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Robust frame synchronization method for FDD-LTE systems

Xu Wenhu Yang Guangqi Liu Jin Hong Wei

(State Key Laboratory of Millimeter Waves, Southeast University, Nanjing 210096, China)

Abstract: The primary synchronization signal and the secondary synchronization signal are respectively used to fulfill the sub-frame and frame synchronization in the long term evolution (LTE) systems. Based on the assumption that the channel frequency response of the primary synchronization signal symbol is nearly the same as that of the secondary synchronization symbol in frequency division duplex-LTE (FDD-LTE), a new synchronization method is proposed. The frame synchronization success probability is simulated in different wireless channel models and the Mento-Carlo method is used in the simulation. Simulation results show that if the LMMSE channel estimation is adopted, the proposed method is robust at a low signal noise ratio (SNR) scenario and works well when carrier frequency offset and fast Fourier transform (FFT) window timing offset are considered in practical applications. The frame synchronization success probability can still exceed 99% with an SNR of 0 dB when the maximum Doppler shift is very large, which means that this robust frame synchronization method can be applicable in most mobile situations. Simulation results also show that the success probability of the proposed frame synchronization method is higher than that of the method which fulfills the frame synchronization through correlating the received secondary synchronization symbol with local sequences in practical applications.

Key words: frame synchronization; long term evolution; cell search; channel estimation

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The long term evolution (LTE) is a new order mobile communication standard specified by the 3GPP within Release 8[1]. The 3GPP LTE systems aim to support more reliable and higher data rate communications over time-dispersive (frequency-selective) channels with limited spectra than current 3G systems. The orthogonal frequency division multiple access (OFDMA) technique is chosen as the downlink multiple access scheme of LTE systems. It provides several advantages, such as high spectral efficiency, simple equalization implementation in the receiver, and robustness in a multi-path environment with the aid of the cyclic prefix (CP)[2].

In a cellular system, the first physical layer procedure is the cell search which usually includes timing synchronization, frequency synchronization and cell ID detection[3]. The existing frame synchronization algorithms for OFDM can be broadly grouped into CP-based synchronization techniques and data-aided synchronization techniques[4-6]. In order to obtain good cell search performance, the LTE adopts the second one, and two dedicated synchronization signals, the primary synchronization signal (PSS) and the secondary synchronization signal (SSS), are defined[1]. The PSS is used to obtain the sub-frame synchronization which can be achieved by correlating the received signal with a replica of the transmitted primary synchronization signal (i.e., using a matched filter), thereby, identifying a correlation peak at the proper symbol timing[7]. After the sub-frame synchronization is found, the SSS is used to fulfill the frame synchronization. And the cell ID can be uniquely confirmed after the PSS and SSS are detected.

Once the PSS is confirmed, the correlating method, which makes use of the correlation property of the SSS[8], is also used to detect the frame synchronization. In this paper, a new method is proposed to fulfill the frame synchronization. The proposed method takes advantage of the correlation of the transmission channel estimated through the PSS and the SSS, respectively. This assumed correlation is usually true, especially in a relative low speed scenario, since the PSS and the SSS are placed close to each other in the radio frame of the FDD-LTE.

1 Radio Frame Structure and Synchronization Signals

According to 3GPP LTE specifications[1], there are two operation modes, the TDD mode and the FDD mode. In this paper, we focus on the FDD mode. The downlink data of the physical layer are organized into radio frames with a duration of 10 ms in the FDD mode. Each radio frame consists of 10 sub-frames. Each subframe has two consecutive 0.5 ms slots, and each slot consists of seven OFDM symbols. The PSS and the SSS are allocated in the last and the second last symbol of slot #0 and slot #10, respectively; the two primary synchronization signals in the two slots are identical, but the two secondary synchronization signals are different. Thus, the sub-frame boundary can be detected through the PSS and the frame boundary must be detected through the SSS. The downlink radio frame structure of the FDD mode is illustrated in Fig. 1.

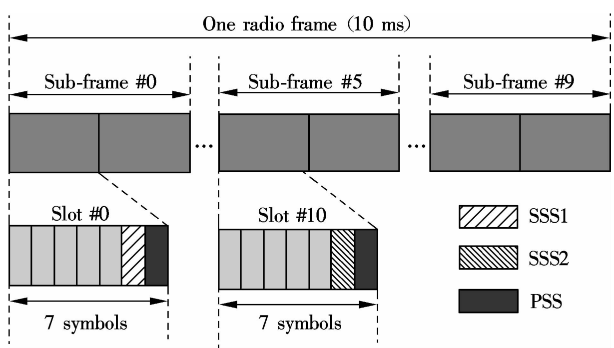

Fig. 1 Downlink radio frame structure in FDD mode

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Biographies: Xu Wenhu (1980—), male, graduate; Hong Wei (corresponding author), male, doctor, professor, weihong@seu.edu.cn.

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The LTE systems support a variable bandwidth between 1.4 MHz and 20 MHz. Tab. 1 shows the parameters of different operation bandwidths. The sub-carrier spacing is 15 kHz; the sampling rate and the FFT size are proportional to the operation bandwidth.

Tab. 1 Parameters for different operation bandwidth configurations

Operation bandwidth/MHz	Sub-carriers	Sample frequency/MHz	FFT size
1.4	73	1.92	128
3	181	3.84	256
5	301	7.68	512
10	601	15.36	1 024
15	901	23.04	1 536
20	1 201	30.72	2 048

The PSS is defined with three frequency-domain Zadoff-Chu sequences, each of which represents a sector identity (0 to 2) within a cell. The SSS carries the information of the cell identity (0 to 167) and it is a binary sequence encoded with a scrambling sequence depending on the PSS. Both the synchronization signals have a length of 62 and they are always assigned to be transmitted on the central 62 sub-carriers located symmetrically around the DC-carrier regardless of the system bandwidth.

2 System Model and Proposed Frame Synchronization Method

2.1 System model

The basic idea underlying OFDM is the division of the available frequency spectrum into several sub-carriers. Serial data stream is converted into parallel blocks of size N_u and these blocks are modulated on corresponding sub-carriers. After guard sub-carriers of size $N-N_u$ are inserted, the time domain samples can be obtained from frequency domain samples using inverse fast Fourier transform (IFFT) as

$$x_l(n) = \mathrm{IFFT}\{X_l(k)\} = \sum_{k=0}^{N-1} X_l(k)\,\mathrm{e}^{\mathrm{j}2\pi nk/N} \qquad 0 \leqslant n \leqslant N-1 \tag{1}$$

where $X_l(k)$ is the transmitted data symbol at the k-th sub-carrier of the l-th OFDM symbol; N is the IFFT size. In order to eliminate any interference between adjacent OFDM symbols, a CP which is longer than the overall channel impulse response is appended. The transmitted signal is then sent to a mobile radio channel.

At the receiver, the signal is received along with noise. After synchronization, down-sampling, and CP removal, the received l-th OFDM symbol $y_l(n)$ is transformed to the frequency domain using fast Fourier transform (FFT). The simplified base-band model of the received l-th OFDM symbol in the frequency domain can be formulated as

$$Y_l(k) = \mathrm{FFT}\{y_l(n)\} = X_l(k)H_l(k) + W_l(k) \qquad 0 \leqslant k \leqslant N-1 \tag{2}$$

where H_l is the channel frequency response (CFR) of the l-th OFDM symbol and W_l is the Fourier transform of additive white Gaussian noise (AWGN) at the l-th OFDM symbol.

If the downlink synchronization symbols of LTE systems are considered, let $X_{\mathrm{SS}}(k)$ and $Y_{\mathrm{SS}}(k)$ represent the k-th element of the transmitted and received synchronization signals, respectively, and a more compact matrix equation can be used:

$$\boldsymbol{Y}_{SS} = \boldsymbol{X}_{SS}\boldsymbol{H}_{SS} + \boldsymbol{W}_{SS} \tag{3}$$

where $\boldsymbol{Y}_{\mathrm{SS}}$ is the received frequency-domain synchronization signal vector $\boldsymbol{Y}_{\mathrm{SS}} = [Y_{\mathrm{SS}}(0), Y_{\mathrm{SS}}(1), \ldots, Y_{\mathrm{SS}}(61)]^{\mathrm{T}}$; $\boldsymbol{X}_{\mathrm{SS}}$ is the transmitted frequency-domain synchronization signal matrix $\boldsymbol{X}_{\mathrm{SS}} = \mathrm{diag}(X_{\mathrm{SS}}(0), X_{\mathrm{SS}}(1), \ldots, X_{\mathrm{SS}}(61))$; $\boldsymbol{H}_{\mathrm{SS}}$ is the CFR vector of central 62 sub-carriers at the synchronization symbols, and $\boldsymbol{W}_{\mathrm{SS}}$ is the frequency-domain AWGN vector of central 62 sub-carriers at the synchronization symbols.

2.2 Proposed frame synchronization method

According to Eq. (3), since the synchronization signals are known to the receiver, the CFR vector of central 62 sub-carriers at the synchronization symbols can be estimated as

$$\hat{\boldsymbol{H}}_{\mathrm{SS}} = \boldsymbol{X}_{SS}^{-1}\boldsymbol{Y}_{\mathrm{SS}} \tag{4}$$

In the LTE specification, there are totally 168 SSS and 3 PSS. Once a synchronization signal pair is selected in the transmitter, two scrambled SSS can be generated and assigned to the SSS symbol in each half-frame. As Fig. 1 shows, the PSS symbol is next to the SSS symbol in each half-frame, so the $\hat{\boldsymbol{H}}_{\mathrm{PSS}}$ estimated on the PSS can be assumed to be nearly equal to the $\hat{\boldsymbol{H}}_{\mathrm{SSS}}$ estimated on the SSS. After the PSS and sub-frame boundary are detected, the SSS and frame boundary detection can be fulfilled with the following steps:

1) Estimate channel frequency responses $\hat{\boldsymbol{H}}_{\mathrm{PSS}}$ and $\hat{\boldsymbol{H}}_{\mathrm{SSS}}$ based on the detected PSS and the potential scrambled SSS, respectively.

2) Calculate $|\hat{\boldsymbol{H}}_{\mathrm{SSS}}\hat{\boldsymbol{H}}_{\mathrm{PSS}}^{\mathrm{H}}|$ and find the index of peak value PEAK_INDEX, where $(\cdot)^{\mathrm{H}}$ represents the Hermitian transpose.

3) If PEAK_INDEX < 168, the SSS number is equal to PEAK_INDEX and $\hat{\boldsymbol{H}}_{\mathrm{PSS}}$ is the CFR of the PSS symbol in the former half-frame; if PEAK_INDEX ⩾ 168, the SSS number is equal to PEAK_INDEX-168 and $\hat{\boldsymbol{H}}_{\mathrm{PSS}}$ is the CFR of the PSS symbol in the latter half-frame.

The frame synchronization success probability of the proposed method is evaluated using the Monte-Carlo method under different SNR conditions and three multi-path channel models (EPA, EVA and ETU) recommended in LTE specifications, assuming that the operation bandwidth of the LTE system is 15 MHz and the frequency and sub-frame synchronizations are ideal. The simulation times are 10^4 and the simulation results are given in Fig. 2.

Fig. 2 shows that the proposed method can work well when the SNR is high. This result is expected since Eq. (4) is a least squares (LS) estimation of channel frequency response. Without using any knowledge of the statistics of the channels, the LS estimation can be calculated with low complexity, but it suffers from a high mean squared error (MSE) especially under low SNR conditions. The best linear estimator in terms of the MSE is the linear minimum mean squared error estimator (LMMSE). But the high computational com-

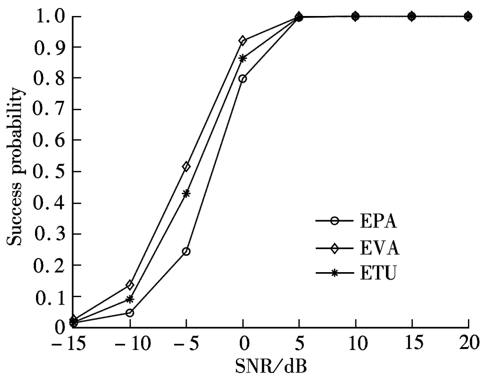

Fig. 2 Frame synchronization success probability under LS channel estimation in ideal synchronization situations

plexity restricts its practical application. A simplified LMMSE can be represented as[9]

$$\hat{\boldsymbol{H}}_{\mathrm{LMMSE}} = \hat{\boldsymbol{R}}_{\mathrm{HH}} \left(\hat{\boldsymbol{R}}_{\mathrm{HH}} + \frac{\beta}{\mathrm{SNR}} \hat{\boldsymbol{I}} \right)^{-1} \hat{\boldsymbol{H}}_{\mathrm{LS}} \tag{5}$$

where $\hat{\boldsymbol{H}}_{\mathrm{LMMSE}}$ and $\hat{\boldsymbol{H}}_{\mathrm{LS}}$ are simplified LMMSE and LS estimations of channel frequency responses, respectively. $\hat{\boldsymbol{R}}_{\mathrm{HH}}$ is the channel auto-correlation matrix. β is a constant depending on the signal constellation and SNR is the average signal-to-noise ratio. It is proved that by using a uniform power delay profile, making the SNR a fixed high value and singular value decomposition, the computational complexity of this simplified LMMSE can be reduced greatly while the performance remains satisfactory[9]. When the simplified LMMSE estimation is used, the success probability of the proposed frame synchronization method is shown in Fig. 3. Obviously, adoption of the simplified LMMSE channel estimation makes the proposed frame synchronization method more reliable in low SNR conditions.

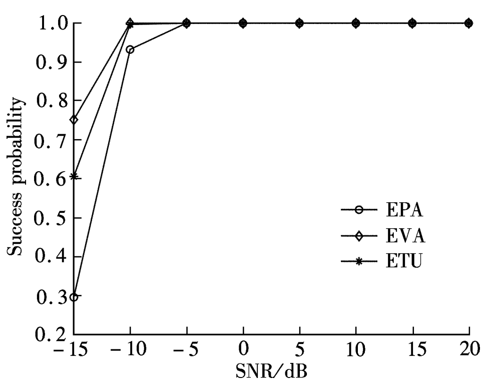

Fig. 3 Frame synchronization success probability under simplified LMMSE channel estimation in ideal synchronization situations

3 Practical Application

3.1 Effect of CFO and timing offset

In section 2, the proposed method is introduced under ideal synchronization situations. In practical mobile applications, the receiver usually has a carrier frequency offset (CFO) with the transmitter owing to the oscillator instability and it experiences the Doppler effects. Although this CFO can be estimated by the PSS, a residual CFO should be considered because some estimation errors always exist. In addition, a perfect sub-frame synchronization or FFT window synchronization can almost not be achieved and this timing offset should also be considered. Fortunately, the effect of the FFT window timing offset can be absorbed into the CFR and has no impact on the system performance as long as the timing offset Δd is in the "safe" range[10]:

$$-N_{\mathrm{g}} + \tau_{\max} < \Delta d \leqslant 0 \tag{6}$$

where N_{g} is the length of CP and $\tau_{\max}$ is the maximum delay dispersion of the radio channel. This FFT window timing offset requirement is relatively easy to be achieved in the sub-frame synchronization phase. Thus, when the residual CFO and FFT window timing offset are taken into account, Eq. (2) can be rewritten as[11-12]

$$\begin{aligned} Y_l(k) = {} & \mathrm{e}^{\mathrm{j}2\pi(k+\varepsilon)\Delta d/N} \mathrm{e}^{\mathrm{j}2\pi\varepsilon l(N_{\mathrm{g}}+N)/N} \mathrm{e}^{\mathrm{j}2\pi\varepsilon N_{\mathrm{g}}/N} \cdot \\ & \alpha(\varepsilon) X_l(k) H_l(k) + I(\varepsilon) + W_l(k) = \\ & \mathrm{e}^{\mathrm{j}2\pi\varepsilon l(N_{\mathrm{g}}+N)/N} X_l(k) \widetilde{H}_l(k) + I(\varepsilon) + W_l(k) \end{aligned} \tag{7}$$

where ε is the frequency offset normalized to the sub-carrier spacing while $\alpha(\varepsilon)$ and $I(\varepsilon)$ are the attenuation factors and inter-carrier interference (ICI) caused by the residual frequency offset, respectively.

According to Eq. (7), only $\mathrm{e}^{\mathrm{j}2\pi\varepsilon l(N_{\mathrm{g}}+N)/N}$ is related to symbol index l, then $\widetilde{H}_{\mathrm{PSS}}(k)$ and $\widetilde{H}_{\mathrm{SSS}}(k)$ can be assumed to be equal. When excluding the impact of ICI and $W_l(k)$, $|\hat{\boldsymbol{H}}_{\mathrm{SSS}} \hat{\boldsymbol{H}}_{\mathrm{PSS}}^{\mathrm{H}}|$ can be expressed as

$$\begin{aligned} |\hat{\boldsymbol{H}}_{\mathrm{SSS}} \hat{\boldsymbol{H}}_{\mathrm{PSS}}^{\mathrm{H}}| = {} & \left| \mathrm{e}^{\mathrm{j}2\pi\varepsilon(N_{\mathrm{g}}+N)/N} \sum_{k=0}^{61} \widetilde{H}_{\mathrm{SSS}}(k) \widetilde{H}_{\mathrm{PSS}}^{*}(k) \right| = \\ & \sum_{k=0}^{61} |\widetilde{H}_{\mathrm{PSS}}(k)|^{2} \end{aligned} \tag{8}$$

Eq. (8) shows that when the FFT window timing offset is in the "safe" range, the proposed frame synchronization method is only influenced by the excluded AWGN and the ICI caused by the residual CFO.

3.2 Simulations

A residual CFO of 1 500 Hz and an FFT window timing offset of -10 (in the "safe" range) are assumed in the following simulations. Other simulation parameters are the same as those in section 2 and the simulation results are shown in Figs. 4 and 5. The Monte-Carlo method is used and the simulation times is 10^4.

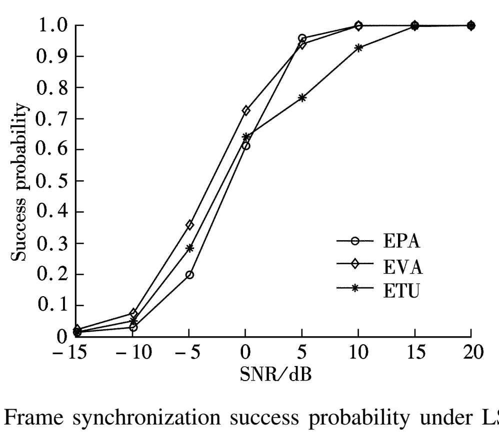

Fig. 4 Frame synchronization success probability under LS channel estimation in practical synchronization situations

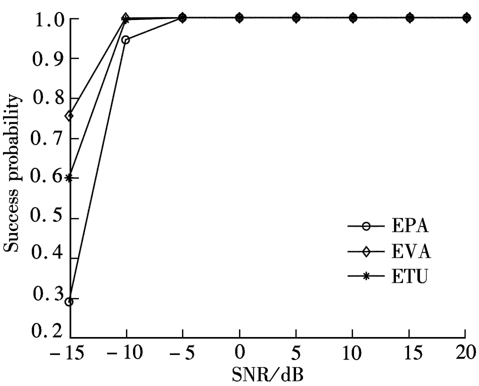

Fig. 5 Frame synchronization success probability under simplified LMMSE channel estimation in practical synchronization situations

Comparing Fig. 4 with Fig. 2, when the LS channel estimation is adopted, it is obvious that the effect of ICI reduces the frame synchronization success probability by about 5% to 20% under relatively low SNR conditions. When the simplified LMMSE channel estimation is applied, it can be seen from Fig. 3 and Fig. 5 that the frame synchronization success probability is nearly the same, which shows that the simplified LMMSE channel estimation can eliminate the effects of ICI as well as that of AWGN. Thus, adoption of the simplified LMMSE channel estimation will make the proposed frame synchronization robust when timing and frequency offsets exist in practical cell searches.

The channel is assumed to be quasi-static in the proposed frame synchronization method. In practical wireless applications, Doppler shifts, which arise from relative motion between base-station and user equipment, always exist. The user equipment (UE) moving at a high speed may experience a large Doppler shift, which can destroy the quasi-static channel assumption. Thus, the application of the proposed frame synchronization method may be restricted. The frame synchronization success probability with simplified LMMSE channel estimation under different Doppler shifts is simulated and the results are given in Fig. 6. The success probability of the frame synchronization method in Ref. [8] are also given for comparison. The Jakes Doppler spectrum is assumed in the simulation. A CFO of 1 500 Hz and a FFT window timing offset of −10 are also assumed here, and the EVA channel model is adopted.

It can be seen from Fig. 6(a) that the frame synchronization success probability of the proposed frame synchronization method declines with the increasing maximum Doppler shift in a low SNR situation. When the SNR is above 0 dB, the frame synchronization success probability is still beyond 99% even if the UE experiences a large Doppler shift of 300 Hz. It is because the symbol duration of the PSS plus the SSS is far less than the coherence time of the wireless channel even in a high Doppler shift situation owing to the very small chip duration of the LTE (only about 32. 55 ns). So, the proposed frame synchronization method can work well in most mobile communication situations. Fig. 6 shows that the frame synchronization success probability of the proposed method is obviously larger than that of the method in Ref. [8] in practical applications. The effect caused by the FFT window timing offset and parts of the effect caused by the CFO can be absorbed into the CFR; thus, the CFR correlation between the PSS and the SSS is little affected. But the same effects of FFT window timing offset and CFO can ruin the orthogonality of the SSS, which makes the frame synchronization success probability decline even in a high SNR scenario.

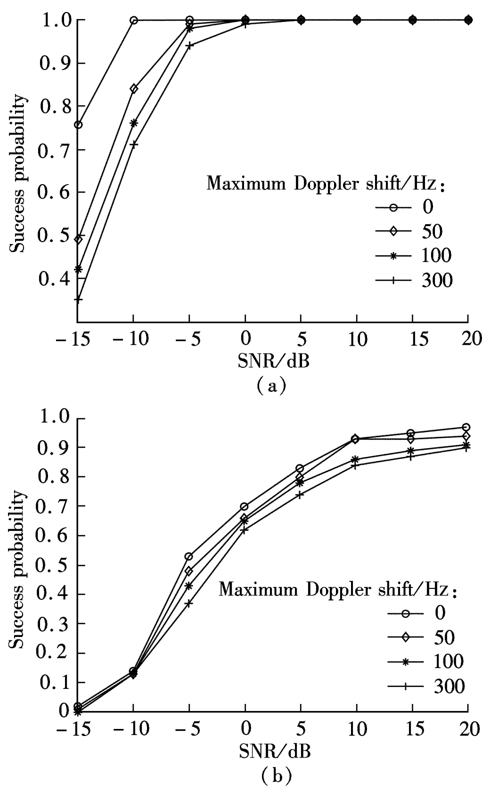

Fig. 6 Frame synchronization success probability under different Doppler shifts. (a) Proposed frame synchronization method; (b) Frame synchronization method in Ref. [8]

4 Conclusion

In this paper, a new frame synchronization method in the cell search of the LTE is proposed. This method makes use of the channel correlation between the PSS symbol and the SSS symbol in the downlink radio frame of the LTE. The impacts of a residual CFO and timing offset are also considered since these offsets are unavoidable in practical cell search. The success probability of this frame synchronization method is evaluated and the simulation results illustrate that the proposed method performs well in three multi-path channel models recommended in the LTE specification even in a low SNR scenario when the simplified LMMSE estimation is applied. The Doppler shift effect on frame synchronization success probability is evaluated using the Monte-Carlo method. Simulations show that the proposed frame synchronization method can work well in most mobile situations and its success probability is higher than that of the method proposed in Ref. [8].

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FDD-LTE 系统中的鲁棒帧同步方法

徐文虎　杨广琦　刘　进　洪　伟

（东南大学毫米波国家重点实验室，南京 210096）

摘要：长期演进（LTE）协议中规定的主同步信号和辅同步信号分别用来完成子帧同步和帧同步. 基于频分双工长期演进（FDD-LTE）无线帧中主同步信号和辅同步信号的信道频响基本相等的假设，提出了一种帧同步方法. 采用蒙特卡罗方法对该同步方法在不同信道模型下的帧同步成功概率进行了仿真. 仿真结果表明：当采用线性最小均方差信道估计时，该方法的性能在存在载波频偏和快速傅立叶变换（FFT）窗定时偏差的实际应用环境中仍然很好，并且在低信噪比条件下保持鲁棒. 通过在不同多普勒频移条件下进行仿真和分析，发现当信噪比大于 0 dB 时，即使在高多普勒频移环境下，该方法的帧同步成功概率仍超过 99%，这意味着此帧同步方法能适用于大多数移动通信环境. 通过与利用辅同步信号的正交性，采用在频域把接收到的辅同步信号和本地序列进行相关操作完成帧同步的方法对比，该方法在存在载波频偏、FFT 窗定时偏差和多普勒频移的移动应用环境中的帧同步成功概率具有明显优势.

关键词：帧同步；长期演进；小区搜索；信道估计

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