ISSN 2348 – 9928
IJAICT Volume -1, Issue-6, October 2014 Doi:01.0401/ijaict.2014.01.22 Published Online 05 (05) 2014

AN EFFICIENT RECEIVER FOR ICI CANCELLATION IN OFDM SYSTEMS BASED ON PRCC SCHEME USING MMSE EQUALIZER

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Abstract— ***This paper presents a cyclic prefixed conjugate transmission technique with adaptive receiver to cancel out the ICI in OFDM systems using MMSE equalizer. The receiver design is based on the phase rotated conjugate cancellation (PRCC) concept, where two individual phase rotations are employed on the two receive paths, rather than only one phase rotation is adopted for the two transmit paths in the PRCC scheme. Cyclic prefix increases signal spacing and makes the signal more robust to ISI. The two phase rotations are chosen properly using the criterion of maximizing the carrier-to-interference ratio such that an additional phase distortion on the detected symbol could be completely removed. Block least mean-squared algorithm is applied to adaptively update the two phase rotations with the frequency offset variation. BER performance of the proposed method with MMSE and Zero Forcing Equalizer is compared. Simulation results shows that MMSE equalizer based approach can further improve the performance of proposed scheme at low to medium SNRs.***

Keywords— ***Inter Carrier Interference (ICI), Adaptive Receiver, Frequency Offset, OFDM, MMSE, Block Least Mean Square Algorithm.***

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is the multi-carrier transmission technique used for high data rate transmission over the broadband wireless communication systems. OFDM is a Multi-Carrier Modulation technique in which a high rate bit-stream is split into (say) N parallel bit streams of lower rate and each of these is modulated using one of N orthogonal sub-carriers.

In OFDM the basic idea is to divide the available spectrum into many orthogonal narrowband sub channels so that each sub channel experience almost flat fading. OFDM can provide large data rates with sufficient resistance to radio channel impairments like multipath fading. So it becomes a very efficient technique for data transmission over multipath fading environment due to its properties like a) high bandwidth efficiency and b) resistance to multipath fading. OFDM has been adopted in the European digital audio and video broadcast radio system and is being investigated for broadband indoor wireless communications. Standards such as HIPERLAN2 (High Performance Local Area Network) and IEEE 802.11a and IEEE 802.11g. Its implementation becomes easier with the help of Fast Fourier Transform and Inverse Fast Fourier Transform for demodulation and modulation respectively.

The major problem of such a highly efficient modulation system is the sensitivity to the frequency offset, which may result either from mismatch between the oscillator and the Doppler shift. In such situations, the orthogonality of the carriers is no longer maintained, which results in inter carrier interference (ICI). If ICI is not properly compensated it results in power leakage among the subcarriers. Also the frequency offset may damage the orthogonality among OFDM subcarriers and causes a number of impairments including attenuation and rotation of each of subcarriers and ICI between subcarriers, which degrades the overall system performance.

Some recent methods for reducing ICI using conjugate transmission is analyses in this paper. This paper also proposes cyclic prefixed conjugate transmission technique with adaptive receiver to cancel out the ICI using MMSE Equalizer. The receiver design is based on the phase rotated conjugate cancellation (PRCC) concept, where two individual phase rotations are employed on the two receive paths, rather than only one phase rotation is adopted for the two transmit paths in the PRCC scheme. Cyclic prefix makes the signal more robust to ISI by increasing the signal spacing.

The zero-forcing equalizer removes all ISI, and is ideal when the channel is noiseless. However, when the channel is noisy, the zero-forcing equalizer will amplify the noise greatly at frequencies f where the channel response $H(j2\pi f)$ has a small magnitude (i.e. near zeroes of the channel) in the attempt to

ISSN 2348 – 9928
IJAICT Volume -1, Issue-6, October 2014 Doi:01.0401/ijaict.2014.01.22 Published Online 05 (05) 2014

invert the channel completely. A more balanced linear equalizer in this case is the MMS Equalizers, which does not usually eliminate ISI completely but instead minimizes the total power of the noise and ISI components in the output. Hence we go for MMSE equalizer in the proposed method.

The paper is organized as follows. The section II gives the background of ICI cancellation schemes using conjugate transmission. Section III describes the proposed method for ICI reduction using conjugate transmission. Simulation results are presented in section IV .Conclusion is presented in section V.

II. BACKGROUND

The most intuitive way to solve the CFO problem is to synchronize the carrier frequency of the received signal with that of the transmitted signal. In this case, it is necessary to estimate the CFO and then to perform compensation according to the estimated result. Some methods using conjugate transmission is discussed below.

2.1. Conjugate Transmission Method

H.-G. Yeh *et.al* [5] proposed a tow path algorithm for multicarrier communication systems including OFDM. The first path employs the regular OFDM algorithm. The second path uses the conjugate transmission of the first path. After combining the received signals from the two paths, the ICI in one path is suppressed by that in the other path.

Fig1 represents the transmitter of conjugate transmission method. Data is converted from serial to parallel. After modulation data given to IFFT. OFDM signal is generated. OFDM signal and its conjugate are transmitted in two path using multiplexing. TDM, FDM etc can be used.

Fig2 represents the receiver section. After de-multiplexing conjugate of 2nd path again is taken. Both two paths converted from serial to parallel. After FFT block demodulation is done. Then parallel to serial conversion of data is done and then given to diversity combiner. Combiner gives a single improved signal after ICI cancellation.

2.2. OFDM System Model

The complex baseband OFDM signal after the IFFT block at the transmitter can be expressed as

$$t_n = \frac{1}{N}\sum_{k=0}^{N-1} T_k\, e^{\frac{j2\pi nk}{N}},\; n = 0,1 \ldots\ldots N-1 \qquad \text{(1)}$$

Where N is the total number of subcarriers and T_k is the transmitted symbol on the kth subcarrier. At the receiver, the time-domain received signal suffering from a frequency offset and an additive white Gaussian noise (AWGN) can be written As

$$r_n = t_n\, e^{\frac{j2\pi n\varepsilon}{N}} + w_n,\; n = 0,1,\ldots\ldots\ldots N-1 \qquad \text{(2)}$$

Where ε represents the frequency offset normalized by the frequency spacing of two adjacent subcarriers and w_n is a zero-mean AWGN. After the fast Fourier transform (FFT) block, the frequency domain signal at the lth subcarrier is given as

$$\begin{aligned} R_l &= \sum_{n=0}^{N-1} r_n\, e^{\frac{-j2\pi nl}{N}} \\ &= \sum_{n=0}^{N-1} \left(t_n\, e^{\frac{j2\pi n\varepsilon}{N}} + w_n\right) e^{\frac{-j2\pi nl}{N}} \\ &= \frac{1}{N}\sum_{k=0}^{N-1} T_k \sum_{n=0}^{N-1} e^{\frac{-j2\pi n(l-k-\varepsilon)}{N}} + \sum_{n=0}^{N-1} w_n\, e^{\frac{-j2\pi nl}{N}} \end{aligned} \qquad \text{(3)}$$

Let W_l be the discrete fourier transform of w_n and ($l-k-\varepsilon=v$)

$$\begin{aligned} S(v) &= \frac{1}{N}\sum_{n=0}^{N-1} e^{\frac{-j2\pi nv}{N}} \\ &= \frac{\sin \pi v}{N \sin\left(\frac{\pi v}{N}\right)}\, e^{\frac{j\pi v(1-N)}{N}} \end{aligned} \qquad \text{(4)}$$

Then (3) can be written as follows:

$$T_l S(-\varepsilon) + \sum_{k=0,k\neq l}^{N-1} T_k S(l-k-\varepsilon) + W_l,\; l = 0,1,\ldots\ldots N-1 \qquad \text{(5)}$$

S(v) is usually referred to as the ICI weighting coefficient function . The first term in (5) contains the desired information T_l with amplitude attenuated by a factor S(-ε), and the second term is regarded as the sum of interferences resulted from T_k multiplied by S(l-k-ε), the ICI weighting coefficient from the *k*th subcarrier to the *l*th subcarrier. If there is no frequency offset, since the orthogonality is preserved (i.e., S(l-k) = 0), the second term of (5) is zero. However, in the presence of frequency offset, one can observe that the information symbol T_l is not only attenuated by S(-ε) , but also interfered by other N-1 subcarriers. This problem cannot be solved by simply increasing the transmission power because both the desired and ICI terms will be increased if a higher transmission power is used. Therefore, the ICI cancellation researches focus on reducing the sensitivity of OFDM signals to frequency offsets (i.e., to diminish or remove the effect of the second term in (5).

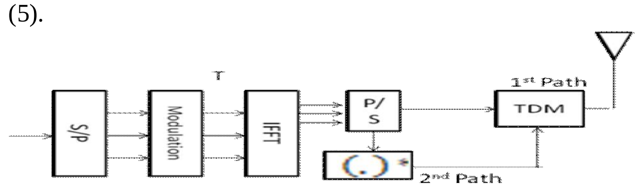

Fig1: Transmitter block diagram of CC scheme

ISSN 2348 – 9928
Doi:01.0401/ijaict.2014.01.22 Published Online 05 (05) 2014

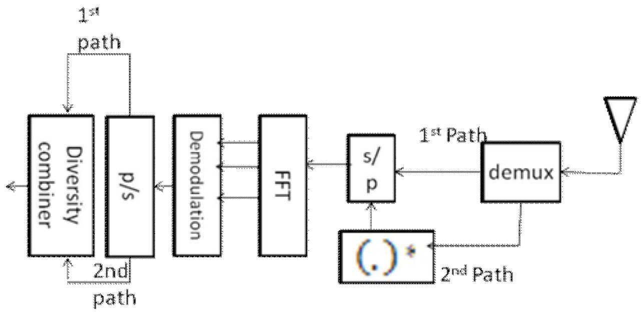

Fig2: Receiver block diagram of CC scheme

2.3 Conjugate Cancellation Scheme

The CC scheme transmits two independent paths such that the ICI weighting coefficient for one path could have an opposite polarity of that for the other path. At the receiver, the time-domain received signal of the first path is the same as (2) and the signal of the second path can be expressed as

$$r_n' = t_n^* e^{\frac{j2\pi n\varepsilon}{N}} + w_n', \quad n = 0,1,\dots N-1 \qquad (6)$$

Where $(.)^*$ denotes the conjugate operation and w_n' is a zeromean AWGN. By employing a conjugate operation on (6) and passing the resulting signal through the FFT block, we have

$$R_l' = \sum_{n=0}^{N-1} (r_n')^* e^{\frac{-j2\pi nl}{N}} = \sum_{k=0}^{N-1} T_k\, S(l-k-\varepsilon) + W_l' \qquad (7)$$

Assuming that both outputs of a regular OFDM system and a conjugate OFDM system can be combined coherently without Interfering with each other at the receiver by using a division multiplexing technique, such as FDM, or TDM, or CDM, the final detected symbol is then chosen as the averaged detected symbols of the regular OFDM receiver and the conjugate algorithm. Averaging the FFT results of the two transmission paths yields

$$Z_l' = \frac{1}{2}(R_l + R_l')$$

$$= \frac{1}{2}\{\sum_{k=0}^{N-1} T_k (S(l-k-\varepsilon) + S(l-k-\varepsilon)) + (W_l + W_l')\} \qquad (8)$$

This is called the conjugate cancellation (CC) scheme.
To compare various ICI cancellation schemes, it is useful to examine their theoretical CIRs.

The CIR of the CC scheme can be defined as

$$CIR_{CC} = \frac{|S(-\varepsilon) + S(\varepsilon)|^2}{\sum_{k=1}^{N-1} |S(k-\varepsilon) + S(k+\varepsilon)|^2} \qquad (9)$$

CC scheme achieves pretty high CIR values when the frequency offset is small. The CIR curve of CC scheme declines more rapidly than those of other ICI cancellation schemes. This property makes the CC scheme undesirable at high frequency offset situation.

2.4. General Phase Rotated Conjugate Cancellation Scheme

C.-L. Wang and Y.-C. Huang [6] proposed PRCC scheme for ICI cancellation in OFDM systems. Like the CC scheme, this scheme adopts two-path transmission, but introduces a new variable; Fig3 shows the block diagram of PRCC scheme.

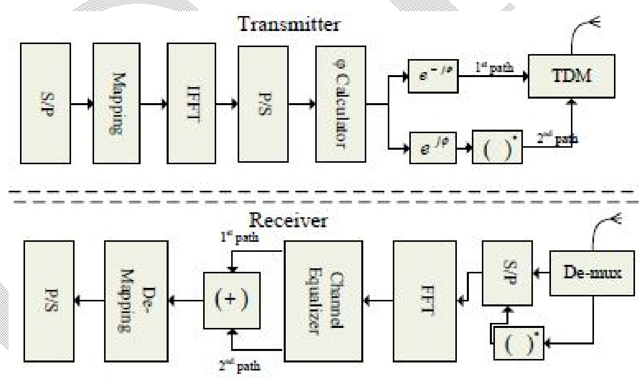

Fig3: Block diagram of PRCC scheme

For the PRCC scheme, the first path employs the standard OFDM signal with artificial phase rotation of □ while the second path adopts the conjugate of the standard OFDM signal with artificial phase rotation of -□, i.e., $(e^{j□}T_n)$ and $(e^{-j□}T_n)^*$, respectively. In the presence of a frequency offset ε, the received signals of the two transmission paths can be expressed as

$$r_n^{(1)} = t_n e^{j\phi} e^{\frac{j2\pi n\varepsilon}{N}} + w_n^{(1)}, n = 0,1,\dots N-1 \qquad (10)$$

And

$$r_n^{(2)} = x_n^* e^{j\phi} e^{\frac{j2\pi n\varepsilon}{N}} + w_n^{(2)}, n = 0,1,\dots N-1 \qquad (11)$$

where $w_n^{(1)}$ and $w_n^{(2)}$ are AWGN.

The receiver first passes $r_n^{(1)}$ and the conjugate of $r_n^{(2)}$ through the FFT block to obtain the following frequency domain signals

$$R_l^{(1)} - FFT\{r_n^{(1)}$$

$$= \sum_{k=0}^{N-1} T_k \{e^{j\phi} S(l-k-\varepsilon)\} + W_l^{(1)} \qquad (12)$$

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And

$$R_l^{(2)} = FFT\left\{r_n^{(2)*}\right\}$$
$$= \sum_{k=0}^{N-1} T_k S(l-k-\varepsilon)\} + W_l^{(2)} \qquad (13)$$

Where $W_l^{(1)}$ and $W_l^{(2)}$ are the discrete fourier transforms of $w_n^{(1)}$ and $w_n^{(2)}$, respectively.

Taking an average of results (12) and (13) we obtain

$$Z_l = \frac{1}{2}\left(R_n^{(1)} + R_n^{(2)}\right)$$

$$= \frac{1}{2}\left\{\sum_{k=0}^{N-1} T_k\left(e^{j\varphi} S(l-k-\varepsilon) + e^{-j\varphi} S(l-k+\varepsilon)\right) + (W_l^{(1)} + W_l^{(2)})\right\} \qquad (14)$$

The ICI terms will cancel each other.

It is shown that the previous conjugate cancellation (CC) scheme is equivalent to a special case of the proposed scheme where =0. The general PRCC scheme not only inherits advantages of the conventional CC scheme, such as backward compatibility with the existing OFDM systems, low receiver complexity, and two-path diversity, but also provides better performance, especially at high frequency offset situations. Although PRCC work well for time-invariant channels, they might not provide satisfactory performance for time-variant channels where the CFO changes with time. In addition, the receiver in PRCC must feed the CFO estimate back to the transmitter to determine the optimal phase rotation, and this induces an additional signaling overhead in OFDM system.

2.5. Receiver PRCC

C.-L. Wang *et.al* [7] proposed an adaptive receiver that works with the conjugate transmission developed in the CC scheme in terms of a time-division multiplexing (TDM) realization. The adaptive receiver applies a common phase rotation on the two receiving paths in a similar manner with PRCC's transmitter. Besides, by introducing the frequency offset estimator, a normalized BLMS algorithm is employed to adapt the phase rotation to the time-varying frequency offset. Hence, even if the frequency offset changes, the phase rotation could still be updated to approach the optimal value.

Nevertheless, the adaptive receiver in [7] has a defect that a "quasi-static" assumption should be applied to the considered time-varying frequency offset, i.e. the frequency offset doesn't vary across two consecutive OFDM symbols (or two TDM paths), which is only reasonable in a slow time varying channel. For a general time varying channel where the frequency offsets seen in the two paths are expressed by ε and $\varepsilon + \Delta\varepsilon$ respectively, the bit error rate (BER) performance of [7] may degrade with an increasing frequency offset variation $|\Delta\varepsilon|$.

III. PROPOSED SCHEME

This paper proposes cyclic prefixed conjugate transmission technique with adaptive receiver to cancel out the ICI using MMSE equalizer. This receiver design is based on PRCC concept , where two individual phase rotations are employed on the two receiver paths, rather than only one phase rotation is adopted for the two transmitter paths in the PRCC scheme. Cyclic prefix makes the signal more robust to ISI. . The two phase rotations are chosen properly using the criterion of maximizing the carrier-to-interference ratio such that an additional phase distortion on the detected symbol could be completely removed. For practical use, the block least mean-squared algorithm is applied to adaptively update the two phase rotations with the frequency offset variation. It provides good ICI cancellation at both large and small CFO. Feeding back the CFO information is eliminated and so complexity is reduced. Compared to CC , PRCC and RPRCC it can be used in time varying channels with fast CFO variations. Fig4 represents the transmitter block diagram of proposed scheme. Fig 5 represents the block diagram of receiver of proposed scheme.

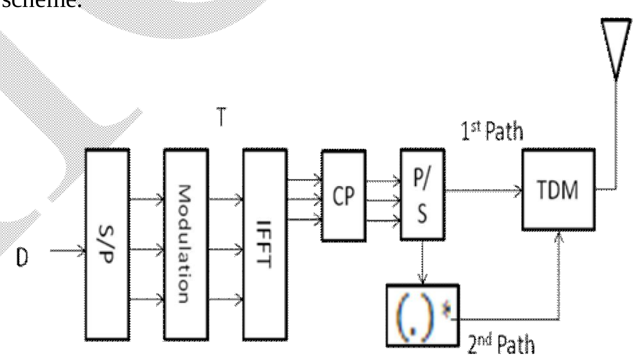

Fig 4: Block diagram of proposed transmitter

3.1 Proposed System Model

The proposed scheme is dependent primarily on the transmitter using cyclic prefixed conjugate transmission technique. The data symbols are converted from serial to parallel. Symbols are modulated and converted to frequency domain using IFFT. The frequency domain symbols are cyclic prefixed and converted from parallel to serial. OFDM signal at the transmitter can be expressed as

$$t_n = \frac{1}{N}\sum_{k=0}^{N-1} T_k\, e^{\frac{j2\pi nk}{N}}, \quad n = 0,1 \ldots\ldots N-1 \qquad (15)$$

Where N is the total number of subcarriers and T_k is the transmitted symbol on the kth subcarrier.

ISSN 2348 – 9928
Doi:01.0401/ijaict.2014.01.22 Published Online 05 (05) 2014

OFDM signal is transmitted in the first path and its conjugate replica is transmitted in the second path. Both signals are transmitted using time division multiplexing.

We consider an AWGN channel and denote the frequency offsets seen in the two paths by ε and Δε, respectively. In the presence of frequency offsets the received signals of the two transmission paths can be expressed as

$$r_n^{(1)} = t_n e^{\frac{j2\pi n\varepsilon}{N}} + w_n^{(1)}, \; n = 0,1,\ldots.N-1 \quad (16)$$

And

$$r_n^{(2)} = t_n^{*} e^{\frac{j2\pi n(\varepsilon+\Delta\varepsilon)}{N}} + w_n^{(2)}, n = 0,1,\ldots N-1 \quad (17)$$

Where $w_n^{(1)}$ and $w_n^{(2)}$ are AWGN.

The receiver first passes $r_n^{(1)}$ and conjugate of $r_n^{(2)}$ through the FFT block to obtain the frequency domain signals

$$Z_l^{(1)} = FFT\{r_n^{(1)}\} = \sum_{k=0}^{N-1} T_k S(l-k+\varepsilon) + W_l^{(1)} \quad (18)$$

And

$$Z_l^{(2)} = FFT\{r_n^{(2)*}\} = \sum_{k=0}^{N-1} T_k S(l-k-(\varepsilon+\Delta\varepsilon)) + W_l^{(2)} \quad (19)$$

Where $W_l^{(1)}$ and $W_l^{(2)}$ are the Fourier transforms of $w_n^{(1)}$ and $w_n^{(2)}$, respectively. Then the combining output after applying the phase rotation for the two paths becomes

$$Z_{k,proposed} = [e^{j\phi}S(\varepsilon) + e^{-j(\phi+\Delta\phi)}S(-(\varepsilon+\Delta\varepsilon))]T_k + \sum_{l=0,l\neq k}^{N-1}[e^{j\phi}S(l-k+\varepsilon) + e^{-j(\phi+\Delta\phi)}S(l-k-(\varepsilon+\Delta\varepsilon))]T_l + [W_l^{(1)} + W_l^{(2)}] \quad (20)$$

1st term is the desired signal,
2nd term is ICI term,
3rd term is the noise.
CIR of the proposed scheme is

$$CIR_{proposed}(\varepsilon,\Delta\varepsilon,\phi,\Delta\phi) = \frac{|e^{j\phi}S(\varepsilon) + e^{-j(\phi+\Delta\phi)}S(-(\varepsilon+\Delta\varepsilon))|^2}{\sum_{l=1}^{N-1}|e^{j\phi}S(l+\varepsilon) + e^{-j(\phi+\Delta\phi)}S(l-(\varepsilon+\Delta\varepsilon))|^2} \quad (21)$$

Assume ε and $\Delta\varepsilon$ are known, the phase rotations can be optimized by maximizing the CIR.
To maximize the CIR we take partial differentiation on (21) with respect to ϕ and let the result equal to zero ie,

$$\frac{\partial CIR_{proposed}(\varepsilon,\Delta\varepsilon,\phi,\Delta\phi)}{\partial\phi} = 0$$

Equating we get

$$\phi_{opt} = \frac{-\pi\varepsilon(N-1)}{N}$$

And

$$\Delta\phi_{opt} = \frac{-\pi\Delta\varepsilon(N-1)}{N} \quad (22)$$

By determining optimal phase rotation the additional phase distortion on the desired signal can be completely removed.

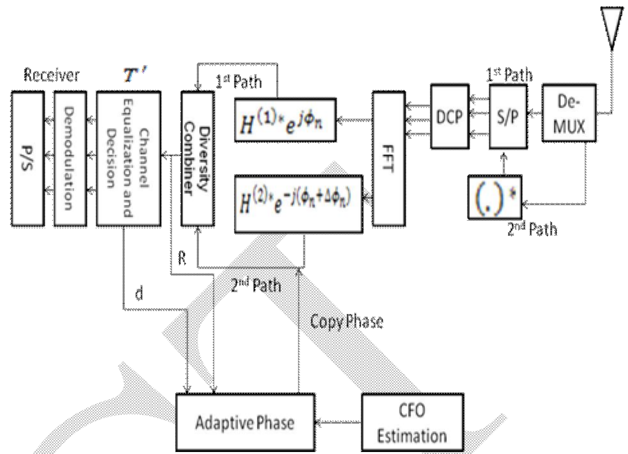

Fig 5: block diagram of proposed receiver

3.2 Adaptation of Phase Rotation and channel equalization.

To ensure that the information contained in every receive signal is reflected uniformly in the stochastic gradient adaptation, we use the normalized BLMS algorithm to alleviate the impact induced by the change of the received signal power due to unexpected factors (e.g., channel fading). The block size is chosen to be equal to the FFT length.

For deriving the adaptive phase rotation, we consider a fast-fading multipath channel and assume that maximum ratio combining (MRC) is exploited to result in the detection output. We rewrite the signals of both paths as follows after individual phase rotations are applied.

$$Z_k^{(1)} = e^{j\phi} H_k^{(1)*} R_k^{(1)} \quad (23)$$

$$Z_k^{(2)} = e^{-j(\phi+\Delta\phi)} H_k^{(2)*} R_k^{(2)} \quad (24)$$

Where $H_k^{(i)}$ is the channel gain on the kth subcarrier for the ith path. ϕ and $\Delta\phi$ are the phase rotations for the (2n-1)th and 2nth OFDM symbols respectively. Then the MRC ouput can be expressed as

$$Z_k = Z_k^{(1)} + Z_k^{(2)}$$

$$= [e^{j\phi}S(\varepsilon)|H_k^{(1)}|^2 + e^{-j(\phi+\Delta\phi)}S(-(\varepsilon+\Delta\varepsilon))|H_k^{(2)}|^2]T_k + \sum_{l=0,l\neq k}^{N-1}[e^{j\phi}S(l-k+\varepsilon)H_k^{(1)*}H_l^{(1)} + e^{-j(\phi+\Delta\phi)}S(l-k(\varepsilon+\Delta\varepsilon))H_k^{(2)*}H_l^{(2)}]T_l + [e^{j\phi}H_k^{(1)*}W_k^{(1)} + e^{-j(\phi+\Delta\phi)}H_k^{(2)*}W_k^{(2)}] \quad (25)$$

ISSN 2348 – 9928
IJAICT Volume -1, Issue-6, October 2014 Doi:01.0401/ijaict.2014.01.22 Published Online 05 (05) 2014

To perform channel equalization on the MRC output, the current CFO ε must be known to calculate the combinatory gain. Assuming that the phase rotations ϕ and $\Delta\phi$ have approached their optimal values after sufficient adaptations, the CFOs can be estimated as follows:

$$\varepsilon_n^{'} = \frac{\phi_n N}{\pi(N-1)} \qquad (26)$$

And

$$\Delta\varepsilon_n^{'} = \frac{\Delta\phi_n N}{\pi(N-1)} \qquad (27)$$

This corresponds to CFO's of (2n-1)th and 2nth path respectively.

With (26) and (27) detected symbol can be obtained by

$$T_k^{'} = dec\left(\frac{Z_k}{|S(\varepsilon_n^{'})|H_k^{(1)}|^2 + |S(-(\varepsilon_n^{'} + \Delta\varepsilon_n^{'}))|\,|H_k^{(2)}|^2}\right) \qquad (28)$$

Subsequently error term ($e_k = d_k - R_k$) can be calculated after reconstructing the desired signal.

$$d_k - \left\{|S(\varepsilon_n^{'})|H_k^{(1)}|^2 + \left|S\left(-(\varepsilon_n^{'} + \Delta\varepsilon_n^{'})\right)\right|\,|H_k^{(2)}|^2\right\} T_k^{'} \qquad (29)$$

By averaging the squared error terms of all the subcarriers, a cost function can be defined by

$$J_n(\phi_n, \Delta\phi_n, \varepsilon_n^{'}, \Delta\varepsilon_n^{'}) = E_n\{|e_k|^2\} = \frac{1}{N}\sum_{k=0}^{N-1} |e_k|^2 \qquad (30)$$

As a result, the two phase rotations can be adaptively updated using the normalized block least mean square algorithm. MMSE Equalizer tries to minimize the cost function.

IV. SIMULATION RESULTS

To examine the performance of proposed adaptive receiver in time varying channel where cfo's for the two paths are distinct, we consider both awgn channel and multipath Rayleigh fading channel. BER performance of ofdm system with 64 QAM modulations is performed.

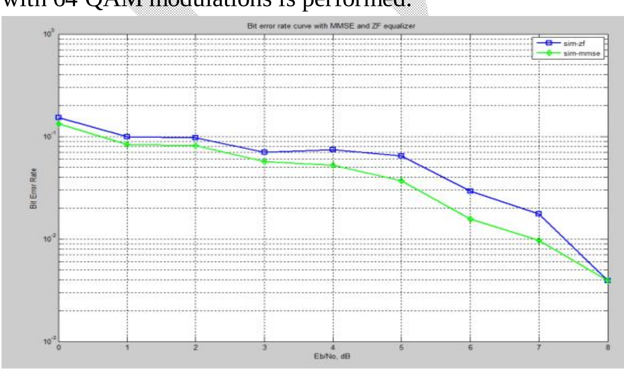

Fig6 : BER curve with zero forcing and mmse equalizer for 64 QAM ofdm system and ε_{fix}=.05

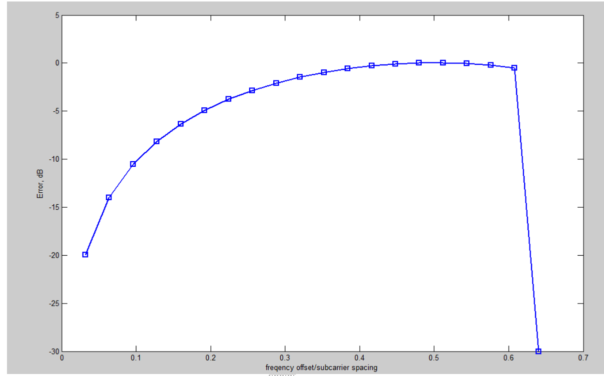

Fig 7 : Error(dB) vs frequency offset/subcarrier spacing

(28)

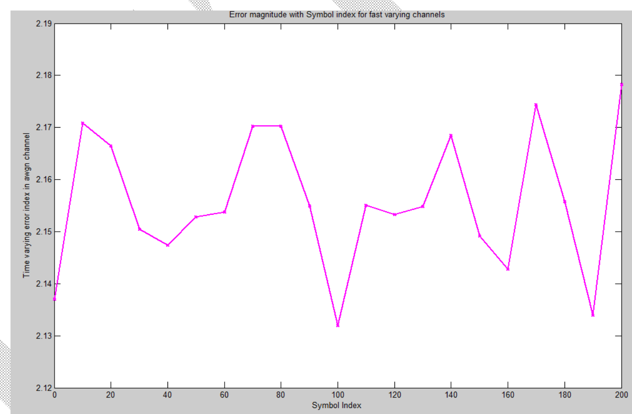

Fig8 : Time varying error index in awgn channel vs symbol index

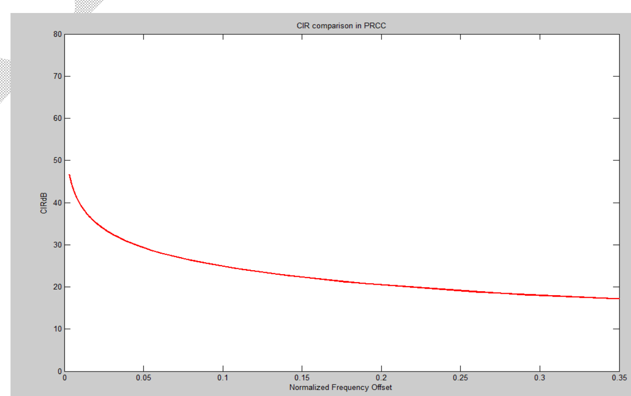

Fig 9 : CIR dB vs Normalised carrier frequency offset

V. CONCLUSION

A cyclic prefixed conjugate transmission technique with adaptive receiver for ICI cancellation in OFDM systems based on PRCC scheme with MMSE equalizer is carried out. Unlike PRCC which applies only one phase rotation for the two paths at the transmitter, the proposed scheme uses two artificial phase rotations on the two receive paths at the receiver to further address the problems under the fast time varying channels. An optimal phase rotation that maximises the CIR are derived and selected deliberately to preclude the undesired phase distortion to the received signal and by which an adaptive process based on the normalised BLMS algorithm has been developed in order to make the phase rotation keep up with the CFO variations. Compared to CC and PRCC proposed method provides better performance. MMSE equalizer minimises the total power of noise and ISI components. Simulation results shows that compared to zero forcing equalizer MMSE equalizer provides better performance at low to medium SNRs for the proposed method.

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