A Synchronization and Cell Searching Technique Using Pilot Tones for OFDM Cellular Systems

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Abstract

In this paper, a pilot structure and an efficient algorithm for downlink synchronization and cell searching in OFDM-based cellular systems are proposed. The pilots, randomly allocated in the frequency domain, allow us to minimize inter-cell interference (ICI) as well as to increase cell searching capability, estimation range of integer carrier frequency offset (CFO), and estimation accuracy of symbol timing offset (STO). The proposed low-complexity joint algorithm for integer CFO estimation, cell searching, and downlink detection is robust to ICI, multipath channel, STO and fine CFO. It is shown by simulation that the proposed synchronization and cell searching algorithm performs well in a bad cellular environment.

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 intra-cell interference. Unlike the conventional OFDM-based wireless systems such as digital audio broadcasting (DAB), digital video broadcasting (DVB), IEEE 802.11a, and Hiperlan/2[1], OFDM-based cellular systems require robust synchronization and cell searching capability even in a bad cellular environment. However, these conventional OFDM systems are not appropriate for the cellular environment with a frequency reuse factor equal to 1 since they cannot discriminate signals from different cells. In [2], a synchronization and cell searching technique using the preamble in the time domain was proposed for OFDM-based cellular systems. In this paper, a new pilot structure and an efficient algorithm for downlink synchronization and cell searching in the frequency domain are proposed. The proposed pilots are randomly inserted in the frequency domain and allocated to each cell so that we can avoid or minimize inter-cell interference (ICI) as well as to increase cell searching capability, estimation range of integer carrier frequency offset (CFO), and estimation accuracy of symbol timing offset (STO) in the process of synchronization and cell searching. The synchronization and cell searching technique using the proposed pilots includes integer CFO estimation, cell searching, downlink detection, fine STO estimation, and fine CFO after initial time and frequency synchronization in the time domain. After describing the proposed pilot allocation scheme in Section 2, we propose the synchronization and cell searching technique using the pilots in Section 3. In Section 4, the performances of the proposed techniques are verified via simulation. Conclusions are made in Section 5.

2. A Pilot Allocation Scheme for OFDM(A)-based Cellular Systems

Frame structure and pilot structure for OFDM(A)/TDD-based cellular systems are shown in Fig. 1. The pilot location index set (PLIS) assigned to the k -th cell is defined as $P_k = \{ p_{k,m} : 0 \le m \le N_p - 1,\ 0 \le p_{k,m} \le N_u - 1 \}$ where N_u and N_p denote the number of used subcarriers and pilots, respectively. The PLIS is constructed such that the spacing between adjacent pilots are random and $P_{k_1} \cap P_{k_2} = \varnothing$ for different cell ID numbers of k_1 and k_2. In this paper, the pilots required for channel estimation are not considered for the sake of simplicity. Therefore, additional pilots are needed for channel estimation. By employing the random pilot pattern instead of the conventional pilot pattern placed on equidistance subcarriers, we can significantly increase the estimation range of integer CFO and the number of cells to be searched. Also, better performance can be achieved for fine STO estimation when the random pilot pattern is used. An IFFT output signal of a base station at the k -th cell is given by

$$x_k(n) = \frac{1}{N}\left(\sum_{\substack{l=0 \\ l \notin P_k}}^{N_{FFT}-1} D(l) \cdot e^{j2\pi ln/N_{FFT}} + \sum_{l \in P_k} S_k(l) \cdot e^{j2\pi ln/N_{FFT}} \right), \qquad (1)$$

where $D(l)$ denotes the complex symbol such as transmit data, pilot for channel estimation, and virtual carrier for the l -th subcarrier of an OFDM symbol. Also, $S_k(l)$ denotes the pilot symbol on the l -th subcarrier of the k -th cell. Here, N_{FFT} denotes the number of entire subcarriers.

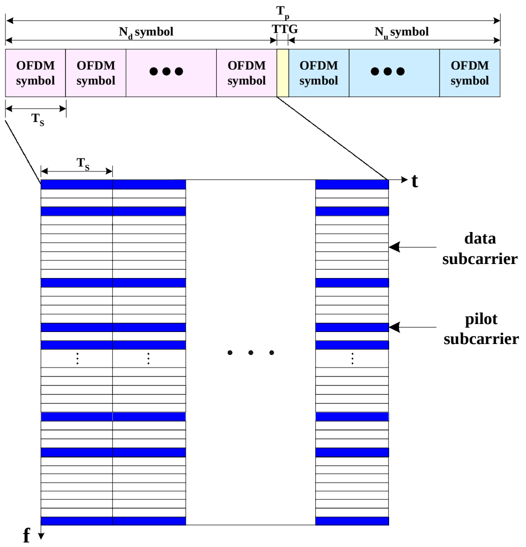


Fig. 1. Frame structure and pilot structure for OFDM(A)/TDD-based cellular systems

When the number of mutually exclusive PLISs is equal to or greater than the number of cells (N_c), i.e., $N_u \geq N_c \cdot N_p$, the PLIS, P_k, for the k-th cell is given by

$$P_k = \left\{ r_{k+m\cdot N_c} : r_{k+m\cdot N_c} \in R_{N_u}, 0 \leq m \leq N_p - 1 \right\}, \tag{2}$$

where $R_{N_u} = \{ r_i : 0 \leq i \leq N_u - 1 \}$ denotes the integer set where the numbers from 0 to $N_u - 1$ are rearranged in a random order. The same set R_{N_u} must be used for all the cells.

In the case of $N_u < N_c \cdot N_p$, it is not possible to assign mutually exclusive PLISs to all the cells by using (2). If the PLIS assigned to a cell has the same element as the one assigned to another cell, there exists ICI between these two cells in cell searching and synchronization process [3]. In order to minimize the ICI in synchronization and cell searching process, we assign the PLISs to adjacent cells such that $P_{k_1} \cap P_{k_2} = \varnothing$ for $k_1 \neq k_2$. Here, all the cells are partitioned into cell groups with N_G cells each. For the k-th cell, the cell group number and the number in a cell group are defined by $i = k / N_G$ and $j = k \bmod N_G$, respectively, where $x \bmod y$ denotes the remainder. The cells with the same number j must be deployed at the same location in all the cell groups. Here, it is assumed that N_c is a multiple of N_G. Fig. 2 shows an example of a cell deployment when N_c and N_G are set to 49 and 7, respectively. The formula for construction of PLIS, P_k, when $N_u < N_c \cdot N_p$, is given by

$$P_k = P_{i,j} = Q_{i,j} \bigcup_{\substack{m=0 \\ m\neq i}}^{N_c/N_G - 1} \left\{ q_{m\cdot(N_c/N_G)+n} : q_{m\cdot(N_c/N_G)+n} \in Q_{m,j}, 0 \leq n \leq \left(N_p - \lfloor N_u / N_p \rfloor \right) / \left(N_c / N_G \right) - 1 \right\}$$

$$\text{where } Q_{i,j} = \left\{ q_n : 0 \leq n \leq \lfloor N_u / N_p \rfloor - 1 \right\} \tag{3}$$

$$= \left\{ r_{(i\cdot N_G + j)+n\cdot N_C} : r_{(i\cdot N_G + j)+n\cdot N_C} \in R_{N_u}, 0 \leq n \leq \lfloor N_u / N_p \rfloor - 1 \right\}$$

Here, $\lfloor x \rfloor$ denotes the nearest integer number less than or equal to x. P_k in (3) is composed of a mutually exclusive set, $Q_{i,j}$, allocated to each cell according to i and j with a cardinality of $\lfloor N_u / N_p \rfloor$ and subsets, $Q_{m,j}$ for $m \neq i$, with a cardinality of $(N_p - \lfloor N_u / N_p \rfloor)$. The PLISs for adjacent cells or cells in the same cell group, obtained by (3), are always mutually exclusive. Also, the PLIS of one cell has the same $2 \cdot (N_p - \lfloor N_u / N_p \rfloor)$ elements as the PLIS of the cells (N_C / N_G) with the same j but different i. However, the ICI between these cells can be ignored due to significant path loss between non-adjacent cells. In the case of cell deployment shown in Fig. 2, P_{16} and all other PLISs except P_2, P_9, P_{23}, P_{30}, P_{37}, P_{44} are mutually exclusive.

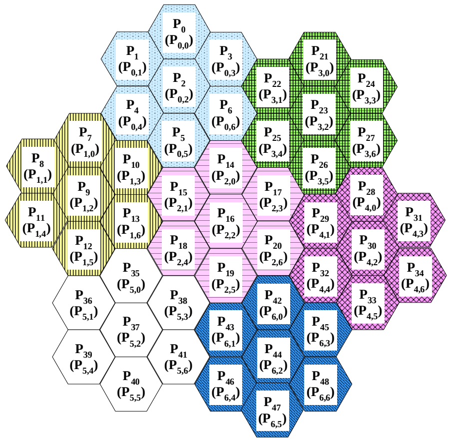


Fig. 2. An example of a cell deployment $(N_u < N_c \cdot N_p)$

3. A Synchronization and Cell Searching Technique

Fig. 3 shows the flowchart of synchronization and cell searching for OFDM(A)/TDD-based cellular systems. In this section, it is assumed that the initial STO and fractional CFO are estimated by the conventional approach using cyclic prefix in the time domain to find the coarse starting point of FFT and to reduce the interchannel interference, respectively [1][4].

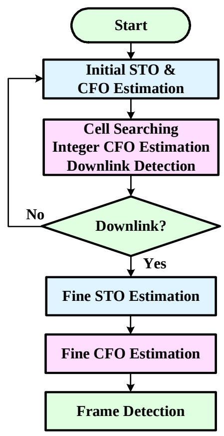


Fig. 3. Flowchart of synchronization and cell searching for OFDM(A)/TDD-based cellular systems

Cell searching and integer CFO estimation are performed in the frequency domain by using the pilots described in Section II. When an integer CFO, ε_I, is present, all subcarriers experience cyclic rotation by ε_I in the frequency domain. A symbol transmitted at the pilot tone, $p_{k,m} \in P_k$, appears at the subcarrier location, $(p_{k,m} + \varepsilon_I) \bmod N_{FFT}$. If a mobile at the k-th cell has an integer CFO, ε_I, the autocorrelation between two consecutive OFDM symbols in the frequency domain has the highest peak at the subcarriers corresponding to a particular set, i.e., ε_I shifted version of P_k. Therefore, the integer CFO, ε_I, and cell ID number, k, can be jointly estimated by using the pilots transmitted at the subcarrier locations $p_{k,m} \in P_k$ as follows:

$$(\hat{k},\hat{\varepsilon}_I) = \max_{k}\left\{\max_{\varepsilon_I}\left\{\left|\sum_{l=(p_{k,m}+\varepsilon_I)\bmod N_{FFT}} Y_i(l)\cdot Y_{i-1}^*(l)\right|\right\}\right\}, \quad (4)$$
$$where\ p_{k,m} \in P_k, -\varepsilon_{I_{\max}} \le \varepsilon_I \le \varepsilon_{I_{\max}}$$

Note that (4) is insensitive to remaining STO and channel frequency selectivity since the estimates are obtained only by using the received sequences. If the conventional comb-type pilots, placed on equidistance subcarriers, are used, the capability of cell searching and integer CFO estimation will become very limited since the autocorrelation peaks of the comb-type signal occur periodically. The cell searching capability and estimation range of integer CFO can be significantly increased by the proposed algorithm in (4) due to the random feature of PLIS.

Since both downlink and uplink channels share the same frequency band in OFDM(A)/TDD-based cellular systems, a mobile receives not only downlink signals from a base station but also uplink signals from adjacent mobiles in different time slots. If the mobile synchronizes its carrier frequency and timing to uplink signals, system performance will be significantly degraded. That is because, in OFDM systems, the uplink signal from each mobile has different timing advance (the uplink signal in OFDMA systems is the sum of the uplink signals coming from randomly distributed mobiles), which prevents the mobile from estimating correct timing. The incorrect timing estimation also results in the degradation of carrier frequency estimation. Moreover, it is difficult to estimate carrier frequency accurately using the uplink signal because of different frequency offsets and Doppler shifts among mobiles. In order not to be synchronized to uplink signal, the mobile needs to decide whether the received signal comes from other mobiles or from its base station. The downlink detection can be performed by using downlink PLIS and uplink PLIS, which are mutually exclusive, as follows:

$$\Gamma = \left|\sum_{l=(p_{k,m}+\varepsilon_I)\bmod N_{FFT}} Y_i(l)Y_{i-1}^*(l)\right|, p_{k,m} \in P_k, \quad (5)$$
$$if\ \Gamma > threshod,\quad Downlink$$

If Γ is greater than a given threshold, the mobile considers the received signal as downlink signal and continues to proceed remaining synchronization and tracking process. If Γ is less than the threshold, the mobile waits for random back-off time and restarts from the initial synchronization. Since Γ in (5) corresponds to the case where the autocorrelation value of (4) becomes maximum, it can be obtained from (4) without any additional computational complexity. Performances of cell searching, integer CFO estimation, and downlink detection can be improved as more downlink OFDM symbols are used for noise and interference reduction.

After joint estimation of cell searching, integer CFO, and downlink detection, the remaining fine synchronization is preceded using the pilots transmitted at the subcarriers of P_k. The conventional techniques such as fine STO estimation using channel impulse response and fine CFO estimation using phase shift between pilots in two consecutive OFDM symbols can be applied [4]. Accurate estimation of STO can be obtained due to random feature of PLIS.

4. Simulation

In order to evaluate the proposed cell searching and synchronization technique using the random pilots, we use the following parameter set for computer simulation: carrier frequency (f_c) = 2GHz, bandwidth= 20MHz, FFT size (N_{FFT}) = 2048, guard interval (N_{CP}) = 25.6us, and the number of pilots (N_P) = 48. Pilots are boosted over the average power in data by 3dB. ITU-R SISO model is used for multipath fading channel.

Fig. 4 shows the autocorrelation characteristic of the pilots, given by (2), when SNR is 5dB, normalized CFO is 1.1, STO is -10, and mobile speed of Vehicular Channel A is 100km/h. Fig. 5 shows the performances of the cell searching technique using the pilots in various channel environments. Here, the performances are measured at 5dB SNR with a cell radius equal to 10km. Hata model, proposed in COST-231, is used for path loss between a base station and a mobile. It is assumed that the propagation delay between the base station and mobile is $3.3\mu s/km$. Fig. 5(a) shows the performance of cell searching, obtained by (4), when 2 symbols are used. The probability of identifying the correct cell ID k is greater than 94.6% in the distance range between 7km/h and 9km/h for 3 different channels, i.e., 90.2% at 9.5km for AWGN Channel and 80% at 9.5km for Vehicular Channel A (100km/h). When 10 symbols are used for cell searching, the probability of identifying the correct cell ID k is greater than 99.9% in the distance range up to 9.5km as shown in Fig. 5(b). Notice that the cell identifying probability at cell boundary is about 50%. However, it does not necessarily mean that cell identification procedure is failed since the signal powers coming from adjacent cells are similar. In this case, the mobile can be assigned to either cell. Fig. 6 shows the performances of downlink detection in two different channel environments, i.e., Pedestrian Channel B with a mobile velocity of 3km/h and Vehicular Channel A with a mobile velocity of 100km/h, at the SNR of 5dB. In this figure, the false alarm represents the case where the received signal is mistakenly detected as a downlink signal when an uplink signal is actually received while the

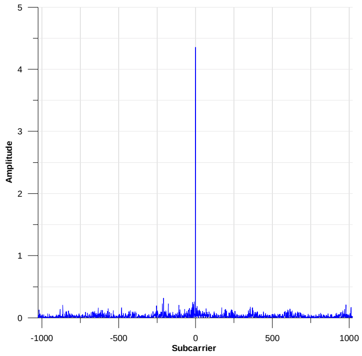
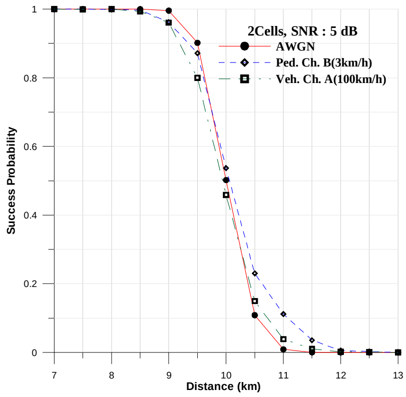
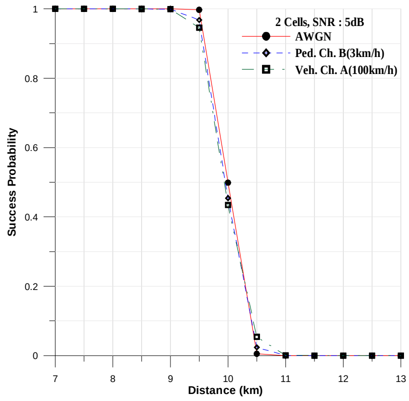


Fig. 4. Autocorrelation characteristic of random pilots (vehicular channel A with 100km/h , SNR: 5dB, normalized CFO: 1.1, STO: -10)

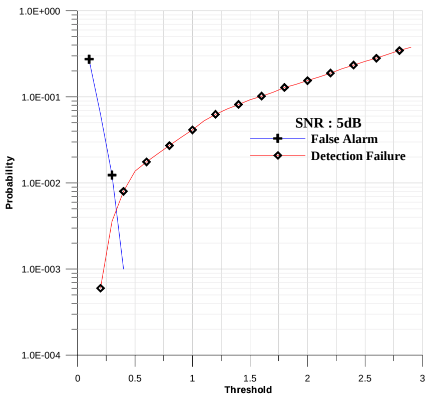


(a) 2 symbol estimation

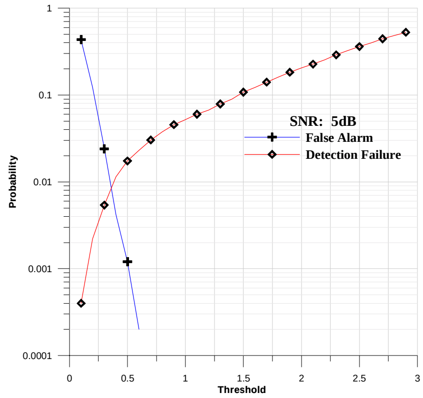


(b) 10 symbol estimation

Fig. 5. Cell searching performance



(a) Pedestrian Channel B (3km/h)



(b) Vehicular Channel A (100km/h)

Fig. 6. Downlink detection performance

detection failure represents the case where downlink signal is not detected when a signal is transmitted from the base station. From Fig. 6(a), one can see that the false alarm probability and detection failure probability are equal to 1.24% and 0.36% at the threshold of 0.3, respectively, when Pedestrian Channel B is used. Also, the false alarm probability and detection failure probability are equal to 2.4% and 0.54% at the threshold of 0.3, respectively, when Vehicular Channel A is used. In this case, the success probability for downlink detection corresponds to 99.46%. Although it is not shown in this paper, the integer CFO is perfectly estimated by (4).

5. Conclusion

In this paper, the pilot allocation scheme and low-complexity joint algorithm for integer CFO estimation, cell searching, and downlink detection in OFDM-based cellular systems were proposed to minimize ICI and to increase cell searching capability, estimation range of integer CFO, and estimation accuracy of STO. Although the pilot structure and the corresponding algorithm are mainly described for OFDM(A)/TDD-based cellular systems in this paper, they can be used for OFDM(A)/FDD-based cellular systems by skipping the downlink detection part. Due to the pilots continuously transmitted in downlink OFDM symbols, the technique, discussed in this paper, can be readily used to track the CFO, STO, and cell searching for handover.

3. References

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