A Preamble-Based Cell Searching Technique for OFDM Cellular Systems

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***Abstract*— In this paper, a novel preamble structure, including a synchronization field (S-field) and a cell searching field (C-field), is proposed. An efficient algorithm for downlink synchronization and cell searching using the preamble is also proposed. The synchronization process includes initial symbol timing estimation using continuously or at least periodically transmitted downlink signal, frame detection, fine symbol timing estimation and frequency offset estimation using the preamble S-field, and cell identification using the preamble C-field. From the simulation results, it is shown that the proposed preamble and cell searching algorithm works well even in bad cellular environment.**

I. 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 intracell interference. Among the conventional OFDM-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 important requirement to provide robust synchronization and cell searching capability. For example, the wideband code division multiple access (WCDMA) system provides a hierarchical three-step cell search using the primary synchronization code (PSC), the secondary synchronization code (SSC), and the common pilot channel (CPICH) [6]. During the initial cell search, a mobile station can obtain the frame timing and the scrambling code number of the best cell site.

In DAB systems, null symbols and phase 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 burst synchronization in IEEE 802.11a and Hiperlan/2 systems, such as frame detection, symbol timing, coarse and fine frequency offset, channel estimation [7]. However, these schemes are not appropriate for a cellular system since they cannot discriminate signals from different cells unless their carrier frequencies are different. Thus, it is required to devise a new synchronization and cell searching technique for OFDM-based cellular systems. In this paper, a new preamble structure, including a synchronization field (S-field) and a cell searching field (C-field), is proposed. An efficient algorithm for downlink synchronization and cell searching using the preamble is also proposed and verified by extensive computer simulations.

II. Preamble Design

In this section, a novel preamble structure for an OFDM based cellular system is proposed. The downlink frame structure considered in this paper is shown in Fig. 1. A preamble, with length T_p, is located at the beginning of the frame and is followed by a number of data slots, where pilot symbols are well spread in time and frequency. The proposed preamble is shown in Fig. 2. It is comprised of two fields, denoted as S-field and C-field. The S-field is designed for time and frequency synchronization and has its length, T_{ps}, equal to the OFDM symbol duration, T_s. The S-field signal is composed of one S symbol and one IS' symbol. The IS' symbol is the first T_G-length part of the π-phase rotated version of the S symbol, and the S symbol is comprised of N_{Ssym} repetitive S_a symbols. One good example for the preamble S-field signal, $P_S(t)$, is

$$P_S(t) = \begin{cases} \sum_{k=0}^{N_F-1} g(k)\varphi_k(t) & 0 \le t < T_d, \\ -\sum_{k=0}^{N_F-1} g(k)\varphi_k(t-T_d) & T_d \le t < T_s, \\ 0 & otherwise, \end{cases} \quad (1)$$

where $\varphi_k(t) = e^{-j2\pi(k-N_F/2)t/T_d}$, $T_d = T_s - T_G$, N_F is the number of FFT points,

$$g(k) = \begin{cases} \mu(i) & k = iN_{Ssym}, \\ 0 & otherwise, \end{cases} \quad (2)$$

and $\mu(i)$ is a pseudo-noise sequence, such as the m-sequence. Among many possible S-field signals given by (1) and (2), the signal with a low peak-to-average power ratio and good correlation property was selected as the preamble. Note that, although the S-field is similar to the preamble used in the Hiperlan/2 [2], the proposed preamble, designed and optimized

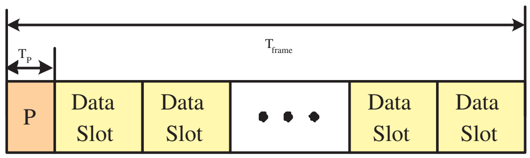

Fig. 1. An abstract downlink frame structure.

for a cellular system, is very different from those used in the Hiperlan/2 in terms of usage and synchronization algorithm.

The C-field is designed for cell search and has its length $N_c T_s$. The C-field signal of the mth cell, $P_C^m(t)$, is defined as

$$P_C^m(t) = \begin{cases} \sum_{k=0}^{N_F-1} c_n^m(k)\varphi_k(t+T_d-T_G), & 0 \le t-nT_s < T_G, \\ \sum_{k=0}^{N_F-1} c_n^m(k)\varphi_k(t-T_G), & T_G \le t-nT_s < T_s, \\ 0, & otherwise, \end{cases} \quad (3)$$

where T_G is the guard interval, n is in the range between 0 and $N_c - 1$, and $c_n^m(k)$ is the frequency domain signal of the nth symbol of the C-field in the mth cell. Let $F = \{f_0, f_1, \cdots, f_{N_u-1}\}$ be the set of used subcarrier set, where N_u represents the number of used subcarrier, and $S = \{s_0, s_1, \cdots, s_{P-1}\}$ be a disjoint partition of F such that, for any $0 \le i \ne j < P$, $s_i \in F$, $s_i \cap s_j = \emptyset$, and $\cup_{i=0}^{P-1} s_i = F$. For the ith partition s_i, we divide it into $s_{i,p}$ and $s_{i,c}$ such that $s_{i,p} \cup s_{i,c} = s_i$ and $s_{i,p} \cap s_{i,c} = \emptyset$. Let $\Psi_i = \{\psi_{i,0}, \psi_{i,1} \cdots, \psi_{i,Q_i-1}\}$ be a set of complex sequences with length equal to the cardinality of $s_{i,c}$, J_i, and with good auto- and cross-correlation property. Further, we define $\bar{\psi}$ as a complex sequence used for known pilot symbol pattern, whose length is equal to the cardinality of $s_{i,p}$. Then, $c_n^m(k)$ is defined as

$$c_n^m(k) = \begin{cases} \psi_{p_n,q_n}(j) & k = s_{p_n,c}(j), \\ \bar{\psi}(j) & k = s_{p_n,p}(j), \\ 0 & otherwise, \end{cases} \quad (4)$$

where $\psi_{p_n,q_n}(j)$, $\bar{\psi}(j)$, $s_{p_n,p}(j)$, and $s_{p_n,c}(j)$ are the jth element of ψ_{p_n,q_n}, $\bar{\psi}$, $s_{p_n,p}$, and $s_{p_n,c}$, respectively,

$$m_n = \sum_{i=0}^{p_n-1} Q_i + q_n, \qquad M = \sum_{i=0}^{P-1} Q_i, \quad (5)$$

and

$$m = \sum_{n=0}^{N_c-1} m_n M^{N_c-n-1}. \quad (6)$$

Here, we can see that, with the proposed C-field, M^{N_c} different cells can be discriminated. As an example, let $N_c = 2$, $P = 8$, $Q_i = \bar{Q} = 8$. Then, the number of different cells is $M^{N_c} = 64^2 = 4096$, which is large enough for a cellular system.

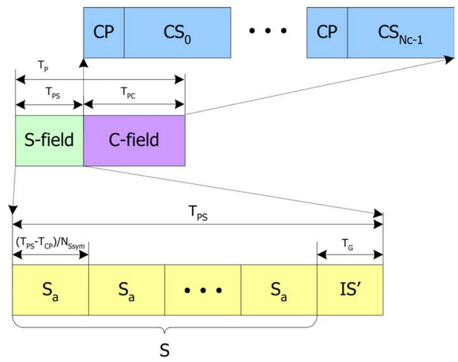

Fig. 2. The proposed preamble structure.

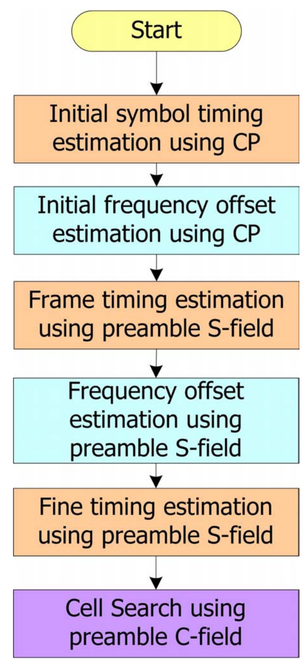

Fig. 3. The proposed synchronization process.

III. Synchronization Algorithm

In Fig. 3, the synchronization process proposed in this paper is shown. In the conventional OFDM-based systems, such as wireless LAN, all initial synchronization process, including signal detection, is done by using the preamble. However, in an OFDM-based cellular system, signal is transmitted continuously or, at least, periodically due to common pilot symbols and common channels used for broadcasting. In this situation, an initial symbol timing and initial frequency offset can be obtained by using the cyclic prefix (CP). After achieving initial synchronization, we estimate the frame timing and fine symbol timing by using the preamble S-field.

A. Initial symbol timing and frequency offset estimation

Let the sampled received signal be $y(n)$. Then, the initial symbol timing, τ_{init}, is estimated as

$$\tau_{init} = \max_{n} \left| \frac{1}{N_{CP}} \sum_{j=0}^{N_{init}-1} z(n + jN_s) \right|, \tag{7}$$

where

$$z(n) = \sum_{r=0}^{N_{CP}-1} y^*(n+r)y(n+r+N_F). \tag{8}$$

Also, N_{CP}, N_s, and N_{init} are the number of samples in the guard interval, the number of samples in an OFDM symbol, and the number of OFDM symbols used in the initial symbol timing estimation, respectively. In addition, we can estimate the initial frequency offset, ϵ_{init}, as

$$\epsilon_{init} = \frac{1}{2\pi} \arg \left\{ \sum_{j=0}^{N_{init}-1} z(\tau_{init} + jN_s) \right\}. \tag{9}$$

Note that only fractional part of frequency offset can be estimated by (9).

B. Frame timing estimation

After obtaining initial synchronization, we have $N_{frame} = T_{frame}/T_s$ candidates for the frame timing. Here, we can utilize the property of the S-field where every OFDM symbol except the preamble S-field has a positive value of auto-correlation due to the cyclic prefix. Note that the correlation between the S_a part and the IS' part in the S-field becomes negative. Then, the frame timing is estimated as

$$\begin{aligned} \tau_f(i) &= aN_s + \tau_{init}, 0 \le a < N_{frame} \\ \tau_{frame} &= \tau_f(i), \;\; if \;\; \Re\{z(\tau_f(a))\} < 0, \end{aligned} \tag{10}$$

where $\Re\{x\}$ is the real part of x.

C. Fine symbol timing and coarse frequency offset estimation

After obtaining the frame timing, we can assume that the starting point of the preamble S-field is around the estimated the frame timing τ_{frame}. Then, we can estimate the fine symbol timing, τ_s, by taking cross-correlation between the received signals and the preamble S-field signal as

$$\tau_s = \max_{n} \left| \sum_{r=0}^{R-1} P_S^*(r+R_s)y(n+r+R_s) \right|, \tag{11}$$

where $P_S(r)$ is the sampled signal of the preamble S-field, R is the number of samples used for the fine symbol timing estimation, and R_s is the starting point for accumulation. We can also estimate frequency offset, ϵ_f, by using the repetitive property of the preamble S-field, as

$$\begin{aligned} \epsilon_f = &\frac{N_{Ssym}}{2\pi} \\ &\cdot \arg \left\{ \sum_{r=0}^{N_{CP}-1} y^*(\tau_s + r)y(\tau_s + r + N_{FFT}/N_{Ssym}) \right\}. \end{aligned} \tag{12}$$

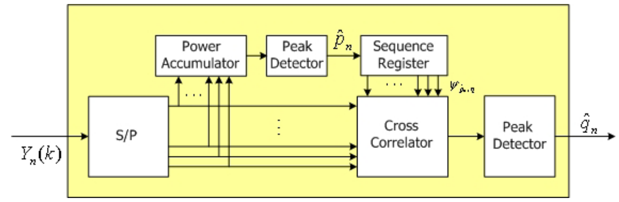

Fig. 4. Schematic for the cell identification.

Note that the range of frequency offset estimated by (12) is $[-N_{Ssym}/2, N_{Ssym}/2]$.

IV. Cell Identification Algorithm

In Fig. 4, the schematic for cell identification, proposed in this paper, is shown. Let $Y_n(k)$ be the frequency domain symbols at the kth sub-carrier in the nth OFDM symbol. Then, for the nth symbol of the preamble C-field, the sub-carrier partition p_n and sequence number q_n can be estimated by

$$\hat{p}_n = \arg\max_{p} \sum_{k \in s_p} |Y_n(k)|^2 \tag{13}$$

and

$$\hat{q}_n = \begin{cases} \arg\max_q \Re\left\{\chi_{\hat{p}_n,q}\right\}, & \chi_{\hat{p}_n,\hat{q}_n} > \chi_{th}, \\ Detection fails, & otherwise, \end{cases} \tag{14}$$

where

$$\chi_{p,q} = \sum_{j=0}^{J_p-1} Y_n(s_{p,c}(j))\hat{H}^*(s_{p,c}(j))\psi_{p,q}^*(j), \tag{15}$$

χ_{th} is the threshold for cell identification, and $\hat{H}(k)$ is the estimated complex channel gain at the kth sub-carrier obtained from $Y_n(k)$, $k \in s_{\hat{p}_n,p}$, and the sequence $\bar{\psi}$. Then, the cell ID is estimated as

$$\hat{m}_n = \sum_{i=0}^{\hat{p}_n-1} Q_i + \hat{q}_n \tag{16}$$

and

$$\hat{m} = \sum_{n=0}^{N_c-1} \hat{m}_n M^{N_c-n-1}. \tag{17}$$

V. Simulation Results

The system parameters used in the simulation are given as follows:

- carrier frequency : 2 GHz
- bandwidth : 20 MHz
- FFT size (N_F): 2048
- data duration (T_d) : 102.4 us
- guard interval (T_G) : 25.6 us
- symbol duration (T_s) : 128 us
- number of symbols used in initial timing estimation (N_{init}) : 3
- number of preamble C-field symbol (N_c) : 1
- number of partitions (P) : 8
- number of sequences in a partition ($\bar{Q}$) : 1
- channel model : ITU-R SISO model

TABLE I

JOINT INITIAL TIMING ESTIMATION AND FRAME DETECTION PERFORMANCE.

Channel (Speed)	SINR=0dB FA	SINR=0dB DF	SINR=5dB FA	SINR=5dB DF
AWGN	$<$ 2.0e-4	$<$ 2.0e-4	$<$ 2.0e-4	$<$ 2.0e-4
Ped. B (3km/h)	1.28e-2	$<$ 2.0e-4	2.0e-4	$<$ 2.0e-4
Veh. A (100km/h)	6.68e-2	4.0e-4	7.4e-3	$<$ 2.0e-4

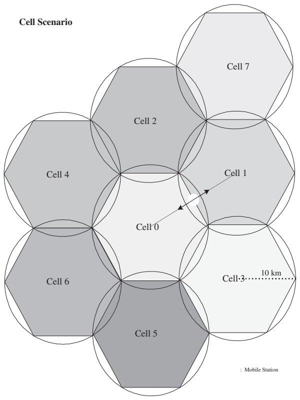

Fig. 5. Simulation scenario

- path loss model : Hata model (COST-231)
- cell radius : 10 km
- cell scenario : see Fig. 5

In table I, the joint performance of initial symbol timing estimation and frame detection is shown. The simulation results were obtained from 5000 trials under the assumption that inter-cell interference can be modelled as an additive white Gaussian noise (AWGN). Here, '<2.0e-4' signifies that no error is found in the 5000 trials. From table I, it is seen that the joint performance of the initial symbol timing estimation and frame detection degrades as the mobile speed increases. When the signal-to-interference-and-noise ratio (SINR) is 5dB and the mobile speed is 100km/h in the Vehicular A channel, we have the false alarm (FA) probability equal to 7.4e-3 and detection failure (DF) probability less than 2.0e-4.

In Fig. 6, the performance of the fine symbol timing estimation is shown. In the simulation, the inter-cell interference is assumed to be AWGN and the normalized carrier frequency offset (CFO) is assumed to be in $[-2.0, 2.0]$. As can be seen from Fig. 6, the performance of the fine symbol timing estimation degrades as the maximum delay spread increases. At the SINR of 5dB and the mobile speed of 3km/h in the Pedestrian B channel, the probability that the timing estimation error less than 30 samples is 0.98 and the maximum timing error occurred in this simulation is 57 samples. In the Vehicular A channel, the probability that the timing estimation error less than 27 samples is 0.99 and the maximum timing error occurred in this simulation is 50 samples.

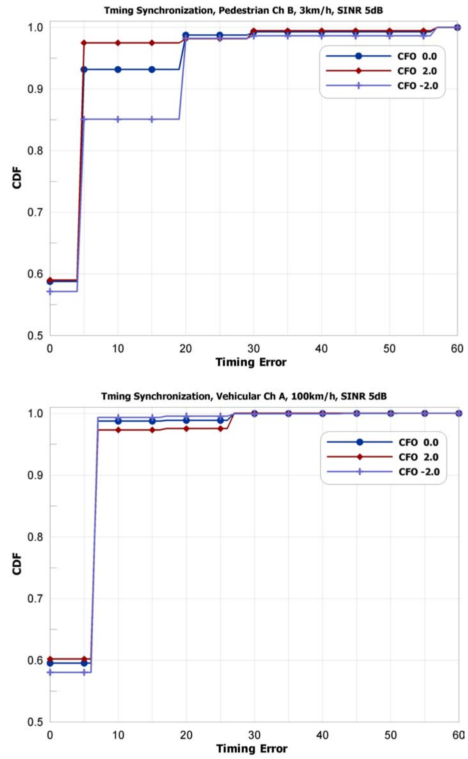

Fig. 6. Fine timing estimation performance.

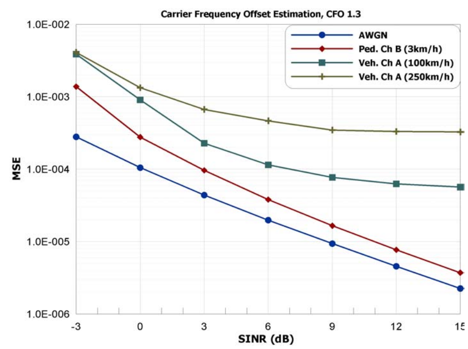

Fig. 7. Frequency offset estimation performance.

In Fig. 7, the overall performance on the frequency offset estimation is shown when the normalized CFO is set at 1.3. From Fig. 7, we can see that the performance degrades as the mobile speed increases. Also, the mean squared error (MSE) at the SINR of 2dB is lower than 1e-3 even in the Vehicular A channel with the mobile speed of 250km/h. Although not shown in this paper, we could observe that there is a negligible performance loss for up to 16-QAM symbol transmission if the MSE of the estimated frequency offset is below 1e-3. In the Pedestrian B channel with the mobile speed of 3km/h, we can achieve the MSE lower than 1e-4 at the SINR of 3dB or greater.

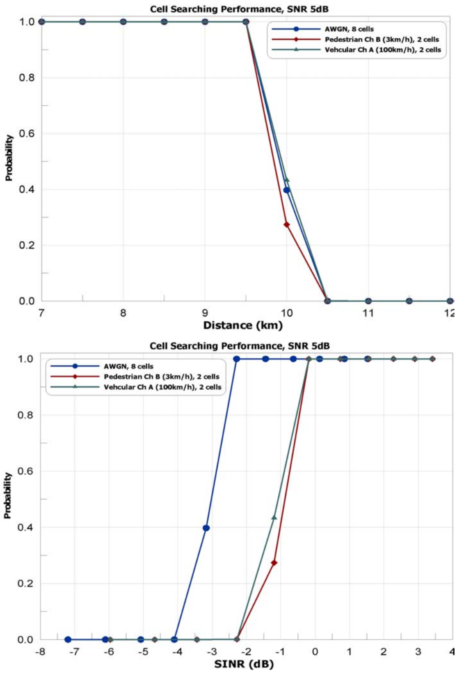

Fig. 8. Cell identification performance.

In Fig. 8, the performance of cell identification in various channel environment is shown. Here, the signal-to-noise ratio is set at 5dB and the distance between the base station in cell 0 and the mobile station varies from 7km to 12km. As the distance varies, the SINR in 8-cell environment varies from 1.53dB to 7.20dB. As can be seen from Fig. 8, the cell ID 0 is estimated with a probability greater than 0.999 in the distance range between 7km and 9.5 km. When the mobile is at the cell boundary, the probability that cell ID 0 is not estimated is around 0.5. However, it does not necessarily mean that the cell identification procedure fails since the estimated cell ID with a stronger power is 1 in this situation. Thus, the cell identification in this case is regarded as successful. From Fig. 8, we can also see that the proposed preamble and cell identification algorithm works well even in fading channel at the SINR of 0 dB.

VI. Conclusion

In this paper, a preamble based synchronization and cell searching technique for OFDM cellular system was proposed. The preamble, composed of S-field and C-field, and the algorithm for synchronization and cell searching were proposed. From simulation results, we confirmed that the proposed approach could achieve very robust synchronization and cell searching performance even in bad cellular environments. Performance analysis on the proposed algorithms and the overall cell searching performance analysis in terms of mean acquisition time is our future work.

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