Intercarrier Interference Cancellation for Wideband OFDM in High Speed Aerial Vehicle Communication

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***Abstract*—It is well known that Orthogonal Frequency Division Multiplexing (OFDM) systems suffer from intercarrier interference (ICI) in mobile environment due to loss of orthogonality among subcarriers caused by Doppler shifts. There exist many ICI mitigation techniques in the literature to improve the performance of OFDM systems. However, most of the existing ICI mitigation techniques assume the OFDM transmission bandwidth is narrow enough that the frequency offsets on all subcarriers are identical. In a wideband OFDM transmission or a non-contiguous OFDM spanning over large bandwidth, the Doppler shifts on different subcarriers are different, especially in high speed aerial vehicle communication systems. In this paper, we analyze the wideband OFDM system in high mobility environment where the frequency offsets vary from subcarrier to subcarrier. We then propose a novel ICI cancellation scheme to eliminate the ICI effect and offer the wideband OFDM system significantly improved BER performance. Simulation results in AWGN channel and multipath fading channel confirm the effectiveness of the proposed scheme in the presence of frequency offset and time variations in the channel, offering the best BER performance available which matches the BER performance of wideband OFDM system without ICI. To our knowledge, this paper is the first to address the ICI problem of varying frequency offsets across subcarriers in wideband OFDM system.**

I. Introduction

It is well known that Orthogonal Frequency Division Multiplexing (OFDM) systems [1] suffer from intercarrier interference (ICI) in high mobility environment due to the loss of orthogonality among subcarriers caused by Doppler shifts [2][3]. Many methods have been proposed in the literature to mitigate the frequency-offset problem to cancel the ICI for OFDM system. Most of such methods use signal processing and/or coding techniques to reduce the sensitivity of the OFDM system to the frequency offset. For example, in [2], authors developed low-complexity minimum mean-square error and decision-feedback equalizer receivers to suppress ICI based on the fact that the ICI power mainly comes from a few neighboring subcarriers. Some researchers proposed schemes to estimate the frequency offset, including data aided estimation [4][5] and blind estimation [6][7][8]. In the light of the same statement, an effective method known as the ICI self-cancellation scheme has been proposed in [3] where copies of the same data symbol are modulated on L adjacent subcarriers using optimized weights. In [9], a generalized ICI self-cancellation scheme has been proposed. In [10], an ICI self-cancellation using data-conjugate method is proposed.

However, all existing ICI mitigation methods assume the frequency offsets on all subcarriers are the same. This is a valid assumption for narrowband OFDM transmission, since the Doppler shift on one subcarrier is almost the same as that on another subcarrier and the difference in Doppler shifts is negligible. But this assumption is no longer true for a wideband OFDM system where the bandwidth is large enough that the Doppler shift on the lowest frequency subcarrier is significantly different from the Doppler shift on the highest frequency subcarrier. This is particularly important for applications with very high mobility such as aerial vehicle communication.

In this paper, we analyze the performance of the wideband OFDM system with different carrier frequency offsets for different subcarriers and propose an effective algorithm to eliminate such ICI. To our knowledge, this paper is the first to address this issue. From our analysis, we show that the wideband OFDM with ICI can be considered as an MC-CDMA (Multi-carrier Code Division Multiple Access) system where all the N data symbols carried by the OFDM transmission are spread over all N subcarriers. In our previous work [11], we proposed a new approach to solve the ICI problem in mobile narrowband OFDM system without estimating frequency offset through training symbols (and without data rate reduction), and real system demonstration confirms the effectiveness and efficiency of this ICI cancellation algorithm [12]. In this paper, we extend this work to account for wideband OFDM with different carrier frequency offsets on different subcarriers. Specifically, we propose to quantize the relative speed between the OFDM transmitter and receiver, which is in a typical range $[V_{min}, V_{max}]$, into M discrete values, leading to M spreading code matrices as candidates (since the carrier frequency offset for each subcarrier is determined by the speed). Next, by decoding the received signal using these M spreading code matrices, M decisions are made on the data symbols. Using these M data symbols to recreate the received signal with ICI and measure the Euclidean distance of the M recreated signals with the actual received signal, the best relative speed is chosen and the best corresponding data symbols are determined. Simulation results demonstrate that the proposed system effectively eliminates ICI and offers the best BER performance available which matches the BER performance of wideband OFDM system without ICI. Furthermore, it is also shown that the complexity of the proposed system is linearly growing with the number of quantization levels M, and M does not need to be a big number to achieve the best performance.

The rest of the paper is organized as follows: Part II analyzes the ICI of wideband OFDM systems in high mobility environment and proves that the received OFDM signal with the presence of ICI can be considered as an MC-CDMA system. Part III describes the proposed ICI cancellation method. Simulation results over AWGN channel and multipath fading channels are provided in Part IV. Conclusion follows.

II. ICI of OFDM Systems

A. ICI of Narrowband OFDM Systems

It is well known that the received OFDM signal on k^{th} subcarrier in AWGN channel with a constant carrier frequency offset ΔF is [3][13]:

$$Y(k) = X(k)S_\varepsilon(0) + \sum_{l=0,l\neq k}^{N-1} X(l)S_\varepsilon(l-k) + n_k, \qquad k = 0,1,\ldots,N-1 \tag{1}$$

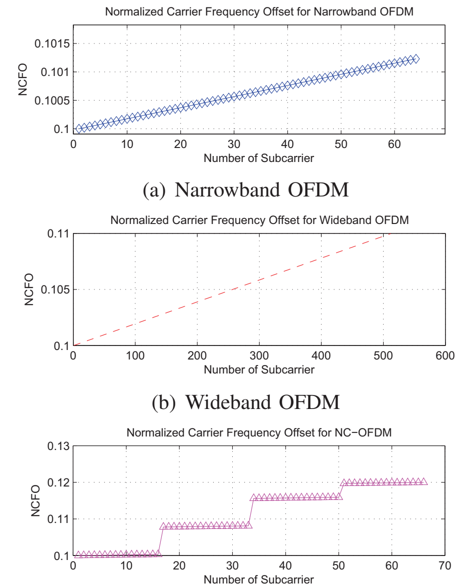
where N is the total number of the subcarriers, $X(k)$ denotes the transmitted symbol ($X(k) \in \{+1,-1\}$ if BPSK is employed, for example) on the k^{th} subcarrier, n_k is the additive Gaussian noise. The sequence $S_\varepsilon(l-k)$ is the ICI coefficient between l^{th} subcarrier and k^{th} subcarrier [3][13]:

$$S_\varepsilon(l-k) = \frac{\sin(\pi(\varepsilon+l-k))}{N\sin(\frac{\pi}{N}(\varepsilon+l-k))} \cdot \exp\left(j\pi\left(1-\frac{1}{N}\right)(\varepsilon+l-k)\right) \tag{2}$$

where ε is the normalized carrier frequency offset (NCFO) given by $\varepsilon = \frac{\Delta F}{\Delta f}$, $\Delta F = \frac{v}{c}(f_c)\cos\theta$ is the frequency offset with relative speed v and angle θ, $c = 3\times10^8 m/s$ is the speed of light, Δf is the subcarrier bandwidth of the OFDM system. It is reasonable to assume that $0 \le \varepsilon < 1$.

B. ICI of Wideband OFDM Systems

For wideband OFDM systems in high mobility environment, it is necessary to consider the scenario that different subcarriers suffer different carrier frequency offsets according to the frequency on each subcarrier. Fig. 1 shows the NCFO for different subcarriers. The NCFO is a linear function of the frequency, and the slope is proportional to the relative speed between the transmitter and receiver. It is also easy to understand that in a narrowband OFDM system, the NCFO can be assumed to be a constant. For example, in a 64 subcarriers narrowband OFDM system shown in Fig. 1(a), the NCFO varies from 0.1 to 0.1012 over all 64 subcarriers, and the difference is negligible. Hence, a constant NCFO 0.1 is assumed in current OFDM ICI mitigation papers. However, for the wideband OFDM system (e.g., an OFDM with 512 subcarriers shown in Fig. 1(b)), the NCFO changes 10% from 0.1 to 0.11 which cannot be ignored. More importantly, with recent progress of cognitive radio, non-contiguous OFDM



(a) Narrowband OFDM

(b) Wideband OFDM

(c) NC-OFDM

Fig. 1. Normalized Carrier Frequency Offsets for Different Subcarriers

(NC-OFDM) is attracting more and more attention. While the effective bandwidth of NC-OFDM might not be large, the active subcarriers in NC-OFDM can spread over extremely large bandwidth to harness multiple spectrum holes together. For such NC-OFDM systems, the NCFO in one subcarrier could be significantly different from that in another subcarrier. For example in Fig. 1(c), when there are only 64 subcarriers in the NC-OFDM system occupying four non-contiguous spectrum holes, the NCFO changes 20% from 0.1 to 0.12, although the effective bandwidth is as small as that in Fig. 1(a).

The received wideband OFDM signal on subcarrier k in AWGN channel is

$$Y(k) = X(k)S_{\varepsilon_k}(0) + \sum_{l=0,l\neq k}^{N-1} X(l)S_{\varepsilon_l}(l-k) + n_k, \qquad k = 0,1,\ldots,N-1 \tag{3}$$

where $S_{\varepsilon_l}(l-k)$ is defined in Eq. (2), ε_l denotes the normalized carrier frequency offset on l^{th} subcarrier, where $\varepsilon_l = \frac{\Delta F_l}{\Delta f}$, and $\Delta F_l = \frac{v}{c}(f_c + l\Delta f)\cos\theta$ is the frequency offset on l^{th} subcarrier.

Now, denote vector $\vec{X}$ as the transmitted symbol $\vec{X} = \{X(0), X(1), \ldots, X(N-1)\}$, vector $\vec{Y}$ as the received signal vector $\vec{Y} = \{Y(0), Y(1), \ldots, Y(N-1)\}$, and $\vec{n} = \{n_0, n_1, \ldots, n_{N-1}\}$, we have:

$$\vec{Y} = \vec{X}\mathbf{S} + \vec{n} \tag{4}$$

where $\mathbf{S}$ is the ICI coefficient matrix, and the p^{th} row and q^{th} column element of $N \times N$ matrix $\mathbf{S}$ is

$$\mathbf{S}_{p,q} = S_{\varepsilon_p}(p-q) \tag{5}$$

From equation (4), it is obvious that the received signal can be viewed as an MC-CDMA signal with N users, the k^{th} user's information symbol is $X(k)$, and the k^{th} user's spreading code is the k^{th} row of matrix $\mathbf{S}$.

Hence, the OFDM signal with ICI at receiver side can be considered as an MC-CDMA system with spreading code matrix $\mathbf{S}$. As a direct result, the ICI can be totally removed from the OFDM signal if we apply a matrix multiplication to the received signal vector $\vec{Y}$:

$$\vec{R} = \vec{Y}\mathbf{S}^{-1} = \vec{X} + \vec{n}\mathbf{S}^{-1} \tag{6}$$

where $\mathbf{S}^{-1}$ presents the inverse of matrix $\mathbf{S}$. Next, we can simply make decision of $\vec{X}$ based on the $\vec{R}$.

Of course, the problem is: the receiver does not know the spreading code matrix $\mathbf{S}$ because the normalized frequency offsets ε_k $(k = 0, 1, ..., N-1)$ are unknown.

III. ICI Total Cancellation for Wideband OFDM System

Here, we propose to use parallel processing with speed quantization to eliminate ICI on wideband OFDM. While the normalized frequency offsets ε_k $(k = 0, 1, ..., N-1)$ are unknown to the receiver, these N unknown variables are determined by only one parameter: relative speed $V = v\cos\theta$ between the transmitter and receiver. Hence, we can quantize the relative speed V in a typical range $[V_{min}, V_{max}]$ into M equally spaced values:

$$V'_m = V_{min} + m \cdot \Delta V, m = 0, 1, \ldots, M-1 \tag{7}$$

where ΔV is the quantization level of relative speed $\Delta V = \frac{1}{M}(V_{max} - V_{min})$, and M is the number of quantization levels. Since the typical $\varepsilon_0 \in [0, 1]$, the typical speed range can be easily computed as since $\varepsilon_0 = \frac{V f_c}{c\Delta f}$; meanwhile, with the support from navigation systems, e.g., GPS, the rough speed estimation helps to shorten the searching range. One of these M quantized V's is the closet to the true relative speed V.

Now, let's build M parallel branches at the receiver. Each branch uses one of the M quantized V's to create the corresponding NCFOs for all the subcarriers, and generate ICI coefficient matrix $\tilde{\mathbf{S}}$ in Eq. (5). Hence, we have M ICI coefficient matrices $\tilde{\mathbf{S}}_0, \tilde{\mathbf{S}}_1, \ldots, \tilde{\mathbf{S}}_{M-1}$.

Using these M matrices, we can have M decisions on the transmitted data vector $\vec{X}$ where the m^{th} branch will make decision on the estimation of $\vec{X}$, e.g., BPSK modulation makes decision $\hat{\vec{X}}_m = \text{sgn}\{\vec{Y}\tilde{\mathbf{S}}_{\mathbf{m}}^{-1}\}$, where $\text{sgn}(X)$ presents the sign of X.

Next, with the data vector estimation $\hat{\vec{X}}_m$, each branch can reproduce the received signal $\hat{\vec{Y}}_m$ by using the data vector estimation $\hat{\vec{X}}_m$ and the ICI coefficient matrix of that branch $\tilde{\mathbf{S}}_{\mathbf{m}}$:

$$\hat{\vec{Y}}_m = \hat{\vec{X}}_m \tilde{\mathbf{S}}_{\mathbf{m}} \tag{8}$$

It is easy to understand that the one branch whose V'_m is the closest to the true value of V should reproduce the received signal $\hat{\vec{Y}}_m$ also closest to the received signal vector $\vec{Y}$. Hence, we only need to calculate and compare the Euclidean distances between the M reproduced received signal vectors $\hat{\vec{Y}}_m$ and the received signal vector $\vec{Y}$ and pick the one with the minimum distance to be the best branch and use estimated data vector on that branch as the final decision:

$$\hat{\vec{X}} = \left\{\hat{\vec{X}}_p | Dis(p) \leq Dis(m); \forall\, m \neq p\right\} \tag{9}$$

where $Dis(m) = ||\hat{\vec{Y}}_m - \vec{Y}||^2$ represents the Euclidean distance between vector $\hat{\vec{Y}}_m$ and vector $\vec{Y}$. Fig. 2 illustrates the Euclidean distance verses the relative error $(V' - V)\frac{f_c}{c\Delta f} = (\varepsilon'_0 - \varepsilon_0)$ for different SNR, and it is clear that when there is no noise, $||\hat{\vec{Y}}_m - \vec{Y}||^2$ reaches to the optimum when $V' = V$ or $\varepsilon'_0 = \varepsilon_0$. Meanwhile, at high SNR, the optimum also occurs when $|\varepsilon'_0 - \varepsilon_0|$ is very small.

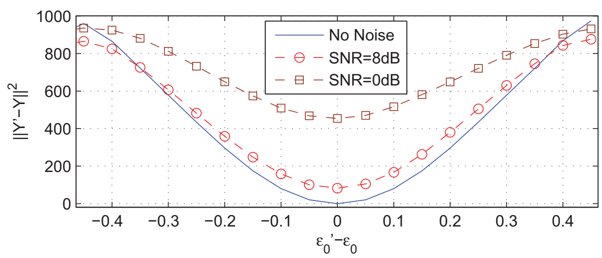


Fig. 2. Euclidean Distance v.s. relative error $(V'_m - V)/V$

It is important to note that the complexity of the proposed ICI cancellation method is linearly growing with the quantization level M, keeping the computational complexity reasonable. Furthermore, the M ICI coefficient matrix $\tilde{\mathbf{S}}_{\mathbf{m}}$ $(m = 0, 1, .., M-1)$ and the inverse of these matrices only depend on the quantized speed which can be pre-computed and stored. For each OFDM symbol, the proposed ICI cancellation scheme requires $2M$ matrix multiplications and M comparisons. The increased complexity is insignificant, especially when M is small.

The block diagram of the proposed ICI cancellation scheme is shown in Fig. 3.

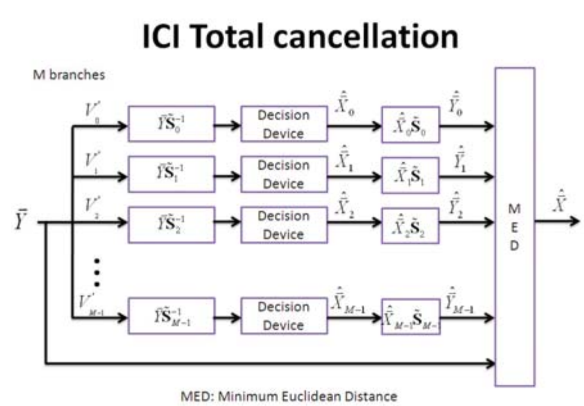


Fig. 3. Block Diagram of the ICI Total Cancellation

IV. Analysis in Multipath Fading Channels

In a multipath fading channel, let's denote the complex fading gain on the k^{th} subcarrier is α_k. Then the received OFDM signal after transmission through such a fading channel with frequency offset is:

$$\vec{Y} = \vec{X}\alpha\mathbf{S} + \vec{n} \tag{10}$$

where α is a diagonal matrix $\alpha = diag\{\alpha_0, \alpha_1, \ldots, \alpha_{N-1}\}$.

Similar to the analysis in AWGN channel, the received OFDM signal represented in equation (10) can be viewed as an N user MC-CDMA system with spreading code matrix $\mathbf{S}$ and the k^{th} user's data symbol is $\alpha_k X(k)$. Hence, if the spreading code matrix $\mathbf{S}$ is known, we can eliminate the ICI by multiplying $\mathbf{S}^{-1}$ to the received vector $\vec{Y}$.

So the ICI cancellation scheme works the same way as in AWGN channel with only one exception: the fading channel characteristics α needs to be estimated at the receiver side (which is required for OFDM transmission) and the reproduced received signal vector now has to consider the fading effects:

$$\hat{\vec{Y}}_m = \hat{\vec{X}}_m\alpha\tilde{\mathbf{S}}_{\mathbf{m}} \tag{11}$$

V. Simulation Results

In this section, we use numerical simulation results to show the effectiveness of the proposed scheme. We provide BER simulation results for the proposed ICI cancellation scheme for wideband OFDM system in both AWGN channel and multipath fading channel. All system are assumed to have $N = 512$ subcarriers and employ BPSK modulation.

A. AWGN Channel with Constant Frequency Offsets

The simplest way to examine the effectiveness of the proposed scheme is to transmit signals through an AWGN channel with carrier frequency offsets (ε_k maintains the same and $\varepsilon_k \neq \varepsilon_l$ when $k \neq l$). Fig. 4 illustrates the simulation result when the normalized carrier frequency offset ε_k varies from $\varepsilon_{min} = 0.1$ to $\varepsilon_{max} = 0.1998$ for different subcarriers and Fig. 5 shows the case when ε_k varies from $\varepsilon_{min} = 0.1498$ to $\varepsilon_{max} = 0.3494$. $M = 20$ quantization levels are applied for the ICI Total Cancellation scheme. In both of the two figures, the black dots correspond to the BER performance of wideband OFDM without ICI, the blue line is the performance for wideband OFDM with ε_k varying from ε_{min} to ε_{max} for different subcarriers; the green line marked with triangles represents the performance for the case $\varepsilon_k = \varepsilon_{max}, (k = 0, 1, ..., N-1)$, and the red line marked with rectangles represents the performance for the case $\varepsilon_k = \varepsilon_{min}, (k = 0, 1, ..., N-1)$; the purple line marked with circle is that of our proposed ICI Total Cancellation scheme.

It is clear that the BER performance for wideband OFDM with ε_k varying from ε_{min} to ε_{max} has better performance than that of the OFDM with all the subcarriers suffering the same NCFO ε_{max}, and worse performance than that of OFDM with all the subcarriers suffering the same NCFO ε_{min}. Meanwhile, when the ε_{min} increases or the range $(\varepsilon_{max} - \varepsilon_{min})$ increases, the BER performance of OFDM significantly degrades, but the ICI Total Cancellation scheme eliminates the ICI and provides the same BER performance as that of an OFDM without ICI.

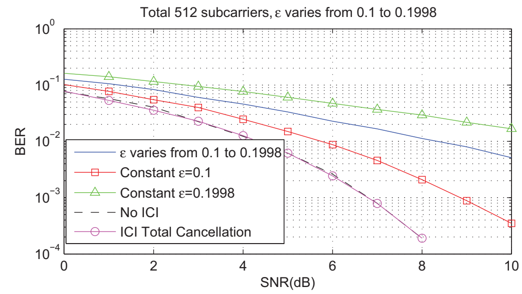


Fig. 4. Simulation 1 in AWGN and ε varies from 0.1 to 0.1998 among subcarriers

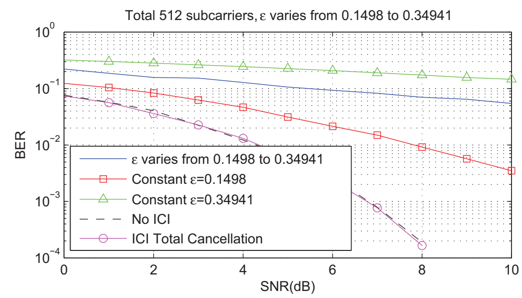


Fig. 5. Simulation 2 in AWGN and ε varies from 0.1498 to 0.3494 among subcarriers

Fig. 6 shows the BER performance versus NCFO on the first subcarrier $\varepsilon_0 = \frac{Vf_c}{c\Delta f}$. When $\varepsilon_0 = 0$ (no ICI), the proposed system has the same performance as traditional OFDM system. However, when the speed increases or carrier frequency offset increases, the performance of traditional OFDM system degrades significantly, while the ICI Total Cancellation algorithm helps the OFDM system maintain as good performance as there is no ICI.

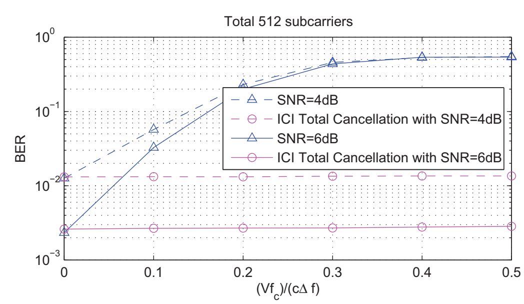


Fig. 6. Simulation 3 in AWGN at Fixed SNR

B. Multipath Mobile Channels

In a practical mobile multipath radio channel, time-variant multipath propagation leads to Doppler frequency shift which is a random variable. Here we measure the performance of the proposed ICI Total Cancellation method in multipath fading channels. As a measure of Doppler frequencies, we use the normalized maximum Doppler spread ε_{B_0}, which is defined as the ratio between the channel maximum Doppler spread on the first subcarrier ($\frac{Vf_c}{c}$) to the subcarrier bandwidth Δf.

Fig. 7 shows the case when $\varepsilon_{B_0} = 0.3$. In the ICI Total Cancellation scheme, we use $M = 20$. In this figure, the black dots represent the BER performance of OFDM without ICI, the blue line represents the performance of OFDM with ICI, and the purple line marked with circle represents that of our proposed ICI Total Cancellation scheme. It is evident from this figure that the proposed ICI Total Cancellation technique entirely eliminates the effect of ICI and matches the performance of the OFDM without ICI in fading channels as well.

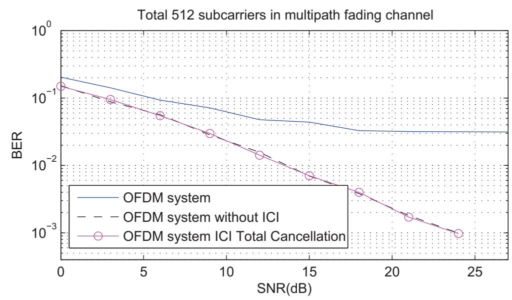


Fig. 7. Simulation 1 in Fading Channel and $\varepsilon_{B_0} = 0.3$

Fig. 8 illustrates the effect of the number of quantization levels M on the performance of the proposed ICI Total Cancellation scheme. In this figure different quantization levels $(M = 1, 2, 4, 8, 16, 32)$ are applied and NCFO varies from 0.15 to 0.3496 among these 512 subcarriers. In Fig. 8, three BER versus M curves of different SNRs are shown. It is easy to understand that when M increases, more quantization levels are used and better ICI coefficient matrix estimation is achieved, so the performance of the proposed scheme will also improve. As shown in Fig. 8, when M increases, the ICI Total Cancellation converges fast and provides ICI cancellation and BER improvement quickly. When M is larger than 8, there is no noticeable performance gain to increase the quantization level. This can be explained as the following: when the quantization step ΔV is small enough, the ICI Total Cancellation's ICI cancellation capability is enough to remove all the intercarrier interference and there is no need to decrease ΔV anymore. It is evident from Fig. 8 that the computational complexity of the proposed scheme is reasonable.

VI. Conclusion

In this paper, we analyze the performance of the wideband OFDM system in high mobility environment where the frequency offset varies from subcarrier to subcarrier, and propose an effective algorithm to eliminate the ICI effect. To our knowledge, this paper is the first to address such issue. Specifically, we apply the algorithm, called *ICI Total Cancellation*, for mobile wideband OFDM systems to mitigate the ICI effect and improve the BER performance. Taking

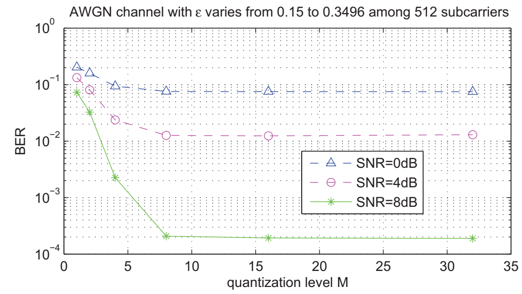


Fig. 8. Effect of NCFO Quantization Levels, AWGN, $\frac{Vf_c}{c\Delta f} = 0.1$

invertible property of the ICI coefficient matrix, the proposed ICI cancellation scheme can eliminate the ICI experienced in wideband OFDM systems and provide significant BER improvement. The proposed scheme provides excellent performance without reducing data rate and bandwidth efficiency. Simulations over AWGN channel and multipath fading channel confirm the effectiveness of the proposed scheme. We also show that the proposed scheme achieves such performance at reasonable computational complexity which linearly grows with the number of normalized frequency offset quantization.

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