Synchronization Signal Design for Cell Search in 3GPP-LTE HCN

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Abstract In this paper, the SSs for cell search are designed in multi-cell systems. The proposed SSs minimize the maximum magnitude of the cross-correlation function for a given length and the maximum number of supportable cells within a group is obtained for a given SS length and the maximum allowed cross-correlation value among the sequences. The simulation results show that the proposed signals have a distinct advantage in multi-cell environments.

key words: *synchronization signal, multi-cell environments, maximum magnitude of the cross-correlation function, maximum number of available sequences.*

1. Introduction

Although there has been a dramatic increase in demands for data traffic during the past few years and a stricter quality of service (QoS) for a user is required for new mobile applications [1], the spectral efficiency (bps/Hz) is approaching the theoretical limit with the 3rd generation partnership project long term evolution (3GPP-LTE). Using a mix of macro, pico, femto and relay base stations (BSs) enables flexible and low-cost deployments and provide a uniform broadband experience to users anywhere in the network [2][16] and in 3PP-LTE Advanced (3GPP-LTE-A), a heterogeneous cellular network (HCN) is considered as the next generation network topology to satisfy the future demand for an explosively increasing data traffic [4]. Although the HCN can improve the system capacity of a cellular system, such a deployment potentially results in much higher interference power and good inter-cell interference (ICI) management techniques are required.

In an orthogonal frequency division multiplexing (OFDM) cellular system, the synchronization and the cell search procedure are the essential part as the initial procedure for the communication. Thus, various algorithms have been proposed in the OFDM system such as IEEE 802.11a, DVB-H, IEEE 802.16e and 3GPP-LTE [5]–[8]. Furthermore, in HCN, a lot of small BSs can exist within a macro BS so that it is required that the synchronization signals (SSs) should not only alleviate high interference but also distinguish more BSs and BS groups. Since the time synchronization is performed by finding the peak of the cross correlation function between the received sequence and the SS of each BSs, in order to reduce the inter-cell interference (ICI), one reasonable criterion is to minimize the maximum magnitude of the cross-correlation function [9]. It is well known that some sequences have relatively good correlation properties, such as pseudo-noise sequences or Chu sequences, and have been adopted in many commercial cellular standards such as the 3GPP-LTE [8]. However, no general SS design for an arbitrary sequence length is given.

In this paper, the SS design guideline is suggested to improve the cell search performance in the 3GPP-LTE HCN by using the cross-correlation properties of Chu sequences [10]. The organization of this paper is as follows. In Section II, we describe the system model of interest. In Section III, our cell search processing is explained. In Section IV, we design the SS in order to mitigate the ICI and the maximum number of supportable BS per group is obtained for a given SS length and the maximum allowed cross-correlation value among the sequences. In Section V, the performance using the proposed SSs are shown and compared to the SS signals based randomly selected Chu sequences via computer simulations. Finally, concluding remark is given in Section VI.

$Notation$: Bold characters represent matrices or vectors. Uppercase characters and lowercase characters represent FD and TD signals, respectively. $|\mathbf{B}|$ stands for the cardinality of a set $\mathbf{B}$. Furthermore, $(\cdot)^T$ and $(\cdot)_N$ denote transpose and the modulo-N operation, respectively.

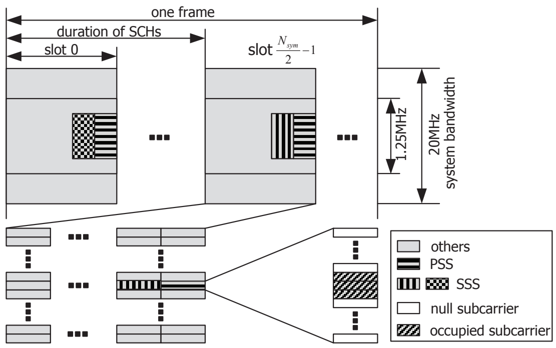

Fig. 1: Frame structure.

2. System Model

The frame structure of the 3GPP-LTE downlink (DL) considered is shown in Fig. 1. The LTE system, specified under the 3GPP-LTE standards, has 10ms radio frame length which is composed of 20 equally size slots and a slot duration is 0.5ms. SSs are placed in slot 0 and slot 10 and the PSS is located the last OFDM symbol and the SSS is located before the PSS. In the FD, an RB is formed by 12 subcarriers and 6 RBs for transmission of SSs (i.e., 72 subcarriers), but SSs use only 62 subcarriers of the 72 reserved subcarriers. Let the set of the group indices and the set of cell indices (within the group) be $\mathbf{N}_G$ and $\mathbf{N}_B$, respectively, where $|\mathbf{N}_G| = N_G$ and $|\mathbf{N}_B| = N_B$. In the current LTE standard, a cell ID is derived from the set of the group indices, $\mathbf{N}_G = \{0, \cdots, 167\}$ and the set of cell indices, $\mathbf{N}_B = \{0, 1, 2\}$. Here, 3 Chu sequences with the length-63 are used and the selected roots are 25, 29, 34 for the PSSs. The SSS are constructed by two cyclic shifted m-sequences and a scrambling sequence. The cyclic shift

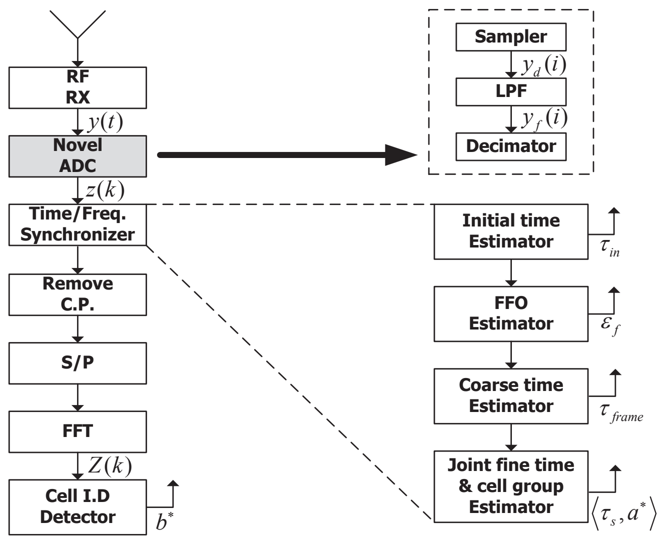

Fig. 2: The Block diagram for a typical the cell search procedure.

indices of the m-sequences is derived from a function of the the group index [8].

Let $\mathbf{X}_s \triangleq \left\{ \mathbf{X}_s^{(a,b)} \middle| a \in \mathbf{N}_G, b \in \mathbf{N}_B \right\}$, $s \in \{0,1\}$, be the reference sequence set of the primary synchronization signals (PSSs) or the secondary synchronization signals (SSSs). Here, $\mathbf{X}_0^{(a,b)}$ denotes the reference sequence set of the PSSs of the b^{th} BS in the a^{th} group and $\mathbf{X}_1^{(a,b)}$ denotes the reference sequence set of the SSSs of the b^{th} BS in the a^{th} group. Then, the FD reference sequence of the b^{th} BS in the a^{th} group can be written as

$$\mathbf{X}_s^{(a,b)} = [X_s^{(a,b)}(0)\ X_s^{(a,b)}(1) \cdots X_s^{(a,b)}(N-1)]^{\mathbf{T}}, \quad (1)$$

where $\sum_{n=0}^{N-1} \left| X_s^{(a,b)}(n) \right|^2 = 1$ and $\left| X_s^{(a,b)}(n) \right| > 0$ only when $n \in \mathbf{M} = \{n_0, \cdots, n_M\}$. Here, $\mathbf{M}$ denotes the set of reference symbol locations and n_m denotes the $(m+1)^{\text{th}}$ smallest element in $\mathbf{M}$. Let $\mathbf{S}^{(a,b)}$ be the transmitted FD OFDM symbol including the SS for the b^{th} BS of the a^{th} group and P be the transmitted power, which can be written as

$$\mathbf{S}_s^{(a,b)} = [\,S_s^{(a,b)}(0)\ S_s^{(a,b)}(1) \cdots S_s^{(a,b)}(N-1)]^{\mathbf{T}}, \quad (2)$$

where $S_s^{(a,b)}(n) = \sqrt{P} X_s^{(a,b)}(n)$, $n \in \mathbf{M}$ and, for $n \notin \mathbf{M}$, the null or data symbol is allocated to the n^{th} subcarrier. Let $W_N(i) = \exp\left(j\frac{2\pi i}{N}\right)$ and the inverse discrete fourier transform (DFT) is performed to obtain $s_s^{(a,b)}(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} S_s^{(a,b)}(n) W_N(nk)$ for $k = 0, \cdots, N-1$. During the propagation, the transmitted signal is first corrupted by multipath fading plus additive white Gaussian noise (AWGN). Then, the received signal is given by

$$y(t) = \sum_{a=0}^{N_G-1} \sum_{b=0}^{N_B-1} s_s^{(a,b)}(t) * \alpha^{(a,b)} h^{(a,b)}(t) + n(t), \quad (3)$$

where $*$ denotes convolution, $n(t)$ are the continuous-time representation of the noise; $\alpha^{(a,b)}$ is the average attenuation factor between for the b^{th} BS of the a^{th} group;$h^{(a,b)}(t)$ denotes the channel impulse response for the b^{th} BS of the a^{th} group.

3. A typical Design of the synchronization signal

The cell search procedure assumed in this paper is shown in Fig. 2. At a mobile station (MS), the received signal sampled at a rate corresponding to the maximum possible bandwidth. After the sampling, a low-pass filtering is performed and then the decimation is performed for an efficient synchronization. Then, the synchronization and cell search scheme procedure is summarized as follows.

1. Do the initial timing estimation by using the cyclic prefix (CP) correlation.
2. Perform the fractional frequency offset estimation by using the CP correlation.
3. Acquire the frame detection boundary by using the cross-correlation of received signal and the reference signal.
4. Obtain the fine timing point and the cell group index using the cross-correlation between the received signal and the reference signal.
5. Find the cell index by using the differential vector made by the SSS.

The performance of the cell search is determined by the auto-correlation of the received signal and the cross-correlation between the received signals and reference sequences. Therefore, searching the root sequences of the SSs with good auto-correlation function and cross-correlation function properties is important in the SS design. Chu sequences have the perfect auto-correlation and are known to be the Welch bound equality signal sets [11]–[13]. Thus, it is a natural consequence to adopt the Chu sequences in the 3GPP-LTE. A set of Chu sequences with length-N is defined as $\mathbf{C}_N = \{\boldsymbol{a}_N^r \,|\, r \in \mathbf{R}_N\}$, where $\mathbf{R}_N = \{\, n \,|\, 0 < n < N, \gcd(N,n) = 1\}$ and the kth element of $\boldsymbol{a}_N^r$, $a_N^r(k)$, is defined as

$$a_N^r(k) = W_N\left(\frac{rk\,(k + (N)_2)}{2}\right). \quad (4)$$

In the current standard of the 3GPP-LTE, the selected roots (r=25, 29, 34) for three Chu sequences are used for the sequence length of $N = 63$. However, such a PSS reuse with the reuse factor of 3 is not enough for an HCN and a modified PSS design with an arbitrarily given number of cells per group is required. In [10], when the maximum magnitude of the cross-correlation among the sequences is constrained, a tight upper bound on the maximum number of available Chu sequence were proposed. For the length $N = \prod_{i=0}^{k-1} p_i^{c_i}$, where k is the number of prime factors of N and p_i denotes the $(i+1)^{\text{th}}$ smallest prime factor of N, the maximum number of available sequences is bounded by [10]

$$N_S \leq \varphi\left(g_N(\theta)\right), \quad (5)$$

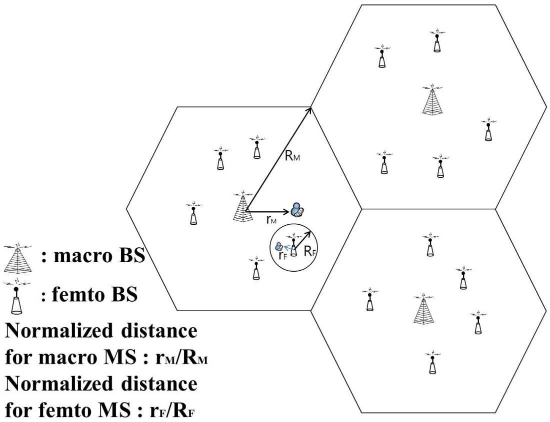

Fig. 3: 2-tier HCN model used for the simulations.

where $g_N(\theta) \triangleq \max\left(\arg\min_{g\in\mathbf{G}_N(\theta)} \varphi(g)\right)$, $\mathbf{G}_N(\theta) \triangleq \{g \,|\, N\theta^2 \le g < Np_0\theta^2, g \in \{N'\text{s divisor}\}\}$ and $\varphi(N) = \prod_{i=0}^{k-1} p_i^{c_i-1}(p_i - 1)$ denotes the Euler's totient function [14]. Let $\mathbf{R}_N^\theta$ be the largest partial index set of $\mathbf{R}_N$ satisfying that, for any $r, s \in \mathbf{R}_N^\theta$, $\gcd(N, r-s) \le \sqrt{N}\theta$. Then, the maximum magnitude of the cross-correlation function of the following reference sequence set of the PSSs is smaller than θ as long as the maximum number of supportable neighboring BSs ($|\mathbf{R}_N^\theta|$) is smaller than N_S. Then,

$$\mathbf{X}_1 = \left\{ \mathbf{X}_1^{(a,b)} \middle| X_1^{(a,b)}(n_m) = a_M^{r_a}(m) \text{ for } n_m \in \mathbf{M}, \right. \left. X_1^{(a,b)}(n_m) = 0 \text{ for } n_m \notin \mathbf{M} \text{ where } r_a = \left[\mathbf{R}_M^\theta\right]_{a+1} \right\}, \tag{6}$$

where $[\mathbf{R}]_a$ denotes the a^{th} smallest element of a set $\mathbf{R}$. Table 1 describes the maximum number of supportable BSs within a group for various N and θ. It is seen that sufficient number of sequences is available even for very small θ when the smallest prime factor of N is not small.

The reference sequences of the SSS, $\mathbf{X}_2^{(a,b)}$, are the sequences by multiplication of the cyclic shifted two m-sequences and two scrambling sequences which is similar to the 3GPP-LTE SSS.

$$X_2^{(a,b)}(2n) = \begin{cases} d_0^{(l_0)} c_0(n) & \text{in slot } 0, \\ d_1^{(l_1)} c_0(n) & \text{in slot } 10, \end{cases}$$
$$X_2^{(a,b)}(2n+1) = \begin{cases} d_1^{(l_1)} c_1(n)\, z_1^{(l_0)}(n) & \text{in slot } 0, \\ d_0^{(l_0)} c_1(n)\, z_1^{(l_1)}(n) & \text{in slot } 10, \end{cases} \tag{7}$$

where $d_0^{(l_0)}$ and $d_1^{(l_1)}$ are defined as two different cyclic shifts of the m-sequence where $d_i^{(l_i)}(n) = 1 - 2\left(v_d(n + l_i) \bmod 31\right)$, $v_d(j+5) = (v_d(j+2) + v_d(j)) \bmod 2$, $0 \le j \le 25$, with initial conditions $v_d(0) = 0, v_d(1) = 0, v_d(2) = 0, v_d(3) = 0, v_d(4) = 1$. $c_0(n)$ and $c_1(n)$ are two scrambling sequences which dependent on the PSS are defined by two different cyclic of the m-sequences where $c_i(n) = 1 - 2\left(v_c\left(n + l_i + b + (N_B)^i\right) \bmod 31\right)$, $v_c(j+5) = (v_c(j+3) + v_c(j)) \bmod 2$, $0 \le j \le 25$, with initial conditions $v_c(0) = 0, v_c(1) = 0, v_c(2) = 0, v_c(3) = 0, v_c(4) = 1$. Also, $z_1^{(l_0)}(n)$ and $z_1^{(l_0)}(n)$ are the scrambling sequences by a cyclic shift where $z_i(n) = 1 - 2\left(v(n + l_i \bmod 8) \bmod 31\right)$, $v_z(j+5) = (v_z(j+4) + v_z(j+3) + v_z(j+2) + v_z(j+1) + v_z(j)) \bmod 2$, $0 \le j \le 25$, with initial conditions $v_z(0) = 0, v_z(1) = 0, v_z(2) = 0, v_z(3) = 0, v_z(4) = 1$. The cyclic shift indices, m_0 and m_1, of the m-sequences are derived from a function of the group indices.

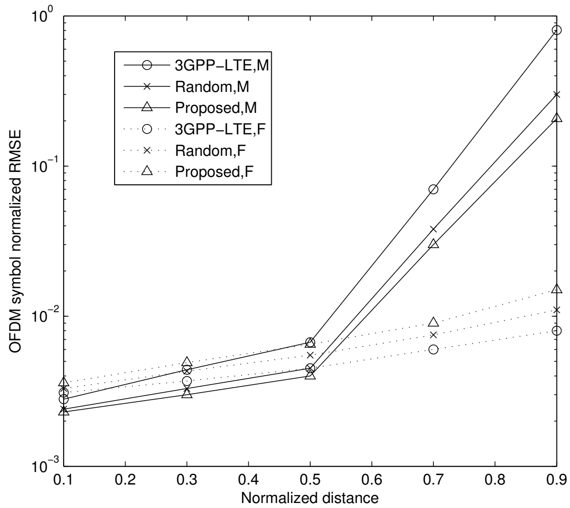

Fig. 4: The RMSE performance of the fine timing estimation (M : macro MS, F : Femto MS)

4. Simulations

In this section, we evaluate the performance of the various SSs for the macro/femto two-tier networks as Fig. 2 under the following channel model under the urban microcell (1km distance for BS to BS) with other channel parameters as described in [15]. $\mathbf{N}_B = \{0, \cdots, 5\}, \mathbf{N}_G = \{0, 1, 2\}$ and the total transmission powers of macro-BS and femto BS are set as 43 dBm and 21 dBm, respectively, and the number of femto BSs per hexagon of Fig. 2 is 5. Macro BSs are distributed according to a hexagonal grid-based model and femto BSs are randomly distributed according to a homogeneous Poisson point process [16]. We use the proposed SSs with $M = 62$ and $\theta^2/N = 0.0322$. For comparison, the PSSs of the 3GPP-LTE (root indices set of macro cells={25,39,34}, root indices set of femto cells=$\mathbf{R}_{63} - \{25, 39, 34\}, M = 63$) and those with randomly selected Chu sequences in $\mathbf{R}_{62}$.

In Figs. 4 and 5, the root mean square error (RMSE) performance for the fine timing ($E\left[|\tau_s - \hat{\tau}_s|/N\right]$) and the detection error rate of the group of the target cell ($\sum_{t=0}^{N_c-1} \delta(a^* - \hat{a}^*)/N_c$) where a^* is the index of the target cell, $\hat{a}^*$ is the detected cell index and N_c is the the number

Table 1: The maximum number of supportable cells in a group for various N and θ.

θ	≤ 0.02	≤ 0.04	≤ 0.06	≤ 0.08	≤ 0.1
N	N_S	N_S	N_S	N_S	N_S
$62(2 \cdot 31)$	·	·	30	30	30
$63(3^2 \cdot 9)$	·	2	2	6	6
$64(2^6)$	·	·	2	4	4
$126(2 \cdot 3^2 \cdot 7)$	·	2	6	6	6
$128(2^7)$	·	4	4	8	8
$129(3 \cdot 43)$	2	42	42	42	42
$244(2^2 \cdot 61)$	2	60	60	60	60
$256(2^8)$	4	8	8	16	16
$268(2^2 \cdot 67)$	66	66	66	66	66
$508(2^2 \cdot 127)$	126	126	126	126	126
$512(2^9)$	8	16	16	32	32
$516(2^2 \cdot 3 \cdot 43)$	4	42	42	42	42

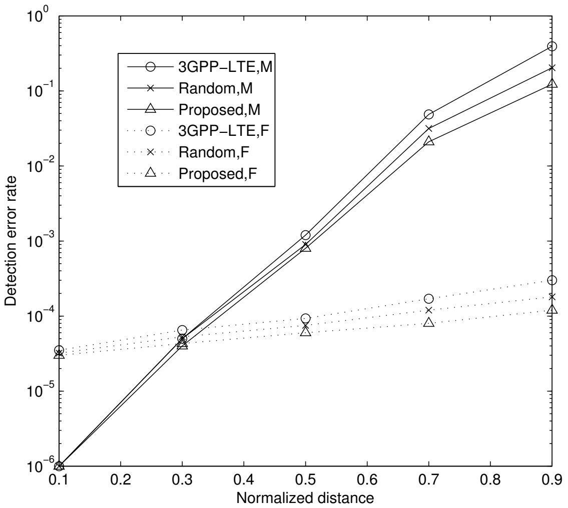

Fig. 5: The detection error rate performance comparison (M : macro MS, F : Femto MS).

of the channel realizations) using 10^5 channel realizations. From the results, we can see that the performance gain for the RMSE and the detection error rate increases as the macro MS and the Femto MS move to the cell boundary increase because the the ICI power increases and the power of the target BS decreases.

5. Conclusions

This paper provides a guideline for the SS designs in the 3GPP-LTE HCN. The proposed SSs are designed to minimize the maximum magnitude of the cross-correlation function between the PSSs among a cell group for an arbitrarily given PSS length. From the simulation results, it was shown that the proposed SSs are more appropriate when applied in HCN.

Acknowledgments

This research was supported by the MKE (The Ministry of Knowledge Economy), Korea, under the ITRC (Information Technology Research Center) support program supervised by the NIPA (National IT Industry Promotion Agency (NIPA-2011-(C1090-1111-0005)).

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