A Preamble-based Cell Search Scheme for OFDMA Cellular Systems

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Abstract

This paper proposes a preamble-based cell search scheme for OFDMA cellular systems. The first training symbol is common to all cells enabling a fast and robust synchronization in cellular environment. The synchronization includes frame detection, the integral part and fractional part of carrier frequency offset, fine symbol timing. The second training symbol is cell specific. Inference inter-cells or inter-sectors can be mitigated by modulating different subcarrier sets in frequency domain. Furthermore, to compensate the channel impairments, a differentia-based cell identification algorithm in frequency domain is proposed. Simulation results show that the proposed preamble-based cell search scheme is robust and efficient in cellular environment in multipath fading channel.

1. Introduction

Recently, orthogonal frequency division multiplexing (OFDM) has been widely accepted as the most promising radio transmission technology for the next generation wireless systems due to its advantages such as the robustness to multipath fading, granular resource allocation capability, and no intercell interference. Among the conventional OFDMA based wireless systems, digital audio broadcasting (DAB), digital video broadcasting, IEEE 802.11a, and Hiperlan/2 are well known [1-5]. For cellular systems, it is one of the most requirements to provide robust synchronization and cell searching capability.

In DAB systems, null symbols and phases reference symbols are used for synchronization such as frame detection, symbol timing, integer and fractional part of frequency offset. On the other hand, a short preamble and a long preamble are used for bust synchronization in IEEE 802.11a and Hiperlan/2 systems, such frame detection, symbol timing, coarse and fine frequency offset, channel estimation. However, these schemes are not appropriate for a cellular system.

In this paper, we proposed a preamble-based cell search scheme for OFDMA cellular systems in broadband multipath fading channel. The preamble satisfies the following requirements:

- Supporting easy deployment of system
- Fast and accurate initial synchronization
- Channel estimation performance
- Enough number of cell IDs
- Reliable cellular sector search performance

The rest of the paper is organized as follows. In section 2, the system model is described. Synchronization algorithms and cell identification algorithm for cellular OFDMA systems are presented in section 3. Section 4 gives numerical results. Conclusions are drawn in section 5.

2. System model

The samples of the transmitted baseband OFDM signal, assuming ideal Nyquist pulse shaping, can be expressed as

$$x_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N_u-1} X_k e^{j\frac{2\pi kn}{N}} \quad -G \le n \le N-1 \quad (1)$$

where X_n is the modulated data or subcarrier symbol, N is the number of inverse fast Fourier transform(IFFT) points, $N_u(\le N)$ is the number of used subcarriers, G is the number of guard samples. The OFDM samples are pulse-shape filtered at every $1/T_s$ and the filter output is up converted for signal transmission.

The impulse response of the multipath fading channel is assumed to be in the form

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The research is mainly funded by Nature Science Fund of China (NSFC), Project NO.60302025

$$h(\tau;t)=\sum_{l=0}^{L_p-1} h_l(t)\delta(\tau-\tau_l) \qquad (2)$$

where L_p is the number of resolvable multipaths and $h_l(t)$ and τ_l represent the equivalent low pass impulse response and delay time of the lth path, respectively. It is assumed that $GT_s>\tau_{max}=(L_p-1)T_s$, that is, the guard interval is larger than the maximum delay spread of the channel so that ISI can be completely eliminated.

If the received signal is affected by the CFO f_0, the output signal of the channel is

$$r(t)=e^{j2\pi f_o t}\int_{-\infty}^{\infty} x(t-\tau)h(\tau;t)\,d\tau+w(t) \qquad (3)$$

where $x(t)$ is the baseband OFDM signal and $w(t)$ is a zero-mean complex additive white Gaussian noise (AWGN). The received signal is matched filtered and sampled at the OFDM sample rate $1/T_s$. Assuming that the matched filter is flat within the transmitter bandwidth and the symbol timing is obtained within the guard interval region such that $-GT_s+\tau_{max}\leq n_oT_s\leq 0$, the samples belonging to the first effective OFDM symbol, after the timing synchronization is performed, can be written as

$$y_n=e^{j\theta_o}e^{j2\pi f_o nT_s}\sum_{l=0}^{L_P-1} h_l\big((n+n_o)T_s\big)x_{n-n_l}+w_n \qquad (4)$$

for $n=0,1,\ldots N-1$

where $\theta_0=2\pi f_0 n_0 T\text{s}$, $n_l=[-n_0+\tau_l/T_s]$, and w_n is the sampling output of the AWGN.

To clearly see the effect of the CFO on the FFT output, let us assuming that the channel is time invariant during one OFDM symbol duration, i.e., $h_l(nT_s)=h_l$, $n=0,1,\ldots,N-1$. Then the FFT output is given by

$$\begin{aligned} Y_m &= \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} y_n e^{-j\frac{2\pi nm}{N}} \\ &= e^{j\theta_o}\sum_{k=0}^{N_u-1} H_k X_k \frac{1}{N}\sum_{n=0}^{N-1} e^{j\frac{2\pi n(k-m+\varepsilon_o)}{N}}+W_m \end{aligned} \qquad (5)$$

where

$$H_k=\sum_{l=0}^{L_P-1} h_l e^{-j(2\pi k n_l/N)} \qquad (6)$$

$$W_m=\left(1/\sqrt{N}\right)\sum_{n=0}^{N-1} w_n e^{-j(2\pi nm/N)} \qquad (7)$$

and $\varepsilon_0=f_0NT_s$ is the relative frequency offset (RFO).Let the RFO be expressed as $\varepsilon=2\varepsilon_I+\varepsilon_F$, where $2\varepsilon_I$ is the integral part of the RFO(IFO) that is even and ε_F is the fractional part of the RFO(FFO) with $|\varepsilon_F|<1$. Then (5) can be rewritten as

$$\begin{aligned} Y_m &= e^{j\theta_o} H_{m-2\varepsilon_I} X_{m-2\varepsilon_I} e^{j\left(\frac{N-1}{N}\right)\pi\varepsilon_F} \frac{\sin(\pi\varepsilon_F)}{N\sin\left(\frac{\pi\varepsilon_F}{N}\right)}+ \\ & e^{j\theta_o}\sum_{k\neq m-2\varepsilon_I} H_k X_k \cdot\{e^{j\pi\varepsilon_F}\sin(\pi\varepsilon_F) \\ & /e^{j\frac{\pi(m-k-2\varepsilon_I)}{N}} N\sin\left(\frac{\pi(k-m+2\varepsilon_I+\varepsilon_F)}{N}\right)\}+W_m \end{aligned} \qquad (8)$$

It is worthy to note that IFO alters the order of the FFT outputs while the FFO causes the interchannel interference (ICI) in the FFT outputs.

3. Synchronization algorithm

3.1. Frame detection

The first training symbol has the property $x_{n+N/2}=x_n$, $n=0,1,N/2-1$, which is achieved by transmitting a PN sequence over the even subcarriers and zeros over the odd subcarriers. The coarse symbol timing can be then efficiently searched by minimizing the metric[6][7]:

$$\Lambda(d)=\frac{E(d)-2|P(d)|}{E(d)} \qquad (9)$$

where

$$E(d)=\sum_{i=0}^{N/2-1}\left(\left|r(i+d+N/2)\right|^2+\left|r(i+d)\right|^2\right) \qquad (10)$$

$$P(d)=\sum_{i=0}^{N/2-1} r(i+d+N/2)r^*(i+d) \qquad (11)$$

After the coarse symbol timing is obtained, the FFO can be estimated by:

$$\hat{\varepsilon}_F=\text{angle}\big(P(d)\big)/\pi \qquad (12)$$

3.2. Frequency acquisition

After the FFO of the training OFDM symbol is corrected by multiplying the OFDM samples by $\exp\left(-j2\pi n\hat{\varepsilon}_F/N\right)$, the FFT outputs of the training symbols assuming perfect correction can be written as

$$Y_m=\sqrt{2}e^{j\theta_0}H_{m-2\varepsilon_I}X_{m-2\varepsilon_I}+W_m \qquad (13)$$

$m=0,1,\ldots,N-1$

where $X_m=0$ if m is odd or $m>N_u$. While the ICI may exist in (13), if the FFO estimation error exists as noted already in (8) it is very small at reasonable signal-to-noise ratio(SNR) values so that the effect of the residual CFO error may be ignored.

Let us define a sequence

$$C_k = \frac{X_{2k}}{X_{2k+2}}\ , k=0,1,\ldots,N_u/2\text{-}2 \tag{14}$$

which has the differential coding structure in the frequency domain . Let us assume that the symbol timing is perfectly found and the FFO is compensated without error. The quotient Y_{2k}/Y_{2k+2} is then approximately equal to C_k except that it would be shifted by $2\varepsilon_I$ in the frequency domain due to the uncompensated IFO. While the difference between the phases of Y_{2k}/Y_{2k+2} and C_k may exist due to the difference between H_{2k} and H_{2k+2}, it can be ignored since fading components of adjacent subchannels are strongly correlated for OFDM systems with a large number of subcariers. Therefore, an estimate of ε_I is $\hat{g}=g$ which maximizes the metric

$$F(g) = \frac{\left|\sum_{k\in\kappa} Y_{2k+2g} C_k^* Y_{2k+2g+2}^*\right|^2}{\left(\sum_{k\in\kappa}\left|Y_{2k+2g}\right|^2\right)^2} \tag{15}$$

where $\kappa=\{0,1,\ldots,N_u/2\text{-}2\}$ and the denominator is used to normalize the metric value..

3.3. Fine Symbol Synchronization

The perfect autocorrelation property of PN sequence can be used for OFDM time synchronization. The PN-based time synchronization function is given by

$$\gamma(d) = 1/M^2 \cdot \left(\sum_{m=0}^{M-1} a^*(m) z(d+m)\right)^* \times \left(\sum_{m=0}^{M-1} a^*(m) z(d+m+M)\right) \tag{16}$$

where $z(n)$ is the carrier frequency offset compensated received signal in time domain and $a(n)$ is the training signal in time domain.

3.4. Cell Identification Algorithm

After achieving time and frequency synchronization, the cross-correlations of the FFT output vector of cell specific training symbol with all possible frequency domain preamble patterns are computed in frequency domain for cell identification.

Since the channel estimation requires a priori knowledge of $\mathrm{ID}_{\mathrm{cell}}$ to be associated, the initial cell search is performed without channel compensation. Thus, in most multipath fading channel environments, the frequency domain cross-correlation is likely to corrupt in case of either frequency selective fading or nonzero OFDM symbol timing offset. Therefore, differential demodulation is employed in frequency domain prior to the cross-correlation in order to mitigate the corruption.

The inference from neighboring cells or sectors is mitigated by modulating different nonzero pilot subcarrier sets in frequency domain. In our scheme, the total P_u nonzero pilot subcarriers are divided into three segments. Let $X_n(k)$ be cell specific random codes in frequency domain, the differential vector $B_n(k)=X_n(k)/X_n(k+1)$, for $k=0,1,2,\ldots P_u\text{-}1$ and n is a cell ID. Let $Y(k)$ be the frequency domain symbols at the kth sub-carrier after the FFT. For each of the three segments, compute the differential-based vector for every third subcarrier

$$Z_s(k) = Y_s(k)/Y_s(k+1) \tag{17}$$

where $s=0,1,2$. The correlation function between the nth cell and the sth differential vector is

$$m_n(s) = \frac{\sum_{k=0}^{P_u-1} Z_s(k)\cdot B_n^*(k)}{\sum_{k=0}^{P_u-1}\left|Z_s(k)\right|^2} \tag{18}$$

4. Simulation results

The proposed cell search scheme is evaluated in multipath fading channels. The carrier frequency is 2GHz and the sampling frequency is 16MHz. The FFT size is N=1024 and the G is composed of 128 samples. The used carriers N_u is 864. The Rayleigh fading channel model adopted is ITU vehicular channel A which is composed of six paths with path delays of 0, 4, 11, 17, 27, 40 samples. 128 random codes are generated as the frequency domain cell specific patterns with $\mathrm{ID}_{\mathrm{cell}}$=0,1,…,127 and the RFO is in [-40 40].

For the worst case, we consider the case when the preamble signals from three adjacent base stations are Rayleigh faded independently from each other and arrive at an SS at an identical average power level at the same time. Let us call the cells as cell A, cell B and cell C and their cell ID is 10, 21 and 33 respectively.

Fig. 1 shows the histogram of timing error after the coarse symbol synchronization with an SNR=9dB. We can see that the coarse symbol timing estimation has a large standard deviation. Fig.2 shows the mean squared errors of coarse carrier frequency offset estimation.

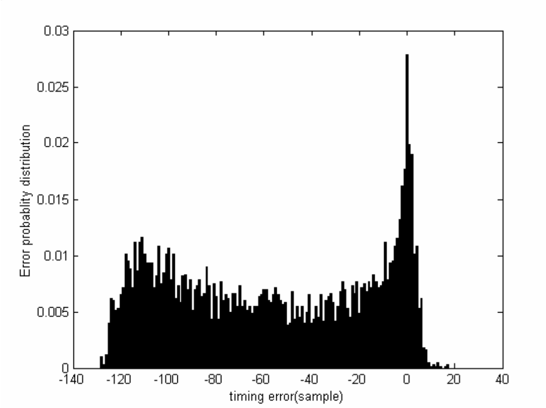

Fig.1. The histogram of symbol timing errors after the coarse symbol synchronization

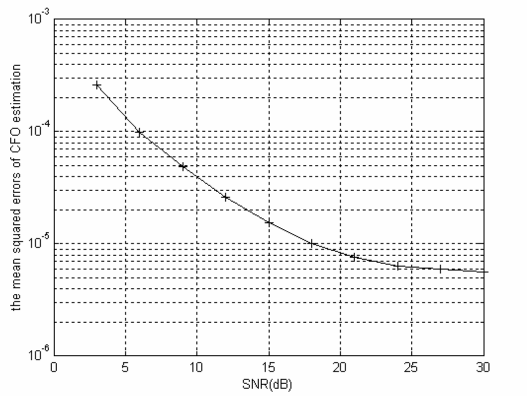

Fig. 2. The mean squared error of fractional frequency offset

Fig.3 plots the magnitude waveforms of IFO estimator obtained with an SNR=3dB and an RFO=34.53. The calculated FFO is 0.5151 and the coarse symbol timing error is -15(sample). Here the IFO estimation is $\hat{g}$=2×17=34.

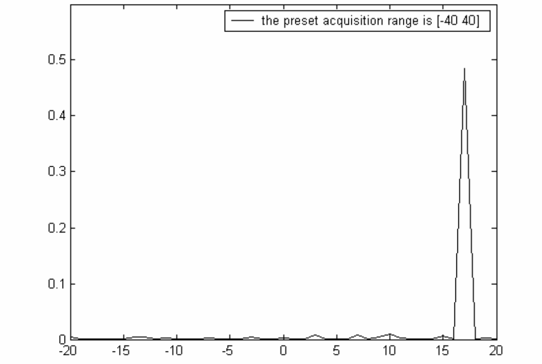

Fig.3. The magnitude waveforms of integer frequency offset estimator

Fig.4 shows the fine symbol timing synchronization function. The PN-based synchronization signal has a peak for each of the resolvable channel taps in multipath channels. Fig.5 shows the histogram of the symbol timing error after the fine symbol timing estimation is done. The algorithm acquires mostly the first path or the second path. In the ITU vehicular A channel, the first path is strongest but the second path is only low 1dB in average power. The acquisition of the first path can be done by channel estimation [9] which is not discussed here.

Fig.6 shows the differential-based cell identification function in frequency domain. Fig.7 shows the probability of selecting cell A, cell B and cell C. The probability of selecting the other cells is observed to be zero. The signals from different cells undergone independent channel impairments and the SS choose the best one.

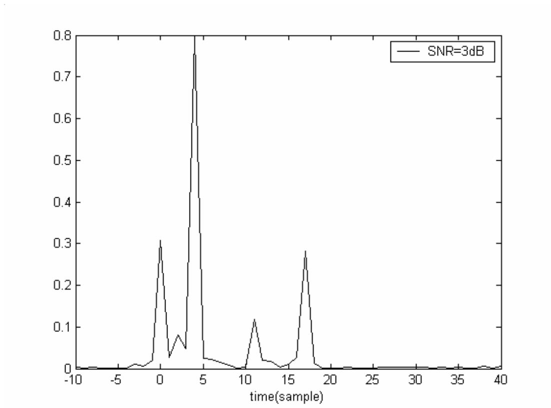

Fig. 4. The amplitude of fine symbol synchronization function

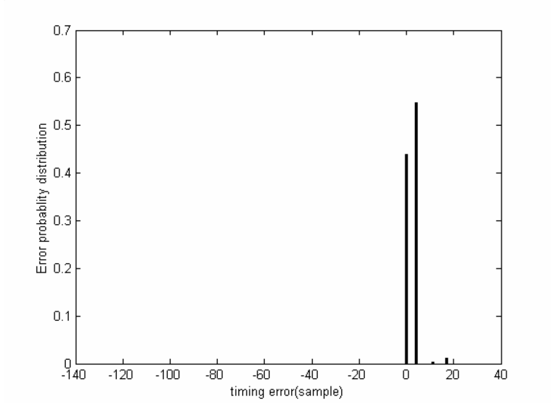

Fig. 5. The histogram of symbol timing error after the fine symbol synchronization

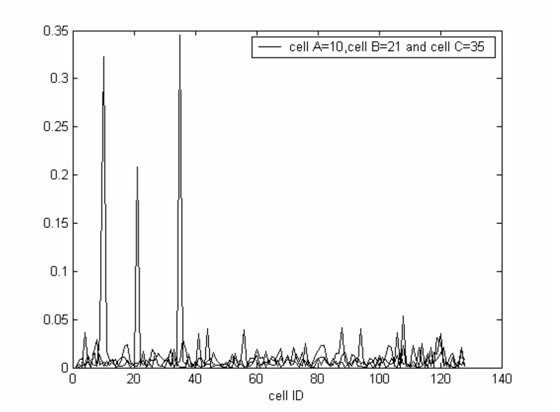

Fig. 6. The magnitude waveforms of cell identification function

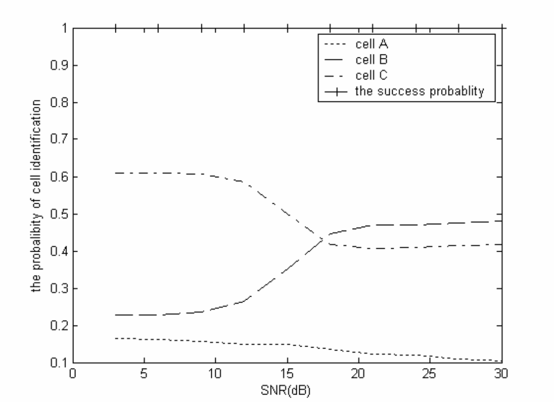

Fig.7. The probability of selecting cell A, B and C in three adjacent cellular environment

5. Conclusions

This paper presents a preamble-based synchronization and cell identification scheme for OFDMA cellular systems. The proposed scheme can obtain a fast and robust synchronization in cellular systems in multipath fading channel. The cell identification algorithm based on differential vector in frequency domain is proven to be efficient. Simulation results show that our scheme is robust and efficient in cellular environments.

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