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A Review On Various Interference Effects In A MIMO-OFDM System

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Abstract:

The performance of a MIMO-OFDM system is severely degraded in presence of RF impairments like phase noise and I/Q imbalance and other interferences like ICI (intercarrier interference) and NBI (narrowband interference). Low-complexity estimation and compensation techniques that can jointly remove the effect of these impairments are highly desirable. In this paper, we present a study of various interference effects in a MIMO-OFDM system and their compensation techniques.

1. Introduction

The demand of high data rates over wireless communication channels is ever-increasing. To meet such demands, a reliable and robust technology has to be implemented which provides high-data-rate wireless access with high QoS (quality of service). MIMO (Multiple-Input-Multiple-Output) wireless technology meets these demands by offering increased spectral efficiency through spatial-multiplexing gain and improved link reliability due to antenna diversity gain. OFDM is a widely used technology due to its robustness against ISI (Inter-symbol Interference) and frequency-selective fading. The combination of MIMO and OFDM system is an attractive air-interface solution for next generation wireless communication systems. It has been specified as a standard in IEEE 802.11n WLAN and in IEEE 802.16e WMAN and provides a maximum data rate of up to 600 Mbps. It is yet to be standardized for the upcoming WLAN standard amendment i.e., IEEE 802.11ac. However a MIMO-OFDM system suffers from major RF impairments like phase-noise and I/Q imbalance due to non-idealities in the transmission chain components. It is also known as dirty-RF signal processing. Phase noise causes a CPE (common-phase-error), which is constant phase rotation common to all the subcarriers in an OFDM symbol, and ICI, due to interference from the neighbouring subcarriers. I/Q mismatch occurs when the analog components on the I and Q rails are not exactly matched. Figure. 1 and 2 below shows an $N_T \times N_R$ MIMO-OFDM system affected by phase noise and I/Q mismatch. θ and A represents I/Q phase and amplitude mismatch respectively and φ(t) represents random phase variations.

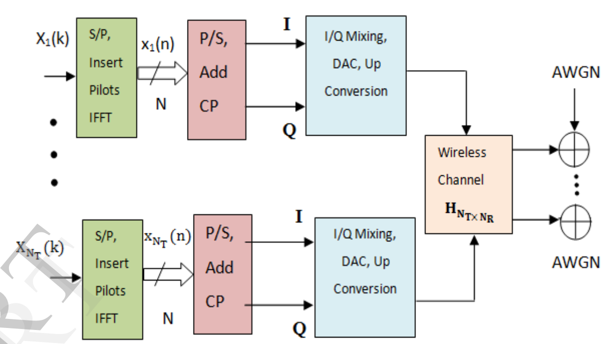

Figure 1. MIMO-OFDM transmitter with N_T transmit branches

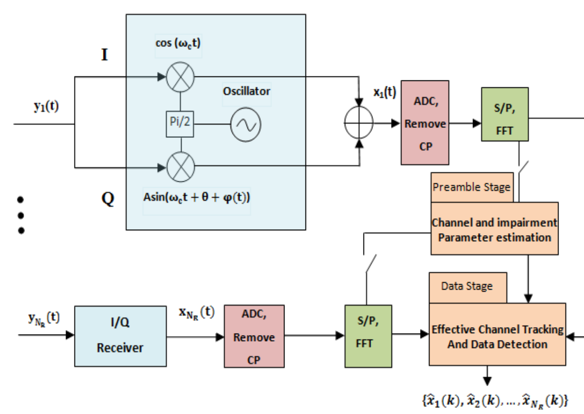

Figure 2. MIMO-OFDM receiver with N_R receive branches affected by phase noise and I/Q imbalance

In addition to phase noise and I/Q imbalance, the performance of a MIMO-OFDM system is severely degraded due to narrowband interference. NBI arises when two different systems operate in the same frequency band. For e.g., this kind of interference is mainly found in unlicensed frequency bands like the ISM (Industrial Scientific Medical) band, where systems such as Bluetooth or microwave ovens interfere with OFDM based WLAN (Wireless Local Area Networks). In this review paper, we present a study of above mentioned interference effects namely, phase noise, I/Q mismatch, ICI and NBI in a MIMO-OFDM system and their compensation techniques.

2. Phase Noise (PN)

Phase Noise is caused due to non-linearities in the local oscillator and can be considered as a parasitic phase modulation of the oscillator's signal. A general signal-level model for a noisy oscillator can be expressed as

$$\alpha_{osc}(t) = e^{(j2\pi f_c t)*} e^{(j\varphi(t))} \tag{1}$$

where $\varphi(t)$ denotes the time-varying PN and f_c is the nominal oscillating frequency i.e., carrier frequency for oscillators. The variation in phase can either be continuous or dicrete. Discrete phase variation produces discrete signals called spurious frequencies and continuous phase fluctuations causes phase noise. The PN of a free running oscillator is assumed to follow Brownian motion (Weiner process). PN causes the PSD (power spectral density) to exhibit skirts around the carrier frequency resulting in a Lorentzian spectrum. It is measured in units of dBc/Hz. When a strong RF blocker signal convolves with the skirts of the Lorentzian spectrum in the mixer (reciprocal mixing), the reciprocal noise produced would dominate the PN. Thus the errors caused by phase noise cannot be neglected. The interference due to phase noise can be separated into a CPE and an ICI. CPE refers to a constant phase rotation which is common to all the subcarriers in an OFDM symbol [3]. ICI corresponds to neighbouring subcarriers interfering with each other. When the ratio of the phase noise bandwidth and OFDM intercarrier spacing is small, CPE dominates and when the ratio is closer to unity, ICI dominates [4].

2.1. Phase Noise Modeling

In a general OFDM system with N subcarriers, the time-domain waveform samples are obtained by N-point IFFT (inverse fast Fourier transform) of the subcarrier data symbols. Thus, at m-th OFDM symbol interval, these samples can be written as

$$x_m(n) = \frac{1}{N}\sum_{k=0}^{N-1} X_m(k)\, e^{j2\pi nk/N} \tag{2}$$

where $X_m(k)$ denotes the k-th subcarrier data symbol during m-th OFDM symbol interval. A cyclic prefix of size N_g samples is added to an OFDM symbol to combat ISI in a time dispersive channel. PN is modeled separately for transmitter and receiver side. However the impact of PN at the receiver dominates the overall PN effect [1]. Considering receiver side PN, the vector of received samples for m-th OFDM symbol after the impact of a multipath channel and removal of the CP is

$$\mathbf{y}_m = \mathrm{diag}(e^{j\boldsymbol{\varphi}_m})\,(\mathbf{x}_m \otimes \mathbf{h}_m) + \mathbf{n}_m \tag{3}$$

where $\otimes$ is the circular convolution operator, $\mathbf{x}_m$ is the vector of samples of m-th transmitted OFDM symbol, $\mathbf{h}_m$ is the channel impulse response, and $\mathbf{n}_m$ is AWGN (Additive White Gaussian Noise) vector. $\boldsymbol{\varphi}_m$ is a vector containing PN realization samples within m-th OFDM symbol, $\boldsymbol{\varphi}_m = [\varphi_m(0),..., \varphi_m(N-1)]^T$. The received frequency domain signal vector is given by

$$\mathbf{R}_m = \mathbf{J}_m \otimes (\mathbf{X}_m \cdot \mathbf{H}_m) + \boldsymbol{\eta}_m \tag{4}$$

$\mathbf{X}_m$ is the vector of transmitted subcarrier symbols, $\mathbf{H}_m$ is the channel transfer function, $\boldsymbol{\eta}_m$ is the FFT of AWGN, and $\mathbf{J}_m$ is the FFT of exp($j\boldsymbol{\varphi}_m$). The received signal can be expressed as a summation of two terms

$$R_m(k) = X_m(k)\, H_m(k)\, J_m(0) + \eta_m(k) + \sum_{l=0, l\neq k}^{N-1} X_m(l) H_m(l) J_m(k-l) \tag{5}$$

The first and the second parts of the signal are the CPE and ICI terms respectively. For a MIMO-OFDM system with N_T transmit and N_R receive antennas and N subcarriers in one OFDM symbol, considering PN both at the transmitter and receiver, the received samples at receiver antenna n from each of N_T transmit antennas are written as

$$y_n(l) = e^{j\varphi_{rx,n}(l)} \sum_{m=1}^{N_T} (h_{nm}(l) \otimes x_m(l) e^{j\varphi_{tx,m}(l)}) + n_n(l) \tag{6}$$

where $e^{j\varphi_{rx}}$ and $e^{j\varphi_{tx}}$ are PN at transmitter and receiver side respectively. h_{nm} is the multipath channel from transmitter m to receiver n. Thus in MIMO systems the PN increases linearly with the increase in the number transmitters.

2.2. Phase Noise Compensation

One of the most common ways of phase noise mitigation is estimation using pilot symbols or a known training sequence. Based on the estimation of frequency offset on known pilot symbols, the frequency offset is compensated on other data sub-carriers. Correction of CPE is relatively simpler as compared to ICI. According to [1], the CPE term is estimated using known pilot subcarriers S_p. From (5) it results in eq. (7)

$$R_m(k) = X_m(k)H_m(k)J_m(0) + \varepsilon_m(k) \quad (7)$$

where $k \epsilon S_p$. The ICI and AWGN term are combined into a single $\varepsilon_m(k)$ term. Assuming a known channel response $H_m(k)$, the term $J_m(0)$ can be estimated using a Least Squares (LS) estimation which is given as

$$\hat{J}(0) = \frac{\sum_{k\epsilon Sp} R_m(k)X_m^*(k)H_m^*(k)}{\sum_{k\epsilon Sp} |X_m(k)H_m(k)|^2} \quad (8)$$

In [3] the estimate of CPE is given as

$$\Phi = \frac{\sum_{i=1}^{Ns} \gamma l_{c_{i,l}} \varphi l_{c_{i,l}}}{\sum_{i=1}^{Ns} \gamma l_{c_{i,l}}} \quad (9)$$

where $\gamma l_{c_{i,l}}$ is the reliability estimate, for instance the estimated subchannel amplitude for subchannel $c_{i,l}$ at symbol l and $\varphi l_{c_{i,l}}$ is the phase difference between the transmitted phase of subchannel $c_{i,l}$ and the received phase and N_s is the number of pilot symbols. For ICI estimation, spectral components around the center frequency are considered in [1] because PSD of phase noise has typically steeply descending lowpass natured spectrum around the nominal oscillating frequency. Thus only the spectral components around the center frequency is considered with circular subcarrier indexing $k \in \{-u,..., u\}$. Thus the received symbol becomes

$$R_m(k) = \sum_{l=-u}^{u} X_m(k-l)\, H_m(k-l)J_m(l) + \zeta_m(k) \quad (10)$$

The variable $\zeta_m(k)$ has the AWGN terms and all non-estimated ICI terms in it. Only a subset of subcarriers $k \in \{l_1,...,l_P\}$ is considered, $p > 2u+1$ the received symbol is given as

$$\mathbf{R}_{m,p} = \mathbf{A}_{m,u}\mathbf{J}_{m,u} + \boldsymbol{\zeta}_{m,u} \quad (11)$$

where $A_m(k) = X_m(k)\, H_m(k)$. It is assumed that both $X_m(k)$ and $H_m(k)$ are known for the considered subcarriers and that estimating $J_{m,u}$ is done using the pseudo inverse of $A_{m,u}$ as

$$\hat{\mathbf{J}}_{m,u} = (\mathbf{A}_{m,u}^H \mathbf{A}_{m,u})^{-1}\mathbf{A}_{m,u}^H\, \mathbf{R}_{m,p} \quad (12)$$

The resulting PN spectrum estimate can then be used to deconvolve the effect of the PN out of the system, i.e., ICI can be removed. In [5] a matched filtering approach is utilized for phase noise mitigation. The channel is first estimated using an MMSE (Minimum Mean Square Error) equalizer. Further for phase noise, a semi-blind adaptive equalizer based on an LMS (Least Mean Square) algorithm is used because the phase noise is randomly varying and only a few pilot tones are available. [6] uses a SSD-LMS (Step-size-delta Least Mean Square) adaptive algorithm to deal with the phase error. It assumes a varying step-size, to deal with time-varying channel. It uses squared error between the desired response and the filter output, to calculate the updated weights. [9] uses a Zero-Forcing solution for MIMO decoding on a per subcarrier basis i.e., the estimated kth symbol is $\hat{X}_k = W_k Y_k$ where W_k is the weight matrix. The ICI and CPE terms are estimated and corrected by using continuous pilots. In [16] an iterative approach is used where first the CPE is estimated using Least Squares (LS) estimation. As the preamble also suffers from a phase rotation, a second level LS estimation is done and the obtained estimate is used for intial correction. The remaining CPE in data symbols is equalised by MMSE equaliser. ICI which is referred to as higher order phase noise is compensated by linear MMSE estimation.

3. I/Q Mismatch

I/Q imbalance is the effect when the in-phase and quadrature-phase branch in the RF front-end are not exactly identical. In SISO/MIMO-OFDM systems I/Q mismatch causes interference from the conjugate of the data on the frequency mirror subcarriers which scales with the number of transmit antennas. It can be modelled as a gain, phase and delay mismatch between the I and Q-rails. It is categorized as frequency dependent or frequency independent. Frequency independent I/Q imbalance occurs when the effects are constant over the bandwidth of interest and frequency dependent I/Q imbalance occurs when there is a difference in the low-pass filters of both branches. I/Q gain and phase mismatches are frequency independent whereas I/Q delay mismatch is frequency dependent [8]. In the presence of I/Q gain, delay and phase mismatch, expressed in continuous time complex baseband notation, the transmit sequence is expressed as

$$\hat{x}_m(t) = A_{mt}\, x_{mr}(t - \tau_{mti})e^{j\varphi_{mti}} + jB_{mt}\, x_{mi}(t - \tau_{mtq})e^{j\varphi_{mtq}} \quad (13)$$

where A_{mt}, B_{mt} are the gains, φ_{mti}, φ_{mtq} are the phase offsets and τ_{mti}, τ_{mtq} are the delay offsets on the two rails at transmitter m. x_{mr} and x_{mi} are the real and imaginary parts of $x_m(t)$. $\hat{x}_m(t)$ convolves with the channel from transmitter m to receiver n and adds with data from other transmitters at receiver n

$$r_n(t) = \sum_{m=1}^{N_T}(\hat{x}_m(t) \otimes h_{nm}(t)) + n_n(t) \quad (14)$$

Considering I/Q mismatch at the receiver front-end, the corrupted received signal is

$$\hat{r}_n(t) = A_{nr} r_{ni}(t - \tau_{nri}) e^{j\varphi_{nri}} + jB_{nr} r_{nq}(t - \tau_{nrq}) e^{j\varphi_{nrq}} + n_n(t) \qquad (15)$$

Substituting (13) and (14) in (15), after taking FFT, substituting $X_{real}(k) = 0.5(X(k) + X^*(-k))$ and $X_{imag}(k) = 0.5(X(k) - X^*(-k))$, gives the expression for frequency domain received subcarrier at receive antenna n which contains the interference terms from the conjugate of the data on the frequency mirror subcarriers of all the transmitters.

3.1. I/Q Mismatch Compensation

I/Q mismatch mitigation has been studied extensively both for SISO and MIMO-OFDM systems. In [8], the received signal vector for the kth subcarrier is expressed as $Y_k = C_k X_k + V_k$ where C_k is the matrix containing the desired and interference terms for the kth subcarrier and V_k is the AWGN vector at a given receiver. A MMSE solution is used for estimating X_k from Y_k i.e., $\hat{X}_k = W_k Y_k$ and the weight vector W_k is updated using LMS or RLS (Recursive Least Squares) algorithms. It is shown in [9] that as the number of receive antennas increases, the number of observations for a given mirror frequency subcarrier, increases, which separates the desired subcarrier from interfering subcarriers and that the I/Q mismatch can be fully cancelled if the number of receive antennas is twice the number of transmit antennas. However the performance is still degraded because the signal energy that leaked into the mirror frequencies is lost. [2] uses a DD-LMS (decision-directed least mean-square) adaptive algorithm for a 2-tap transversal filter with the received carrier symbol and the complex mirror symbols as inputs to the filter. The system is initially trained with a known phase reference symbols which then swiches to decision-directed mode of operation which in turn forms the desired response of the adaptive filter. It uses two adjacent subcarriers to compensate for a single symbol.

4. ICI

Intercarrier interference arises due to a number of sources. ICI is created when the channel delay spread is larger than the cyclic prefix, when the channel varies during one OFDM symbol (Doppler shift), when the residual timing offset is large, due to asynchronicity between users in a multiuser scenario because of delay differences between users and also due to phase noise[10]. The baseband representation of the received signal in time domain with ICI is given as

$$y(n) = x(n)e^{j(\frac{2\pi n\epsilon}{N})} \otimes h(n) + w(n) \qquad (16)$$

Here x(n) represents the nth sample of the transmitted signal, ϵ represents the normalized frequency offset and is given by $\Delta f \cdot NT_s$. Δf is the Doppler shift, T_s is the subcarrier symbol period. The frequency domain representation is

$$Y(k) = X(k)S(0) + \sum_{l=0, l\neq k}^{N-1} X(l)S(l-k) + n_k \qquad (17)$$

The first term represents the desired signal without frequency errors and the second term represents ICI interference. S(l) is the FFT of $e^{j(\frac{2\pi n\epsilon}{N})}$. For MIMO-OFDM the ICI is modeled as

$$Y_n(k) = \sum_{m=1}^{N_T} X_m(k) H_{mn}(k) S_m(0) + \sum_{m=1}^{N_T} I_{mn}(k) + n_k \qquad (18)$$

where $H_{mn}(k)$ is the channel frequency response from the mth transmitter to the nth receiver for the kth subcarrier. $I_{mn}(k)$ represents the interference on the kth subcarrier for a given m and n transmitter-receiver pair and is given as

$$I_{mn}(k) = \sum_{n=0, n\neq k}^{N-1} X_m(n) H_{mn}(n) S_{mn}(n-k) \qquad (19)$$

This indicates that for MIMO-OFDM systems, there is interference from neighbouring subcarriers of all the transmit antennas.

4.1. ICI Compensation

A lot of ICI mitigation techniques have been investigated extensively in literature both for SISO and MIMO-OFDM systems which include ICI self cancellation [13][14], frequency domain equalization [11], frequency offset estimation and compensation [7] and time-domain windowing [12]. The basic idea of an ICI self-cancellation scheme is to modulate a single data symbol onto two adjacent subcarriers but with opposite polarity i.e., $X'(k) = X(k)$ and $X'(k+1) = -X(k)$ so that the ICI coefficients on each data symbol are self-cancelled by addition at the receiver. This scheme is called adjacent data conversion. There are many variants of self-cancellation scheme like adjacent data conjugate method ($X'(k) = X(k)$ and $X'(k+1) = -X^*(k)$), symmetric data conversion method ($X'(k) = X(k)$ and $X'(N-k-1) = -X(k)$), symmetric data conjugate method ($X'(k) = X(k)$ and $X'(N-k-1) = -X^*(k)$) and weighted conjugate transformation ($X'(k) = X(k)$ and $X'(k+1) = e^{j\pi/2}X^*(k)$) [23]. Time-domain windowing involves using an adaptive Nyquist window to suppress the side lobes extending beyond the OFDM symbol interval. Frequency domain equalization technique [11] uses a linear and decision feedback equalization. These schemes were proposed for SISO-OFDM systems. However the self-cancellation scheme was utilised for designing the Space-Time-Frequency block codes in [18] for MIMO systems. [15] uses a block processing and matched filtering approach for ICI mitigation by assuming perfect knowledge of channel gain and frequency offset. [7] estimates the frequency offset from pilot symbols and the estimated frequency offset is applied to other data subcarriers through a polynomial curve fitting approach. [19] uses a planar Extended Kalman filter for normalized Doppler frequency offset estimation.

5. Narrowband Interference (NBI)

Narrowband interference arises when two different systems operate on same frequency bands. This kind of interference is found in the unlicensed frequency bands e.g., the ISM band (Industrial Scientific Medical), coming from systems such as Bluetooth devices, microwave ovens which interfere with OFDM based Wireless Local Area Networks. In an OFDM system, unless the frequency of the NBI coincides with a subcarrier frequency, the spectrum of the NBI will span the whole bandwidth of the system. The received time-domain signal is given by

$$\mathbf{r} = \mathbf{d} + \mathbf{i} + \mathbf{n} \tag{20}$$

where **r**, **d**, **i** and **n** are $(N+N_g) \times 1$ vector of the received signal, transmitted OFDM symbol, narrowband interference samples and Gaussian noise samples. The components of **i** are given by

$$i_n = \sqrt{E_i}\, e^{j(2\pi n f_i T_s + \theta)} \tag{21}$$

where E_i is the interference power, T_s is the original symbol period, θ is the random phase uniformly distributed in $[-\pi,\pi]$. The frequency of interference f_i is defined by

$$f_i = (m + \alpha)\frac{f_s}{N}\ ,\ 0 \le m < N\text{-}2\ ,\ -0.5 \le \alpha \le 0.5 \tag{22}$$

where f_s is the sampling frequency, m is the subcarrier closest to the interference and α is the position of the interference between tones m – ½ and m + ½. When α = 0, the interference is located directly on one of the subcarriers and therefore is orthogonal to the tones. Non-orthogonal interference is accounted for when α = 0.

5.1. NBI compensation

The NBI suppression techniques for OFDM systems include frequency excision, frequency identification and cancelling, adaptive narrowband filtering[20] and prediction error filtering[17]. In frequency excision technique, the narrowband interference, which manifests as a peak in the spectra of the received signal, is eliminated by comparing it with a threshold value. Drawbacks of this technique is the inability to completely remove NBI from the data subcarriers. In frequency identification and cancelling technique, the amplitude and phase of the NBI is estimated from the maximum amplitude of the received spectra by applying the Maximum Likelihood solution. An adaptive narrowband bandpass filter is also used whose transfer function is given in [20]. The center frequency of this filter is adjusted to match with that of the narrowband interference frequency and the filter weights are updated by applying LMS algorithm. For MIMO-OFDM systems, precoding and space-block coding schemes are used at the transmitter side to obtain maximum diversity and to suppress NBI. The main idea behind using space block coding is that if the error probability of receiving a message by transmission over a wireless channel is p, then with the simultaneous transmission of n orthogonal copies of the message over n independent wireless channels, the total error probability is p^n. Thus diversity helps in suppressing NBI.

6. Conclusion

In this review paper, we presented a study of various interference effects in a MIMO-OFDM system and their compensation techniques. Among the techniques discussed, most of them use estimation and compensation process using either pilot symbols or preamble. The different forms of interferences have been studied extensively individually but joint consideration of all interferences has not been studied so far in literature. Hence an efficient algorithm has to be framed which takes into account all the interferences and is a part of our future work.

7. References

[1] Ville Syrjälä, Mikko Valkama, Nikolay N. Tchamov, and Jukka Rinne, "Phase Noise Modelling and Mitigation Techniques in OFDM Communications Systems", *WTS'09 Proceedings, Conference on Wireless Telecommunications Symposium*, 2009, pp-209-215.

[2] Alexander R. Wright and Patrick A. Naylor, "I/Q Mismatch compensation in Zero-IF OFDM receivers with application to DAB", *IEEE International Conference on Acoustics, Speech and Signal Processing*, 2003, pp. 329-332.

[3] Patrick Robertson and Stefan Kaiser, "Analysis of the Effects of Phase-Noise in Orthogonal Frequency Division

Multiplex (OFDM) Systems", *IEEE International Conference on Communications - ICC*, 1995

[4] Ana García Armada, "Understanding the Effects of Phase Noise in Orthogonal Frequency Division Multiplexing (OFDM)", *IEEE Transactions on Broadcasting*, 2001, vol. 47, Issue 2, pp. 153 – 159.

[5] Wonzoo Chung, "A Matched Filtering Approach for Phase Noise Suppression in CO-OFDM Systems", *IEEE Photonics Technology Letters*, 2010, vol. 22, no. 24, pp. 1802-1804.

[6] Chia-Hsin Cheng, Kai-Jie Chen, Gwo-Ruey Lee and Yung-Fa Huang, "Phase Error Cancellation for OFDM Systems Using Adaptive Filters" *International Conference on Broadband, Wireless Computing, Communication and Applications (BWCCA)*, Nov. 2010, pp. 643-647.

[7] Elnaz Ershadi and Hamidreza Bakhshi, "A Novel Pilot-based Frequency Offset Compensation Method in MIMO-OFDM Systems", *ICIAS*, June 2010, pp. 703-707.

[8] Raghu Mysore Rao, Babak Daneshrad, "I/Q Mismatch Cancellation for MIMO-OFDM Systems", *Proceedings of the IEEE 15th International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC,* Sept. 2004, pp. 2710-2714.

[9] Raghu Mysore Rao and Babak Daneshrad, "Analog Impairments in MIMO-OFDM Systems", *IEEE Transactions on Wireless Communications (TWC)* 2006, 5(12) pp. 3382-3387.

[10] Taiwen Tang and Robert W. Heath, "Space-Time Interference Cancellation in MIMO-OFDM Systems", *IEEE Transactions on Vehicular Technology*, 2005, vol. 54, no. 5, pp. 1802 – 1816.

[11] J. Ahn and H. S. Lee, "Frequency domain equalization of OFDM signals over frequency non-selective Rayleigh fading channel", *IEEE Electronics Letters*, 1993, vol. 29, no. 16, pp. 1476-1477.

[12] Claus Muschallik, "Improving an OFDM reception using an adaptive Nyquist windowing", *IEEE Transactions on Consumer Eletronics*, 1996, vol. 42, no. 3, pp. 259-269.

[13] Yuping Zhao and Sven-Gustav Häggman, "Intercarrier Interference Self-Cancellation Scheme for OFDM Mobile Communication Systems", *IEEE Transactions on Communications*, 2001, vol. 49, no. 7, pp. 1185-1191.

[14] Alireza Seyedi and Gary J. Saulnier, "General ICI Self-Cancellation Scheme for OFDM Systems", *IEEE Transactions on Vehicular Technology*, 2005, vol. 54, no. 1, pp. 198 – 210.

[15] Peng Tan and Norman C. Beaulieu, "ICI Mitigation in MIMO-OFDM Systems", *IEEE WCNC*, 2007, pp. 847-851.

[16] Steffen Bittner, Ernesto Zimmermann and Gerhard Fettweis, "Iterative Phase Noise Mitigation in MIMO-OFDM Systems with Pilot Aided Channel Estimation", *VTC* 2007.

[17] Arun Batra and James R. Zeidler, "Narrowband Interference mitigation in OFDM systems", *IEEE MILCOM*, 2008, pp. 1-7.

[18] A.Idris, K. Dimyati and Sharifah K.Syed-Yusof, "Space Time Frequency Block Codes for MIMO-OFDM system using Intercarrier Interference Self-Cancellation Schemes" *International Conference on Communications, Signals and Coding* (*MIC-CSC)*, Jordan, 2008.

[19] Qiang Shi, "ICI Mitigation for OFDM Using PEKF", *IEEE Signal Processing Letters*, Dec. 2010, vol. 17 no. 12.

[20] Vladimir Poulkov, Miglen Ovtcharov, Georgi Iliev and Zlatka Nikolova, "Narrowband Interference Suppression in MIMO Systems", *INTECH*, 2011, pp. 367-394

[21] Zhongshan Wu, "MIMO-OFDM Communication Systems: Channel Estimation and Wireless Location" PhD. Thesis May 2006.

[22] Azlina Idris, Kaharudin Dimyati, Sharifah Kamilah Syed Yusof, Darmawaty Mohd Ali and Norsuzila Yacob, "CIR and BER Performance of STFBC in MIMO OFDM System", *Australian Journal of Basic and Applied Sciences*, 2011, vol. 5, no.12 3179-3187.

[23] Yong Soo Cho, Jaekwon Kim, Won Young Yan and Chung G. Kang, *MIMO-OFDM Wireless Communications with Matlab*, IEEE Press, John Wiley & Sons (Asia) Pte Ltd., 2010

[24] Upena Dalal, *Wireless Communications*, Oxford University Press, 2009.

[25] Simon Haykin, *Adaptive Filter Theory*, Pearson Education, Fourth Edition, 2011.