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Rapid cell search in OFDM based cellular systems

Yong-Hwan Lee and Jin-Woo Lee

***Abstract*— Cell search is one of the most challenging tasks in cellular systems. There have been large efforts on the synchronization problem in OFDM based cellular systems. Conventional synchronization schemes, however, still have problems in initial timing acquisition and cell identification, requiring a large cell search time. In this contribution, we propose a novel three-step cell search scheme with the use of a new preamble for OFDM-based cellular systems. Simulation results show that the proposed cell search scheme can significantly reduce the mean cell search time in multi-cell environment, while reducing the computational complexity.**

***Index Terms* — OFDM, cell search, initial acquisition, cell identification, cell search time**

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has been considered as one of the most promising transmission techniques for wideband wirelsee systems [1, 2]. Recently, it has attracted much attention for the next generation (called 4G) wireless access system. When applied to the cellular system, it may need a rapid cell search scheme in mobile channel environment. The cell search process includes the acquisition of initial symbol/frame timing and identification of cell.

There have been a number of researches on the acquisition of initial timing in OFDM systems. However, few results have been reported on the acquisition in multi-cell environment. The use of a cyclic prefix (CP) has widely been used for the timing acquisition due to its simplicity [4]. However, the CP is often corrupted by inter symbol interference (ISI) in multi-path channel environment. Moreover, since many schemes find out the synchronization based on the correlation with the CP, directly proportional to the transmit power from the base station, the user can be synchronized to an adjacent base station having higher power than the correct base station. As a result, the larger the number of users in the cell, the more likely the users are synchronized to this base station with high power, yielding severe unbalancing in the cellular network load. The preamble has also been used to obtain accurate symbol timing. The computational complexity can be reduced by using a preamble comprising two repetitive patterns [7]. However, this method may suffer from high ambiguity in the timing metric at the boundary of symbol timing instant, degrading the synchronization performance. Moreover, it does not consider multi-cell environment.

In multi-cell environment, initial cell search can efficiently be achieved by using a multi-step approach [8]. Although many results have been reported on the CDMA system, but not much on the OFDM system. In this contribution, we propose a novel preamble-based cell search scheme for OFDM based cellular systems. We consider the use of a three-step approach for rapid cell search. However, unlike conventional schemes [5, 6], we first detect the frame timing in a computationally efficient manner, significantly reducing the computational complexity. By using a new preamble pattern, it can reduce the ambiguity in the timing metric, providing robust performance in multi-path channel environment.

Section II describes the OFDM system model. In Section III, we propose a novel cell search scheme with the use of a new preamble pattern. The performance of the proposed cell search scheme is analyzed and verified by computer simulation in terms of the mean cell search time in Section IV.

The computational complexity issues are also discussed. Finally, conclusions are given in Section V.

II. OFDM SYSTEM MODEL

The OFDM transmitter converts the frequency domain information symbol $X\left[k\right]$ into a time domain signal through the inverse fast Fourier transform (IFFT). The last N_g samples are inserted as a CP to form a OFDM symbol $s\left[n\right]$ represented as

$$s\left[n\right]=\frac{1}{\sqrt{N_c}}\sum_{k=0}^{N_c-1}X\left[k\right]e^{j2\pi\left(k/N_c\right)n},-N_g\le n\le N_c-1 \tag{1}$$

where N_c denotes the number of subcarriers and $j=\sqrt{-1}$. The signal $s\left[n\right]$ is transmitted over a frequency selective multi-path channel whose impulse response is represented as

$$h\left[n\right]=\sum_{l=0}^{L-1}h_l\left[n\right]\delta\left[n-n_l\right] \tag{2}$$

where h_l denotes the complex channel coefficient, n_l denotes the time delay of the l-th multi-path component, and L denotes the number of multi-paths.

The received signal $r\left[n\right]$ can be represented as

$$r\left[n\right]=h\left[n\right]*s\left[n\right]+i\left[n\right] \tag{3}$$

where $i\left[n\right]$ represents the noise plus interference term and $*$ denotes the convolution process. If the timing is perfectly synchronized, the received symbol $Y\left[k\right]$ is obtained by FFT after discarding the CP of N_g samples from $r\left[n\right]$, given by

$$Y\left[k\right]=X\left[k\right]H\left[k\right]+I\left[k\right] \tag{4}$$

where k denotes the subcarrier index, $I\left[k\right]$ represents the noise in the frequency domain and $H\left[k\right]$ is the frequency response of the channel represented as

$$H\left[k\right]=\sum_{l=0}^{L-1}h_l\left[n\right]e^{-j2\pi\left(k/N_c\right)n_l} \tag{5}$$

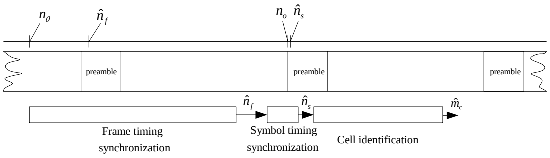

Fig. 1. Proposed cell search process

When the timing is not perfectly acquired, the received signal in (3) can be expressed as

$$r\left[n\right]=\sum_{l=0}^{L-1}h_l\left[n+n_\varepsilon\right]s\left[n+n_\varepsilon-n_l\right]+i\left[n+n_\varepsilon\right] \tag{6}$$

where n_ε denotes the amount of timing offset. If n_ε is in the range of $\left[n_{L-1}-N_g,0\right]$, the information symbol can be recovered without the effect of inter carrier interference (ICI) and ISI. If not, the demodulated signal can be represented as [3]

$$Y\left[k\right]=\frac{N_c-n_\varepsilon}{N_c}X\left[k\right]e^{j2\pi\left(k/N_c\right)n_\varepsilon}+I_{sum}\left[k\right] \tag{7}$$

where $I_{sum}\left[k\right]$ denotes the noise plus interference term due to ISI and ICI. Note that, in addition to the interference, the magnitude of the received symbol is attenuated in proportion to the timing offset. Thus, it is required to acquire accurate timing during the initial cell search process.

III. PROPOSED CELL SEARCH SCHEME

We consider a three-step process for the cell search as illustrated in Fig. 1. The frame timing $\hat{n}_f$ is first acquired by performing a block-wise autocorrelation. It detects the preamble position in the frame. Then, the symbol timing $\hat{n}_s$ is acquired by auto-correlating the first half-symbol with the second half-symbol. The start timing of the FFT window can be acquired with an accuracy of within a preamble range. Finally, the target cell is identified by crosscorrelating the signal with the cell-specific preamble pattern. It detects the cell identification code $\hat{m}_c$ of the nearest cell. In each-step, the decision is achieved by comparing the associated metric with a threshold.

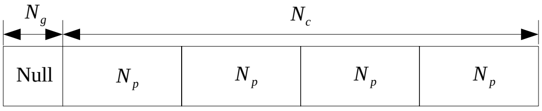

Fig. 2. Structure of the proposed preamble in the time domain

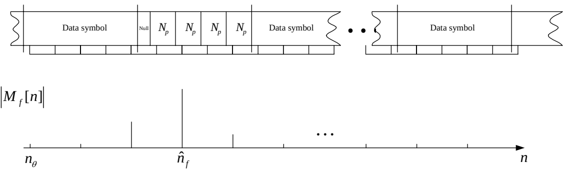

Fig. 3. Frame timing synchronization process

To improve the performance, we propose the use of a new preamble pattern as illustrated in Fig. 2. The proposed preamble comprises four repetitions of a signal with period N_p and a guard interval N_g. We can optimally perform the block-wise autocorrelation using a four-time repetitive pattern. Note that the proposed preamble does not send any signal in the guard interval to make the symbol timing metric have a sharp Λ shape.

For the cell identification, each cell has its own unique preamble pattern, distinguishable from each other. Thus, the preamble signal of the k-th subcarrier and the m-th cell in the frequency domain can be represented as

$$P[k,m] = \begin{cases} 2q[k/4,m], \; k = 0,4,8,\cdots,N_c - 4 \\ 0 \qquad\qquad\qquad\quad , \; otherwise \end{cases} \tag{8}$$

where $q[k,m]$ denotes a cell-specific code with length N_p. We consider the use of an extended PN sequence as the cell-specific code, which has good autocorrelation and crosscorrelation characteristics. The IFFT of $P[k,m]$ yields a periodic signal with period N_p in the time domain as illustrated in Fig. 2. Note that the constant scaling factor 2 in (8) makes both the preamble and OFDM symbol have the same normalized average power.

The frame timing can be detected from the preamble position. Define a timing index set by

$$\Phi_f \triangleq \{ n : n = n_\theta + 2N_p \cdot i, i = 0,1,\cdots,I_\theta \}, \quad 0 \le n_\theta \le N_f - 1 \tag{9}$$

where N_f is the number of samples per frame, n_θ denotes the initial timing offset and $I_\theta = \lfloor N_f/(2N_p) - 1 \rfloor$. Here, $\lfloor x \rfloor$ denotes the largest integer less than or equal to x. The set Φ_f comprises the time instants of the correlation from time n_θ. To obtain the preamble position, the receiver performs a block-wise correlation defined as

$$W_f[n] = \sum_{i=0}^{N_p - 1} r^*[n+i] r[n+i+N_p], \; n \in \Phi_f \tag{10}$$

Letting $R_f[n]$ be the received energy during the second quarter-symbol

$$R_f[n] = \sum_{i=0}^{N_p - 1} \left| r[n+i+N_p] \right|^2, \; n \in \Phi_f \tag{11}$$

we can have a normalized frame timing metric defined as

$$M_f[n] = \frac{|W_f[n]|^2}{R_f^2[n]}, \; n \in \Phi_f \tag{12}$$

The frame timing can be found from the timing index $\hat{n}_f$ such that

$$\hat{n}_f = \arg\max_{n \in \Phi_f} |M_f[n]|, \; if \; \max |M_f[n]| \ge \lambda_f \tag{13}$$

where λ_f denotes a detection threshold for the frame timing.

The block-wise autocorrelation can significantly reduce the computational complexity of the frame timing acquisition process as illustrated in Fig. 3. The proposed scheme requires about N_p complex multiplications and N_p complex additions to proceed $2N_p$ samples, while the method in [7] requires $2N_p$ complex multiplication and $4N_p$ complex additions. Even after initial cell search, the mobile ceaselessly needs to search the frame timing to detect other-cell's preamble for handover. Thus, the proposed scheme can significantly save the computational power of cell searching for handover.

After finding the frame time $\hat{n}_f$, the timing uncertainty is reduced to within a preamble interval. Then, the symbol timing can be found by performing the following

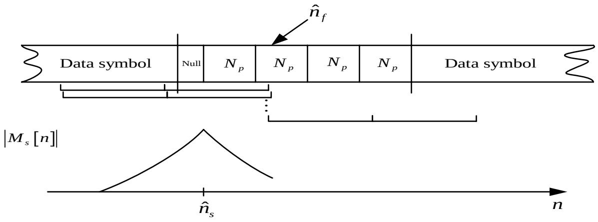

Fig. 4. Symbol timing synchronization process

autocorrelation

$$W_s[n] = \sum_{i=0}^{2N_p-1} r^*[n+i]\, r[n+i+2N_p],\ n \in \Phi_s \quad (14)$$

where $\Phi_s \triangleq \{\hat{n}_f - N_c + 1,\ \hat{n}_f - N_c + 2,\ \cdots, \hat{n}_f\}$. To reduce the correlation complexity, $W_s[n]$ can iteratively be calculated as in [7]. Letting $R_s[n]$ be the received energy during the second half-symbol defined as

$$R_s[n] = \sum_{i=0}^{2N_p-1} \left| r[n+i+2N_p] \right|^2,\ n \in \Phi_s \quad (15)$$

we can have a normalized symbol timing metric defined as

$$M_s[n] = \frac{|W_s[n]|^2}{R_s^2[n]},\ n \in \Phi_s \quad (16)$$

The symbol timing can be found from the timing index $\hat{n}_s$ such that

$$\hat{n}_s = \arg\max_{n \in \Phi_s} |M_s[n]|, if\ \max|M_s[n]| \ge \lambda_s \quad (17)$$

where λ_s is a detection threshold for the symbol timing.

Since no signal is transmitted during the guard interval, the timing metric has a sharp Λ shape as illustrated in Fig. 4, improving the detection performance. Note that the estimated symbol timing $\hat{n}_s$ can be deviated from the correct symbol timing n_o by a small amount when the multi-path channel has a large delay spread. If $\hat{n}_s - n_o (= n_\varepsilon) > 0$, the estimated symbol timing should be adjusted to prevent the demodulated signal from being corrupted by the ISI and ICI.

The sample position of the FFT window, $\hat{n}_w$, can be determined by

$$\hat{n}_w = \hat{n}_s - n_b \quad (18)$$

where n_b should be chosen to be larger than the mean shift of the timing point due to the channel dispersion. Because $\hat{n}_w$ is less than n_o due to the adjustment, the demodulated symbol can suffer from phase rotation as in (7). Thus, the cell identification process should consider this phase rotation effect. To alleviate this phase rotation issue, we detect the cell-specific code using the following differential crosscorrelation

$$W_c[m] = \sum_{k=0}^{N_p-2} \left(P^*[4(k+1), m]\, R_{\hat{n}_w+2N_p}[2(k+1)] \right)^* \cdot \left(P^*[4k, m]\, R_{\hat{n}_w+2N_p}[2k] \right),$$
$$m \in \Phi_c \triangleq \{0, 1, 2, \cdots, m_{cell} - 1\} \quad (19)$$

where $R_{\hat{n}_w+2N_p}[k]$ denotes $2N_p$-point FFT at ($\hat{n}_w + 2N_p$). Note that zero power during the guard interval of the preamble may cause an ICI effect in the frequency domain. This problem can be avoided by using $R_{\hat{n}_w+2N_p}[k]$ which is free from the delayed signal due to multi-path delay, instead of $R_{\hat{n}_w}[k]$. Since the amount of phase rotation is proportional to the subcarrier index k, the differentially crosscorrelated outputs can be combined coherently.

Letting $R_c[m]$ be the received signal energy defined as

$$R_c[m] = \sum_{k=0}^{N_p-2} \left| R_{\hat{n}_w+2N_p}[2k] \right|^2,\ m \in \Phi_c \quad (20)$$

we can have a normalized cell identification metric defined as

$$M_c[m] = \frac{|W_c[m]|^2}{R_c^2[m]},\ m \in \Phi_c \quad (21)$$

Finally, the cell-specific code number can be found from the code index $\hat{m}_c$ such that

$$\hat{m}_c = \arg\max_{m \in \Phi_c} |M_c[m]|, if\ \max|M_c[m]| \ge \lambda_c \quad (22)$$

where λ_c is a detection threshold for the cell identification. Note that the use of differential crosscorrelation can provide the performance robust to frequency selective fading, since the phase differentiated term between the adjacent carriers experiences nearly the same fading.

IV. PERFORMANCE EVALUATION

The performance of the proposed cell search scheme can be analyzed using a signal flow diagram method. We evaluate the performance in terms of the mean cell search time as in [9, 10].

The misdetection probability P_{M_1} in the first step can be defined as the probability that no frame timing metric exceeds λ_f. In this case, the metric should be recalculated using new samples in the set Φ_f corresponding to the next frame interval (i.e., it will take additional T_f seconds). If one or more metric values exceed λ_f, the time corresponding to the largest one is chosen as the framing time. Let P_{D_1} and P_{F_1} be the probability of correct and false detection of the frame time, respectively. Similarly, we can define the probabilities P_{D_2}, P_{D_3}, P_{M_2}, P_{M_3}, P_{F_2} and P_{F_3}, by the probability of correct detection, miss detection and false detection of the symbol time and the cell identification, respectively. If a misdetection occurs in the second or third step, the process goes back to the first step. If a false timing or cell code identification occurs, we assume that the process goes back to the first (i.e., frame timing acquisition) step after a penalty time of T_p seconds.

Fig. 5 depicts the signal flow of the proposed cell search process. Defining the branch gain functions $H_1(z)$, $H_2(z)$, $H_3(z)$, $H_4(z)$ and $H_5(z)$ by

$$H_1(z) = (1-P_{M_1})P_{D_2}P_{D_3}z^{2T_f} \qquad (23)$$

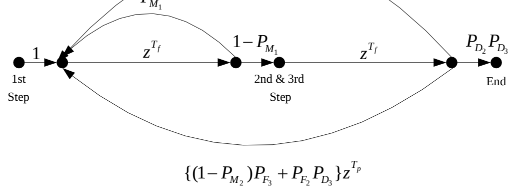

Fig. 5. Signal flow diagram of proposed cell search process

TABLE I
SIMULATION PARAMETERS

Signal bandwidth	8.75 MHz
Number of subcarriers	1024
Size of FFT and IFFT	1024
Data modulation	QPSK
Frame interval	5 msec
Symbol duration	102.4 μ sec
Guard interval duration	12.8 μ sec
False alarm penalty time	1000ms
Number of cell codes	96
Pre-advanced samples	64
Channel environment	ITU-R M.1225 channel

$$H_2(z) = P_{M_1}z^{T_f} \qquad (24)$$

$$H_3(z) = (1-P_{M_1})\left\{P_{M_2}+(1-P_{M_2})P_{M_3}\right\}z^{2T_f} \qquad (25)$$

$$H_4(z) = (1-P_{M_1})\left\{(1-P_{M_2})P_{F_3}+P_{F_2}P_{D_3}\right\}z^{2T_f} \qquad (26)$$

$$H_5(z) = z^{T_p} \qquad (27)$$

we can show that the overall generating function is represented as

$$H(z) = \frac{H_1(z)}{1-H_2(z)-H_3(z)-H_4(z)H_5(z)} \qquad (28)$$

Thus, the mean cell search time can be obtained by

$$E\left[T_{search}\right] = \frac{d}{dz}H(z)\Big|_{z=1} = \frac{\left(2-P_{M_1}\right)T_f+\left(1-P_{M_1}\right)\left\{\left(1-P_{M_2}\right)P_{F_3}+P_{F_2}P_{D_3}\right\}T_p}{\left(1-P_{M_1}\right)P_{D_2}P_{D_3}} \qquad (29)$$

To verify the analytic results, we evaluate the performance by computer simulation. The simulation parameters are summarized in Table I [11, 12]. A successful cell search is claimed when the estimated FFT window timing is detected within a guard interval range and correct cell identification code is obtained. We assume that the symbol timing is finely tracked within an ISI and ICI free region (i. e., $[n_{L-1}-N_g, 0]$) after the initial acquisition.

Fig. 6 depicts the mean search time of the proposed schemes as a function of the CIR. The thresholds are optimally set to get the best performance in each channel. For fair comparison, we applied the proposed cell identification scheme to the scheme in [7]

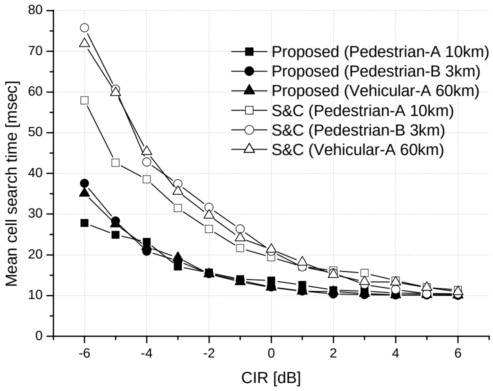

Fig. 6. Mean cell search time

that does not consider cell identification. It can be seen that the proposed scheme significantly reduce the mean acquisition, particularly at low CIR. This is mainly due to efficient reduction of the uncertainty in the first step and timing metric in the second step with the use of new preamble. Since it has the strongest power in the dominant paths, the proposed scheme has the best cell search performance in the pedestrian-A (10km) channel at low CIR (e.g., less than -5dB). However, unless the CIR is too low (e.g., larger than -4dB), the performance is best in the pedestrian-B (3km) channel due to the frequency diversity effect.

Table II compares the computational complexity in terms of the real addition, multiplication and division of the proposed scheme with the well known scheme in [7]. It can be seen that the proposed scheme requires low computational complexity.

V. CONCLUSION

TABLE II
COMPUTATIONAL COMPLEXITY

	Addition	Multiplication	division
Proposed	$3N_f$	$3N_f$	$2N_f / N_c + N_c$
Scheme in [7]	$10N_f$	$6N_f$	N_f

In this contribution, we have considered initial cell search problem in an OFDM-based cellular system. We have proposed a three-step based cell search scheme with the use of a new preamble signal. The proposed preamble can generate a timing metric with a sharp shape, significantly reducing the uncertainty in finding the frame timing. By employing new processing methods (e.g., block-wise autocorrelation for the frame timing and differential crosscorrelation for the cell identification), the proposed scheme can significantly reduce the cell search time in addition to the reduction of computational complexity. The performance of the proposed cell search scheme has been analyzed in terms of the mean search time and verified by computer simulation. It is shown that the proposed scheme can significantly improve the performance particularly when the channel condition is poor.

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