

Improved Algorithm for Carrier Interference Suppression in UFMC Systems Postprint

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Date: 2018-05-24T00:00:00+00:00

Abstract

To address the problem of excessively low spectral efficiency in UFMC systems caused by ICI self-cancellation algorithms, an improved scheme combining partial self-cancellation and raised cosine windowing is proposed. This scheme specifically suppresses UFMC system interference and improves system spectral efficiency by inserting self-cancellation subcarriers at subband boundaries in the UFMC transmitter and performing time-domain windowing at the UFMC receiver. MATLAB simulation experiments were conducted on the algorithm; when four self-cancellation subcarriers are configured on both sides of the subband, the system carrier-to-interference ratio increases compared to the self-cancellation algorithm, while the system spectral efficiency is improved by 10%. Simulation results demonstrate that the proposed algorithm can effectively suppress ICI, enhance system anti-interference performance, and improve system spectral efficiency.

Full Text

Preamble

Improved Algorithm for Carrier Interference Suppression in UFMC Systems

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Abstract: To address the problem of excessively low frequency band utilization in UFMC systems caused by ICI self-cancellation algorithms, this paper proposes an improved scheme that combines partial self-cancellation with raised cosine windowing. The scheme specifically inserts self-cancelling subcarriers at the subband boundaries of the UFMC transmitter and applies time-domain windowing at the receiver to suppress UFMC system interference while improving

spectral efficiency. MATLAB simulation experiments demonstrate that when four self-cancelling subcarriers are placed on each side of a subband, the system carrier-to-interference ratio increases compared with the self-cancellation algorithm, while spectral efficiency improves by 10%. Simulation results show that the proposed algorithm can effectively suppress ICI, enhance system anti-interference performance, and improve frequency band utilization.

Keywords: Universal Filtered Multi-Carrier; Self Cancellation; Inter-carrier Interference; Raised Cosine Window; Frequency Utilization

0 Introduction

The rapid development of communication technology is closely related to increasing communication demands and user experience requirements. Orthogonal Frequency Division Multiplexing (OFDM), as a key technology in the fourth generation of mobile communications (4G), has been widely adopted in mainstream international standards such as Long Term Evolution (LTE) and Wireless Fidelity (WIFI) due to its outstanding anti-interference capability and high spectral efficiency [1]. However, the 5G era brings new communication scenarios with demanding requirements for massive connectivity, ultra-low latency, high spectral efficiency, and service diversification—requirements that OFDM technology can no longer satisfy. Consequently, Universal Filtered Multi-Carrier (UFMC) [2] has been proposed as a candidate waveform for 5G.

UFMC combines the technical characteristics of OFDM and Filter Bank Multi-Carrier (FBMC). On one hand, it eliminates the cyclic prefix (CP) on the foundation of OFDM technology, thereby improving the spectral efficiency of symbols. On the other hand, it employs a subband division mechanism, providing greater flexibility for 5G services. Finally, the subband-based filter design also reduces inter-subband interference. Compared with FBMC systems, UFMC features shorter symbol lengths and lower system complexity [3,4].

When UFMC systems experience Carrier Frequency Offset (CFO) due to transmitter and receiver oscillator discrepancies and Doppler effects, it not only causes Inter-Carrier Interference (ICI) within subbands and Inter-Band Interference (IBI) between subbands [5], but also destroys the orthogonality among subcarriers within subbands. Even small CFO values can cause UFMC system performance to degrade sharply. Therefore, effectively mitigating interference caused by CFO in UFMC systems has become a hot research topic in this field.

Currently, relatively few studies address interference cancellation in UFMC systems. To investigate interference suppression techniques under UFMC, a comprehensive understanding of existing interference suppression techniques for OFDM systems is necessary. Reference [6] proposes using adaptive filters to eliminate ICI caused by carrier frequency offset in OFDM systems, adjusting filter coefficients to minimize error and obtain output signals at the receiver.

Reference [7] adapts the Active Interference Cancellation (AIC) algorithm from cognitive radio systems for UFMC systems, reducing inter-subband interference caused by CFO, though this method has high implementation complexity. Reference [8] mentions ICI self-cancellation algorithms, which primarily modulate opposite numbers onto adjacent subcarriers and exploit the similarity of interference coefficients among neighboring subcarriers to achieve interference self-cancellation. While effective at eliminating ICI, this algorithm reduces spectral efficiency by 50% because modulated subcarriers occupy half of the data subcarriers.

This paper addresses the problem of excessively low frequency band utilization in ICI self-cancellation (SC) algorithms by proposing a joint improvement scheme combining partial self-cancellation and windowing. In the new algorithm, a certain proportion of self-cancelling subcarriers are placed at the boundaries of each subband in the UFMC system, achieving preliminary interference suppression through the similarity of interference coefficients among boundary subcarriers. Simultaneously, raised cosine windowing is applied before FFT at the receiver [9] to further suppress ICI in the system. The new scheme enhances both anti-interference performance and spectral efficiency compared with the original self-cancellation algorithm, while remaining simple and effective to implement.

1 System Model

The UFMC system block diagram is shown in [Figure 1: see original paper]. The total of N subcarriers are equally divided into B subbands, where a single subband in UFMC can be viewed as a Physical Resource Block (PRB) in LTE systems. Each subband contains N_B consecutive subcarriers. The frequency-domain signal $S_i(k)$ for subband i can be expressed as:

$$S_i(k) = \begin{cases} s_i(n), & k \in \mathbb{N}_i \\ 0, & k \notin \mathbb{N}_i \end{cases}$$

where \mathbb{N}_i is a non-empty set containing the subbands of the UFMC symbol. The output signal after subband filtering $x_i(n)$ is the discrete linear convolution of FIR filter $f_i(n)$ and time-domain signal $s_i(n)$:

$$x_i(n) = s_i(n) * f_i(n)$$

where $*$ denotes the convolution operator. After N -point IDFT transformation, the time-domain signal $x(n)$ of length N is obtained:

$$x(n) = \frac{1}{\sqrt{N}} \sum_{i=0}^{B-1} \sum_{l=0}^{L-1} S_i(k) f_i(l) e^{j2\pi k(n-l)/N}, \quad n = 0, \dots, N + L - 1$$

Assuming the normalized frequency offset in the channel is ε , the received signal after passing through an AWGN channel can be expressed as:

$$y(n) = x(n)e^{j2\pi\varepsilon n/N} + w(n)$$

where $w(n)$ is additive white Gaussian noise. After $2N$ -point FFT transformation at the receiver, the received symbol on the m -th subcarrier is:

$$Y(m) = \frac{1}{\sqrt{2N}} \sum_{n=0}^{2N-1} y(n)e^{-j2\pi mn/(2N)} = \sum_{i=0}^{B-1} \sum_{k \in \mathbb{N}_i} S_i(k)I(k, m) + W(m)$$

where the inter-carrier interference coefficient $I(k, m)$ is:

$$I(k, m) = \frac{1}{2N} \sum_{n=0}^{2N-1} \sum_{l=0}^{L-1} f_i(l)e^{j2\pi\varepsilon n/N} e^{j2\pi k(n-l)/N} e^{-j2\pi mn/(2N)}$$

From equation (6), we can see that system ICI is caused by the normalized frequency offset ε and increases with ε . To analyze the interference in detail, we use Carrier-to-Interference Ratio (CIR) as the evaluation metric. The CIR calculation formula is:

$$\text{CIR} = \frac{E[|C(0)|^2]}{E[|I(m)|^2]} = \frac{E[|C(0)|^2]}{\sum_{k \neq m} E[|I(k, m)|^2]}$$

From equation (7), it is evident that CIR decreases as CFO increases. Eliminating the inter-carrier interference caused by CFO in UFMFC systems is of great significance.

ICI Self-Cancellation Scheme

The self-cancellation (SC) algorithm is a traditional method for eliminating inter-carrier interference, originally applied in OFDM systems. This subsection applies the SC algorithm to UFMFC.

In UFMFC systems, equation (6) shows that the interference experienced by adjacent subcarriers within each subband from other subcarriers is very similar. Therefore, modulating opposite numbers onto adjacent subcarriers can cancel most interference from neighboring subcarriers, while interference from other subcarriers is also weakened due to the opposite-number modulation relationship. The algorithm is detailed below.

At the UFMFC system transmitter, original data and its opposite value are modulated onto corresponding adjacent subcarriers within the subband. The data modulation relationship in subband i is:

$$S_i(0) = -S_i(1), \quad S_i(2) = -S_i(3), \dots, S_i(N_B - 2) = -S_i(N_B - 1)$$

where N_B is the number of subcarriers in a single subband. After passing through the channel, the system experiences a normalized frequency offset of ε . The expression for the received symbol on the m -th subcarrier after $2N$ -point FFT transformation at the receiver is:

$$Y(m) = \sum_{i=0}^{B-1} \sum_{k=0}^{N_B-1} S_i(k)I(k, m)$$

After self-cancellation demodulation at the receiver (i.e., subtracting the received symbol on the $(m + 1)$ -th subcarrier from that on the m -th subcarrier), the final symbol obtained is:

$$Y'(m) = Y(m) - Y(m + 1) = \sum_{i=0}^{B-1} \sum_{k=0}^{N_B-1} S_i(k)[I(k, m) - I(k, m + 1)]$$

The ICI coefficient after self-cancellation demodulation is further attenuated, with the coefficient expressed as:

$$I'(k, m) = I(k, m) - I(k, m + 1)$$

The mathematical expression for the system's carrier-to-interference ratio (CIR) after demodulation (the following CIR corresponds to the expression for the 0-th subcarrier in each subband) is:

$$\text{CIR} = \frac{E[|C(0)|^2]}{E[|I_{\text{even}}(1) - 2I_{\text{even}}(0) + I_{\text{even}}(-1)|^2]} = \frac{E[|C(0)|^2]}{\sum_{k \neq 0} E[|I_{\text{even}}(k-1) - 2I_{\text{even}}(k) + I_{\text{even}}(k+1)|^2]}$$

3 Partial Self-Cancellation and Windowing Scheme

To solve the problem of low frequency band utilization in traditional SC algorithms while maintaining system anti-interference performance, we propose a partial self-cancellation and windowing scheme, hereafter uniformly referred to as the "UFMC-PSC Windowing System."

Traditional self-cancellation algorithms achieve only 50% frequency band utilization. In UFMC systems, subcarriers are grouped by subbands. Considering that inter-subband interference decreases gradually from subband boundaries toward the interior, frequency band utilization can be effectively improved by proportionally applying self-cancelling subcarriers only at subband boundaries

—that is, modulating opposite numbers only onto adjacent subcarriers at sub-band edges. This improved method is called Partial Self-Cancellation (PSC). However, reducing the proportion of self-cancelling subcarriers also reduces the anti-interference capability of the UFMC system. To enhance anti-interference performance, raised cosine windowing is applied to the signal at the receiver before the $2N$ -point FFT transformation. After time-domain windowing, the out-of-band (OOB) attenuation of subcarriers is effectively suppressed, thereby reducing ICI in the UFMC system. The improved scheme is detailed below.

First, at the UFMC system transmitter, data is modulated using the partial self-cancellation algorithm, which only applies adjacent sign inversion to subcarriers at subband boundaries. Assuming there are only two self-cancelling subcarriers on each side of a subband, the data modulation relationship in each subband is:

$$S_i(0) = -S_i(1), \quad S_i(2) = -S_i(3), \dots, S_i(N_B-4) = S_i(N_B-3), \quad S_i(N_B-2) = -S_i(N_B-1)$$

The received signal at the receiver is $y(n)$. Before FFT processing, the signal must be windowed. The mathematical expression for the raised cosine window function $p(n)$ is:

$$p(n) = \begin{cases} 0.5 \left[1 - \cos \left(\pi \frac{n+L/2}{L/2} \right) \right], & n \in [-L/2, L/2] \\ 1, & n \in (L/2, N - L/2] \\ 0.5 \left[1 + \cos \left(\pi \frac{n-N+L/2}{L/2} \right) \right], & n \in (N - L/2, N + L/2] \end{cases}$$

At the receiver, multiplying the time-domain signal by the window function yields the windowed time-domain signal expression:

$$y_w(n) = y(n) \cdot p(n) = [x(n)e^{j2\pi n/N} + w(n)] p(n)$$

From equation (14), we can see that the window function amplitude is less than 1, so the ICI coefficient after windowing is reduced compared with before windowing, effectively suppressing inter-carrier ICI power. After FFT transformation, UFMC self-cancellation demodulation is required, where only the modulated subcarriers on both sides of each subband in the UFMC symbol need to be demodulated. The demodulated signal expression is:

$$Y'(m) = Y_{\text{even}}(m) - Y_{\text{even}}(m+1) = \sum_{i=0}^{B-1} \sum_{k \in \mathbb{N}_i} S_i(k) [I'(k, m) - I'(k, m+1)]$$

where the carrier interference coefficient expression is:

$$I'(k, m) = \frac{1}{2N} \sum_{n=0}^{2N-1} \sum_{l=0}^{L-1} f_i(l)p(n)e^{j2\pi\epsilon n/N} e^{j2\pi k(n-l)/N} e^{-j2\pi mn/(2N)}$$

The UFMC carrier interference coefficient expression after demodulation is:

$$I''(k, m) = \begin{cases} I'(k, m) - 2I'(k, m+1) + I'(k, m+2), & k \in \{0, 2, 4, \dots, N_B - 2\} \\ I'(k, m) - I'(k, m+1), & k \in [3, 5, \dots, N_B - 3] \end{cases}$$

After PSC windowing demodulation, the system's carrier-to-interference ratio expression is (the following CIR corresponds to the expression for the 0-th subcarrier in each subband):

$$\text{CIR}' = \frac{E[|C(0)|^2]}{E[|I_{\text{even}}(-1) - 2I_{\text{even}}(0) + I_{\text{even}}(1)|^2]} = \frac{E[|C(0)|^2]}{\sum_{k \neq 0} E[|I''(k, m)|^2]}$$

When the system employs a higher proportion of self-cancelling subcarriers, more subcarriers need to be demodulated, resulting in a larger average carrier-to-interference ratio and stronger anti-interference capability. By flexibly setting the number of self-cancelling subcarriers, system performance can be controlled. Analyzing the system's average carrier-to-interference ratio enables performance evaluation and optimization scheme formulation. The PSC windowing system block diagram is shown in [Figure 2: see original paper].

As illustrated, at the UFMC system transmitter, partial self-cancellation modulation is first applied to subcarriers within each subband. After IFFT, filtering, and serial-to-parallel conversion, the time-domain UFMC transmitted signal is obtained. At the receiver, time-domain symbols undergo raised cosine windowing before signal processing such as FFT and equalization. Finally, partial self-cancellation demodulation is performed to recover the original signals on the modulated subcarriers.

4 Simulation and Results Analysis

To verify the interference suppression performance of the SC algorithm and the PSC windowing optimization scheme in UFMC systems, simulation analysis is required. The proportion of self-cancelling subcarriers in the PSC windowing system must be configured: in the UFMC-PSC1 windowing system, two subcarriers on each side of each subband are used for self-cancellation, while in the UFMC-PSC2 windowing system, four subcarriers on each side are used (when the parameter is 5, all subcarriers in the subband use self-cancellation). The simulation parameters are set as shown in .

Table 1 System Simulation Parameters - IFFT Points: $2N$ - Subcarriers per Subband: N_B - Filter Type: Chebyshev Filter - Filter Length: L - Filter Attenuation Coefficient: α - Window Type: Raised Cosine Window (RC)

[Figure 3: see original paper] shows the average CIR performance simulation for various systems when SNR is 20 dB. The figure clearly illustrates that average CIR decreases with increasing normalized frequency offset, with the rate of decrease slowing down, indicating that as normalized frequency offset increases, system interference becomes more severe (i.e., smaller carrier-to-interference ratio), creating a “floor effect.” The UPMC-SC windowing system demonstrates the best average CIR performance, while the UPMC system without any algorithm shows the worst performance. The UPMC-SC windowing system achieves 80 dB at a normalized frequency offset of 0.01, and even when the normalized frequency offset reaches 0.3, the carrier-to-interference ratio remains near 40 dB. The UPMC-PSC1 windowing system ranks second, but still shows significant improvement compared with the UPMC system. The results prove that the UPMC-PSC2 windowing system’s average CIR performance surpasses that of the self-cancellation algorithm, though its performance is lower than the UPMC-SC windowing system, indicating that reducing the proportion of self-cancelling subcarriers constrains system performance.

After adopting the PSC windowing scheme, the carrier-to-interference ratio varies significantly for subcarriers at different positions. To properly evaluate system anti-interference capability, the system’s average carrier-to-interference ratio CIR is calculated as:

$$\overline{\text{CIR}} = \frac{1}{K} \sum_{i=0}^{K-1} \text{CIR}_i$$

[Figure 4: see original paper] presents the bit error rate performance comparison between the SC algorithm and its improved versions when the carrier frequency offset is 0.1. The analysis shows that the performance ranking is essentially consistent with [Figure 3: see original paper]. The self-cancellation algorithm significantly improves the UPMC system’s bit error rate performance, and the windowing process also provides substantial performance improvement. The proportion of self-cancelling subcarriers has a major impact on system performance, with the PSC2 windowing system outperforming the PSC1 windowing system.

In terms of frequency band utilization, the UPMC-SC system applies self-cancellation modulation to all data, achieving 50% spectral efficiency. In the UPMC-PSC1 windowing system, each subband has $2 \times 2 = 4$ subcarriers that do not carry effective data, resulting in a spectral efficiency of $16/20 = 80\%$. In the UPMC-PSC2 windowing system, each subband has $4 \times 2 = 8$ subcarriers that do not carry effective data, yielding a spectral efficiency of $12/20 = 60\%$, which represents a 10% improvement over the UPMC-SC system.

5 Conclusion

This paper analyzed the inter-carrier interference in UFMC systems caused by carrier frequency offset and investigated the ICI self-cancellation algorithm's enhancement of system anti-interference capability. To address the algorithm's low frequency band utilization, we proposed a joint optimization scheme combining partial self-cancellation and windowing based on UFMC system characteristics. By configuring self-cancelling subcarriers at subband boundaries and applying windowing before FFT at the receiver, the scheme maintains UFMC system transmission performance while effectively improving spectral efficiency. The algorithm is simple and effective to implement, can flexibly configure the number of self-cancelling subcarriers according to actual communication requirements, and offers adaptability with practical application prospects. Nevertheless, this method only considers the impact of raised cosine windows on system anti-interference capability; future work could further investigate the effects of different window functions on system performance.

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