

# ICI Mitigation Techniques in OFDM System: A Review

**Abhijeet Bishnu**

Deptt. of Elex. and Telecomm  
S.G.S.I.T.S. Indore  
abhijeet.bishnu87@gmail.com

**Anjana Jain**

Deptt. of Elex. and Telecomm  
S.G.S.I.T.S. Indore  
jain.anjana@gmail.com

**Anurag Shrivastava**

Deptt. of Elex. and Telecomm  
S.G.S.I.T.S. Indore  
ashrivastava827@gmail.com

**Abstract** - Carrier frequency offset, phase noise, timing offset and Doppler spread due to frequency error causes Inter Carrier Interference, which degrades the performance of Orthogonal Frequency Division Multiplexing (OFDM). In this paper, we present a comprehensive study of different types of Inter Carrier Interference (ICI) reduction technique, presented in different literature. We compare the performance of different methods by providing their CIR (Carrier to Interference Ratio) and BER (Bit Error Rate) graphs. The result shows that pulse shaping method is better than other methods.

**Keywords** — ICI, OFDM, Carrier Frequency Offset (CFO), Sampling Frequency Offset (SFO).

## I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier multiplexing technique for high-bit-rate transmission in wireless communications. In OFDM [1]-[3], the entire channel is divided into many narrow-band flat fading sub channels, which are transmitted simultaneously to maintain high-data-rate transmission and at the same time, to increase the symbol duration to avoid Inter Symbol Interference (ISI). Due to its robustness against multipath fading, OFDM has implemented in the digital communication systems, including European radio DAB and TV, DVB-T [4]-[5], wireless Local Area Networks (WLAN) [6], Wimax etc. It has also proposed as the core technique for the third (3G) and fourth generation (4G) mobile communication.

As OFDM has many advantages, there are also some disadvantages. One of these is Inter carrier Interference (ICI) causes from Carrier Frequency Offset (CFO), phase noise, timing offset and Doppler spread. The CFO is caused due to misalignment between carrier frequencies of transmitter and receiver oscillators. When the CFO exists, orthogonality among sub-carriers might be imperfect and sub-carrier will interfere with each other leads to ICI, attenuation and rotation of subcarriers [7]-[8]. Several methods have been presented in different papers to reduce ICI, which we will discuss in later section.

The paper is organised as follows. In section II, OFDM system model is described. In section II the concept of ICI is analytically developed. In section IV, different methods of ICI reduction will discuss. In section V, results are discussed and finally conclude the paper in section VI.

## II. OFDM SYSTEM DESCRIPTION

In an OFDM system, the input bit is multiplexed into N symbol, each with symbol period of T, and each symbol stream is used to modulate the parallel subcarriers. The

subcarriers are separated by  $1/NTs$  in frequency domain, so they are orthogonal over  $(0, Ts)$ .

A typical OFDM transceiver system is shown in fig.1. First, serial to parallel converter converts the input bits stream into groups of  $\log_2 M$  bits, Where M is alphabet of size of digital modulation scheme used in different sub-carrier.

A total of N such symbols  $X_m$  are created. Then, the N symbols are mapped to IFFT. These IFFT corresponds to the orthogonal sub-carriers in the OFDM symbol. Therefore, the OFDM symbol can be expressed as:

$$x(n) = \frac{1}{N} \sum_{m=0}^{N-1} X_m e^{j2\pi nm} \quad (1)$$

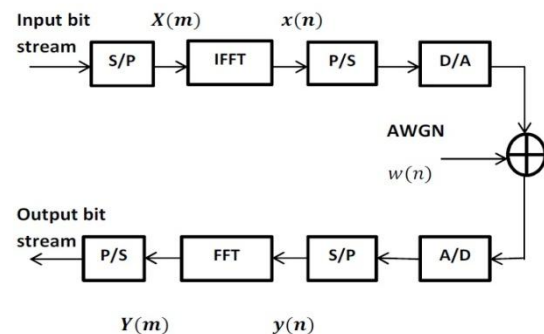


Fig.1. Baseband OFDM transceiver system

The digital-to-analog (D/A) converter produces an analog time-domain signal which is transmitted through the channel. At the receiving side, the signal is converted back to a discrete N point sequence  $y(n)$ , for each sub-carrier. This discrete signal is demodulated using an N-point fast Fourier transform (FFT) operation at the receiver. The demodulated symbol stream is given by:

$$Y(m) = \sum_{n=0}^{N-1} y(n) e^{j2\pi nm} + W(m) \quad (2)$$

Where,  $W(m)$  corresponds to the FFT of the sample of  $w(n)$ , which is AWGN channel. Inter Symbol Interference (ISI) are caused due to multipath distortion which leads to adjacent symbols overlap with each other. This is avoided in OFDM by the insertion of a cyclic prefix in front of OFDM symbols. The length of cyclic prefix must be larger than the maximum delay of the channel. At the receiver, the cyclic prefix is discarded.

## III. ANALYSIS OF INTER CARRIER INTERFERENCE

The main disadvantage of OFDM is its sensitivity to small difference in frequency at the transmitter and receiver known as frequency offset. This frequency offset can be caused by Doppler shift or by difference between

the frequencies of local oscillator at the transmitter and receiver. From Fig.2, the received signal is given by

$$y(n) = x(n)e^{\frac{j2\pi n\epsilon}{N}} + W(n) \quad (3)$$

Where  $\epsilon$  is the normalised frequency offset given by  $\Delta fNT_s$ .  $\Delta f$  is the frequency difference between the transmitted and received carrier frequencies and  $T_s$  is the subcarrier symbol period.  $w(n)$  is the AWGN introduced in the channel. The effect of frequency offset in the received symbol  $Y(k)$  at  $k^{th}$  subcarrier is given by

$$Y(k) = X(k)S(0) + \sum_{l=0, l \neq k}^{N-1} X(l)S(l-k) + nk, k=0,1,..,N-1 \quad (4)$$

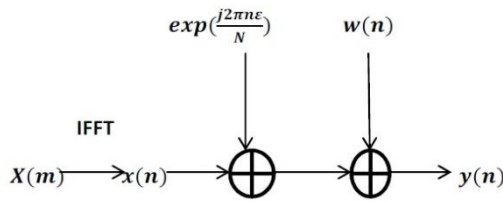


Fig.2. Frequency Offset Model

Where  $N$  is total number of subcarriers,  $X(k)$  is the transmitted symbol for the  $k^{th}$  subcarrier,  $n_k$  is the FFT of  $w(n)$ , and  $S(l-k)$  is the complex coefficients for the ICI of the received signal. The ICI is the interfering signals transmitted on subcarriers other than the  $k^{th}$  subcarrier. The complex coefficients are given by

$$S(l-k) = \frac{\sin(\pi(l+\epsilon-k))}{N \sin(\frac{\pi(l+\epsilon-k)}{N})} e^{j\pi(l-\frac{1}{N})(l+\epsilon-k)} \quad (5)$$

The carrier-to-interference ratio (CIR) given in Eq. 6 is the ratio of the signal power to the power of interference signal.

The derivation assumes that the transmitted data has zero mean and the symbols transmitted on the different subcarriers are statistically independent.

$$CIR = \frac{|S(0)|^2}{\sum_{l=1}^{N-1} |S(l)|^2} \quad (6)$$

#### IV. ICI REDUCTION METHODS

There are following methods presented in literature:

- 1) Frequency Domain Equalization
- 2) Correlative Coding
- 3) Time Domain Windowing
- 4) ICI Self Cancellation
- 5) Pulse Shaping
- 6) Coded OFDM
- 7) ML Estimation
- 8) Kalman Filter

##### A. Frequency Domain Equalization

In [9], the equalization of the received OFDM signal is achieved by the assumption that the channel impulse response is varying in a linear fashion during a block period and compensates for the ICI terms that affect the bit-error-rate (BER) performance.

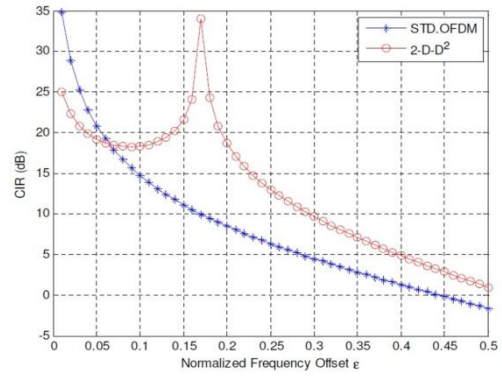


Fig.3. CIR vs  $\epsilon$  of correlative coding

##### B. Correlative Coding

In this method different coding correlation polynomial is used. In [10], (1-D) was proposed. In [16], (1 - D - D2, (2-D-D2) were proposed and shows that the last one outperforms the old coding. The coded symbol for (2 - D - D<sup>2</sup>) is given as [16]

$$b_k = 2a_k - a_{k-1} - a_{k-2}, K \in (1, N)$$

Where  $D$  denotes the unit delay of the subcarrier index  $k$ ,  $a_k$  is input signal sequence. For (2 - D - D<sup>2</sup>), CIR is given as [16] and given by Eqn. (7)

$$CIR = \frac{\sin^2(\pi\epsilon)/(\pi\epsilon)^2}{\sum_{l=1}^{N-1} |S(l)|^2 - P_I - P_{II}} \quad (7)$$

Where

$$P_I = \frac{1}{6} \sum_{l=3}^N [S(l)S^*(l-1) - S(l-1)S^*(l)]$$

$$P_{II} = \frac{1}{3} \sum_{l=3}^N [S(l)S^*(l-2) - S(l-2)S^*(l)]$$

##### C. Time Domain Windowing

In this method Nyquist window function is used to mitigate ICI, which are obtained by sampling the raised-cosine pulse, the "Better Than" Nyquist window and the SOCW pulse. In [17], it shows that the SOCW pulse outperforms the other pulses. The definition of SOCW pulse is given in [18, Eqn. 10], CIR is given in [18, Eqn. 24] and the average bit energy -to-noise ratio is given by:

$$\gamma_b = \frac{0.5\sigma_s}{\sigma_{ICI} + \sum_{m=0}^{N-1} g_m^2 \sigma^2 / N} \quad (8)$$

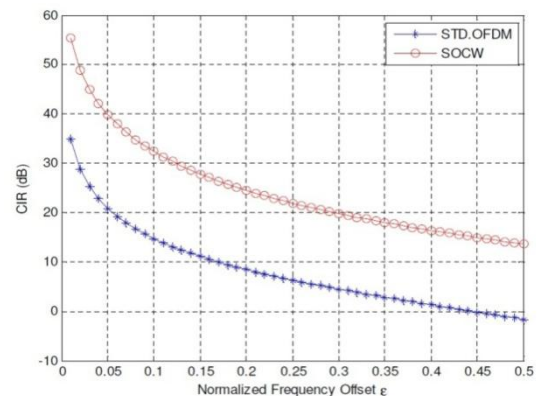


Fig.4 CIR vs  $\epsilon$  of SOCW

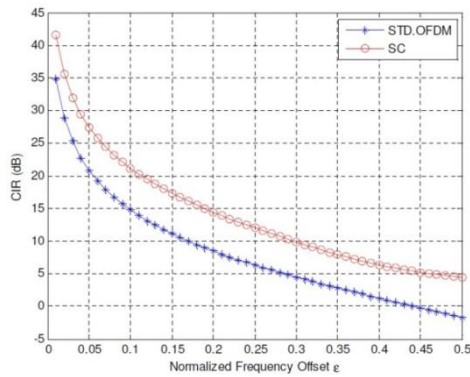


Fig.5. CIR vs  $\epsilon$  of WCT

The bit error rate can be expressed as [18]:

$$P_b = \frac{1}{2} \left( 1 - \sqrt{\frac{\gamma_b}{1+\gamma_b}} \right) \quad (9)$$

#### D. ICI self cancellation

In this scheme, one data symbol is modulating onto the next subcarrier with predefined weighting coefficients. By doing so, the ICI signals generated within a group can be "self-cancelled" each other [11].

In [11] the data-conversion method and in [12] data-conjugate was proposed. In [19] the symmetric data conversion (SDC) was proposed and in [20] weighted conjugate transform (WCT) was proposed, in which data is remapped as

$X'(k) = X(k), X'(k+1) = e^{j\frac{\pi}{2}} X^*(k)$ .  $X(k)$  is data symbol for the  $k^{th}$  parallel branch,  $X'(k)$  is the  $k^{th}$  sub-carrier data symbol after ICI cancellation mapping and  $X^*(.)$  is the conjugate of  $X(.)$ . According to [20] the WCT outperforms the other methods. The CIR of the WCT is given by in [20, Eqn. 19].

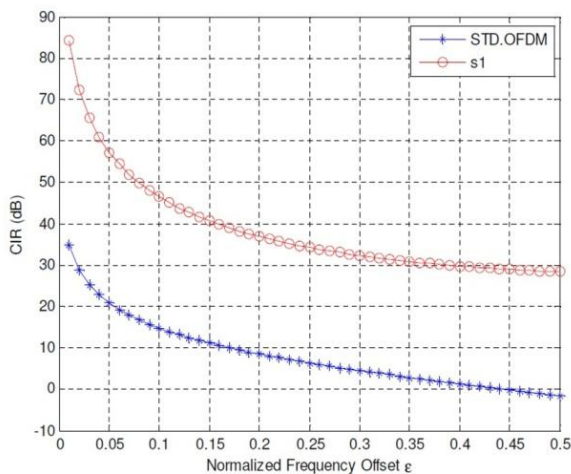


Fig.6. CIR vs  $\epsilon$  of S1 pulse shaping

#### E. Pulse shaping

The purpose of pulse shaping is to reduce the side lobes which lead to the significant decrease in the ICI power. In [13] a number of pulse shaping functions such as Rectangular pulse (REC), Raised cosine pulse (RC), Better than raised cosine pulse (BTRC), Sinc pulse (SP) and Improved sinc power pulse (ISP) for reduction of ICI

power are proposed. In [21] a new S1 pulse shaping is proposed which outperforms the other pulse shaping methods. The function of S1 is given as [21]:

$$P_{s1}(f) = \text{sinc}(afT) \text{sinc}^n(fT) \quad (10)$$

Where  $a$  is a design parameter to adjust the amplitude and  $n$  is the degree of the sinc function. The CIR is expressed as [13]:

$$CIR = \frac{|p(\Delta f)|^2}{\sum_{k=0, k \neq m}^{N-1} |p(\frac{k-m}{T} + \Delta f)|^2} \quad (11)$$

The average BER of an OFDM-BPSK system is given by [21]:

$$BER_{OFDM} = 1 - (1 - BER_{SYMBOL})^N \quad (12)$$

$$BER_{SYMBOL} = \frac{1}{2} (Q_1 + Q_2) \quad (13)$$

Where

$$Q_1 = Q(\cos\theta[p(-\Delta f) + \sqrt{p_{ICI}}]\sqrt{2\gamma_b})$$

$$Q_2 = Q(\cos\theta[p(-\Delta f) - \sqrt{p_{ICI}}]\sqrt{2\gamma_b})$$

$\gamma_b$  is the signal-to-noise ratio,  $\theta$  denotes the carrier frequency noise and  $Q$  the is error function.

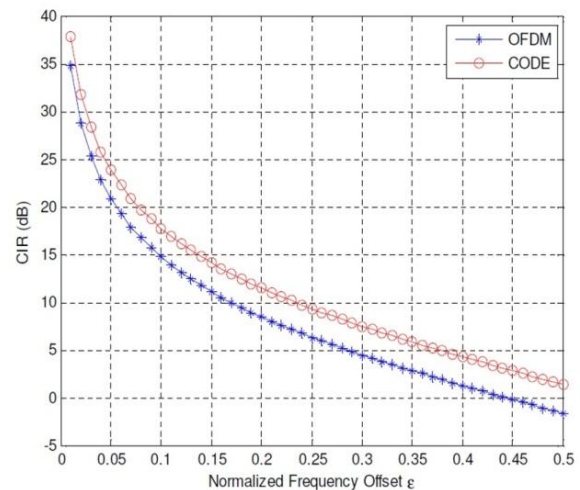


Fig.7. CIR vs  $\epsilon$  of CODED OFDM

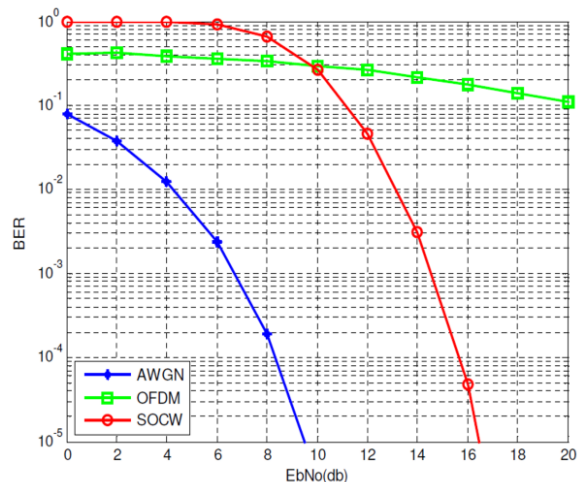


Fig.8. BER versus  $E_b/N_0$  of SOCW

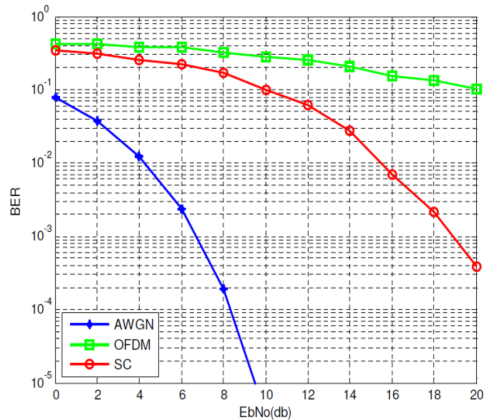


Fig.9. BER versus Eb/No of WCT

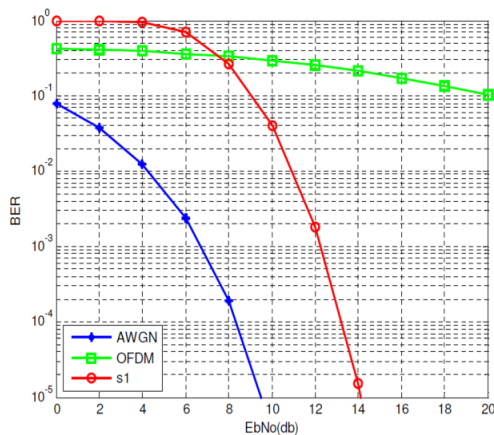


Fig.10 BER versus Eb/No of S1 pulse shaping

### F. Coded OFDM

By this scheme, the frequency separation between adjacent sub-carriers is increases. In order to realise this goal firstly, two adjacent sub-carriers are paired as a group; then, jointly code data information in them. After coding, only one of the two sub-carriers in that pair is transmit over each OFDM symbol interval. As in the coded OFDM system, only half sub-carriers are used for information transmission. Thus CIR can be expressed as [22]:

$$CIR = \frac{2|S(0)|^2}{\sum_{l=1}^{N-1} |S(l)|^2} \quad (14)$$

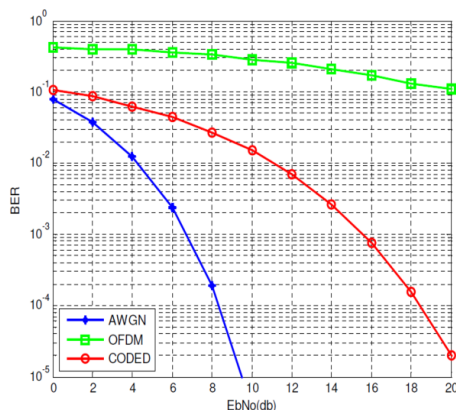


Fig. 11 BER versus Eb/No of CODED OFDM

Table I :CIR for different value of  $\epsilon$ .

METHODS	$\epsilon = 0.15$	GAIN	$\epsilon = 0.35$	GAIN
None	11.10db		2.77db	
Corr. coding	21.5db	10.4db	7.05db	4.28db
SOCW	27.81db	16.71db	17.98db	15.21db
WCT	17.32db	6.22db	7.93db	5.16db
S1 Pulse shaping	40.6db	29.56	30.84db	28.07db
CODED	14.10db	3db	5.77db	3db

### G. ML estimation

In this approach, firstly estimated the frequency offset statistically using maximum likelihood algorithm and cancel out at the receiver. This technique involves the replication of an OFDM symbol before transmission and comparison of the phases of each of the subcarriers between the successive symbols. In [14] frequency-domain fine timing Maximum Likelihood Estimation synchronizer (MLE) is used which superior to first-peak is finding (FPF) synchronizer and maximum energy windowing (MEW) synchronizer.

Table II: Required Eb/No for BER of  $10^{-2}$  for BPSK

METHODS	$\epsilon = 0.3$
None	infinite
SOCW	13.25db
WCT	15.75db
S1 pulse shaping	11db
CODED	11.25db
ML estimation	16db
EKF	13db

### H. Kalman filter

In this method [15], one preamble is known at both transmitter and receiver sides is sent before transmitting the data information.

The received signals are divided into real and imaginary parts. With the relationship between real and imaginary parts, estimate the frequency offset without estimating the original phase of carrier using Extended Kalman Filter (EKF). The Doppler frequency drift information can be updated at each step to get a more accurate result. Then the ICI effect can be mitigated effectively without the original phase error information.

## V. RESULTS

In this section we show CIR and BER graphs of different methods and compare them.

Fig.3 to Fig.7 shows CIR of correlative coding, SOCW, WCT, S1 pulse shaping and CODED OFDM respectively. Fig.8 to Fig.11 shows BER versus Eb/No graphs for SOCW, WCT, S1 pulse shaping and CODED OFDM for  $N=52$ ,  $\epsilon=0.3$  respectively in AWGN channel. Fig.7 [14] shows BER of ML estimation and Fig4.2a [15] shows BER of Extended Kalman Filter.

Table I. provides comparison of different methods in terms of CIR and it shows that pulse shaping is better than other as it gives highest CIR than other . Pulse shaping method is again better than other in terms of BER as given in Table II as it requires least Eb/No for same BER.

## VI. CONCLUSION

In this paper, various ICI mitigation techniques are presented. Table I shows the CIR performance of different methods and Table II shows the BER performance. Both the table shows that pulse shaping technique is best than other methods. But we can employ different methods depends on application. The first 6 methods does not require complex hardware circuit. In correlative coding, precoding is must before modulation so that the error does not propagate to decoding process. Due to the redundancy of 2 for each sub-carrier, the self-cancellation method is not bandwidth efficient. The EKF is bandwidth efficient and the last two methods required complex hardware and software as they are based on estimation and cancellation, so they required preamble before sending data.

## ACKNOWLEDGMENT

I would like to thank Prof. Anjana Jain and Prof. Anurag Shrivastava for their continuous encouragement, invaluable supervision, timely suggestions, and inspired guidance and helped us through the entire duration of my work. Finally I extend our gratitude to one and all who are directly or indirectly involved in the successful completion of this work.

## REFERENCES

- [1] J. Chuang, "The effect of time delay spread on portable radio communications channels with digital modulation" *IEEE Journal in Sel. Areas Commu.*, vol. 5, no. 5, Jun. 1987, pp. 879-889,.
- [2] L.J. Climini, Jr., "Analysis and simulation of a digital mobile channel using OFDM," *IEEE Trans. on Commun.*, vol. 33, no. 7, Jul. 1985, pp. 665-675.
- [3] S. Weinstein and P. Ebert, "Data Transmission by frequency division multiplexing using the discrete Fourier transform," *IEEE Trans. On Commun. Tech.*, vol. 19, no. 5, Oct. 1971, pp. 628-634.
- [4] European standard (telecommunications series), Radio Broadcasting Systems; Digital Audio Broadcasting(DAB) to mobile, Portable and Fixed Receivers," vol. ETSI EN 300 401 V1. 3.3 (2001-2005), 2001.
- [5] European standard (telecommunications series), Radio Broadcasting Systems; Framing Structure, Channel Coding and Modulation for Digital Terrestrial Television." vol. ETSI EN 300 744 V1.4.1 (2001-2002), 2001.
- [6] Part11: Wireless Ln Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High-speed Physical Layer in the 5GHz Band, IEEE Standard 802.11a-1999, 1999.
- [7] L. Rugini and P. Banelli, "BER of OFDM Systems Impaired by CFO in Multipath Fading channels", *IEEE Trans. on Wireless Commu.*, vol. 4, no. 5, Sep. 2005, pp. 2279-2288.
- [8] J. Armstrong, "Analysis of New and Existing methods of Reducing ICI due to CFO in OFDM", *IEEE Trans. on Commu.*, vol. 47, no. 3, Mar. 1999, pp. 365-369.
- [9] W.G. Jeon, K.H. Chang, Y.S. Cho, "An Equalization Technique for Orthogonal Frequency-Division Multiplexing Systems in

- Time-Variant Multipath Channels", *IEEE Trans. on Commu.*, vol. 47, no. 1, Jan. 1999, pp. 27-32.
- [10] Y. Zhao, J.-D. Leclercq, S.-G. Haggman, "Intercarrier Interference Compression in OFDM Communication Systems by Using Correlative Coding", *IEEE Commu. Lett.*, vol. 2, no. 8, Aug. 1998, pp. 214-21.
- [11] Y. Zhao and S.G. haggman, "Intercarrier interference self-cancellation scheme for OFDM mobile communication systems", *IEEE Trans. On Commu.*, vol.49, no. 7, Jul. 2001, pp. 1185-1191.
- [12] H.G. Ryu, Y. Li, J.S. Park, "An Improved ICI Reduction Method in OFDM Communication System", *IEEE Trans. Broadcasting*, vol. 51, no. 3 pp. 395-400, Sep. 2005.
- [13] V. Kumbasar and O. Kucur, "ICI reduction in OFDM systems by using improved sinc power pulse", *Digital Signal Processing 17*, 2007, pp. 997-1006.
- [14] H. Zhou and Y-F Huang, "A Maximum Likelihood Fine Timing Estimation for Wireless OFDM Systems", *IEEE Trans. on Broadcasting*, Vol. 55, No. 1, Mar 2009, pp. 31-41.
- [15] V.J. Naveen and K. RajaRajeswari, "ICI Reduction using Extended Kalman Filter in OFDM system", *Inter. Journal of Computer Appl.*, vol. 17, no. 7, Mar. 2011, pp. 15-21.
- [16] EL-madnay, Rizk, "Modified Correlative Coding for Frequency Offset Mitigation in OFDM Systems", *International conference on Computer Technology and Development*, vol. 1, Nov. 2009, pp. 112-115.
- [17] D. Jing and L. Curan, "Improved Nyquist Windows for Reduction of ICI in OFDM Systems", IEEE 4th inter. symposium on MAPE, Nov. 2011, pp. 438-441.
- [18] N.C. Beaulieu and P. Tan, "Receiver Windowing for Reduction of ICI in OFDM Systems with Carrier Frequency Offset", *IEEE GLOBECOM'05*, Vol. 5, Dec. 2005, pp. 2680-2684.
- [19] Y. Fu and C.C. Ko, "A new ICI self cancellation scheme for OFDM systems based on a generalized signal mapper", *5th Symposium on wireless Personal Multimedia Communications*, vol. 3, Oct. 2002, pp. 995-999.
- [20] Q. Shi, Y. Fang, M. Wang, "A novel ICI self-cancellation scheme for OFDM systems", *5th Inter. Conference on WiCom., Sep. 2009*, pp. 1-4.
- [21] A.L. Onofrei and N.D. Alexandru, "The effect of ICI in OFDM Systems Using Improved Phase Modified Sinc Pulse", in *ISSCS'09*, Jul. 2009, pp. 1-4.
- [22] M. Chuanhui, G.E. Atkin, Z. Chi, W. Ting, "A novel bandwidth efficient coded OFDM system for ICI and PAPR reduction", *IEEE MILCOM'08*, Nov. 2008, pp. 1-6.

## AUTHOR'S PROFILE



### Abhijeet Bishnu

was born on 2nd Sep 1987 in India. He received B.E. degree in Electronics and Communication Engineering from Technocrat Institute of Technology, Bhopal, India in 2010. He is currently studying M.E. degree in Electronics and Telecommunication Engineering from S.G.S.I.T.S. Indore, India. His research interests include OFDM system and Multi-carrier systems.



### Mrs. Anjana Jain

was born on 2nd Feb 1967 in India. She received B.E. degree (1989) in Electronics and Telecommunication from M.A.C.T., Bhopal, India and M.E. degree (1996) in electrical engineering from Shri G.S. Institute of Technology and Science, Indore, India in 1996. Her major field of study is Electronics and Communication. She has teaching experience of 21 years and currently Associate professor in the Department of Electronics and Telecommunication in Shri G.S. Institute of Technology and Science, India. She has published papers in National and International Journals, Conferences. Her research interest in Characterisation and Parameter Estimation of Mobile Radio Channel, Reliability and Availability computation of Fading Channels and its Modelling. Mrs. Jain is member of IEEE, TWAWS, IACSIT, IETE, ISTE, IE (I).



**Mr. Anurag Shrivastava**

was born on 27th Aug 1976 in India. He received B.E degree (2000) in Electronics and Communication Engineering from SVITS Indore, India and M.Tech degree in Communication Engineering from IIT Bombay, India in 2009. He has teaching experience of 11 years and currently

Assistant professor in the Department of Electronics and Telecommunication in Shri G.S. Institute of Technology and Science, India. He has published many papers in National and International Journal and Conferences. His research interest in Embedded systems, Signal processing and Telecommunication networking. He is member of IETE, IE and ISTE.