INTER CHANNEL INTERFERENCE IN HIGH MOBILITY OFDM

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Abstract: In broadband wireless system, the signal energy is scattered and reflected from objects in the environment, components of the signal arriving at the receiver are spared out over a longer period of time than is desirable. The challenge is then to provide a high performance reliable data link that can operate with the restricted receiver power levels, severe channel fading due to multipath reflections and interfering energy from other devices nearby. The Performance of the Orthogonal Frequency Division Multiplexing (OFDM) is degrade due to Doppler frequency or frequency drift between transmitter and receiver oscillator which causes frequency offset and leads to Inter- Carrier-Interference (ICI). This paper represents, a general reduced-rate orthogonal frequency division multiplexing (OFDM) transmission scheme for inter-sub channel interference (ICI) self-cancellation over high-mobility fading channels.

Keywords: ICI, OFDM, Channel fading, Doppler frequency

I. INTRODUCTION

In orthogonal frequency division multiplexing (OFDM) modulation a high-data rate channel is divided into N number of low data-rate sub-channels with each sub channel is modulated in different sub-carrier. Due to which each Sub-channel experiences a flat-fading and equalization at the receiver is less complex, providing high spectral efficiency and resistance to the multi-path interference. So the principles of OFDM modulation have been employed to high-rate wireless data transmission systems like wireless LAN, terrestrial mobile communication, digital terrestrial TV broadcasting, Worldwide Interoperability for Microwave Access (WiMAX) and so on, because of its inherent capability to resist multipath fading in broadband wireless communications. However, the variation of a wireless channel within an OFDM system, destroys the orthogonality and causes inter-sub channel interference (ICI), will degrade system performance and result at the receiver end, if it is not cancelled and the bit error occurs in the presence of carrier frequency offset or Doppler frequency shift because of the inter-carrier interference (ICI) in OFDM. In this paper, we present the effect of ICI caused by Doppler frequency shift on BER calculation in OFDM modulation.

II. ICI ANALYSIS IN OFDM

In OFDM modulation, a serial bit stream input is converted into parallel by S/P, then mapped into symbols using modulation, then perform IFFT on N-parallel subcarriers and transmitted after adding cyclic prefix and converted to serial data. The addition of cyclic prefix is used to cancel inter-symbol interference (ISI). At the receiver side, the cyclic prefix is removed from received data after S/P and then performs FFT, demapped into bits and back to serial data using P/S. In OFDM system, the time-domain transmitted signal is given as:

\[ x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X(k)e^{j2\pi kn/N} \]

where x (n) denotes the nth sample of transmitted signal, X(k) denotes the modulated symbol for the kth subcarrier (k=0,1,......N) and N is number of subcarrier. The received signal in time-domain is given as:

\[ y(n) = x(n)e^{-j2\pi fcT_s/n} + w(n) \]

\( \epsilon(\Delta f T_s) \) is the normalized frequency offset, \( \Delta f \) is the Doppler frequency shift, \( T_s \) is symbol duration and \( w(n) \) is AWGN introduced in the channel.

III. EFFECT CAUSED BY DOPPLER FREQUENCY SHIFT

When the carrier \( \cos(2\pi f_c t) \) passes through the multipath channels, the received signal is affected by Doppler frequency shift \( f_d \cos(\theta) \), where \( f_d \) is the maximum Doppler frequency and \( \theta \) is the arriving angle of the carrier with respect to the moving direction of the mobile terminal. Therefore the received signal \( r(t) \) can be expressed as:

\[ r(t) = \cos(2\pi f_c t) - 2\pi f_d t \cos(2\pi f_c t) \sin(2\pi f_d t) \]

The second term of the above equation is the interference caused by Doppler frequency shift.
IV. ICI IN HIGH-MOBILITY OFDM

Let us consider \( X = (X_0, X_1, \cdots, X_{N-1})^T \) as the frequency domain transmitted signal vector and \( F_N \) as the \( N \times N \) discrete Fourier transform (DFT) matrix with the \((n_1, n_2)\) element given by \([01]\)

\[
F_N(n_1, n_2) = \frac{1}{\sqrt{N}} e^{-j2\pi n_1 n_2/N}, 0 \leq n_1, n_2 \leq N - 1
\]

and then the time-domain transmitted signal vector is given by \( x = F_N X \), where \((\cdot)^H\) denotes the conjugate transpose operator. Suppose that ISI is avoided by cyclic prefix, and then the time-domain received signal vector at the OFDM receiver is given by \( y = H x + w \), where \( w \) denotes the additive white Gaussian noise vector and \( H \) denotes the \( N \times N \) time domain channel matrix. The corresponding frequency-domain received signal vector can be obtained as \( Y = F_N Y = G X + W \), where \( W = F_N W \) denotes the frequency-domain white noise vector and \( G = F_N H F_N^H \) denotes the frequency-domain channel matrix over the \( N \) OFDM sub channels.

V. PRINCIPLE OF REDUCED-RATE OFDM TRANSMISSION

The time-domain variation of a wireless channel within an OFDM symbol causes ICI. While it has been proposed to estimate the off-diagonal elements of the frequency-domain channel matrix and perform ICI cancellation accordingly, this method requires a large amount of pilots and decreases spectral efficiency significantly. On the other hand, the existing pilot-free full-rate OFDM transmit/receive processing schemes [02], [03], [04] only have limited ICI mitigation capabilities and still suffers considerable residual ICI. In contrast, the half-rate ICI self-cancellation scheme proposed in [05] has been demonstrated to reduce ICI significantly. In this section, we extend the work in [05] and develop a general reduced-rate OFDM transmission framework for ICI self-cancellation in a high-mobility environment. In reduced-rate OFDM transmission, \( K \) data symbols are loaded over \( N \) subcarriers with \( K \) defined as the transmission rate and \( n = N/K \) as the rate-reduction factor (RRF). By reducing transmission rate, we are able to design a structure of the transmitted signal vector so that it has inherent ICI self-cancellation capability. In [05], Yoping Zhao and Sven-Gustav Hagman have proposed a simple but efficient ICI self-cancellation scheme, denoted as the Zhao’s scheme in the following. The Zhao’s scheme is a special half-rate OFDM transmission scheme with \( K = N/2 \). In particular, the frequency-domain transmit and receive processing matrices equivalently utilized in the Zhao’s scheme are

\[
V = U^T = \begin{bmatrix}
1 & -1 & 0 & 0 & \cdots & 0 & 0 \\
0 & 0 & 1 & -1 & \cdots & 0 & 0 \\
0 & 0 & 0 & 0 & \cdots & 0 & 0 \\
0 & 0 & 0 & 0 & \cdots & 1 & -1
\end{bmatrix}
\]

Therefore, the actually transmitted signal vector in the Zhao’s scheme is given by

\[
X = (S_0, -S_0, S_1, -S_1, \cdots, S_{K-1}, -S_{K-1})^T
\]

Essentially, the Zhao’s scheme is based on the conjecture that \( G (m, k) \approx G (m, k - 1) \) and as a result, with the transmitted signal structure as given in above equation, interference over the \( m \)th subcarrier from subcarriers \( k \) and \( k - 1 \) cancels each other approximately, resulting a significantly reduced ICI level. In [06], Ming-Xian Chang has proposed another ICI self-cancellation scheme, denoted as the Chang’s scheme in the following. In contrast with the Zhao’s scheme that is based on integer RRFs only, the Chang’s scheme is applicable to both integer and fractional RRFs. In the Chang’s scheme, the original transmitted signal sequence is extended periodically in the time domain at the transmitter, at the receiver, the Chang’s scheme performs a matched filter based combination to take advantage of the temporal diversity created at the transmitter for ICI self-cancellation. Equivalently, the Chang’s scheme applies one time-domain transmit processing matrix for temporal periodic extension at the transmitter, and another time domain receive processing matrix for temporal combination at the receiver. Therefore, the Chang’s scheme is also a special reduced-rate OFDM transmission scheme.

VI. DESIGN OF TRANSMIT AND RECEIVE PROCESSING MATRICES

For the reduced-rate OFDM transmission, our objective is to design the transmit processing matrix, \( U \) or \( A \), and the receive processing matrix \( V \) or \( B \), so that the transformed K-subcarrier OFDM system has significantly reduced ICI. The frequency-domain received signal over the \( m \)th equivalent sub channel can be expressed as:

\[
R_m = \tilde{G}(m, m) S_m + \sum_{k=0; k \neq m}^{K-1} \tilde{G}(m, k) S_k + \tilde{W}_m
\]

where the first and the second terms denote the desired signal and the ICI, respectively. Assume that the transmitted signals over different equivalent sub channels, \( S_k \)’s, are independent with zero mean and variance \( \sigma^2 \)’s, and then the average SIR over the \( m \)th equivalent sub channel can be obtained as:

\[
\text{SIR}_m = \frac{P(m, m)}{\sum_{k=0; k \neq m}^{K-1} P(m, k)}
\]

Where \( P(m, k) = E[|\tilde{G}(m, k)|^2] \)

denotes the average power gain from the \( k \)th to the \( m \)th equivalent sub channel. In this paper, we consider an OFDM system with the same modulation scheme over each sub channel. Thus the objective of reduced-rate OFDM transmission is to apply specially designed transmit and receive processing matrices so as to maximize the minimum average SIR over the \( K \)
Hence the optimization objective turns to designing the time-domain processing matrices, A and B, so that different taps in the equivalent time-domain channel, \( \mathbf{H} = \mathbf{BHA} \), are uncorrelated and a common SIR over all equivalent sub channels is guaranteed.

Since \( \mathbf{H} = \mathbf{BHA} \), we have

\[
\mathbf{H}(1,j) = \sum_{n_1=0}^{N-1} \sum_{n_2=0}^{N-1} B(n_1,n_2) H(n_1,n_2) A(n_2,j)
\]

Without loss of generality, we construct A so that the time-domain transmit processing can be realized by simple periodic extension and windowing, i.e.,

\[
A = \begin{bmatrix}
\alpha_0 & \alpha_1 & \cdots & \alpha_{N-1}
\end{bmatrix}
\]

where \( \alpha_0, \alpha_1, \cdots, \alpha_{N-1} \) denote the transmit processing coefficients. The corresponding time-domain receive processing matrix must have the following structure.

\[
B = \begin{bmatrix}
\beta_0 & \beta_1 & \cdots & \beta_{N-1}
\end{bmatrix}
\]

where \( \beta_0, \beta_1, \cdots, \beta_{N-1} \) denote the receive processing coefficients. After determining the structure of time-domain processing matrices, A and B, we further investigate the corresponding frequency-domain processing matrices, U and V by using Fourier transform. Hence the optimization problem can be formulated as

\[
\max_{\alpha, \beta} \quad \text{SIR} = \frac{P_d}{P_l}, \quad \text{s.t.} \quad \sum_{n=0}^{N-1} |\alpha_n|^2 = N \quad \text{and} \quad \sum_{n=0}^{N-1} |\beta_n|^2 = N
\]

Where

\[
P_d = \sum_{r_1=0}^{N-1} \sum_{c_1=0}^{N-1} \sum_{r_2=0}^{N-1} \sum_{c_2=0}^{N-1} V(0,r_1) U(c_1,0) f(r_1, c_1, r_2, c_2) V^*(0,r_2) U^*(c_2,0)
\]

\[
P_l = \sum_{k=1}^{N-1} \sum_{r_1=0}^{N-1} \sum_{c_1=0}^{N-1} \sum_{r_2=0}^{N-1} \sum_{c_2=0}^{N-1} V(0,r_1) U(c_1,k) f(r_1, c_1, r_2, c_2) V^*(0,r_2) U^*(c_2,k)
\]

And

\[
f(r_1, c_1, r_2, c_2) = \sum_{l=0}^{L-1} s_l e^{j2\pi (c_2-c_1) r_2 / N} \]

VII. SIMULATION RESULTS
In our simulation, a 32-subcarrier ($N = 32$) high-mobility OFDM transmission system is considered. We model the time-varying wireless channel as a 4-tap one, i.e., $L = 4$. Figure 2(a) shows the SIR versus the normalised Doppler frequency for the proposed, the Zhao’s, and the Chang’s schemes when $K = N/2$. Such a half-rate OFDM transmission scheme is suitable for high Doppler frequencies to trade transmission rate for ICI mitigation in a high-mobility environment. Both the Zhao’s and the Chang’s schemes have a common SIR over all $K$ equivalent sub channels in the special case of half-rate transmission. As demonstrated in Fig. 2(a), the proposed reduced-rate OFDM transmission achieves significant SIR gains of around 15 dB over the Zhao’s scheme and around 5 dB over the Chang’s scheme, respectively. Moreover, we observe that the SIR gain of the proposed scheme over the Chang’s scheme increases with $F_d$ slowly. Figure 2(b) shows the corresponding BER versus the normalized Doppler frequency when 64-QAM modulations applied over each equivalent sub channel. Figure 2(b) further shows the BER versus the normalized Doppler frequency for the proposed, the Zhao’s, and the Chang’s schemes. Figure 2(b) demonstrates that the proposed scheme achieves remarkable BER improvement over the Zhao’s and the Chang’s schemes, especially in high $F_d$ regions. Figure 3(a) shows the SIR versus the normalised Doppler frequency for the proposed and the Chang’s schemes when $K = 3/4N$; Figure 3(b) shows the corresponding BER versus the normalized Doppler frequency when 16-QAM modulations applied over each equivalent sub channel. In contrast with the half-rate scheme suitable for high Doppler frequencies, such a 3/4-rate one is suitable for relatively low Doppler frequencies to achieve a tradeoff between transmission rate and ICI mitigation.

CONCLUSION

In this paper, we have developed a general reduced-rate OFDM transmission scheme for ICI self-cancelation over high-mobility fading channels. By transmit and receive processing, we have transformed the original OFDM system into an equivalent one with fewer subcarriers and significantly reduced ICI. In particular, we have developed a general structure of transmit and receive processing matrices to guarantee a common average SIR over all equivalent sub channels in the transformed OFDM system. Both numerical and simulation results have demonstrated the remarkable performance improvement of the proposed reduced-rate transmission over the existing ICI self-cancelation schemes even in the presence of significant uncertainties in channel statistics.

REFERENCES


