Improving Space-Time-Frequency MIMO-OFDM with ICI Self-Cancellation Scheme using Least Square Error Estimator

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ABSTRACT

Channel estimation techniques for Multiple-input Multiple-output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) based on comb type pilot arrangement with least-square error (LSE) estimator was investigated with space-time-frequency (STF) diversity implementation. The frequency offset in OFDM effected its performance. This was mitigated with the implementation of the presented inter-carrier interference self-cancellation (ICI-SC) techniques and different space-time subcarrier mapping. STF block coding in the system exploits the spatial, temporal and frequency diversity to improve performance. Estimated channel was fed into a decoder which combined the STF decoding together with the estimated channel coefficients using LSE estimator for equalization. The performance of the system was compared by measuring the symbol error rate with a PSK-16 and PSK-32. The results show that subcarrier mapping together with ICI-SC were able to increase the system performance. Introduction of channel estimation was also able to estimate the channel coefficient at only 5dB difference with a perfectly known channel.

Keywords: *Inter-carrier interference self-cancellation (ICI-SC), Multiple-input Multiple-output (MIMO), Orthogonal Frequency Division Multiplexing (OFDM), channel estimation, Least-square Error (LSE).*

INTRODUCTION

The demand for high speed mobile internet access and high quality streaming multimedia prompted the advancement in digital communication system. This created a demand in the industry for reliable and high capacity link within a limited spectral bandwidth. MIMO-OFDM is a system that uses MIMO antenna configuration with OFDM carrier. It provides the spectral efficiency and multipath fade resistance of OFDM with the throughput and diversity gains of a MIMO system [1-3]. OFDM is an effective method in handling frequency-selective fading by converting a wideband frequency selective channel into parallel narrowband frequency subcarrier.

OFDM has longer symbol duration and higher spectral efficiency, increasing immunity against inter symbol interference (ISI). OFDM orthogonality between subcarriers in time-dispersive environment eliminates crosstalk by the addition of cyclic prefix (CP) [3] . A sufficiently long duration of CP not only prevents ISI but also transforms the linear convolutions onto circular convolutions [4] preserving system's orthogonality and preventing frequency and phase shift errors [5]. MIMO systems offer increase capacity in fading channels with beam forming capabilities, robustness to multi-path delay, spatial diversity and spatial multiplexing [6-9].

Space-time (ST) method improves upon the reliability of data transmission by using multiple transmit antennas. It works by transmitting redundant copies of the data stream to the receiver. Working on the whole block of data at once improves coding and diversity gain and is known as space-time block code (STBC). Space-frequency (SF) coding is applied within a single OFDM block, increasing spatial and frequency diversity gain. When the STBC length is longer than the number of OFDM subcarriers, the code word will span over several OFDM symbols. The whole system is then known as space-time-frequency block code (STFBC) OFDM. Figure 1 shows the STFBC block diagram used in the system. Coding applied across multiple OFDM blocks exploit the spatial, temporal, and frequency diversities available in frequency selective MIMO channels. It was shown in [3,10,11] that coding across blocks in STFBC offers significantly increased diversity order [3,6,9,11,12]. ST performs better in high frequency selective environments since ST requires adjacent OFDM symbols to experience similar fading. ST performance deteriorates if the channel varies quickly against time. SF on the other hand is sensitive to frequency variations. MIMO-OFDM benefits from the implementation of frequency diversity scheme with the use of the orthogonal subcarriers as it removes multipath fading and avoids burst error.

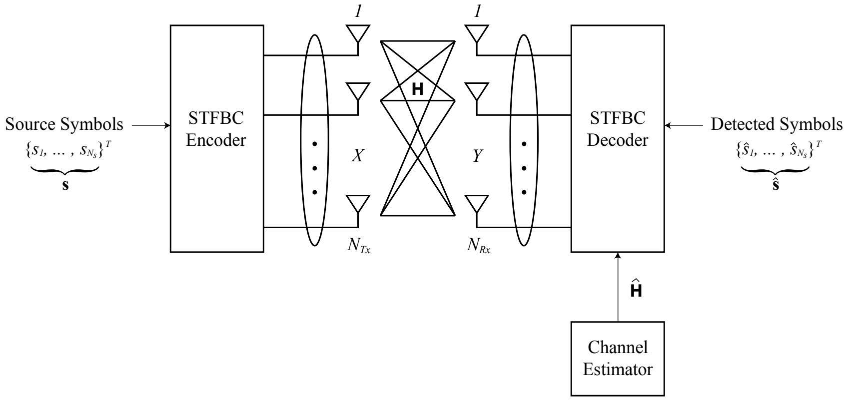

Figure 1: Block Diagram of STFBC

Frequency offset in mobile radio channels distort orthogonality between subcarriers resulting in inter carrier interference (ICI). Various methods for reducing ICI exists; frequency-domain equalization, frequency-domain offset estimation/compensation, time-domain equalization, time-domain windowing schemes and ICI-SC. ICI-SC offers the most direct and simplest approach to counter ICI with excellent performance. The only drawback is the reduced channel bandwidth but can be compensated with the use of higher order modulation or higher coding gain.

ICI-SC is also less complex and more efficient compared to other estimation and correction schemes listed [2,13-15]. It is known that the ICI coefficient between two consecutive subcarriers is very small. One of the carriers would carry modulated symbol with a predefined inversed weighting coefficients, “-1” generating a data pair (1, -1) modulated on two adjacent subcarriers (*l*, *l*+1). By doing so, generated ICI components can cancel each other at the receiver since ICI in *l* would be cancelled by the same ICI in *l*+1. ICI-SC would lower the throughput and bandwidth efficiency by a factor of two due to the redundancy in the carrier. This can be further compensated by using higher order modulation scheme with a high transmission rate [14,16,17].

All reference to ICI-SC scheme showed and proved significant improvement in system performance, ICI and bit-error rate, BER. A data conjugate method which is capable of both error correction and ICI reduction was explained in [2]. The result is compared to data-conversion method and is found to have better performance. Complex conjugate method is shown to have 2dB improvement compared to non-conjugate ICI-SC. A comparison was also made between MIMO (2×2) and SISO with ICI-SC with an improvement of 5dB between them in favor of MIMO [15]. System with no ICI-SC is shown to be adversely affected by carrier frequency offset (CFO).

Channel effects estimates are required at the receiver in order to recover the received data and is used as the channel parameters [5,9]. Two types of channel estimation are pilot based and blind channel estimation. Blind channel estimation uses the correlation between the data being sent and received by the system. A large number of symbols are needed at the receiver in order to extract statistical properties to be used for estimation and usually perform worse than other conventional channel estimation techniques [9]. Blind channel estimation has higher spectral and power efficiency when compared to pilot signaling but is more complex and is only suitable for slow varying channels. Pilot based channel estimation works by obtaining impulse response of pilot symbols inserted in the transmitter.

OFDM due to its orthogonality, was very sensitive to ICI between transmitter and receiver. This may occur due to Doppler shift or multipath channel propagation. The channel is always unknown at the receiver thus channel equalization to compensate for multipath shifts cannot be done. In this paper, a self-cancellation scheme is proposed to combat the effects of ICI. Least-square error (LSE) channel estimator is also implemented to estimate the unknown channel for improved channel equalization in real world application.

SYSTEM INFORMATION

A model of the proposed system is illustrated in Figure 2. Space-time-frequency (STF) implementation consists of two encoders applying both diversities to introduce redundancy in time and frequency domain through multiple transmission antennas. ST signals are further remapped [18] and interleaved to improve immunity to noise. Detail performance and system comparison of different mapping techniques are explained in [1, 9]. ICI-SC is another simple and effective scheme working on the principle of modulating one data symbol on a group of subcarriers with predefined inversed weighting coefficient $(X_k, X_{k=1} = -X_k)$ which will mutually cancel the ICI generated between the two sub-carriers [13].

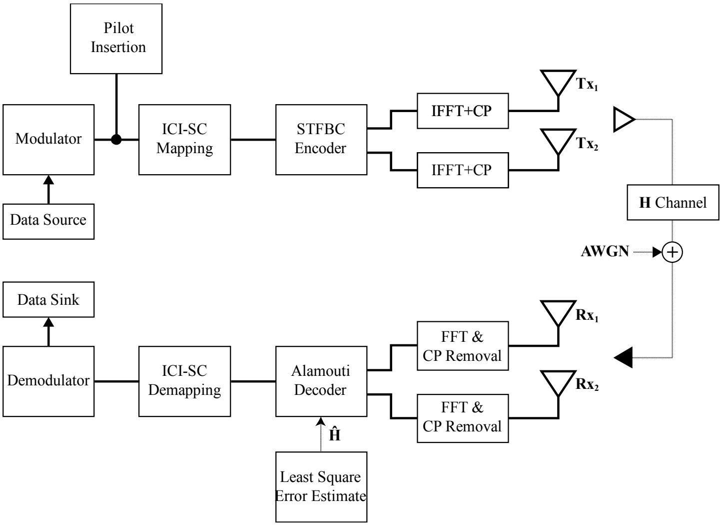

Figure 2: STFBC MIMO-OFDM with CE

The CFO of the transmission link from transmitter antenna m and receiver n antenna $\varepsilon_{m,n}$. is described in Eq.(1). STF mapping is then applied for adjacent, symmetry and median given Eq.(2-4) respectively.

$$Y_n(k) = \sum_{m=1}^{M} C_m(k) H_{m,n}(k) S_{m,n}(0) + I_n(k) + \omega_n(k) \tag{1}$$

$$X'_{2k} = X_k, \quad X'_{2k+1} = -X_k \tag{2}$$

$$X'_k = X_k, \quad X'_{N-1-k} = -X_k \tag{3}$$

$$X'_k = X_k, \quad X'_{N-1-k} = -X_k \tag{4}$$

For ICI-SC scheme, assuming the transmitted symbols are constrained. The modulation is designed to work in such a way that each signal at the k+1th subcarrier (k denotes even number) is multiplied by '-1' and then summed with the one at the kth subcarrier and is represented a Eq.(5) and the ICI coefficient for ICI self-cancellation scheme is denoted in Eq.(6).

$$
\begin{aligned}
Y''(k) &= Y'(k) - Y'(K+1) \\
&= \sum_{l=0,even}^{N-2} \begin{aligned}[t] &X(1)\{S(1-k) - S(l+1-k) \\ &\quad \ldots - [S(l-k-1) - S(l-k)]\} + n'(k+1) \end{aligned} \\
&= X(\mathrm{k})\left\{-S(-1) + 2S(0) - S(1)\right\} \\
&\quad + \sum_{l=0,\mathrm{l}\neq\mathrm{k},even}^{N-2} \begin{aligned}[t] &X(l)\{-S(l-k-1) - 2S(l-k) \\ &\quad \ldots - S(l+1-k)\} + n'(k+1) \end{aligned}
\end{aligned}
\tag{5}
$$

$$
S''(l-k) = -S(l-k-1) + 2S(l-k) - S(l+1-k) \tag{6}
$$

CHANNEL ESTIMATION (CE)

Block type pilot insertion is suitable for frequency selective channels. Pilot symbols are inserted into each subcarrier with a specific pilot distance. Comb type pilot symbols arrangement is distributed into evenly spaced subcarriers within each OFDM block. It provides higher retransmission rate and better resistance against fast-fading channels [9,19,20].

Different methods exist to estimate the channel based on the received pilot symbols. Minimum mean-square error (MMSE) estimator performs better than a least-square error (LSE) estimator but the computation is significantly more complex and the complexity increases with the number of subcarriers. LSE estimator is widely used due to its simplicity and a good complexity/performance system ratio. However in a more complex system, LSE is often used to get an initial estimates of the pilots which are then further improved via different methods [4,5,7,9,20]. Pilot insertion for channel coefficient estimation, N_p pilot signals are uniformly inserted into X(k) according to Eq.(7), Where L = number of carriers / N_p and $x_p(m)$ is mth pilot carrier value. The frequency response of the channel is defined as in Eq.(8) with $Y_p(k)$ and $X_p(k)$ being the output and the input at the kth pilot sub-carrier respectively.

$$X(k) = X(mL+l) = \begin{cases} x_p(m), & l = 0 \\ \text{inf data} & l = 1,\ldots,L-1 \end{cases} \tag{7}$$

$$H_e = \frac{Y_p}{X_p} \qquad k = 0,1,\ldots,N_p-1 \tag{8}$$

Least-square error, LSE estimator method finds the channel estimate $\hat{\mathrm{H}}$ in such a way that the following cost function in Eq.(9) is minimized. Setting derivative function with respect to $\hat{\mathrm{H}}$ to zero, We have $X^H X\hat{\mathrm{H}} = X^H Y$ which gives the solution to the LSE channel estimation as in Eq.(10).

$$\begin{aligned} J = \left(\hat{\mathrm{H}}\right) &= \left\| Y - X\hat{\mathrm{H}} \right\|^2 \\ &= \left(Y - X\hat{\mathrm{H}}\right)\left(Y - X\hat{\mathrm{H}}\right)^H \\ &= Y^H Y - Y^H X\hat{\mathrm{H}} - \hat{\mathrm{H}}^H X^H Y - \hat{\mathrm{H}}^H X^H X\hat{\mathrm{H}} \end{aligned} \tag{9}$$

$$\hat{\mathrm{H}}_{LS} = (X^H X)^{-1} X^H Y = X^{-1} Y \tag{10}$$

Let us denote each component of the LSE channel estimate $\hat{\mathrm{H}}LS$ by $\hat{\mathrm{H}}LS(k)$, k = 0,1,2,…,N-1. In the decoder, taking the received signal in k and k+1 time slot as in the following and assuming channel remains constant in both frame, we get the following matrix in Eq.(11) where Y_n^m is the received information, Z_n^m is the noise and Hmn is the channel from nth received antenna to the mth transmit antenna. X_1, X_2 are the transmitted symbols. Combining equations at time k and k+1 gives Eq.(12).

$$\begin{bmatrix} Y_1^1 \\ Y_2^1 \end{bmatrix} = \begin{bmatrix} \mathrm{H}_{11} & \mathrm{H}_{12} \\ \mathrm{H}_{21} & \mathrm{H}_{22} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} Z_1^1 \\ Z_2^1 \end{bmatrix}$$
$$\begin{bmatrix} Y_1^2 \\ Y_2^2 \end{bmatrix} = \begin{bmatrix} \mathrm{H}_{11} & \mathrm{H}_{12} \\ \mathrm{H}_{21} & \mathrm{H}_{22} \end{bmatrix} \begin{bmatrix} -X_2^* \\ X_1^* \end{bmatrix} + \begin{bmatrix} Z_1^2 \\ Z_2^2 \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} Y_1^1 \\ Y_2^1 \\ Y_1^{2*} \\ Y_2^{2*} \end{bmatrix} = \begin{bmatrix} \mathrm{H}_{11} & \mathrm{H}_{12} \\ \mathrm{H}_{21} & \mathrm{H}_{22} \\ \mathrm{H}_{12}^{*} & -\mathrm{H}_{11}^{*} \\ \mathrm{H}_{22}^{*} & -\mathrm{H}_{21}^{*} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} Z_1^1 \\ Z_2^1 \\ Z_1^{2*} \\ Z_2^{2*} \end{bmatrix} \tag{12}$$

Thus to solve for X1 and X2, we need to find the inverse of the channel estimation matrix $\hat{\mathrm{H}}$ given by Eq (10). The pseudo inverse of the equation results in the decoding of the transmitted symbols.

$$\begin{bmatrix} \\ \\ \end{bmatrix} = \left(\mathrm{H}^{\mathrm{H}}\mathrm{H}\right) \ \mathrm{H}^{\mathrm{H}} \begin{bmatrix} \\ \\ {}^{2*} \\ {}^{2*} \end{bmatrix} \tag{13}$$

SYSTEM PERFORMANCE EVALUATION

The symbol-error rate, SER curves are used to evaluate and compare various aspects of the proposed system. System is designed and simulated in Matlab®. A quasi-static Rayleigh fading channel with varied additive white Gaussian noise, AWGN is used throughout the simulations. Rayleigh fading is selected since it closely model the statistical effect model of tropospheric and ionospheric radio signal propagation and urban city environment with no line of sight, LOS.

Figure 3 illustrates the performance difference between different mapping techniques. Selected ST median subcarrier mapping is able to provide an average improvement of 3.5dB compared to unmapped carriers. This shows that interleaving and remapping subcarriers would increase immunity against burst noise and long channel fade. Median subcarrier mapping will be used in the paper due to better performance compared to the other mapping techniques. Implementation of ICI-SC in the system was able to give a significant improvement of 4dB as shown in Figure 4. The shift in carrier frequency due to the applied Doppler in the transmission medium was mitigated effectively by ICI-SC.

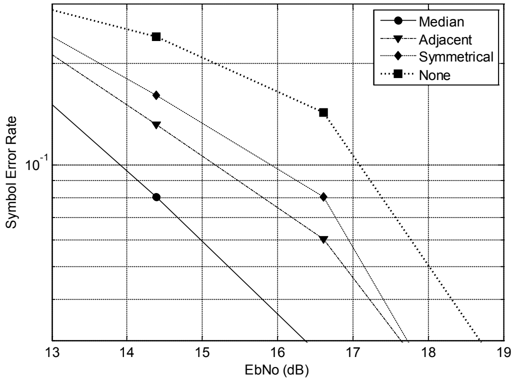

Figure 3: Performance Comparisons of Different ICI-SC Mapping Techniques

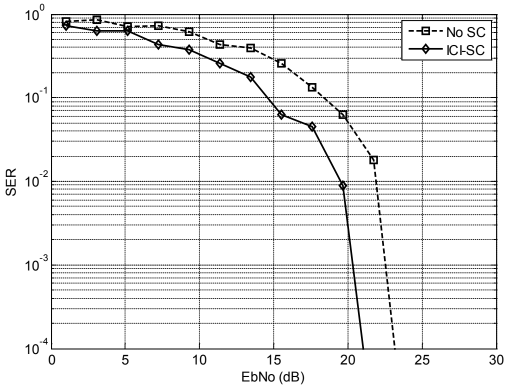

Figure 4: Performance Improvement with and without ICI-SC Using Median Method

A comparison of the LSE estimator is done between known channel and estimated channel together with the result without channel estimation. Rayleigh fading is used as the propagation channel. PSK-16 and PSK-32 modulations were performed to examine how the system performance scales with larger symbol size. Pilot symbols are arranged in block with 16 subcarriers acting as pilots with a spacing of eight subcarriers in between. Spectral energy of pilots is amplified by a factor of two. The increase in pilot symbols and reduction of pilot distance between each other would increase the overall system performance at the expense of actual data transmission.

Comb pilot arrangement is found to be dependent on the rigorousness of the pilot symbol placement and the estimator performance is closely related to the estimator algorithm implemented. The final performance of the proposed system is evaluated with the parameters in Table 1. The performance of the system was compared with two symbol sizes in a multi-path Rayleigh fading channel with Doppler shift. The performance difference is linearly static between both PSK-16 and a PSK-32 modulation. The LSE comb pilot symbol estimation was able to estimate channel $\hat{H}$ providing a performance difference of only 5dB compared to the perfect known channel H as shown in Figure 5. A blind channel (no estimation) provided no improvement whatsoever. The whole data block is irrecoverable.

Table 1: General Simulation Parameters for STFBC MIMO-OFDM with ICI-SC with LSE Estimator

Parameters	Value
Number of Subcarriers	128
Size of Subcarrier	8192
Cyclic Prefix	256
Modulation	PSK-16 & 32
Pilot Arrangement	Block
Number of Pilot SC	16
Pilot SC Spacing	8

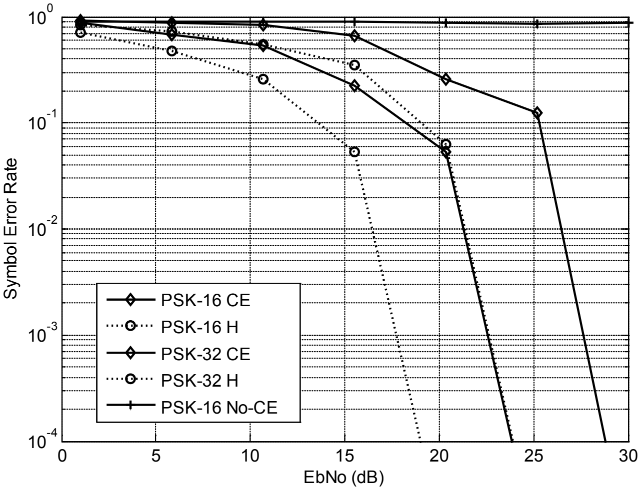

Figure 5: Performance Comparison of Least Square Error Estimation with Different Modulation Techniques

CONCLUSION

This paper explored different channel coding approach towards STF diversity to achieve maximum diversity order. MIMO system in OFDM proved to be versatile in combating ISI effects with its orthogonal properties. However, CFO significantly impact OFDM performance. ICI-SC has shown great performance with significant improvements over its simplicity to combat CFO in OFDM. The subcarrier mapping methods further improved upon STF bare performance. This approach offers the benefits of simplicity by eliminating the interpolator and combining the channel equalization in the STF MIMO decoder. Applying the channel estimator to recover the channel coefficient H gave significant improvement over a bare system with no channel estimation. This shows the importance of channel estimation in an unknown channel medium. Further improvements to the estimated $\hat{H}$ channel could be implemented with more complex and better performing minimum mean-square error (MMSE) and singular value decomposition (SVD) paired with channel interpolation as presented in references [4,5,19].

REFERENCES

[1] A. Idris, K. Dimyati, S. K. S. Yusof, and D. M. Ali, 2011. Pairwise Error Probability of a New Subcarrier Mapping Scheme (ICI-SC Technique) for STFBC MIMO-OFDM System, *Australian Journal of Basic and Applied Science, vol. 5.*

[2] A. Idris, K. Dimyati, and S. K. S. Yusof, 2008. Interference Self-Cancellation Schemes for Space Time Frequency Block Codes MIMO-OFDM System, *IJCSNS Internatonal Journal of Computer Science and Network Security, vol. 8*, pp. 139-148.

[3] A. F. Molisch, M. Z. Win, and J. H. Winters, 2002. Space-Time-Frequency (STF) Coding for MIMO-OFDM Systems, *IEEE Communications Letters, vol. 6,* pp. 370-372.

[4] A. U. Ahmed, S. C. Thompson, and J. R. Zeidler, 2008. Channel Estimation and Equalization for CE-OFDM in Multipath Fading Channels.

[5] J. J. V. d. Beek, O. Edfors, M. Sandell, S. K. Wilson, and P. O. Borjesson, 1995. On Channel Estimation in OFDM Systems, *Vehicular Technology Conference, vol. 2.*

[6] L. M. Cortes-Pena, 2009. MIMO Space-Time Block Coding (STBC): Simulations and Results, Personal and Mobile Communications.

[7] M. E. S. Coleri, A. Puri & A. Bahai. A Study of Channel Estimation in OFDM Systems, IEEE Vehicular Technology Conference.

[8] S. Adegbite, B. G. Stewart, and S. G. McMeekin, 2013. Least Square Interpolation Methods for LTE System Channel Estimation over Extended ITU Channels, *International Journal of Information and Electronics Engineering, vol. 3.*

[9] Y. S. Cho, J. Kum, W. Y. Yang, and C.-G. Kang, 2010. MIMO-OFDM Wireless Communications with MATLAB: Wiley.

[10] Z. S. a. K. J. R. L. W.Su, 2005. Towards Maximum Achieveable Diversity in Space, Time and Frequency : Performance Analysis and Code Design, *IEEE Transactions on Wireless Communications, vol. 40.*

[11] M. Qinghua, Y. Luxi, and H. Zhenya, 2008. Diversitry Analysis of Space-Time-Frequency Coded Broadband MIMO-OFDM System with Correlation Across Space Time and Frequency, *Frontier in Electrical and Electronic Engineering, vol. 3,* pp. 295-300.

[12] H. J. A. R. C. V. Tarokh, 1999. Space-Time Block Codes from Orthogonal Designs, *IEEE Transactions on Information Theory, vol. 45.*

[13] B.S. Kumar, K.R.S. Kumar, and R. Radhakrishnan, 2009. An Efficient Inter Carrier Interference Cancellation Schemes for OFDM System, 2009. *International Journal of Computer Science and Information Security, vol. 6.*

[14] A. Idris, K. Dimyati, and S. K. S. Yusof, 2011. Evaluating A New Subcarrier Mapping ICI-SC Scheme Using Linear Maximum Likelihood Alamouti Combiner (LMLAC) Decoding Technique, *Journal of Engineering Science and Technology, vol. 6,* pp. 664-673.

[15] N. Fisal, S. Kamilah, and A.Izzati. Intercarrier Interference Self-Cancellation for Space-Time-Frequency MIMO-OFDM System.

[16] L. Zhao, 2006. A New ICI Self-Cancellation Scheme Based on Repeated Symbol in OFDM Systems, 2006. International Conference on Communications, Circuits and Systems Proceedings, vol. 2, pp. 1216-1220.

[17] Y.H. Peng, Y.C. Kuo, G.R. Lee, and J.H. Wen, 2007. Performance Analysis of a New ICI-SELF-Cancellation-Scheme in OFDM Systems, IEEE, pp. 1333-1338.

[18] A. Idris, K. Dimyati, S. K. S. Yusof, D. M. Ali, and N. Ya'acob, 2011. CIR and BER Performance of STFBC in MIMO OFDM System, *Australian Journal of Basic and Applied Science, vol. 5,* pp. 3179-3187.

[19] M. H. Hsieh and C. H. Wei, 1998. Channel Estimation for OFDM Systems based on COMB-Type Pilot Arrangement in Frequency Selective Fading Channels, *IEEE Transactions on Consumer Electronics, vol. 44.*

[20] F. D. Y. Sun, 2009. Pilot Aided Channel Estimation for MIMO-OFDM Systems, London Communication Symposium.