An Improved Symbol Timing Synchronization Algorithm in FBMC Systems

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Abstract. A novel symbol timing synchronization algorithm by iterative method is proposed for FBMC/OQAM systems. In the iterative process, different methods are used for rough timing synchronization and fine timing synchronization. Firstly, the ZC (Zadoff-Chu) sequence delay correlation is used to estimate the coarse timing by cross-correlation. After the coarse timing synchronization compensation, the auto-correlation is used to estimate the carrier frequency offset, so that better frequency offset estimation performance can be obtained. Then, the estimated frequency offset is subjected to sequence compensation, and finally, the fine symbol timing synchronization is performed using the compensated sequence. Compared with other algorithms, it can be concluded that the proposed algorithm can obtain high precision of timing accuracy when there is frequency offset in the system.

1. Introduction

There are many new requirements for the next generation wireless communication system [1, 2]. In view of these characteristics, the filter bank multicarrier technology with offset quadrature amplitude modulation (FBMC/OQAM) has been extensively studied recently [3]. Compared with the CP-OFDM technology, the FBMC/OQAM has demonstrated excellent performances both in spectrum utilization and spectral leakage, and has become an alternative technology solution of the OFDM technology as one of 5G physical layer modulation schemes in the future [4]-[6]. Unlike OFDM, FBMC/OQAM does not use a cyclic prefix (CP), so it has a very high spectral efficiency.

However, like other multi-carrier technologies, the major disadvantage of FBMC systems is their sensitivity to carrier frequency and symbol timing errors. As a result, symbol timing synchronization algorithm of FBMC system has been widely studied in academia. Existing symbol timing synchronization algorithms can be divided into two categories: blind and data-aided synchronization algorithm [7-13]. A blind synchronization timing estimation algorithm is proposed in [9], which using the cyclic redundancy of the pulse shaping to achieve better estimation performance, but this method requires a large number of data symbols and time-consuming. And Zeng Y et al. used the idea of Schmidl algorithm [14] to construct two special data blocks in the frequency domain, so that the data blocks have repeated redundancy in the time domain, and the delay correlation is used for symbol timing. In [11], the algorithm constructs a training sequence with repeated redundancy in the time domain transmit data frame, and obtains the time offset value by seeking the largest correlation output at the receiver side. The algorithm has low symbol timing
reliability. Fusco T et al. normalized the synchronization sequence of the entire delay-related region in the [10], and improved the accuracy of symbol timing. On the basis of [7], Hua Wu et al. consider some disturbed sequences in delay correlation, and therefore improve the timing synchronization performance, but the peak is not sharp enough. Lu Mi et al. considers the influence of noise on the basis of [12], using the least squares estimation method to determine the symbol timing, a sharp peak can be obtained on the Gaussian channel, but the method is extremely sensitive to the frequency offset and has poor performance under the multipath channel where the Doppler shift is 2KHZ.

In view of the above problems, this paper combines the algorithms of [7][12] and [13] to perform timing synchronization estimation in an iterative manner. This new algorithm can also obtain sharp peaks in the case of frequency offset. The entire synchronization estimation process is completed in the time domain, avoiding the FFT operation on the received symbols, the calculation amount is small, and the transmission efficiency is high. Simulation analysis shows that the new algorithm has higher symbol timing estimation performance under multipath fading channel with Doppler shift.

2. System Model

We consider a FBMC/OQAM baseband model with M subcarriers, and the subcarrier spacing is \(1/\tau\), where, the \(\tau\) is the interval of complex-valued symbol in time domain, the transmit signal of FBMC/OQAM can be written as:

\[
s(l) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} a_{m,n} e^{j2\pi mnM} g(l-nM/2)
\]  

(1)

Where \(a_{m,n}\) is the real-valued transmitted symbols at frequency index \(m\) and time instant \(n\), \(g(l)\) is the symmetric real-valued prototype pulse function with total energy is one and the length is \(L_g\), and the filter function on time-frequency point \((m,n)\) can be defined as:

\[
g_{m,n}(l) = g(l-nM/2) e^{j\pi (m+n)} e^{-j\pi M/2}
\]  

(2)

After sampling at intervals of \(\tau\), a discrete baseband transmission signal is obtained:

\[
x(n) = \sum_{m=0}^{N-1} \sum_{k=0}^{K-1} s[m]g[n-Mnk] e^{j2\pi nk(n-mN)}
\]  

(3)

The sampling frequency of the system is:

\[
f_s = 1/T_c = KF = N/\tau
\]  

(4)

Where \(F\) is the subcarrier spacing, \(L\) is the number of sampling points in one symbol period, usually \(N \ll L\), \(L\) is the truncation length of the filter, and when \(K = N\), \(TF = 1\) corresponds to the critical sampling in the time-frequency analysis. After the transmitted signal passes through the channel, the resulting baseband signal can be expressed as:

\[
r(n) = x(n-d) e^{j2\pi \Delta f + \Delta \phi} + v(n)
\]  

(5)

\(d\) is the symbol timing offset, \(\Delta f\) is the frequency offset, \(\Delta \phi\) is the phase offset of the carrier, \(v(n)\) is the additive white Gaussian noise with a mean of 0 and a variance of \(\sigma_v^2\).
3. Timing Synchronization Algorithm

This paper proposes a new algorithm that uses an iterative approach and the symbol timing still has sharp peaks in the presence of carrier frequency offset.

3.1 Training Sequence Structure

ZC sequences are widely used to design training sequences due to their good modulus constant, auto-correlation and cross-correlation properties, which can improve the timing and frequency offset estimation performance in multipath fading channel environments. Let \( \{a(n)\} \) be a ZC sequence of length \( N \) (\( N \) is even). According to the literature [15], the ZC sequence \( a(n) \) can be expressed as:

\[
a(n) = \exp\left(\frac{j \pi \mu n^2}{N}\right)
\]

Where \( n \in [0, N-1] \), \( \mu \) and \( N \) are prime number, and both are positive integers. The correlation of the CAZAC sequence can be expressed as:

\[
\sum_{k=0}^{N-1} a(k) a^*(k + \tau) = \begin{cases} N, & \tau = 0 \\ 0, & \tau \neq 0 \end{cases}
\]

In this paper, we use the training sequence structure in [12] to transmit a set of consecutive and identical ZC sequences, which length is \( L \), and \( m \in [0, L_{TR} - 1] \), \( s_k^{TR}[m] = s_k^{TR} \). Let the filter have a cut-off range of \(-L/2 \leq n \leq L/2 - 1\). In order to overcome the smearing effect of the filter in the time domain, let \( L_{TR} = \lfloor L/N \rfloor + Q - 1 \), \( \lfloor . \rfloor \) denote rounding, and \( Q \) should be a reasonable positive integer according to the specific situations. The synthetic time domain expression for this set of training sequences is:

\[
x_{TR}(n) = \sum_{k=0}^{K-1} s_k^{TR} e^{j 2 \pi \frac{k}{K} m N} \sum_{m=0}^{L_{TR}-1} g_r(n - mN) e^{-j 2 \pi \frac{k}{K} m N}
\]

where \( L/2 \leq n \leq (L_{\nu} - 1)N + L/2 - 1 \). Training symbols can be represented as figure 1.

As can be seen from the figure 1, the time domain synthesis signal transmitted by the FBMC system is much more complicated than OFDM. This is mainly because the filter used by it does not use rectangular pulses like OFDM, which causes time-domain inter-symbol interference. In the figure, the length of AB and DE are \( L - N \), which is the area affected by the overlap of data symbols before and after the \( L_{\nu} \) training symbols. Schmidl T M et al. has proved that the training sequence of the BD has the redundancy characteristics of \( Q \) times \( N \) repetition delays, so these data can be used for symbol timing estimation.

3.2 Symbol Timing Synchronization

Since the peaks of the timing algorithms of Fusco algorithm [7] and WH algorithm [12] are not sharp enough, the timing algorithm of the ML algorithm [14] is sharp in the Gaussian channel, but the system cannot have frequency offset. This paper combines the timing estimation method of literature [7][12] and
The structure of synchronous training symbol [13], uses the iterative method to make the FBMC system with the carrier frequency offset, the symbol timing curve peak is sharp. The principle of the algorithm is as follows:

Step 1: The cross-correlation of the local sequence and the synchronization sequence is used to obtain the coarse symbol timing estimation. Since the local sequence is not subject to channel interference, the performance of the symbol timing obtained by delaying the autocorrelation of the synchronization sequence is better, combined with the Fusco algorithm and the WH algorithm to get the symbol timing, the defined synchronization metric function is expressed as follows:

\[
\left| P(d) \right| = \sum_{n=0}^{L_{22}+L-N-P-1} | r^* (n+d)x_{Tx} (n) \times r (n+P+d)x_{Rx} (n+P) | \right|
\]

\[
R(d) = \sum_{n=0}^{L_{22}+L-N-P-1} | x_{Tx} (n) |^2 | x_{Rx} (n+P) |^2
\]

where \( P= N \). So the maximum likelihood synchronization estimate is:

\[
\hat{d} = \arg \max \left( \left( M(d) \right)^2 \right)
\]

Since the algorithm is applied under a multipath channel, the following correction is made to (12):

\[
\hat{d}_{coarse} = \arg \max \left( \sum_{n=0}^{D-1} \left( M(d+m) \right)^2 \right)
\]

in which \( D > r_m \), \( r_m \) is the maximum multipath delay.

Step 2: The obtained symbol timing is time-compensated for the synchronization sequence, and then the compensated sequence is used for delay autocorrelation and the carrier frequency offset is obtained. Since the sequence of delay autocorrelation is affected by the channel, compared with the method that obtained the frequency offset by use the cross-correlation between the local sequence and the synchronization sequence, the performance of proposed method is better. Then the Fusco algorithm is used to find the carrier frequency offset, which is expressed as follows:

\[
\Delta \hat{f} = \frac{1}{2\pi P} \angle \left\{ P(\hat{d}_{coarse}) \right\}
\]
Step 3: Perform frequency offset compensation on the training sequence by the obtained frequency offset.

Step 4: Repeat the above steps until the remaining frequency offset reaches the system requirements.

Step 5: Perform the iteratively compensated training sequence, that is, the training sequence with almost no frequency offset, using the ML algorithm for symbol timing synchronization. The specific algorithm is as follows:

$$d_{free} = \arg\max \{2 | P(d) | / (R_1(d) + R_2(d)) \}$$

(15)

In which:

$$P(d) = \sum_{n=0}^{L_{TD} + L_{TR} - P-1} | r^\ast(n + d) x_{tr}(n) \times r(n + P + d) x_{tr}(n + P)|$$

(16)

$$R_1(d) + R_2(d) = \sum_{n=0}^{L_{TD} + L_{TR} - P-1} | x_{tr}(n) |^2 x_{tr}(n + P)^2 + | r(n + P) |^2 | r(n + P + d) |^2$$

(17)

Similarly, in the multipath channel, the equation (15) is modified similarly to the equation (13), and fine symbol timing synchronization can be obtained. From the above five steps, even in the case of having a frequency offset, a sharp peak of symbol timing can be obtained.

4. Discussion and Numerical Simulations

In order to verify the effectiveness of the new algorithm, the paper carries out the MATLAB simulation of the above algorithm in different channel environments. This paper uses the simulation parameters in [12], as shown in table 1.

| Table 1. Simulation parameters. |
|-------------------------------|
| simulation parameters       | value |
| FFT point(K)               | 64    |
| Symbol sampling rate(N)    | 72    |
| Filter type                | SRRC filter |
| Filter roll-off factor     | 0.125 |
| The length of filter(L)    | 576   |
| Number of training symbols(LTR) | 23      |
| Subcarrier spacing(KHz)    | 500   |
| Sampling frequency(MHz)    | 32    |
| Carrier frequency(MHz)     | 1800  |
| µof zc sequence            | 63    |

As can be seen from table 1, the length L of the filter is an integer multiple of the number of sampling points and FFT points, that is, L = 8N = 9K. Thus, each superimposed synthesized symbol contains a trailing superposition of adjacent 8 symbols, so 7 symbols in the training symbol are subject to superposition interference of other data symbols. From this, we can calculate that the number of training symbols without interference is Q = L_{TR} - 7 = 16, that is, the BD portion in Fig. 2, the length is 16N, then q = 8, AB = DE = 7N. The multipath fading channel uses a 6-path ITU-VA channel model, the parameters is [0, 310, 710, 1090, 1730, 2510] ns, and the power distribution is [0, -1, -9, -10, -15, -20] dB. The above
parameters can calculate the maximum Doppler shift of about 2KHz, the number of iterations is 1, and the simulation is performed 5000 times per SNR.

Figure 2 is a comparison of the timing metric curves of several algorithms in the Gaussian channel. It can be seen that the Fusco algorithm has a platform effect and the symbol timing accuracy is not high. The WH algorithm changes the length of the correlation sequence, the accuracy is improved, but there is still a platform effect. The ML algorithm ignores the frequency offset and only considers the influence of noise, so it can obtain sharp peaks, but only solves the peak problem of timing metric curve and accurate timing in Gaussian channel. It can be seen from figure 3 that under the multipath fading channel with carrier frequency offset, the timing metric curves of Fusco algorithm and WH algorithm still have problems such as peak sharpness and timing blur. Compared with figure 2, it is found that the timing error of these two algorithms becomes larger in the multipath channel (the highest point of the curve is offset under the higher channel), while the ML algorithm has a peak, its peak height is less than 0.2. It can be said that the algorithm can hardly be applied under the channel, because the ML algorithm ignores the influence of the frequency offset on the symbol timing.

Figure 2. Timing performance of Gaussian channel.

Figure 3. Timing performance of multipath channel.

It can be seen from figure 4 that after an iterative frequency offset compensation, the timing metric curves of these algorithms are similar to those of figure 2, but they are different from figure 2 because the frequency offset is not completely eliminated. The Fusco algorithm and the WH algorithm still have platform effect problems and timing ambiguity, this is because the data of AB and DE are not considered or only partial data of AB and DE are considered. However, the improved algorithm has no platform effect and the peak value is sharp. This is because the algorithm is applied in the multipath fading channel, and the synchronous metric function of the coarse synchronization and the fine synchronization is summed, the frequency offset is eliminated by using the iterative method. In different environments, coarse synchronization and fine synchronization use different timing algorithms to ensure optimal performance. As seen from figure 4, the timing metric curve of the algorithm is sharp, although there are many peaks beside the peak, but the height of the peak does not exceed half of the main peak. When performing symbol timing synchronization, as long as the threshold is set reasonably value, the good symbol timing performance can be got. Figure 5 is a comparison of the rms timing errors of several algorithms in the ITU-VA channel. It can be seen from the figure that with the change of SNR, the proposed algorithm is better than other algorithms. The good performance verifies the feasibility and accuracy of the algorithm.
5. Conclusion

In this paper, based on the idea of iterative elimination of frequency offset and several algorithm ideas, the improved algorithm can also produce sharp peaks and accurate timing in multipath channels with Doppler shift. The algorithm only needs to be iterated once, which can overcome the shortcomings of the traditional algorithm (the platform effect and timing error are large), and effectively improve the accuracy of the synchronization estimation. The symbol timing estimation is completed in the time domain, which reduces the FFT operation on the training symbols, the calculation amount is small, and the system transmission efficiency is higher. Simulation and analysis results show that the proposed algorithm is suitable for multipath fading channels with frequency offset.

Acknowledgments

First and foremost, I appreciate my college which gives me a comfortable learning atmosphere. Second, I would like to show my deepest gratitude to my tutor, professor Luo, who has walked me through all the stages of the writing of this paper. Without his illuminating instruction and patience, this paper could not have reached its present form. My sincere appreciation also goes to all my classmates, who are my proud of my life. Last but not least, I want to thank all my friends for their encouragement and support.

References

[1] Lu Yang. Industry 4.0: A Survey on Technologies, Applications and Open Research Issues [J]. Journal of Industrial Information Integration, 2017, 6: 1–10
[2] Tao Jiang, Shiwen Mao, el al.Special issue on "next generation wireless communication technologies"[J].Digital Communications and Networks, 2016, 2(4): 259-260
[3] Saeedi-Sourck H, Wu Y, et al. Complexity and performance comparison of filter bank multicarrier and OFDM in uplink of multicarrier multiple access networks[J]. IEEE Transaction on Signal Processing, 2011, 59(4): 1907–1912
[4] Ronald N and Markus R .OFDM and FBMC-OQAM in Doubly-Selective Channels: Calculating the Bit Error Probability [L].IEEE Communications Letters, 2017, 21(6): 1297-1300
[5] Siohan P, Siclet C, and Lacaille N. Analysis and design of OQAM-OFDM systems based on filter bank theory[J]. IEEE Transaction on Signal Processing, 2002, 50(5): 1170-1183
[6] Shanzhi Chen, Jian Zhao, et al. The requirements, challenges, and technologies for 5G of terrestrial mobile telecommunication [J].IEEE Communications Magazine, 2014, 52(5): 36–43
[7] Fusco T, Petrella A, Tanda M. Data-aided symbol timing and CFO synchronization for filter bank multicarrier systems [J]. *IEEE Transactions on Wireless Communications*, 2009, 8(5):2705-2715.

[8] Stitz T H, Ihalainen T, Renfors M. Practical issues in frequency domain synchronization for filter bank based multicarrier transmission [C]. *International Symposium on Communications, Control and Signal Processing*, 2008:411 - 416.

[9] Fusco T, Petrella A, Tanda M. Blind CFO Estimation for Non-critically Sampled FMT Systems [J]. *IEEE Transactions on Signal Processing*, 2008, 56(6):2603-2608.

[10] Zeng Y, Meng W C. Joint time-frequency synchronization and channel estimation for FBMC [C]. *IEEE International Symposium on Personal, Indoor, and Mobile Radio Communication*, 2015:438-442.

[11] Tonello A M, Rossi F. Synchronization and channel estimation for filtered multi-tone modulation [J]. *IEEE Wireless Personal Multimedia Communication* 2014: 590-4.

[12] Hua Wu and Fanxin Zeng, et al. High-precision symbol timing estimation for filter bank multi-carrier systems [J]. *High-tech communication*, 2011, 21(4): 369-373.

[13] Lu Mi and Qin Shu. Improved algorithm for symbol timing synchronization of FBMC system based on training sequence [J]. *Application Research of Computers*, 2012, 29(6): 2109-11.

[14] Schmidl T M, Cox D C. Robust Frequency and Timing Synchronization for OFDM [J]. *IEEE Transactions on Communications*, 1997, 45(12):1613-1621.

[15] Huaizong Shao, Yang Li, Jiajia Tan. Robust timing and frequency synchronization based on constant amplitude zero autocorrelation sequence for OFDM systems [C] *IEEE International Conference on Communication Problem-solving* (China), 2014: 14-17.