Pilot-Aided ICI Self-Cancellation Scheme for OFDM Systems

Wei-Wen Hu$^{1}$, and Chih-Peng Li$^{2}$

$^{1,2}$ Institute of Communications Engineering, National Sun Yat-Sen University, Kaohsiung, Taiwan.

Abstract — In this paper, a novel pilot-aided inter-carrier interference (ICI) self-cancellation scheme is proposed for use in orthogonal frequency division multiplexing (OFDM) systems. The proposed scheme maps both modulated data symbols and pre-defined pilot symbols onto non-neighboring sub-carriers with weighting coefficients of +1 and -1. With the aid of pilot symbols, a more accurate estimation of frequency offsets can be obtained, and the ICI self-cancellation demodulation can be operated properly.

Key Words — OFDM, inter-carrier interference, synchronization, pilot.

I. INTRODUCTION

In recent years, orthogonal frequency division multiplexing (OFDM) has become the most attractive transmission scheme for digital communication. It is used in a variety of wireless communication systems, such as digital audio broadcasting (DAB), digital video broadcasting (DVB), and wireless local area networks (WLANs). One of the advantages of OFDM systems is that they have spectral efficiency because of the orthogonality among sub-carriers. In addition, because of the cyclic prefix (CP), inter-symbol interference (ISI) due to multiple paths is essentially eliminated. Nevertheless, compared with single carrier systems, OFDM systems are very sensitive to timing errors and frequency offsets. This is the major drawback to OFDM systems [1]. In addition, when fractional CFO exists, sub-carriers are not orthogonal to each other, and inter-carrier interference (ICI) severely degrades system performance. Two major approaches have been developed to eliminate the impact of CFO [2-5]: (1) a well-designed time domain windowing function, and (2) ICI self-cancellation mechanisms. The main idea of the latter approach is that each modulated data symbol and its negative version are mapped onto two adjacent or non-adjacent sub-carriers. It has been shown that the ICI self-cancellation scheme can increase carrier-to-interference ratio (CIR) by 10dB to 30dB [2,4]. However, the ICI self-cancellation scheme has two major drawbacks: (1) bandwidth efficiency is diminished by half; (2) it has a tolerable cancellation range of only up to 30% of the sub-carrier spacing. If the CFO is larger than 0.3 of the sub-carrier spacing, the performance of the ICI self-cancellation scheme significantly degrades. The former drawback can be easily improved by using higher order modulation schemes. In this letter, a pilot-aided ICI self-cancellation scheme is proposed to overcome the latter drawback [4].

The proposed scheme maps both modulated data symbols and pre-defined pilot symbols onto non-neighboring sub-carriers with weighting coefficients of +1 and -1. At the receiver, the partial CFO is first compensated for with the aid of pilot symbols by using maximum likelihood estimation (MLE). The residual CFO is then small enough such that the ICI can be successfully diminished by the self-cancellation demodulation. With the negligible overhead of pilot symbols, the tolerable cancellation range is significantly improved.

II. SYSTEM ARCHITECTURE AND EVALUATION OF CIR

The block diagram of the proposed pilot-aided ICI self-cancellation scheme is shown in Fig.1. Let $\alpha$ and $\beta$ be the set of indices for the modulated sub-carriers and the pilot symbols, respectively. At the transmitter, after the inverse fast Fourier transform (IFFT) operation, the $n$th sub-carrier of the $i$th OFDM symbol is given by

$$r_{i,n} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_{i,k} e^{j \frac{2\pi kn}{N}}, \quad n = 1, 2, ..., N$$

(1)

where $P_{i,k}$ and $S_{i,k}$ stand for the pilot symbol and the transmitted complex data symbol, respectively. $N$ denotes the size of the IFFT. All the pilot symbols are set to one. In the ICI self-cancellation modulation block, the data symbols and the pilot symbols are mapped onto the non-neighboring sub-carriers $k$ and $(N-k+1)$ with weighting coefficients of +1 and -1; In other words, $X_{i,N} = -X_{i,1}, X_{i,N-1} = -X_{i,2}, \text{etc.}$

At the receiver, after the fast Fourier transform (FFT) operation, the received signal of the $k'$th sub-carrier with normalized frequency offset $\varepsilon$ is expressed as

$$X_{i,k'} = X_{i,k}W_{i,0} + \sum_{k=1}^{N} X_{i,k}W_{i,k-k'} + n_{i,k'}$$

(2)

where $n_{i,k'}$ is the AWGN noise and $W_{i,k-k'}$ is the ICI coefficient between the $k$th and the $k'$th sub-carrier. It is shown in [3] that $W_{i,k-k'}$ is given by:

$$W_{i,k-k'} = \text{sinc}(\varepsilon) \cdot \frac{1}{1 + \frac{k-k'}{\varepsilon}}$$

(3)

In (2), the first term $X_{i,k}W_{i,0}$ represents the signal amplitude attenuation caused by the frequency offset, and
the second term stands for the ICI. Therefore, when the AWGN noise is abridged, the CIR of the traditional OFDM system is given by [2]:

$$CIR_{\text{Traditional}} = \frac{|W_{i,0}|^2}{\sum_{k=1}^{N} |W_{i,k}|^2}$$  \hspace{1cm} (4)

With the proposed architecture, the pilot symbols and the data symbols are simultaneously modulated onto the non-neighboring sub-carrier $k$ and $(N-k+1)$. Consequently, the received signal of the $k$'th sub-carrier becomes:

$$X_{i,k} = \sum_{k=1}^{N} X_{i,k} W_{i,k-k'}$$

$$= \sum_{k=1}^{N} X_{i,k} (W_{i,k-k'} - W_{i,N-k'-k+1})$$  \hspace{1cm} (5)

$$+ \sum_{j=[N-N_p+2)/2}^{N/2} X_{i,j} (W_{i,j-k'} - W_{i,N-j-k'+1})$$

where $N_p$ is the number of pilot symbols. In addition, the received signal of sub-carrier $N-k'+1$ has a representation similar to (5) when $N-k'+1$ is replaced with $k'$. When the ICI self-cancellation demodulation block is considered, the received signal of the $k'$ th sub-carrier is given by

$$X_{i,k'} = X_{i,k} - X_{i,N-k'}$$

$$= 2X_{i,k} W_{i,0}$$

$$\frac{|N-N_p|}{2} + \sum_{k=1}^{N/2} X_{i,k} (W_{i,k-k'} + W_{i,k'-k''} - W_{i,N-k'-k''} - W_{i,N-k''+1})$$  \hspace{1cm} (6)

$$+ \sum_{j=[N-N_p]/2}^{N/2} X_{i,j} (W_{i,j-k'} + W_{i,j-k''} - W_{i,N-j-k''} - W_{i,N-j-k'''})$$

$$\pm 2X_{i,k} W_{i,0} + A + B$$

The first term of (6) is the desired signal destroyed by the frequency offset, the second term is the ICI component caused by the data symbols, and the last term is another ICI element resulting from the pilot symbols. As a consequence, the CIR of the proposed scheme is given by

$$CIR_{\text{Pilot\_Aided}} = \frac{|W_{i,0}|^2}{|A + B|^2}$$  \hspace{1cm} (7)

Numerical results are depicted in Fig. 2. Without pilot symbols, the CIR given in (7) can be simplified to that obtained by Sathananthan [3]. Comparing (7) with (4), the proposed scheme has a better CIR performance than the traditional OFDM systems. Fig. 2 shows that the improvement is about 10–30 dB. However, because of the inserted pilot symbols, extra ICI occurs. Therefore, the CIR of the proposed scheme is 3 dB smaller than that of Sathananthan’s [3]. Nevertheless, since pilot symbols can be adopted to estimate the CFO, the residual frequency offset becomes small enough so that ICI-self cancellation demodulation can be operated properly.

**III. ESTIMATION OF THE PARTIAL CFO**

Estimation of the partial CFO is achieved by applying the MLE to two consecutive OFDM symbols [5]. If we assume that the timing synchronization is perfect, we are able to remove the cyclic prefix correctly. After the FFT operation, the $p'$ th demodulated pilot symbol of the $i$ th OFDM symbol is given by

$$X_{i+p',p'} = \frac{1}{\sqrt{N}} \sum_{n=1}^{N} x_{i+p',n} e^{-j2\pi p'n/N}$$

$$= \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{N} X_{i,k} e^{-j2\pi kn/N} e^{-j2\pi p'n/N}$$  \hspace{1cm} (8)

In addition, the $p'$ th demodulated pilot symbol of the $(i+1)$ th OFDM symbol is given by

$$X_{i+1+p',p'} = \frac{1}{\sqrt{N}} \sum_{n=1}^{N} x_{i+1+p',n} e^{-j2\pi p'n/N}$$

$$= \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{N} X_{i+1,k} e^{-j2\pi kn/N} e^{-j2\pi p'n/N}$$

$$= X_{i,p'} e^{j2\pi p'N/N}$$  \hspace{1cm} (9)

When (8) and (9) are combined, the estimated partial CFO is given by

$$e^{j2\pi p'N/N} = \frac{X_{i+1,p'} - X_{i,p'}}{X_{i+p',p'} - X_{i,p'}}$$

**Fig. 1 The system architecture of the proposed pilot-aided ICI self-cancellation scheme.**
\[
\hat{\varepsilon} = \frac{1}{2\pi} \angle \left( \sum_{p \leq \beta} X^*_{i,p} X_{i+1,p'} \right)
\]  

(10)

where \(\angle(\cdot)\) denotes the angle operation. Equation (10) shows that a more accurate partial CFO estimation can be obtained if more pilot symbols are inserted. In addition, the pilot symbols can be adopted for channel estimation, and the overall system performance can be further improved. However, the pilot symbols decrease bandwidth utilization. The determination of the size of the pilot symbols requires a trade-off between performance and bandwidth utilization.

As shown in (10), if we constrain the argument within the parenthesis of (10) to \(\pm \pi\), the maximum range of the frequency offset estimation is \(\pm 1/2\) sub-carrier frequency spacing as shown in the following:

\[
|\varepsilon| = \frac{1}{2\pi} \angle \left( \sum_{p \leq \beta} X^*_{i,p} X_{i+1,p'} \right) = \frac{1}{2\pi} \pi = \frac{1}{2}
\]

(11)

Therefore, the proposed scheme can tolerate larger CFO than the traditional ICI self-cancellation scheme. The traditional scheme is only suitable for a small CFO. When the CFO is larger, the performance of the traditional scheme significantly degrades.

IV. SIMULATION RESULTS

To evaluate the system performance of the proposed scheme, we studied an OFDM system that had a 64-point FFT operation (i.e., \(N = 64\)) with a cyclic prefix of length \(L = N/4 = 16\). The information sequence was QPSK modulated. The multi-path channel model was an exponentially decaying Rayleigh fading channel for an indoor environment. The channel impulse response was given by [6]

\[
h_k = N \left( \frac{1}{2} \sigma_k^2 \right) + jN \left( \frac{1}{2} \sigma_k^2 \right)
\]

(12)

where \(\sigma_k^2 = \sigma_k^2 e^{-t/T_{\text{aut}}}\), \(\sigma_k^2 = 1 - e^{-t/T_{\text{aut}}}\), and \(T_s\) is the sampling time. In this letter, \(T_{\text{aut}} = 100\)ns and \(T_s = 50\)ns are assumed. The amplitude of each path was independent and was assumed to be Rayleigh distributed with an exponential decay power delay profile. In addition, the phase of each path was uniformly distributed over \(0 - 2\pi\).

The bit error rates of various schemes are shown in Fig. 3 for a CFO of 0.2. It was demonstrated that the proposed scheme has the best performance. In addition, the system performance improved with the number of pilot symbols. However, the difference was not substantial. Simulation results showed that 4 pilot symbols were adequate and the overhead was only 6.25% (4/64).

The bit error rates of various schemes are shown in Fig. 4 for a CFO of 0.4. It is obvious that the performance of Sathanantha’s scheme is poor for a CFO of 0.4. However, the proposed scheme improves the BER significantly with only a few pilot symbols.

Simulation results for 4 pilot symbols per OFDM symbol are shown in Fig. 5 for a CFO of 0.2 and 0.3. It can be seen that the traditional OFDM scheme without ICI self-cancellation performed poorly in both cases. Sathanantha’s ICI self-cancellation scheme substantially improved the performance when the CFO equaled 0.2. However, for a CFO of 0.3, the improvement was only marginal. On the other hand, the proposed pilot-aided ICI self-cancellation scheme significantly improved the traditional scheme in both cases.

The BERs of various schemes for different CFOs are shown in Fig. 6 for SNR=20dB. It is clear from Fig. 6 that K. Sathanantha’s scheme has only marginal improvement for CFOs greater than 0.3. However, the proposed scheme substantially improves the traditional scheme for CFOs up to 0.5. It can also be seen from the figure that Sathanantha’s method and the proposed scheme have similar performance when CFO is small. In particular, when CFO equals zero, Sathanantha’s method slightly outperforms the proposed scheme. This is because that the estimation of CFO is never perfect. Although the actual CFO is identical zero, the CFO estimation result of the proposed scheme will compensate a non-zero CFO to the incoming signals, leading to a slightly worse performance.
Traditional OFDM ICI self-cancellation scheme cannot work properly when the partial CFO is greater than 0.3. In this paper, a pilot-aided ICI self-cancellation scheme was proposed. With the aid of pilot symbols, the partial CFO is compensated for by using maximum likelihood estimation. The residual CFO is then small enough such that the ICI can be successfully diminished by the self-cancellation demodulation. Although CIR is slightly decreased, simulation results demonstrated that the overall system performance can be significantly improved with negligible overhead.

REFERENCES


