On the Synchronization Techniques for Wireless OFDM Systems

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***Abstract*—The latest research works on the synchronization scheme for either continuous transmission mode or burst packet transmission mode for the wireless OFDM communications are overviewed in this paper. The typical algorithms dealing with the symbol timing synchronization, the carrier frequency synchronization as well as the sampling clock synchronization are briefly introduced and analyzed. Three improved methods for the fine symbol timing synchronization in frequency domain are also proposed, with several key issues on the synchronization for the OFDM systems discussed.**

***Index Terms*—Carrier frequency synchronization, continuous mode and burst packet mode transmission systems, OFDM, sampling clock synchronization, symbol timing synchronization.**

I. Introduction

OFDM, associated with other related technologies have found its wide applications in many scientific areas due to its high spectrum efficiency, its robustness against both multi-path and pulse noises, its highly reliable transmission speed under serious channel conditions, adaptive modulation for each sub-carrier according to the channel conditions, and etc. It has become fundamental technology in the future 4G-multimedia mobile communications systems [1].

Many digital transmission systems have adopted OFDM as the modulation technique such as digital video broadcasting terrestrial TV (DVB-T) [2], digital audio broadcasting (DAB), terrestrial integrated services digital broadcasting (ISDB-T), digital subscriber line (xDSL), WLAN systems based on the IEEE 802.11(a) [3] or Hiperlan2, multimedia mobile access communications (MMAC), and the fixed wireless access (FWA) system in IEEE 802.16.3 standard. OFDM has also found its application in Cable TV systems. Technologies fundamentally based on OFDM, such as vector OFDM (V-OFDM), wide-band OFDM (W-OFDM), flash OFDM (F-OFDM) have also shown their great advantages in certain application areas.

There are some disadvantages, however, appeared in the OFDM systems, for example, the large Peak-to Average Power Ratio (PAPR) as well as high sensitivity to the synchronization errors. Synchronization issues are of great importance in all digital communications systems, especially in the OFDM systems. Synchronization errors not only cause inter-symbol interference (ISI) but also introduce inter-carrier interference (ICI) due to the loss of orthogonality among all sub-carriers. In this paper, we focus on the synchronization schemes in the OFDM systems. Fundamental theory for the synchronization is briefly described in Section II and in Section III, the symbol timing scheme and three improved methods for the fine symbol timing in frequency domain are proposed. We then conduct the analysis on the carrier frequency recovery as well as the sampling clock synchronization methods in Sections IV and V respectively. In Section VI, joint estimation of all the synchronization errors including timing, frequency and phase offsets is simply described. Technical forecast is made in Section VII with conclusions drawn in Section VIII.

Manuscript received April 26, 2005; revised October 27, 2005. This work was supported in part by the National Natural Science Funds in China (Nos. 50177001, 60372007, and 60332030) and by the Ministry of Information Industry Foundation under Grant no. 2002291.

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Digital Object Identifier 10.1109/TBC.2006.872990

II. Overview for the Synchronization in OFDM Systems

Synchronization is of great importance for all digital communication systems. OFDM systems are very sensitive to both timing and carrier frequency offset, especially, when combined with other multi-access techniques such as FDMA, TDMA, and CDMA. Therefore, synchronization is extremely crucial to the OFDM systems.

A. Three Synchronization Issues in the OFDM Systems

There are three major synchronization issues in the OFDM systems:

a. The symbol timing synchronization, which is to determine the correct symbol start position before the FFT demodulation at the receiver end.
b. The carrier frequency synchronization (i.e., carrier frequency recovery technique), which is utilized to eliminate the carrier frequency offset caused by the mismatch from the local oscillators between the transmitter and the receiver, nonlinear characteristic of the wireless channel as well as the Doppler shift.
c. The sampling clock synchronization, which is to mitigate the sampling clock errors due to the mismatch of the crystal oscillators.

All these synchronization errors will significantly degrade system performance [4], [5].

B. Synchronization Technologies in the Continuous Mode and Burst Packet Mode Transmission Systems

Accurate synchronization is indispensable to suppress the negative impact of the synchronization errors in the communication systems no matter, whether it is in continuous or burst packet mode transmission systems. However, these two different modes require different synchronization schemes:

a. In the burst packet mode, synchronization ought to be established at any time because when data streams are ready to transmit is unknown The duration of the training symbols used for synchronization in this mode is relatively short and synchronization should be done within a single training symbol time for the systems such as IEEE 802.11(a) [3] and HiperLan/2 to avoid the reduction of the system capacity. It is inappropriate to do averaging over many symbols or pilots because of the stringent requirement on synchronization time and the less number of sub-carriers. It is also important for the systems in this mode to establish the synchronization in time domain and this will greatly reduce the acquisition time since it avoids the feedback from frequency domain.
b. In the continuous mode such as DAB, DVB-T [2] systems, averaging method can be used to improve the estimation accuracy because there is no stringent requirement on the acquisition time. In this mode, large numbers of sub-carriers has been utilized and, it is appropriate to apply the cyclic prefix (CP) or pilots to these synchronization methods.

III. Symbol Timing Synchronization

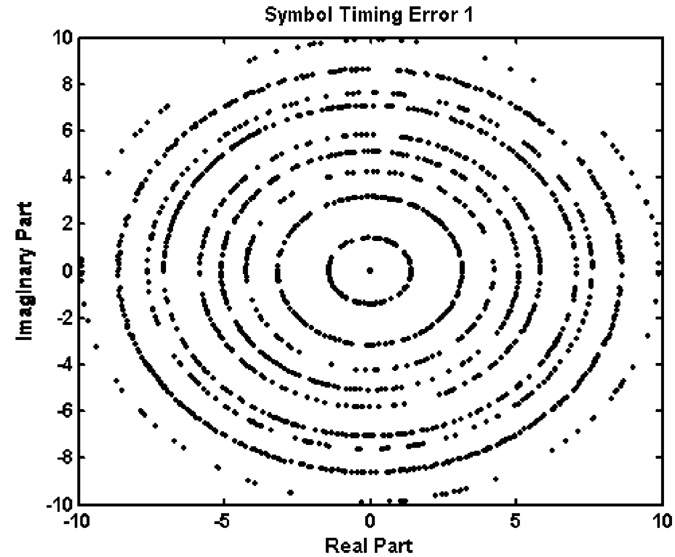
When signals are transmitted through severe channel conditions of multi-path fading, pulse noise disturbance and the Doppler Shift, it is important to solve symbol timing synchronization problem first during the design process of an OFDM receiver.

The symbol timing error can not only disturb the amplitude as well as the phase of the received signal, but also introduce ISI. In order to perform the FFT demodulation correctly, the symbol timing synchronization must be done to determine the starting point (i.e. FFT window) of the OFDM symbol. The cyclic prefix (CP, or Guard Interval, GIB) can be removed afterwards. The concept of the GIB was first proposed by A. Peled [6], which can prevent OFDM symbols from ISI disturbance and keeps the orthogonality among all the sub-carriers. Fig. 1 shows the variation of the signal constellation due to the symbol timing errors. Fig. 1(a) and (1b) represent the symbol starting point within GIB (case 1) and outside ISI-Free region (case 2) respectively. It clearly shows how bad the signal constellation could be due to the symbol timing errors.

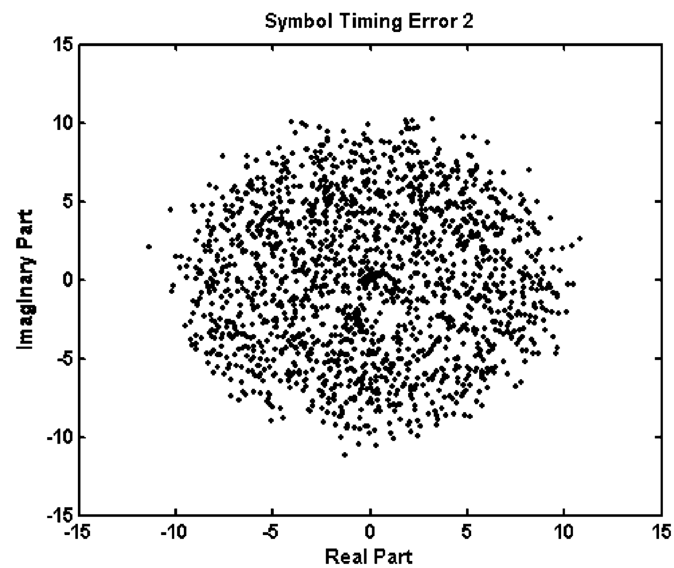
Accurate and steady symbol timing synchronization can be realized through the coarse symbol timing, the fine symbol timing as well as the symbol timing control structure combined together. The coarse symbol timing synchronization is first executed in time domain and then, the fine symbol timing in frequency domain is done to ensure a more accurate estimation. The symbol timing control structure is utilized to coordinate the operations of the coarse and the fine symbol timing.

A. The Coarse Symbol Timing Algorithms in Continuous Mode

The conventional algorithms for the coarse symbol timing synchronization in time domain are MLE (Maximum Likelihood Estimation) utilizing the cyclic prefix of the OFDM symbols. The most representative algorithm was proposed by J. J. Van de Beek [7]. However, good performance achieves



(a)



(b)

Fig. 1. (a) Constellation variation due to the symbol timing error. The total subcarriers $\mathrm{N} = 2048$, cyclic prefix $\mathrm{L} = 128$, 64-QAM mapping. No carrier frequency and sampling clock offset. The normalized symbol timing offset is 36 (samples) Case 1. (b) Constellation variation due to the symbol timing error. The total subcarriers $\mathrm{N} = 2048$, cyclic prefix $\mathrm{L} = 128$, 64-QAM mapping. No carrier frequency and sampling clock offset. The normalized symbol timing offset is 36 (samples) Case 2.

only under the AWGN channel. When the channel condition becomes severely degraded, data in GIB is badly contaminated by ISI, there will be significant fluctuation for the starting point estimated for the OFDM symbol. And such fluctuation will have the significant influence on the carrier frequency offset as well as the sampling clock offset estimation in frequency domain. To improve the performance of ML Estimator, a novel scheme utilizing both CP and pilots to do the coarse symbol timing synchronization was proposed by D. Landström [8]. It has better performance compared to that of [7] under the multi-path fading channel. However, the nonnegligible fluctuation still exists because of the ISI contamination on the data within GIB and the limited number of pilots used for estimation. In order to mitigate the fluctuation, T. M. Schmidl introduced a new method making use of the training symbols in time domain, in which a timing function was defined [9]. It has better performance compared to those proposed by J. J. Van de Beek and D. Landström. Unfortunately, it has a "flat region" in the estimation, which, to a great extent, increases the variance of the symbol timing estimator.

Some new schemes has been proposed in the literatures [10]–[13] in recent years to overcome the defects of the algorithms mentioned above, with the target to decrease the fluctuation of the starting point of the estimated symbol as well as to make the estimation within the ISI-Free region. The convolution characteristic of the cyclic prefix are utilized in literature [10], while, PN sequences are adopted in [11]–[13], to take the advantage of the intrinsic, fairly good correlation property of PN: Kasami sequence is utilized in [11] with the excellent correlation properties; and in [12], [13], a novel timing recovery methods for TDS-OFDM (key techniques for the Terrestrial Digital Multimedia/Television Broadcasting System, namely DMB-T proposed by Tsinghua University [14]) is developed. This scheme is based on the searching and tracking on the correlation peaks of the PN sequences, which is as the GIB for each OFDM symbol. Because of the excellent correlation properties of the so-called m-sequence, the performance of these algorithms [10]–[13] outperforms those from [7]–[9] under the multi-path fading channels.

B. The Fine Symbol Timing Synchronization in Continuous Mode

The fine symbol timing synchronization in frequency domain is often required to guarantee the estimation accuracy. A preamble structure including a synchronization field (S-filed) and a cell-searching field (C-field) is proposed in literature [15] with the fine symbol timing done by using the cell identification method. In [16], a specially designed pilot symbol structure is utilized to generate a fine symbol timing estimation. Computer simulations and analysis verify their good estimation performances but low bandwidth efficiency. The residual symbol timing error may cause the phase rotation of the sub-carriers in frequency domain. In this Section, we propose three improved algorithms to do the fine symbol timing based on the algorithm introduced by [17]. Computer simulations show that these proposed methods have better performance compared with the algorithm in [17] when under serious channel conditions. In the following, we referred the algorithm in [17] as Algorithm 1, and named our proposed methods as Algorithm 2, Algorithm 3 and Algorithm 4 respectively.

Algorithm 2:

$$\Delta\Phi(j) = \frac{2\pi\Delta k}{N} \cdot \frac{T_d}{T_s} \tag{1}$$

$$\Delta\Phi(j) = Arg\left(\sum_{k=1}^{L-1} X_{j,k+1} \cdot X_{j,k}^*\right) \tag{2}$$

Where, L denotes the number of scattered pilots (SP), $X_{j,k}$ is a complex variable for the k^{th} SP in the j^{th} OFDM symbol, $\Delta\Phi(j)$ is the phase deviation of the two adjacent SP's caused by the symbol timing offset of j^{th} OFDM symbol, Δk is the distance between the two adjacent SP's. T_d, T_u, T_s denotes the

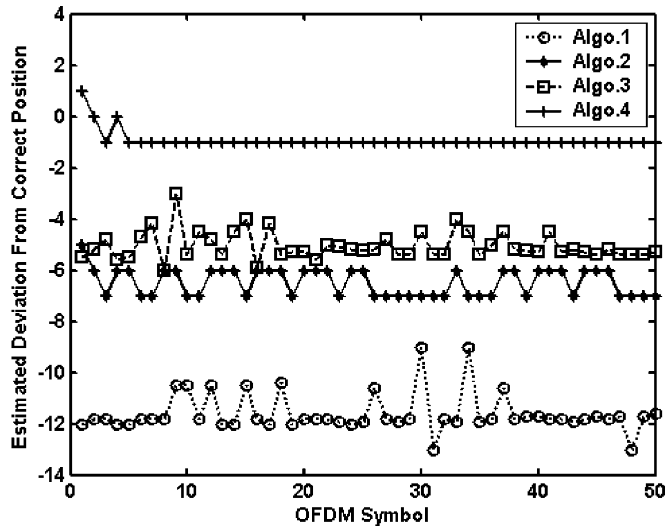


Fig. 2. Performance comparison among Algorithm 1, 2, 3, and 4 for the symbol timing estimation. The total subscribers $\mathrm{N} = 2048$, cyclic prefix $\mathrm{L} = 128$, $\mathrm{SNR} = 5$ dB, Rayleigh fading channel [2], normalized carrier frequency offset is 0.135 and -48 respectively.

integer part of symbol timing offset, useful symbol duration period and the nominal sampling frequency respectively. This algorithm has the same limited estimation range as that in Algorithm 1 and its estimation accuracy is influenced by the carrier frequency offset [17].

Algorithm 3:: Algorithm 1 and 2 perform the estimation on the adjacent SP's within the same OFDM symbol. In algorithm 3 and 4, we derive the offset for the fine symbol timing from the pilots in the two consecutive OFDM symbols (Fig. 2). That is,

$$\Delta\Phi_{k+1,k}(j) = Arg\left(X_{j+1,k+1} \cdot X_{j,k}^*\right) \tag{3}$$

Where, $X_{j,k}^*$ denotes the complex conjugation of $X_{j,k}$,

Algorithm 4:: The same as that in Algorithm 3, SP's of consecutive OFDM symbols can be utilized. But the only different from algorithm 3 is the phase characteristic of known pilots is now given by:

$$\Delta\Phi_{k+1,k}(j) = Arg\left(\sum_{k=1}^{L-1} X_{j+1,k+1} \cdot X_{j,k}^*\right) \tag{4}$$

Lots of computer simulations validate the following conclusions: a. The performances of algorithms 2 and 4 outperform that of algorithms 1 and 3 under multi-path fading channels respectively. This is because the phase characteristic is utilized in algorithms 2 and 4, while, the power characteristic is utilized in algorithms 1 and 3. It is well known that, power characteristic is much more sensitive to the multi-path fading channels than phase characteristic. b. When the normalized decimal carrier frequency offset is less than certain value (about 0.15 that of sub-carrier spacing), the performance of algorithms 3 and 4 outperform that of algorithms 1 and 2 and the best estimation results can be obtained with Algorithm 4. c. When the normalized decimal carrier frequency offset is larger than certain value (about 0.15 that of sub-carrier spacing), the performances of algorithms 1 and 2 outperform that of algorithms 3 and 4 and the best estimation results can be achieved by Algorithm 2. The detailed analysis for the effects of the carrier frequency offset on the fine symbol timing synchronization can be found in [17].

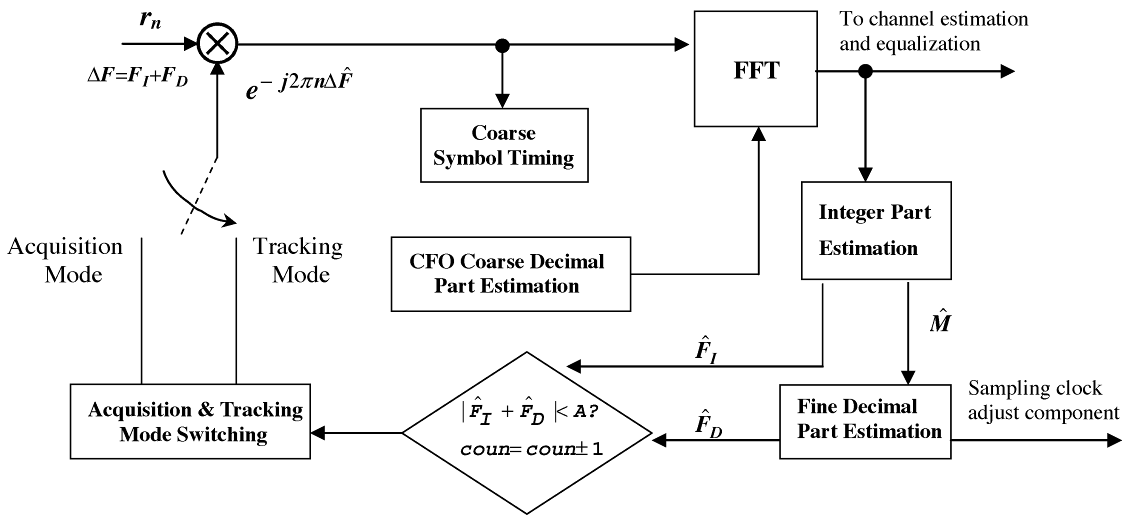


Fig. 3. Frequency synchronization estimator.

C. The Symbol Timing Synchronization Algorithms in Burst Packet Transmission Mode

The synchronization requirements vary with the applications, therefore, we should adopt the appropriate synchronization techniques in both continuous and burst packet transmission modes respectively. As being discussed in Section II-B, it is inappropriate to do the symbol timing synchronization with pilots in the burst packet mode due to the stringent requirements on synchronization time. In [18], a novel scheme to do the coarse symbol timing with training symbols is proposed and, the computer simulations based on IEEE 802.11(a) standard [3] illustrate that more accurate coarse symbol timing synchronization can be achieved by the convolution method in time domain than that by the ordinary MLE method, no matter it is in the office environment [19] or under much severe channel conditions [2]. This really comes from the fully utilization of the convolution property of CP.

D. Symbol Timing Synchronization Control Model

Other than the accuracy of the estimation in the symbol timing synchronization process, the robust and efficient synchronization control structure to ensure the system stability is also requested. A new symbol timing synchronization control model has been proposed in [10]. Similar to those control models in [17], [20], it also has two synchronization states: the acquisition state and the tracking state. The difference is that the threshold and counters are utilized to perform the control process with less computational complexity than those in [17].

IV. Carrier Frequency Recovery Techniques

Carrier frequency offset (CFO) caused by the Doppler shift, local oscillators mismatch between the transmitter and the receiver ends, may introduce ICI and destroy the orthogonality of OFDM sub-carriers, resulting in the losses of SNR. With the insertion of the GIB in OFDM symbols, symbol timing error within a certain range will not introduce ISI and ICI. OFDM system is more sensitive to the CFO and the sampling clock offset (SCO). Regarding to higher modulation modes such as 64-QAM, tiny CFO may introduce severe degradation on the system performance [21].

Carrier frequency offset ΔF puts an extra phase factor of $e^{j2\pi\Delta Ft} = e^{j2\pi Fft}$ in the received signal, where f is the sub-carrier spacing, F is the CFO normalized by f and is usually divided into an integer part F_I, (multiple of the sub-carrier spacing, causing a shift of the sub-carrier indices), and a decimal part F_D, (less than half of the sub-carrier spacing, causes a number of impairments, including attenuation and rotation of the sub-carriers and ICI).

We can divide CFO into three parts: the integer part, the coarse decimal part and the fine decimal part. CFO can usually be compensated for through the following procedures shown in Fig. 3. First, a coarse symbol starting point for the FFT demodulation is provided by the coarse symbol timing module and then, the estimation and correction of the coarse decimal frequency offset in time domain is performed to minimize the ICI impact on the estimation in frequency domain, with the integer part $\hat{F}_I$ estimated in frequency domain to get the correct sub-carrier index. Finally, the residual frequency offset $\hat{F}_D$, i.e. the fine decimal frequency offset is estimated. A tracking loop structure (the Acquisition and the Tracking Mode Switching module) can be exploited to coordinate the coarse decimal part, the integer part and the fine decimal part of the frequency offset. Each of them makes unique contribution to the recovery of the carrier frequency offset [50].

Many literatures have discussed how to make OFDM systems less sensitive to the carrier frequency offset, for instances, perform the windowing on the transmitted signals or use self-cancellation schemes [22], [23]. However, long prefix adopted in systems with these approaches results in low bandwidth efficiency. Generally, we can divide the carrier frequency recovery algorithms into three categories:

a. Methods are based on training symbols or pilots [9], [24]–[33], named Data Aided (DA) method.
b. Methods use of the intrinsic structure of OFDM symbols, e.g. cyclic prefix [7], [34]–[40], which is called Non Data Aided (NDA) method.

c. Blind approaches [41]–[43], which relies on the signal statistics and often has very high computational complexity, some approaches may have extra requirements on the channel statistics.

A. Integer Carrier Frequency Offset

The integer as well as the coarse decimal CFO correction can make the sub-carriers spacing offset less than half of sub-carrier spacing in the present of more than tens of sub-carriers. Most algorithms for the integer CFO estimation [9], [29], [31], [44]–[47] nowadays have two major defects: a. Limited estimation range on CFO; b. Stringent requirement on the symbol timing synchronization. The earliest algorithm in this category was proposed by P. H. Moose [47] with the estimation range limited within $|\varepsilon| \leq 0.5$, that is, only ± 1/2 that of sub-carrier spacing.

P. H. Moose tried to overcome this problem by increasing the sub-carrier spacing to avoid phase offset exceeding $\pm\pi$. However, the increase of sub-carrier spacing f_u satisfying (5) may decrease the useful OFDM symbol duration time T_u, resulting in tighter requirements on the symbol timing synchronization. Besides, the increase of the sub-carrier spacing will not enlarge the range of the integer part estimation to a very large extent.

$$f_u = \frac{1}{T_u} \tag{5}$$

T. M. Schmidl *et al.*, later, proposed an improved algorithm [9] with better performance under multi-path fading channel, and its estimation range was one time wider than that by P. H. Moose [47]. Unfortunately, a large prefix is still needed, for example, in DVB-T [2] systems, $2N = 2 \times 2048$ prefix (2k mode) must be used. On the other hand, its estimation range is still very limited and is sensitive to the symbol timing errors.

Three improved estimation algorithms are proposed in literature [48] to overcome these defects. All of them use the power and phase characteristic of the known pilots, which is insensitive to the symbol timing errors and have a wider estimation range of integer part of CFO (i.e., as large as $N/2$, with N the total number of useful sub-carriers in one OFDM symbol).

B. Coarse Decimal Carrier Frequency Offset

As mentioned earlier, CFO estimation should follow three procedures. If the decimal part of CFO, however, can be estimated in frequency domain, why should we carry out the coarse CFO estimation in time domain first? There are two main reasons:

a. To reduce ICI caused by CFO, which lays the foundation on a more accurate CFO estimation in frequency domain;
b. To estimate and compensate for the CFO all in time domain, reducing the synchronization time, and is suitable for the systems of burst packet transmission mode.

The early-proposed typical algorithm on the coarse decimal CFO estimation was from J. J. Van de Beek *et al.* [7] with CP characteristic exploited. T. M. Schimdl *et al.*, later, proposed a new algorithm named SCA [9]. However, either of them has a very stringent requirement on the symbol timing. An improved algorithm, not so sensitive to the symbol timing errors was proposed recently in literature [49], with only $L/4$ (L is the length of the Guard Interval) correlation window length utilized for estimation, avoiding the data portion contaminated by the incorrect phase information from the symbol timing errors.

Computer simulations show that when the decimal part of the CFO approaches to 0.5 of the sub-carrier spacing, the estimated value may, due to the multi-path fading, the phase noises as well as the discontinuity of the arctangent function, jump to the inverse polarity, as pointed out in literature [47]. For example, if the decimal frequency offset in data streams is 0.498 of the sub-carrier spacing, the estimate result with the typical algorithms mentioned above may be -0.467 of the sub-carrier spacing. The strategy to avoid the above problem in P. H. Moose algorithm is to reduce the length of the DFT and use larger carrier spacing, degrading the overall system performance. A second-order IIR filtering can be used to solve this problem [49].

C. Fine Decimal Carrier Frequency Offset

After correction based on the coarse decimal CFO estimation, the residual decimal CFO in data streams may be reduced to only 1%, and then the fine decimal CFO estimation deals with the residual CFO. The typical algorithm was also proposed by P. H. Moose [47]. However, it suffered a problem of poor bandwidth efficiency. In fact, pilots embedded in the OFDM symbols can be utilized to do the fine decimal CFO.

D. Carrier Frequency Offset Control Model

It is necessary to have a control module to coordinate the operations of the integer CFO, the coarse decimal CFO and the fine decimal CFO [48]. As shown in Fig. 3, this module consists of two modes: the acquisition mode and the tracking mode. After the estimation on the integer part $(\hat{F}_I)$ and fine decimal part $(\hat{F}_D)$ in frequency domain, the counter value COUN will increase or decrease depending on whether the value of $|\hat{F}_I + \hat{F}_D|$ is larger than a constant A (set by the system performance requirement, for example, $\mathrm{A} = 0.01\%$). The value of COUN decides whether it is in the tracking or the acquisition mode. Performance and detailed analysis on this control model is presented in [50] showing excellent performance in estimation, tracking and correction of CFO.

E. Carrier Frequency Offset in the Burst Packet Mode

There is no stringent requirement on acquisition time in the continuous systems such as DAB, DVB-T [2] and DMB-T [14], averaging method or filtering over many OFDM symbols can be adopted to increase estimation accuracy, where it is appropriate to adopt those methods based on CP or pilots. Some literatures make use of the null sub-carriers for power detection to estimate the CFO [51]. However, for systems in the burst packet mode, repetitive structure is often utilized with, no difference either between these null sub-carriers or the idle time between neighboring blocks. Those methods, therefore, are inappropriate in the burst packet mode. Because of the short duration time of packets, it has more stringent requirement on synchronization acquisition time (i.e., acquisition done within a single OFDM symbol). Besides the requirement on estimation accuracy, fast convergence is also needed. The accuracy of the CFO estimation in time domain, nonfeed back synchronization model are equally important to these systems and, the synchronization should be established only in time domain [13], [48].

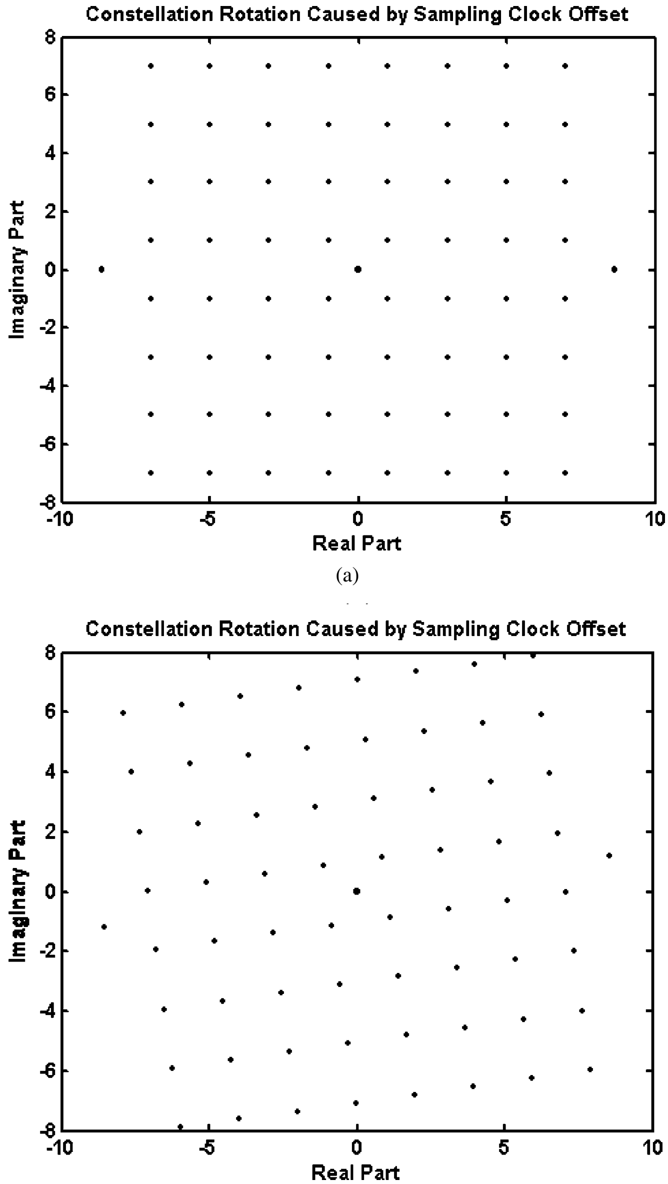


Fig. 4. Constellation variation due to the sampling clock offset. Total sub-carriers $N = 2048$, cyclic prefix $L = 128$, 64-QAM modulation, normalized sampling clock offset is 1 ppm, after 200 OFDM symbols. Other factors follow DVB-T standard [2].

V. Sampling Clock Synchronization

The sampling clock errors are mainly from the mismatch of the crystal oscillators between the transmitter and the receiver. Other factors such as multi-path fading, noise disturbance, symbol timing estimation errors may also contribute to the sampling clock offset (SCO). The sampling clock errors will negatively influence the symbol timing synchronization. For example, assume 1 ppm sampling clock offset in 2 K mode with a GIB of 512 samples in DVB-T [2], the FFT window will move one sample around every 400 symbols. The higher the sampling clock offset, the more the influence on the symbol timing synchronization.

Fig. 4 shows signal constellation variation due to the sampling clock offset. It is obvious that the larger the SCO, the more severe the distortion. Detailed analysis on the effects of sampling clock offset on symbol timing is presented in [52]. In order to analyze the effects of SCO on the system performance in a more explicit way, SCO is divided into two parts: the sampling clock phase offset and the sampling clock frequency offset [17], [20], [53], [54]. Effects of the sampling clock phase offset is similar to that of the symbol timing offset, leading to the signal phase distortion; while the sampling clock frequency offset introduces ICI. By defining Inter-Sample-Interference, effects of the sampling clock offset on system performance could be analyzed deeply [55].

The synchronous sampling and the asynchronous sampling are two different kinds of methods for the sampling clock synchronizations [56]–[58].

1) Timing algorithms are usually used in the synchronous systems to control both phase and frequency of a Voltage Control Crystal Oscillator (VCXO) [53], [59]–[61]. Compared to the asynchronous digital sampling systems, it has large timing fluctuation due to high-level phase noises. The need of the analog circuits makes it inconvenient for the system integration [62].
2) An independent oscillator is often exploited for sampling in an all-digital system. Timing algorithms are used to control NCO (Numerical Control Oscillator) and then use the NCO output to control the interpolator filter. BER performance of the asynchronous system in [54], [62] shows that the asynchronous systems are more sensitive to CFO than the synchronous systems. Computer simulations in [63] demonstrate that unrealistic interpolator may cause cyclic tracking errors in asynchronous systems, which never occurs in the synchronous systems.

The estimated sampling clock offset and decimal part of symbol timing error may be considered as an adjusting variable when we do sampling clock synchronization. This sampling clock adjusting variable is derived in frequency domain and then fed back to time domain to adjust digital oscillator, guaranteeing the stability of the loop control circuit.

VI. Joint Estimation Algorithms

Some algorithms can be utilized for the joint estimation of all the synchronization errors including the symbol timing, the carrier frequency and the sampling clock offsets. Algorithms mentioned in the former sections such as [7]–[9], [47], are the typical algorithms to do the joint estimation of symbol timing and decimal CFO. The decimal CFO estimation utilizing the detected phase of the received frequency-domain complex data in the pilot sub-carriers or training symbols, is to be performed after the estimation of symbol timing errors. However, just as we have analyzed in Section IV-B, they all have stringent requirement on the symbol timing synchronization. Some new joint estimation algorithms are proposed recently [64], [65], in [64], the proposed algorithm with a weighted least squares technique generates offset estimates with minimum RMS errors. Multiple received OFDM symbols as an observation interval are utilized in [65], both of which are less sensitive to the symbol timing errors.

The joint estimation and tracking of symbol timing and sampling clock errors are presented in [17], [53]. The main problem with time synchronization errors is that, until the sampling clock adjustment, the sample rob/stuff phenomenon due to the sampling clock frequency offset leads to the FFT window position offset, a joint algorithm for symbol timing recovery and sampling clock adjustment using such characteristic is proposed [17]. A delay-locked loop (DLL) technique to execute the combined symbol and sampling clock synchronization is presented in [53].

Joint estimation algorithms usually have low computational complexity compared to the separate estimation ones. Its estimation results, however, suffer from another synchronization estimation errors. Take the joint estimation of the symbol timing and the decimal CFO for example, the estimated symbol timing errors may affect the decimal CFO estimation.

VII. Technical Forecast

Synchronization is one of the most critical technologies in the OFDM and other digital communication systems; it has great impact on the technologies such as channel estimation, equalization, decoding and so on to be implemented in this kind of systems. Based on all the introductions and analyzes above, we would like to give the following suggestions:

1) Frequency domain synchronization is often exploited to ensure the estimation accuracy after the coarse synchronization estimation done in time domain. The control model is absolutely necessary to coordinate the whole estimation process between time and frequency domains. This is unfavorable for the burst packet mode systems because the FFT calculation and other factors may significantly increase synchronization time. Therefore, it is of great importance to find the useful schemes performing the synchronization all in time domain with the acceptable estimation accuracy. Short acquisition time and low system complexity should be considered as well.
2) As mentioned in the above, conventional synchronization methods can be divided into three categories: DA, NDA and blind algorithms. Pilots, training symbols or the combination of them are generally applied to the DA-type of methods at the expense of the reduced bandwidth efficiency. For the NDA methods, data used for the estimation may be contaminated by ISI, resulting in the inaccurate estimation. The blind or semi-blind algorithms can improve the estimation accuracy without pilots or training symbols, however, it needs significant amount of statistical information on both signal and channels, leading to high computational complexity. In the future, two major research directions should be considered: efficiently design on the distribution patterns of the pilots or the training symbols; and the low computational complexity for the blind or semi-blind algorithms.
3) Most schemes at present deal with the synchronization and the channel estimation separately. In fact, the channel estimation may be severely affected by the residual synchronization errors, and from the system design optimization point of view, these two operations should be considered jointly.
4) The Doppler shift in wireless mobile communications causes ICI and destroys the orthogonality of OFDM symbols. Phase noises in the OFDM systems may introduce Common Phase Error (CPE) and ICI. There have already been many solutions, yet special attention should be paid in dealing with them in the OFDM systems.

For the criteria selecting the appropriate synchronization algorithms, it greatly depends on the applications. For example, different synchronization algorithms have been adopted with different applications such as DVB-T [2], DMB-T [14], and systems in either continuous mode or, burst packet mode. In the continuous transmission mode, with the synchronization time not that critical, we can exploit frequency synchronization to ensure the more accurate synchronization results. Synchronization time, system complexity, the required system performance and etc. are all the factors that should be considered when choosing the synchronization scheme for the particular system.

VIII. Conclusion

In this paper, we focused on the major key synchronization issues in the OFDM systems. Typical algorithms such as the symbol timing, the carrier frequency and the sampling clock synchronization are discussed with the special emphasis on the difference in choosing of the synchronization technologies between the continuous and the burst packet mode systems. Three improved algorithms to do the fine symbol timing in frequency domain are also proposed with computer simulations validating its performance improvement. The technical forecast on the future trend of synchronization techniques provided at the end of this overview, which is of reference value when addressing the synchronization issues in the OFDM and other related systems.

Acknowledgment

The authors would like to acknowledge the National Natural Science Funds in China (Nos. 50177001, 60372007, and 60 332 030) and the Ministry of Information Industry Foundation under Grant 2002291, and also express their great thanks to Professor Song Jian in Tsinghua University and the anonymous reviewers for their thorough review and constructive suggestions.

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