, overlapping, narrow band subcarriers are transmitted in parallel. These carriers divide the available transmission bandwidth. The separation of the subcarriers is such that there is a very compact spectral utilization. With OFDM, it is possible to have overlapping sub channels in the frequency domain (Figure 1), thus increasing the transmission rate

Figure 1: Power Spectrum of the transmitted signal

In order to avoid a large number of modulators and filters at the transmitter and complementary filters and demodulators at the receiver, it is desirable to be able to use modern digital signal processing techniques, such as fast Fourier transform (FFT). OFDM is a promising candidate for achieving high data rates in mobile environment because of its multicarrier modulation technique and ability to convert a frequency selective fading channel into several nearly flat fading channels.

II. OFDM SYSTEM

Figure 2 shows the block diagram of a typical OFDM system. The transmitter section converts digital data to be transmitted, into a mapping of subcarrier amplitude and phase. It then transforms this spectral representation of the data into the time domain using an Inverse Discrete Fourier Transform (IDFT). The Inverse Fast Fourier Transform (IFFT) performs the 20 same operations as an IDFT, except that it is much more computationally efficient, and so is used in all practical systems. In order to transmit the OFDM signal the calculated time domain signal is then mixed up to the required frequency. The receiver performs the reverse operation of the transmitter, mixing the RF signal to base band for processing, then using a Fast Fourier Transform (FFT) to analyze the signal in the frequency domain. The amplitude and phase of the subcarriers is then picked out and converted back to digital data. The IFFT and the FFT are complementary function and the most appropriate term depends on whether the signal is being received or generated. In cases where the signal is independent of this distinction then the term FFT and IFFT is used interchangeably. The high data rate serial input bit stream is fed into serial to parallel converter to get low data rate output parallel bit stream. Input bit stream is taken as binary data. The low data rate parallel bit stream is modulated in Signal Mapper. Modulation can be BPSK, QPSK, QAM, etc. The modulated data are served as input to inverse fast Fourier transform so that each subcarrier is assigned with a specific frequency. The frequencies selected are orthogonal frequencies. In this block, orthogonality in subcarriers is introduced. In IFFT, the frequency domain OFDM symbols are converted into time domain OFDM symbols. Guard interval is introduced in each OFDM symbol to eliminate Inter Symbol Interference (ISI). All the OFDM symbols are taken as input to parallel to serial data. These OFDM symbols constitute a frame. A number of frames can be regarded as one OFDM signal. This OFDM signal is allowed to pass through digital to analog converter (DAC). In DAC the OFDM signal is fed to RF power amplifier for transmission. Then the signal is allowed to pass through additive white Gaussian noise channel (AWGN channel). At the receiver part, the received OFDM signal is fed to analog to digital converter (ADC) and is taken as input to serial to parallel converter. In these parallel OFDM symbols, Guard interval is removed and it is allowed to pass through Fast Fourier transform. Here the time domain OFDM symbols are converted into frequency domain. After this, it is fed into Signal Demapper for demodulation purpose. And finally the low data rate parallel bit stream is converted into high data rate serial bit stream which is in form of binary.

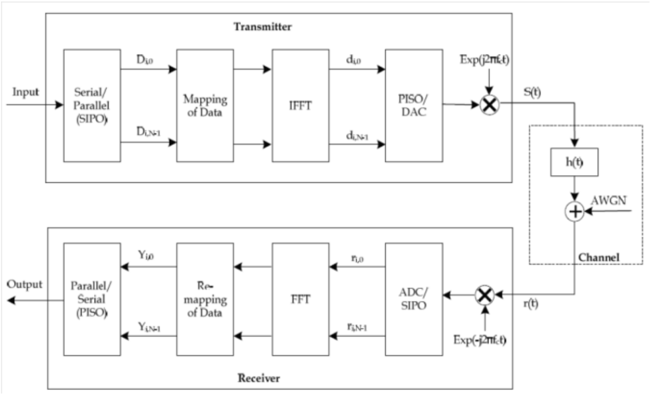

Figure 2: OFDM System Implementation

By the insertion of an extra guard interval between successive OFDM symbols the Inter Symbol Interference (ISI) can be avoided. The guard interval could be a section of all zero samples transmitted in front of each OFDM symbol and its duration should be more than the channel delay spread (L_c). It should be considered that in practical systems the guard interval is not used. Instead, Cyclic Prefix (CP) is inserted to combat the multipath-channel by making the channel estimation simple. The cyclic prefix is a replica of the last L_p samples of the OFDM symbol where $L_p > L_c$. Because of the way in which the cyclic prefix was formed, the cyclically-extended OFDM symbol now appears periodic when convolved with the channel. An important result is that the effect of the channel becomes multiplicative.

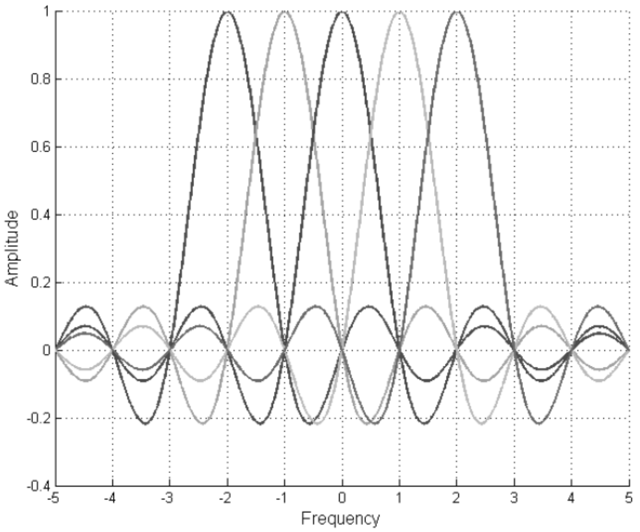

Figure 3: OFDM Spectrum with 5 subcarriers

In this study the phase noise is resolved into two components, namely the Common Phase Error (CPE), which affects all the sub-channels equally and the Inter-Carrier Interference (ICI), which is caused by the loss of orthogonality of the subcarriers.

III. ICI REDUCTION TECHNIQUES

In the OFDM systems, N subcarriers are used for data transmission of N symbols $\{D_{i,0}, D_{i,1}, \ldots., D_{i,N-1}\}$. By using the IFFT operation for the data modulation, rectangular pulse shaping filter is implicitly applied. Thus, the spectrum of each individual subcarrier equals asinc-function defined as $sinc(x) = \frac{\sin(\pi x)}{\pi x}$ and is given by:

$$S_k(z) = D_{i,k}\, sinc(z - z_k), \quad k = 0,1,2, \ldots, N-1$$

where z represents the frequency f shifted to the carrier frequency of the OFDM system f_c and normalized to the sampling frequency $1/T_s$. The normalized frequency is given by:

$$z = (f - f_c) \times T_s$$

Accordingly, $z_k = (f_k - f_c) \times T_s$ is defined as the normalized center frequency of the k-th subcarrier with $f_k$representing the center frequency of the k-th subcarrier. The spectrum of the transmitted OFDM symbol is the superposition of the spectra of all individual subcarriers:

$$S(z) = \sum_{k=0}^{N-1} S_k(z)$$

The side lobe power of this sum signal and also the sidelobe power of each subcarrier spectrum only decays with $1/z^2$ resulting in a high interference caused by the high sidelobes of the adjoining carriers on a particular subcarrier.

Here, some techniques introduced to reduce the power of the interfering components.

A. Pulse shaping

As we have seen in the OFDM spectrum each carrier consists of a main lobe followed by a number of sidelobes with reducing amplitudes. As long as orthogonality is maintained,there is no interference among the carriers because at the peak of the every carrier, there exists a spectral null. That is at that point that the component of all other carriers is zero. Hence the individual carrier is easily separated.In the presence of the frequency offset the orthogonality is lost because the spectral null does not coincide to the peak of the individual carriers. So some power of the sidelobes exists at the centre of the individual carriers which is called ICI power. The ICI power will go on increasing as the frequency offset increases. The purpose of pulse shaping is to reduce the sidelobes which leads to the significant decrease in the ICI power. In a simple OFDM system, symbols are performed using an N-FFT function. This implies that the received signal *r(k)* is shaped in the time domain by a rectangular pulse function. One possible countermeasure to overcome the interference is making the PDS of the OFDM modulated subcarriers $(S_n(z))$ go down more rapidly by shaping the transmit signal of the OFDM subcarriers. This makes the amplitude go smoothly to zero at the symbol boundaries. The N-subcarrier OFDM block with pulse-shaping is expressed as:

$$s(t) = e^{j2\pi f_c t} \sum_{k=0}^{N-1} D_k p(t) e^{j2\pi f_k t}$$

where $p(t)$is the pulse shaping function. The transmitted symbol D_k is assumed to have zero mean and normalized average symbol energy. Also we assume that all data symbols are uncorrelated, i.e.:

$$E[D_k D_m^*] = \begin{cases} 1, & k = m, \quad k,m = 0,1,2,\ldots.,N-1 \\ 0, & k \neq m, \quad k,m = 0,1,2,\ldots\ldots,N-1 \end{cases}$$

where D_m^* is the complex conjugate of D_k. To ensure the subcarrier orthogonality, which is very important for OFDM systems the equation below has to be satisfied:

$$f_k - f_m = \frac{k-m}{T_s}, k,m = 0,1,2,\ldots\ldots,N-1.$$

In the receiver block, the received signal can be expressed as:

$$r(t) = s(t) \otimes h(t) + w(t)$$

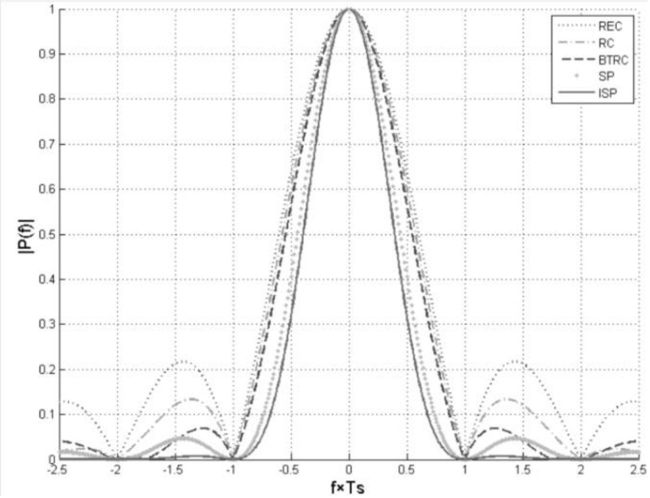

Figure 4: Comparison of REC, RC, BTRC, SP, and ISP Spectrums

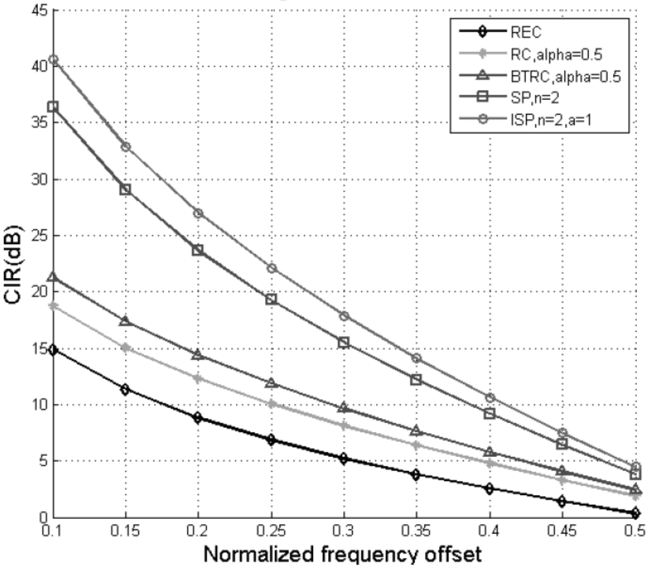

Figure 5: CIR performance for different pulse shapes

The purpose of pulse shaping is to increase the width of the main lobe and/or reduce the amplitude of sidelobes, as the sidelobe contains the ICI power. REC, RC, BTRC, SP, and ISP pulse shapes are depicted in Figure 4 for $a = 1, n = 2, and\ \alpha = 0.5$. SP pulse shape has the highest amplitude in the main lobe, but at the sidelobes it has lower amplitude than BTRC. This property provides better CIR performance than that of BTRC as shown in [Mourad, 2006]. As seen in this figure the amplitude of ISP pulse shape is the lowest at all frequencies. This property of ISP pulse shape will provide better CIR performance than those of the other pulse shapes as shown in Figure 6. Figure 4 shows that the sidelobe is maximum for rectangular pulse and minimum for ISP pulse shapes. This property of ISP pulse shape will provide better performance in terms of ICI reduction than those of the other pulse shapes. Figure 6 compares the amount of ICI for different pulse shapes.

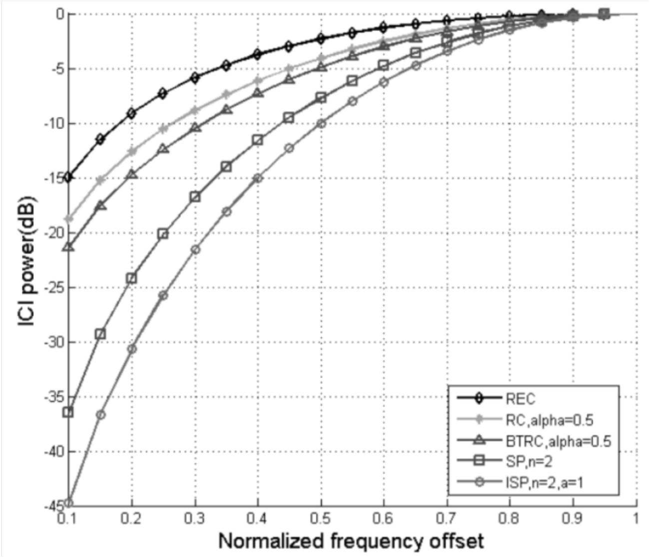

Figure 6: ICI comparison for different pulse shapes

B. *ICI self-cancellation methods*

In single carrier communication system, phase noise basically produces the rotation of signal constellation. However, in multi-carrier OFDM system, OFDM system is very vulnerable to the phase noise or frequency offset. The serious inter-carrier interference (ICI) component results from the phase noise. The orthogonal characteristics between subcarriers are easily broken down by this ICI so that system performance may be considerably degraded. There have been many previous works in the field of ICI self-cancellation methods. Among them convolution coding method, data conversion method and data-conjugate method stand out

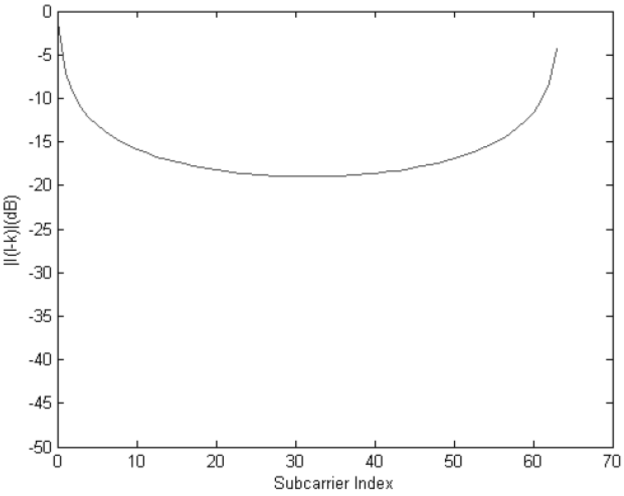

Figure 7: ICI coefficient versus subcarrier index; N=64

For further reduction of ICI, ICI cancelling demodulation is done. The demodulation is suggested to work in such a way that each signal at the $k + 1$ -th subcarrier (now k denotes even number) is multiplied by -1 and then summed with the one at the k-th subcarrier. Then the resultant data sequence is used for making symbol decision. Due to the repetition coding, the bandwidth efficiency of the ICI self-cancellation scheme is reduced by half. To fulfill the demanded bandwidth efficiency, it is natural to use a larger signal alphabet size. For example, using 4PSK modulation together with the ICI self cancellation scheme can provide the same bandwidth efficiency as standard OFDM systems (1 bit/Hz/s).

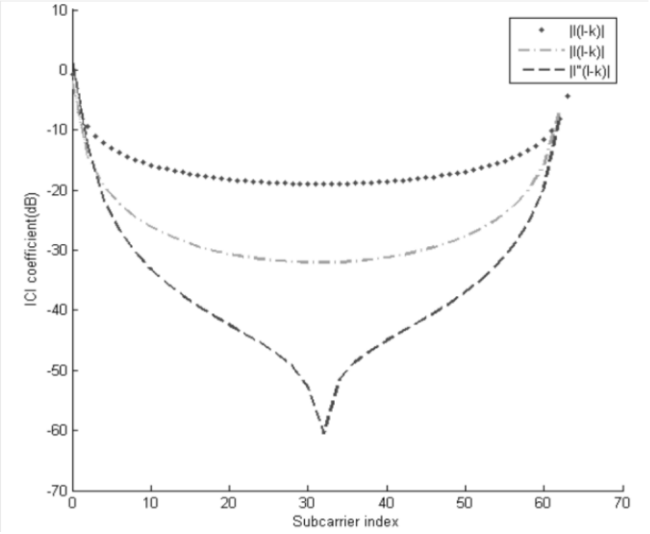

Figure 8: Amplitude comparison of $|I(l-k)|, |I'(l-k)|\ and\ |I''(l-k)|$

C. Data-conjugate method

In an OFDM system using data-conjugate method, the information data pass through the serial to parallel converter and become parallel data streams of *N/2* branch. Then, they are converted into *N* branch parallel data by the data-conjugate method. The conversion process is as follows. After serial to parallel converter, the parallel data streams are remapped as the form of *D'2k = Dk* , *D'2k+1 = -D*k* , (*k = 0, ... , N/2-1*). Here, *Dk* is the information data to the *k*-th branch before data-conjugate conversion, and *D'2k* is the information data to the *2k*-th branch after ICI cancellation mapping. Likewise, every information data is mapped into a pair of adjacent sub-carriers by data-conjugate method, so the *N/2* branch data are extended to map onto the *N* sub-carries. The original data can be recovered from the simple relation of *Z'k = (Y2k – Y*2k+1)*/2. Here, *Y2k* is the *2k*-th sub-carrier data, *Z'k* is the *k*-th branch information data after de-mapping. Finally, the information data can be found through the detection process.

IV. CPE, ICI AND CIR ANALYSIS

A. Original OFDM

In the original OFDM, the k-th sub-carrier signal after FFT is as follows:

$$Y_k = D_k Q_0 + \sum_{\substack{l=0 \\ l\neq k}}^{N-1} D_l \cdot Q_{l-k} + w_k$$

The received desired signal power on the k-th sub-carrier is:

$$E[|Y_{k1}|^2] = E[|D_k Q_0|^2]$$

ICI power is: $E[|Y_{k2}|^2] = E\left[\left|\sum_{\substack{l=0 \\ l\neq k}}^{N-1} D_l Q_{l-k}\right|\right]$

Transmitted signal is supposed to have zero mean and statistically independence. So, the CIR of the original OFDM transmission method is as follows:

$$CIR = \frac{|Q_0|^2}{\sum_{\substack{l=0 \\ l\neq k}}^{N-1} |Q_{l-k}|^2} = \frac{|Q_0|^2}{\sum_{l=1}^{N-1} |Q_l|^2}$$

B. Data-conversion method

In the data-conversion ICI self-cancellation method, the data are remapped in the form of

$$D_{2k} = D_k, \quad D_{2k+1} = -D_k.$$

So, the desired signal is recovered in the receiver as follows:

$$Z_k = D_k + \frac{1}{2} D_k[-Q_{-1} + 2(Q_0 - 1) - Q_1]$$

CPE is as follows:

$$CPE = \frac{j2D_k}{N} \sum_{m=0}^{N-1} sin^2\left(\frac{\pi m}{N}\right) \theta_{tot}(m)$$

C. Data-conjugate method

In the data conjugate method, the decision variable can be written as follows:

$$Z_k = D_k + \frac{1}{2} \sum_{\substack{l=0 \\ l\neq k}}^{\frac{N}{2}-1} D_l [Q_{2l-2k} + Q_{2l-2k}^*]$$

Through the same calculation, CPE, ICI and CIR of the data conjugate method are found.

$$CPE = 0$$

The fact CPE is zero is completely different from the data conversion method whose CPE is not zero like .

V. CONCLUSION

OFDM has been widely used in communication systems to meet the demand for increasing data rates. It is robust over multipath fading channels and results in significant reduction of the transceiver complexity. However, one of its disadvantages is sensitivity to carrier frequency offset which causes attenuation, rotation of subcarriers, and inter-carrier interference (ICI). The ICI is due to frequency offset or may be caused by phase noise. The undesired ICI degrades the signal heavily and hence degrades the performance of the system. So, ICI mitigation techniques are essential to improve the performance of an OFDM system in an environment which induces frequency offset error in the transmitted signal. In this paper, the performance of OFDM system in the presence of frequency offset is analyzed. This topic investigates different ICI reduction schemes for combating the impact of ICI on OFDM systems. A number of pulse shaping functions are considered for ICI power reduction and the performance of these functions is evaluated and compared using the parameters such as ICI power and CIR. Simulation results show that ISP pulse shapes provides better performance in terms of CIR and ICI reduction as compared to the conventional pulse shapes.

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BIOGRAPHY

Mr. Lokesh C is a research student in SJB Institute of Technology, Bengaluru, India. And working as Assistant Professor in the department of Electrical and Electronics Engineering from Vidyavardhaka College of Engineering, Mysuru (India). His research mainly encompasses in the area of Wireless Communication, Application of Communication System in Electrical Engineering for Low Power Analysis. He has published 9 research papers in International Journals. And 6 papers in International Conference.

Dr. Rekha K. R. received PhD in the area of Electronics and Communication and working as Professor in the department of ECE at SJB Institute of Technology, Bangaluru, India. Her research area mainly consists of network design, high speed optical transmission, and wireless sensors. She Published papers in National and International conference and Journals. And published totally 32 articles in various Journals and Conferences.

Dr. Nataraj K.R. received his Ph.D. degree in Electronics and Communication Engineering. Presently he is working as Professor and heading the department of ECE at SJB Institute of Technology, Bangaluru, India. And has an experience of 18 years. His research interest mainly encompasses in the area of Communication, Signal Processing and Communication for Inter satellite. He has published 24 International/ National Conference papers.

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