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An efficient and hybrid timing offset estimation approach for universal-filtered multi-carrier based systems over multipath Rayleigh fading channel ☆

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ABSTRACT

For next generation (i.e., 5G) wireless communication, universal-filtered multi-carrier (UFMC) is a novel multi-carrier modulation technique, which is suitable for short packet and low latency transmissions. Although UFMC has lower sensitivity to synchronization errors compared with orthogonal frequency division multiplexing (OFDM), synchronization is still an important and open problem for UFMC-based systems. In this paper, in order to efficiently address the timing offset (TO) estimation issue of UFMC-based systems over multipath fading channels, a new preamble structure containing the pseudo-random noise (PN) sequences is devised in this paper. And that a robust and hybrid TO estimation approach is also proposed. This approach primarily consists of two steps. According to the devised preamble pattern, an improved timing metric is firstly developed for estimating the symbol TO coarsely. Moreover, a fine timing adjustable range is also offered. Secondly, the accurate estimation of the residual symbol TO is achieved within this adjustable range by utilizing both the threshold criterion and the cross-correlation operation between received signals and the local PN sequence. Finally, numerical simulations and comparisons are presented to confirm the practicability of the proposed algorithm under the condition of Rayleigh fading channels.

1. Introduction

Being a promising waveform candidate for 5G [1,2] wireless communications, universal-filtered multi-carrier (UFMC) [3–5] which is also known as universal-filtered orthogonal frequency division multiplexing (UF-OFDM) [6], is very applicable to low-latency constrained transmissions and many communication scenarios using fragmented available spectrum resource. UFMC does not need to append a cyclic prefix (CP) and has better spectral property of low side-lobe level compared with OFDM [7]. Different from filter bank multi-carrier (FBMC) technique [8,9], the smaller filter length is required in UFMC technique, which can result in a reduced complexity of system receivers. As a matter of fact, UFMC can be regarded as a generalization of the filtered OFDM and FBMC.

The influence of the symbol timing offset (TO) and carrier frequency offset (CFO) on UFMC technique has been simply studied in [10]. With the existence of both the CFO and fractional TO, a concept known as autonomous timing advance, is used to improve the performance of UFMC-based systems which are purely based on open-loop synchronization [11]. The literature [12] also analyzed the effect of symbol TOs on UFMC systems. And that the optimization design method of the finite impulse response (FIR) filter was developed to acquire a great signal-to-interference ratio (SIR) improvement, which could enhance the robustness against both the CFO and TO. Although they enable UFMC systems to become insensitive to synchronization errors, the aforementioned methods only consider the scenario in which perfect synchronization and a timing mismatch are assumed for the user of interest (UoI) and other interfering users, respectively.

In this paper, we primarily address timing synchronization issue of UFMC systems in the scenario where all subband signals are impaired by the TOs. Since UFMC is a modification of popular OFDM, the TO estimation of UFMC systems can refer to that

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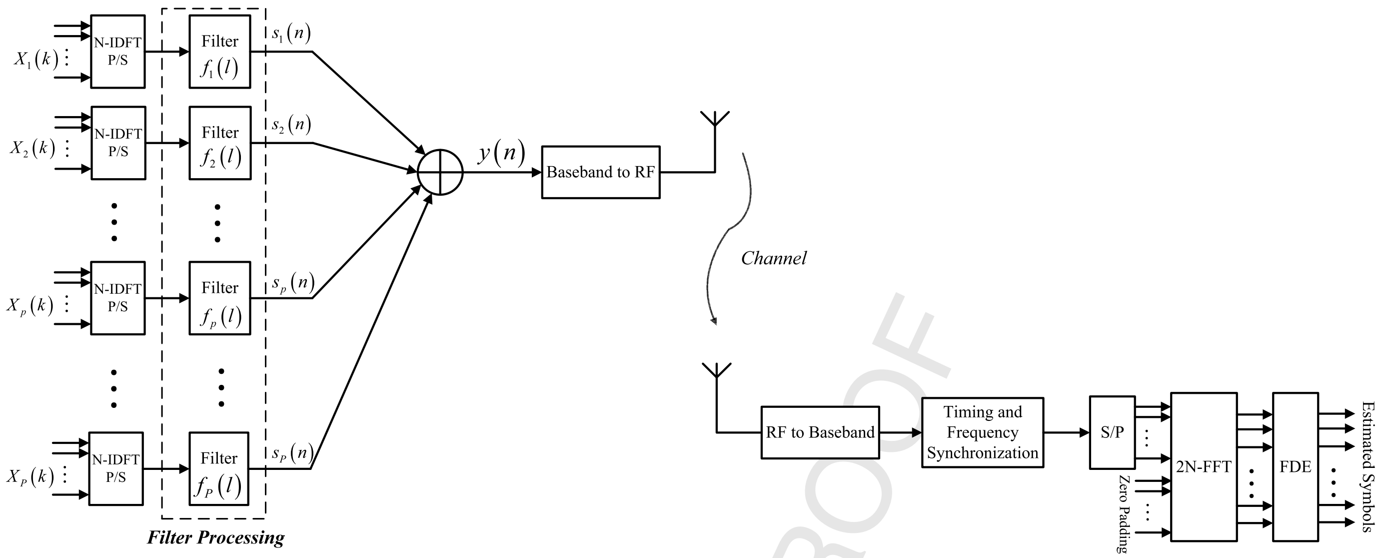

Fig. 1. Block diagram of the UFMC-based system.

of OFDM systems. Currently, there have been many TO estimation methods [13–23] in OFDM systems. Due to the absence of the CP in UFMC transmitted symbols, the timing synchronizer [14] based on the periodic structure of a CP can not be applied directly to UFMC systems. Because there exists a sub-band filtering operation, UFMC systems do not take advantage of the algorithm [18] generating the specific preamble signals from the frequency domain. Using the specific structure of training symbols in the time domain, the methods [13,15,17] [19–21] are adopted in UFMC systems with a minor modification. However, the deficiencies of these methods include the uncertainty plateau in TO estimation, large estimation variance, small estimation ranges or high computational complexity, which can not still be avoided. Additionally, the TO estimators developed in both [22] and [23] utilize a random training sequence but work independent of its structure. But they are very vulnerable to highly multipath fading channels.

Motivated by the limitations of above-mentioned algorithms, we devise a robust and novel timing synchronization scheme for UFMC systems, to further enhance the TO estimation accuracy. To sum up, the main contributions of this paper are twofold.

- A novel preamble pattern containing the pseduo-random noise (PN) sequences is obtained in the time-domain by exploiting appropriate frequency-domain modulated symbols. Moreover, an improved timing metric is also proposed according to this pattern.
- Combining this improved timing metric with the cross-correlation calculations between received signals and the local PN sequence, an efficient TO estimation algorithm is developed for UFMC-based systems.

Since each element of the PN sequence is either −1 or 1, there is a much smaller increase of computational complexity caused by the correlation calculations between received signals and the PN sequence. The following simulations verify that the proposed scheme is feasible in the multipath fading channel.

2. System description

In this section, we mainly present the description of UFMC-based systems. The block diagram of the UFMC system [12] is depicted in Fig. 1. In this figure, "RF" and "FDE" stand for the radio frequency and frequency domain equalization, respectively. As seen from Fig. 1, there exists the filter processing operation in the transmitter and 2N-point fast Fourier transform (FFT) calculation requires to be carried out in system receiver for UFMC systems, which is very different from OFDM technique.

In this UFMC system, we assume that the whole useful signal bandwidth is divided into P sub-bands, that there are N_U consecutive sub-carriers in each sub-band, and that the modulated symbols are denoted as $\boldsymbol{X}$ in the frequency-domain, i.e., $\boldsymbol{X} = [X(0), X(1), \cdots, X(N_{SC}-1)]^T$. Moreover, the frequency domain transmitted signal of the pth sub-band is expressed as

$$X_p(k) = \begin{cases} X(k) & \text{if } k \in \mathbb{S}_p \\ 0 & \text{if } k \notin \mathbb{S}_p \end{cases} \tag{1}$$

where $0 \le p \le P-1$, and $\mathbb{S}_p$ is an integer set consisting of all sub-carrier indexes which belong to the pth sub-band. Furthermore, the size of $\mathbb{S}_p$ is equal to N_U. Additionally, N_{SC} denotes the number of all used sub-carriers in this system, i.e., $N_{SC} = N_U \cdot P$. Note that N_U must satisfy $1 \le N_U < N_{SC}$.

After performing N-point inverse discrete Fourier transform (IDFT) operation, the corresponding time-domain samples of the pth sub-band are obtained as

$$x_p(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_p(k) \cdot \exp(j\frac{2\pi kn}{N}); \; 0 \le n \le N-1 \tag{2}$$

where N is larger than or equal to N_{SC}.

In UFMC systems, the filtering operation is performed on a group of sub-carriers or one sub-carrier, which is different from OFDM technique. After the sub-filtering operation, the final baseband transmitted signal is given by (3) through summing all sub-band-wise filtered signals.

$$\begin{aligned} y(n) &= \sum_{p=0}^{P-1} \left[f_p(n) \otimes x_p(n) \right] \\ &= \sum_{p=0}^{P-1} \sum_{l=0}^{L_F-1} f_p(l) \cdot x_p(n-l); \qquad 0 \le n \le N_G - 1 \end{aligned} \tag{3}$$

where $N_G = N + L_F - 1$, $\otimes$ denotes the linear convolution, L_F is the length of each sub-band filter, and $\{f_p(l);\ l = 0, 1, \ldots, L_F - 1\}$ are tap coefficients of the pth FIR filter. Moreover, these coefficients have to meet the following constraint

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