Intercarrier Interference Self-Cancellation Scheme for OFDM Mobile Communication Systems

Yuping Zhao and Sven-Gustav Häggman

Abstract—**For orthogonal frequency-division multiplexing (OFDM) communication systems, the frequency offsets in mobile radio channels distort the orthogonality between subcarriers resulting in intercarrier interference (ICI). This paper studies an efficient ICI cancellation method termed ICI self-cancellation scheme. The scheme works in two very simple steps. At the transmitter side, one data symbol is modulated onto a group of adjacent subcarriers with a group of weighting coefficients. The weighting coefficients are designed so that the ICI caused by the channel frequency errors can be minimized. At the receiver side, by linearly combining the received signals on these subcarriers with proposed coefficients, the residual ICI contained in the received signals can then be further reduced. The carrier-to-interference power ratio (CIR) can be increased by 15 and 30 dB when the group size is two or three, respectively, for a channel with a constant frequency offset. Although the redundant modulation causes a reduction in bandwidth efficiency, it can be compensated, for example, by using larger signal alphabet sizes. Simulations show that OFDM systems using the proposed ICI self-cancellation scheme perform much better than standard systems while having the same bandwidth efficiency in multipath mobile radio channels with large Doppler frequencies.**

Index Terms—**ICI self-cancellation, intercarrier interference, multicarrier modulation, OFDM.**

I. Introduction

ORTHOGONAL frequency-division multiplexing (OFDM) communication systems [1], [2] require precise frequency synchronization, since otherwise intercarrier interference (ICI) will occur. Currently, three different approaches for reducing ICI have been developed including frequency-domain equalization [3], [4], time-domain windowing [5], [6], and the ICI self-cancellation scheme [7], [8]. This paper concentrates on the further development of the third method.

The ICI self-cancellation scheme is a very simple way for suppressing ICI in OFDM. The main idea is to modulate one data symbol onto a group of subcarriers with predefined weighting coefficients. By doing so, the ICI signals generated within a group can be "self-cancelled" each other. After the works given in [7] and [8], the further discussions of the ICI self-cancellation scheme are presented in [9] and [10], where the scheme is also called polynomial cancellation coding (PCC).[1] In the previous studies, the emphasis has been put on the mechanism analysis of the scheme. The works presented in this paper concentrate on a quantitative ICI power analysis of the ICI self-cancellation scheme, which has not been studied previously. The average carrier-to-interference power ratio (CIR) [11] is used as the ICI level indicator, and a theoretical CIR expression is derived for the proposed scheme. Furthermore, simulation results under different conditions are presented to demonstrate the reliability and advantage of the ICI self-cancellation scheme.

II. ICI Mechanism of Standard OFDM Systems

In an OFDM communication system, assuming the channel frequency offset normalized by the subcarrier separation is ε, the received signal on subcarrier k can be written as

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

where N is the total number of the subcarriers, $X(k)$ denotes the transmitted symbol (M-ary phase-shift keying (PSK), for example) for the kth subcarrier and n_k is an additive noise sample. The sequence $S(l-k)$ is defined as the ICI coefficient between lth and kth subcarriers, which can be expressed as

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

The first term in the right-hand side of (1) represents the desired signal. Without frequency error ($\varepsilon = 0$), $S(0)$ takes its maximum value $S(0) = 1$. The second term is the ICI components. Fig. 1 gives an example of the $S(l-k)$ when $l = 0$ and $N = 16$. The frequency offset values are $\varepsilon = 0.2$ and $\varepsilon = 0.4$. It is evident that as ε becomes larger, the desired part $|S(0)|$ decreases and the undesired part $|S(l-k)|$ increases.

The system ICI power level can be evaluated by using the CIR [11]. While deriving the theoretical CIR expression, the additive

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[1] References [9] and [10] were added in the revised version.

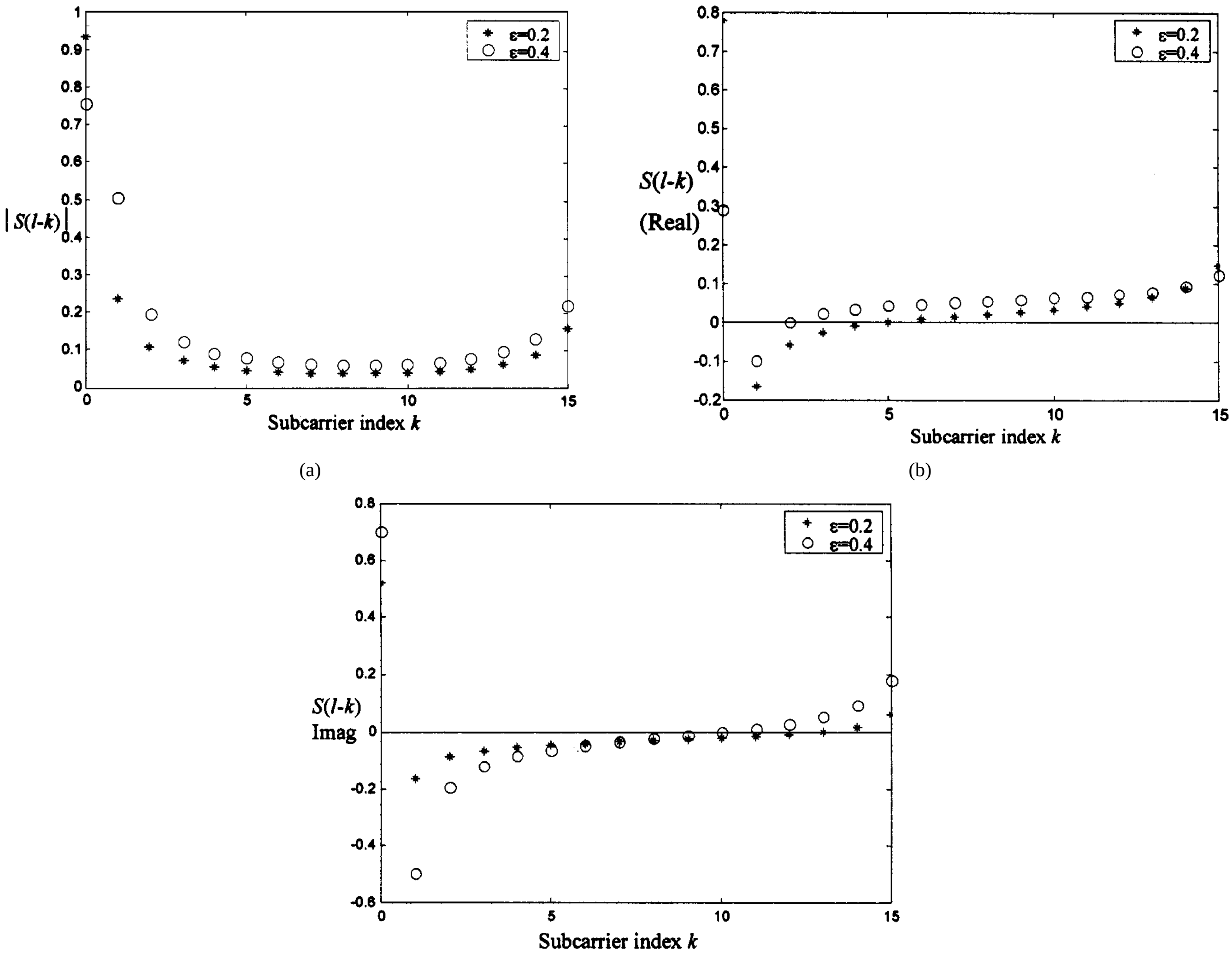

Fig. 1. An example of $S(l-k)$ for $N=16,\ l=0$. (a) Amplitude of $S(l-k)$. (b) Real part of $S(l-k)$. (c) Imaginary part of $S(l-k)$.

noise is omitted. The desired received signal power on the kth subcarrier can be represented as

$$E\lfloor |C(k)|^2 \rfloor = E\lfloor |X(k)S(0)|^2 \rfloor \tag{3}$$

and the ICI power is

$$E\left[|I(k)|^2\right] = E\left[\left|\sum_{l=0,\, l\neq k}^{N-1} X(l)S(l-k)\right|^2\right]. \tag{4}$$

It is assumed that the transmitted data have zero mean and are statistically independent, therefore, the CIR expression for subcarrier $0 \leq k \leq N-1$ can be derived as

$$\mathrm{CIR} = \frac{|S(k)|^2}{\sum_{l=0,\, l\neq k}^{N-1} |S(l-k)|^2} = \frac{|S(0)|^2}{\sum_{l=1}^{N-1} |S(l)|^2}. \tag{5}$$

Fig. 2 shows the CIR (in decibels) as a function of the normalized frequency offset ε, where $N=512$. Simulation results for binary PSK (BPSK), 4PSK, and 16 quadrature amplitude modulation (QAM) modulation are also given, showing good agreement with the theoretical results.

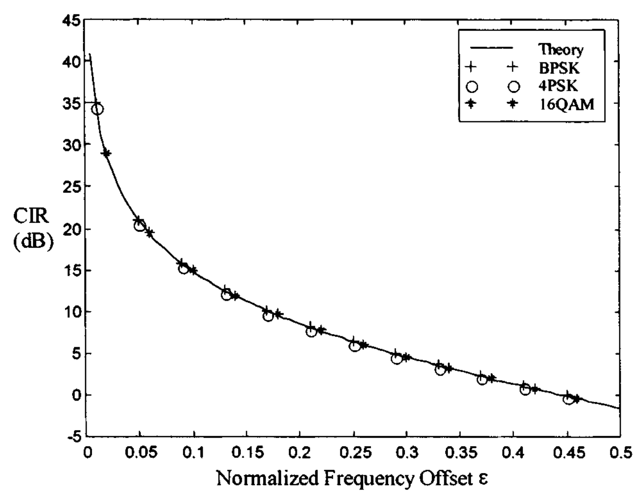

Fig. 2. CIR versus ε for a standard OFDM system.

Equation (5) suggests that the CIR is a function of N and ε. However, the CIR varies very little as a function of N. Analysis shows that the CIR, for a given ε, results in a maximum change of 0.068 dB when $N \geq 8$. Therefore, the CIR of OFDM systems only depends on the normalized frequency offset ε approximately.

III. ICI CANCELLING MODULATION

The conclusion in Section II implies that it is impossible to reduce ICI unless the ε value is decreased. For a certain channel frequency offset, smaller ε values can be obtained by increasing the subcarrier separation. Consequently, the bandwidth efficiency will be reduced since the time-domain symbol length is reduced and, therefore, the guard interval will take a relatively larger portion of the useful signal.

It has been shown in Fig. 1 that both real and imaginary parts of the ICI coefficient are gradually changed with respect to the subcarrier index. For the majority of $l-k$ values, the difference between $S(l-k)$ and $S(l+1-k)$ is very small. Therefore, if a data pair $(a, -a)$ is modulated onto two adjacent subcarriers $(l, l+1)$, where a is a complex data, then the ICI signals generated by the subcarrier l will be cancelled out significantly by the ICI generated by subcarrier $l+1$. This is the ICI cancellation idea proposed in [7].

Assume the transmitted symbols are constrained so that $X(1) = -X(0)$, $X(3) = -X(2), \ldots X(N-1) = -X(N-2)$, then the received signal on subcarrier k becomes

$$Y'(k) = \sum_{\substack{l=0\\ l=\text{even}}}^{N-2} X(l)\,[S(l-k) - S(l+1-k)] + n_k \quad (6)$$

and on subcarrier $k+1$ is

$$Y'(k+1) = \sum_{\substack{l=0\\ l=\text{even}}}^{N-2} X(l)\,[S(l-k-1) - S(l-k)] + n_{k+1}. \quad (7)$$

In such a case, the ICI coefficient is denoted as

$$S'(l-k) = S(l-k) - S(l+1-k). \quad (8)$$

The comparison between $|S(l-k)|$ and $|S'(l-k)|$ is presented in Fig. 3 under the logarithm scale. For most of the $l-k$ values, it is found that $|S'(l-k)| \ll |S(l-k)|$. In addition, the summation in (6) only takes even l values, the total number of the interference signals is reduced to half compared with that in (1). Consequently, the ICI signals in (6) are much smaller than those in (1) since both the number of ICI signals and the amplitudes of the ICI coefficients have been reduced. Such a modulation method is called ICI cancelling modulation.

The idea of ICI self-cancellation scheme and the derived coefficients was also applied to the partial response signaling of OFDM systems [12].

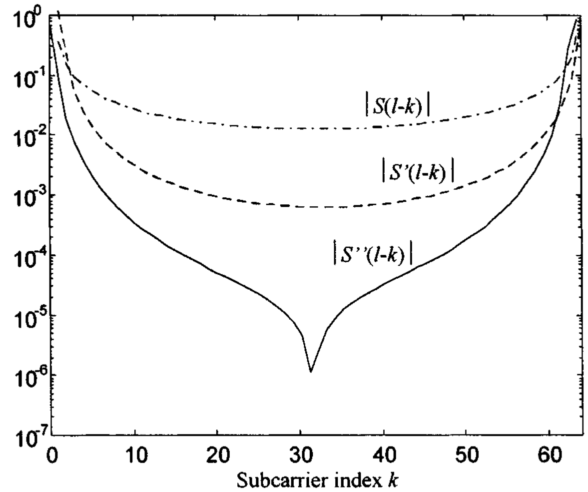

Fig. 3. A comparison between $|S(l-k)|$, $|S'(l-k)|$ and $|S''(l-k)|$, $N = 64$.

IV. ICI CANCELLING DEMODULATION

By using the ICI cancelling modulation, each pair of subcarriers, in fact, transmit only one data symbol. The signal redundancy makes it possible to improve the system performance at the receiver side. In considering a further reduction of ICI, a so-called ICI cancelling demodulation scheme is analyzed here. The demodulation is suggested to work in such a way that each signal at the $k+1$th subcarrier (now k denotes even number) is multiplied by "-1" and then summed with the one at the kth subcarrier. Then the resultant data sequence is used for making symbol decision. It can be represented as

$$\begin{aligned} Y''(k) &= Y'(k) - Y'(k+1) \\ &= \sum_{\substack{l=0\\ l=\text{even}}}^{N-2} X(l)[-S(l-k-1) + 2S(l-k) \\ &\qquad - S(l-k+1)] + n_k - n_{k+1}. \end{aligned} \quad (9)$$

The corresponding ICI coefficient then becomes

$$S''(l-k) = -S(l-k-1) + 2S(l-k) - S(l-k+1). \quad (10)$$

Until now, three types of ICI coefficients are obtained: 1) $S(l-k)$ for the standard OFDM system; 2) $S'(l-k)$ for ICI cancelling modulation; and 3) $S''(l-k)$ for combined ICI cancelling modulation and demodulation. Fig. 3 shows the amplitude comparison of $|S(l-k)|$, $|S'(l-k)|$ and $|S''(l-k)|$ for $N = 64$ and $\varepsilon = 0.3$. Notice the logarithmic scale on the vertical axis. For the majority of $l-k$ values, $|S'(l-k)|$ is much smaller than $|S(l-k)|$, and the $|S''(l-k)|$ is even smaller than $|S'(l-k)|$. Thus, the ICI signals become smaller when applying ICI cancelling modulation. On the other hand, the ICI cancelling demodulation can further reduce the residual ICI in the received signals. This combined ICI cancelling modulation and demodulation method is called the ICI self-cancellation scheme.

It is worth mentioning that the proposed ICI cancelling demodulation also improves the system signal-to-noise ratio. The signal level increases by a factor of 2, due to coherent addition,

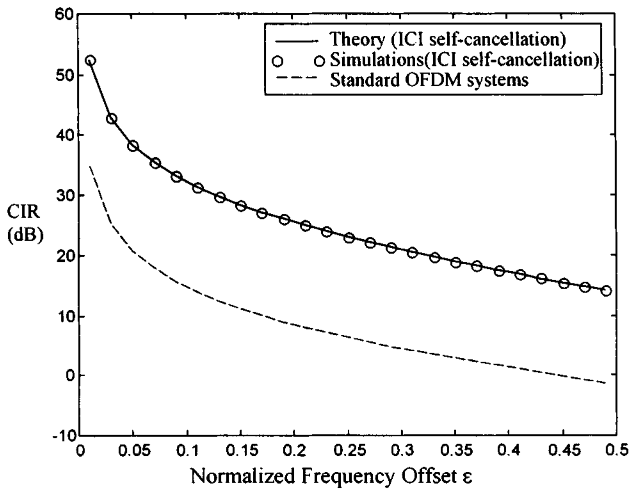

Fig. 4. CIR improvement using ICI self-cancellation scheme.

whereas the noise level is proportional to $\sqrt{2}$ because of noncoherent addition of the noise on different subcarriers. Using ICI coefficient given by (10), the theoretical CIR of the ICI self-cancellation scheme can be derived as

$$\mathrm{CIR} = \frac{|-S(-1)+2S(0)-S(1)|^2}{\displaystyle\sum_{l=2,4,6,\ldots}^{N-1} |-S(l-1)+2S(l)-S(l+1)|^2}. \quad (11)$$

Fig. 4 shows the theoretical CIR curve calculated by (11) together with simulation results. As a reference, the CIR of a standard OFDM system using (5) is also shown. Such an ICI cancellation scheme gives more than 15-dB CIR improvement in the range $0 < \varepsilon \leq 0.5$. Especially for small to medium frequency offsets in the range $0 < \varepsilon \leq 0.2$, the CIR improvement can reach 17 dB.

Due to the repetition coding, the bandwidth efficiency of the ICI self-cancellation scheme is reduced by half. To fulfill the demanded bandwidth efficiency, it is natural to use a larger signal alphabet size. For example, using 4PSK modulation together with the ICI self-cancellation scheme can provide the same bandwidth efficiency as standard OFDM systems (1 bit/Hz/s). When the channel frequency offset is small, the use of a larger signal alphabet size might increase the system bit-error rate (BER) compared to a smaller alphabet size [13]. However, for medium to large channel frequency offsets ($\varepsilon > 0.05$), significant BER improvement is obtained by using the proposed scheme.

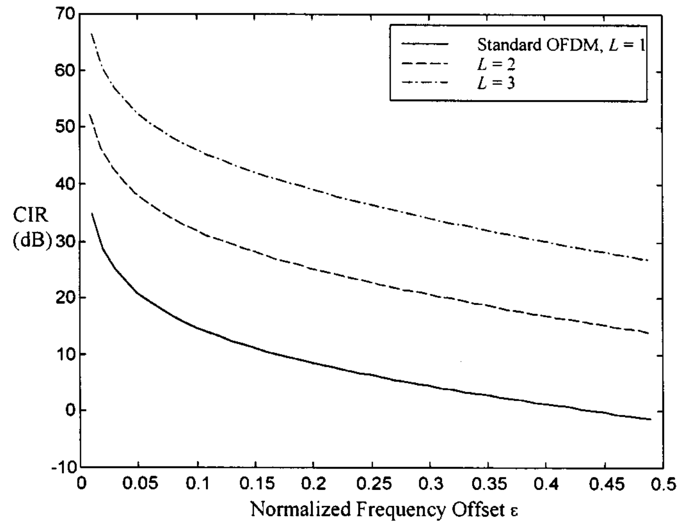

Fig. 5. CIR comparison for different group lengths.

V. Extension to Larger Group Sizes

The ICI self-cancellation scheme can also be extended to larger group sizes. Before modulating a data symbol onto a group of L subcarriers, the data symbol is multiplied with a coefficient vector of length L. It has been found [8] that the optimum weighting coefficients in minimizing system ICI satisfy the polynomial $P(D) = (1-D)^{L-1}$, where D denotes one subcarrier delay in the discrete frequency domain.

In general for a group length L, both ICI cancelling modulation and demodulation require the weighting coefficients satisfying the polynomial $P(D) = (1-D)^{L-1}$. After the ICI cancelling demodulation, the weighting coefficients fulfill the polynomial $P(D) = (1-D)^{2(L-1)}$. Since the coefficient of the ith term in polynomial $P(D) = (1-D)^M$ can be represented as $M!/i!(M-i)!$, the general CIR expression of the ICI self-cancellation scheme of group length L becomes (12), shown at the bottom of the page.

Fig. 5 shows the CIR comparison for $L = 1, 2, 3$. By using $L = 3$, about 30-dB CIR improvement can be found in the range $0 < \varepsilon \leq 0.5$, compared with a standard OFDM system $(L = 1)$.

VI. Simulations

This section gives some BER simulation results for the proposed ICI self-cancellation scheme. The following two types of OFDM system have been considered for comparisons:

1) System 1 (Sys.1): Standard BPSK modulation OFDM system without ICI self-cancellation;

$$\mathrm{CIR} = \frac{\left|\displaystyle\sum_{i=0}^{2(L-1)} (-1)^i \frac{(2(L-1))!}{i!(2(L-1)-i)!} S(i-(L-1))\right|^2}{\displaystyle\sum_{l=L,2L,3L,\ldots}^{N-1} \left|\displaystyle\sum_{i=0}^{2(L-1)} (-1)^i \frac{(2(L-1))!}{i!(2(L-1)-i)!} S(l+i-(L-1))\right|^2} \quad (12)$$

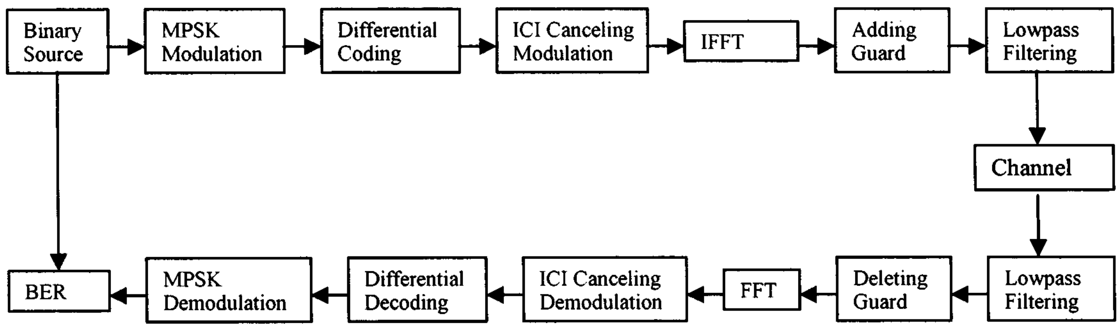

Fig. 6. Simulation block diagram of the proposed system.

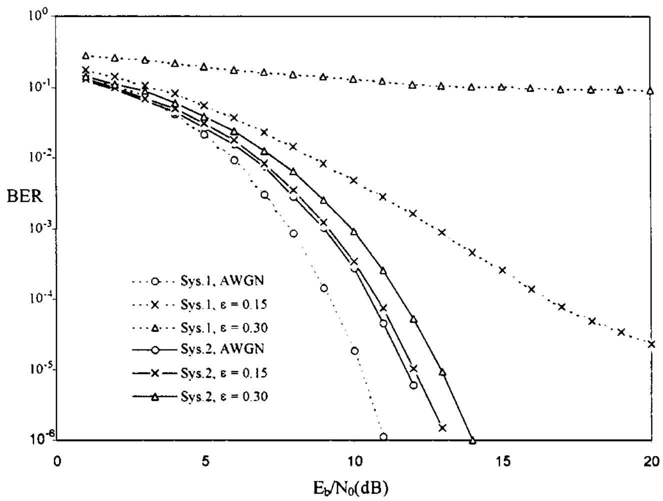

Fig. 7. BER versus E_b/N_0 of two systems for different ε values.

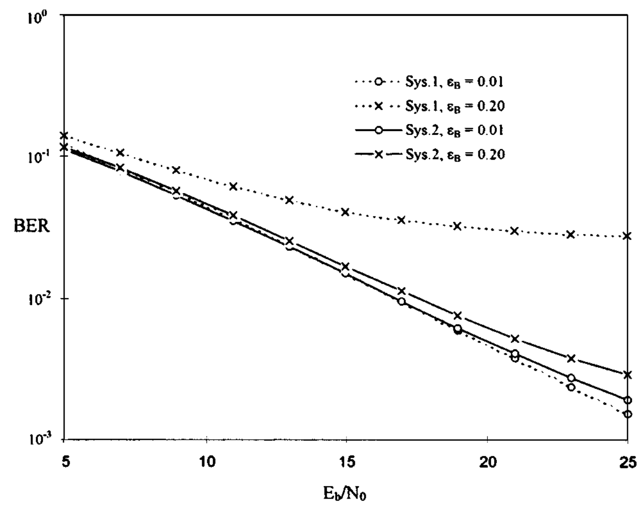

Fig. 8. BER comparison for typical urban area channel model.

2) System 2 (Sys.2): 4PSK modulation OFDM system with ICI self-cancellation.

The simulation block diagram of the proposed system (Sys.2) is shown in Fig. 6, while Sys.1 can be obtained by simply removing the "ICI cancelling modulation" and "ICI cancelling demodulation" blocks. The bandwidth efficiency is 1 bit/Hz/s for both systems. The same values of E_b/N_0 (the signal energy per information bit to noise power spectral density ratio) have been used to examine the BER performance, which yields a fair comparison between them. Frequency-domain differential coding is applied in both systems in order to avoid channel response estimation [14].

In addition, since the ICI self-cancellation scheme in fact is the repetition coding, it will be useful to compare BER performance with a system using error correction coding of the same factor instead of using the proposed scheme.

A. Channel with a Constant Frequency Offset

The simplest way to examine the ICI self-cancellation scheme is to transmit signals through a channel with a constant frequency offset. Simulation results shown in Fig. 7 give the BER performance of these two systems with respect to different frequency offsets. In the additive white Gaussian noise (AWGN) channel where $\varepsilon = 0$, the BER of Sys.1 is lower than that of Sys.2. This is because differential BPSK modulation (Sys.1) performs better than differential 4PSK (Sys.2) in the AWGN channel [13]. Increasing the frequency offset to $\varepsilon = 0.15$, the BER of Sys.2 gives nearly the same values as in the AWGN channel. In fact, even for $\varepsilon = 0.30$, the BER of Sys.2 only shows slight increase. In contrast, Sys.1 cannot work properly due to heavy ICI signals, as shown for the cases $\varepsilon = 0.15$ and $\varepsilon = 0.30$.

B. Multipath Propagation Mobile Channels

In a practical mobile radio channel, time-variant multipath propagation causes Doppler frequency spread. The received signal on each subcarrier can then be considered as a linear combination of signals received via different paths with different Doppler frequencies. The proposed ICI self-cancellation scheme can also be effective in the case of multiple Doppler frequency offsets.

Typical six-tap urban area (TUX) and rural area (RAX) channel models with classical Doppler spectrum are used in the following simulations. The channel parameters are defined in the GSM Recommendation 5.5 [15]. As a measure of Doppler frequencies, we use the normalized maximum Doppler spread ε_B, which is defined as the ratio between the channel maximum Doppler spread to the subcarrier separation.

Figs. 8 and 9 show the BER comparison between Sys.1 and Sys.2. If ε_B is very small ($\varepsilon_B = 0.01$), the BER performance of the two systems is rather similar. For larger Doppler spreads ($\varepsilon_B = 0.2$), the BER of the standard OFDM system (Sys.1) increases significantly, while the BER of the proposed system

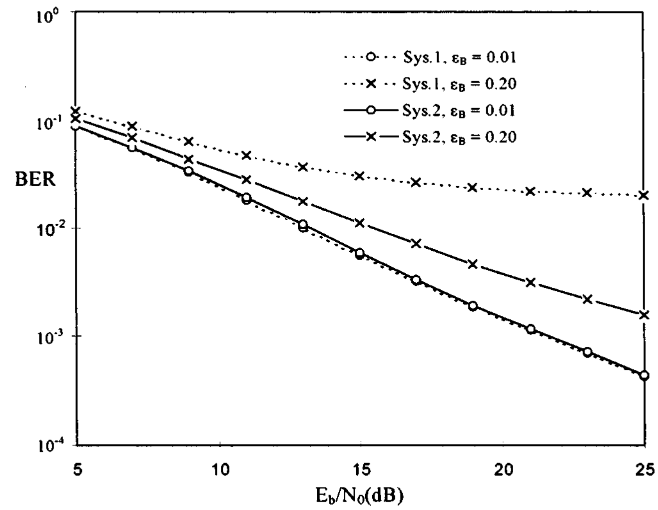

Fig. 9. BER comparison for rural area channel model.

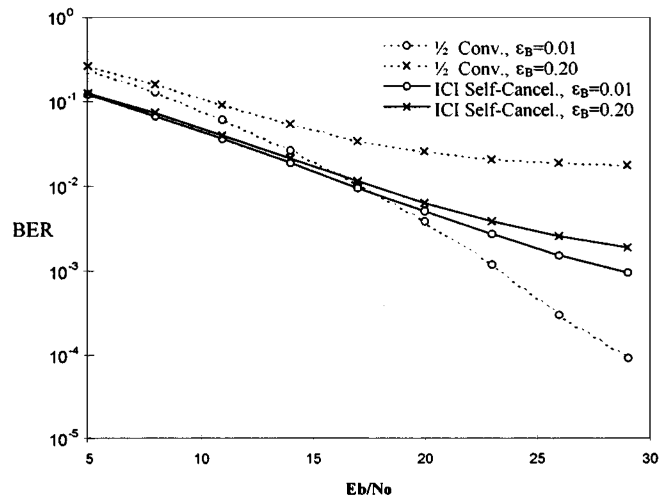

Fig. 10. BER of ICI self-cancellation scheme and error correction coding.

(Sys.2) only increases slightly, compared to the situation where $\varepsilon_B = 0.01$. The proposed ICI self-cancellation scheme works very well in the multipath radio channel.

C. Comparison with Error Correction Coding

Fig. 10 presents BER simulation results of the ICI self-cancellation scheme compared with results for the error correction coding system. The channel is the typical urban area channel, and frequency-domain differential decoding is used in both systems. The comparison will be carried out between two systems. One is a BPSK modulation OFDM applying ICI self-cancellation scheme. The other is BPSK modulation with 1/2 convolutional coding, where the Viterbi algorithm is used for soft-decision decoding. The two systems have the same bandwidth efficiency. Since the ICI self-cancellation scheme is intended to minimize system ICI, it performs better in the case when the ICI signals dominate the channel interference. On the other hand, the convolutional coding will give a larger coding gain when the frequency offsets are small and E_b/N_0 is high.

In addition, the ICI self-cancellation scheme can be combined with error correction coding. Such a system is robust to both AWGN and ICI, however, the bandwidth efficiency is reduced.

VII. Conclusions

This paper investigates an ICI self-cancellation scheme for combating the impact of ICI on OFDM systems. The proposed scheme provides significant CIR improvement, which has been studied theoretically and by simulations. The scheme also works well in a multipath radio channel with Doppler frequency spread. Under the condition of the same bandwidth efficiency and larger frequency offsets, the proposed OFDM system using the ICI self-cancellation scheme performs much better than standard OFDM systems. In addition, since no channel equalization is needed for reducing ICI, the proposed scheme is therefore easy to implement without increasing system complexity.

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