Cell Search Time Performance Using PVS Transmit Diversity in Heterogeneous Networks with the Same Frequency Spectrum

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Abstract—This paper presents the initial cell search time performance based on Long Term Evolution (LTE) synchronization signals employing precoding vector switching (PVS) transmit diversity in heterogeneous networks. We focus on the effect of PVS transmit diversity to mitigate the influence of co-channel interference in heterogeneous networks with the same frequency spectrum between a macrocell and small cells. System-level simulation results show that when using two-antenna receive diversity, the cell search time at the cell ID detection probability of 98% using PVS transmit diversity is decreased by approximately 20 ms than for one-antenna transmission. Moreover, we show that the PVS transmit diversity is more effective for inter-macrocell synchronous operation compared to that for inter-macrocell asynchronous operation. Through the simulation results, we show that PVS transmit diversity is beneficial in achieving fast initial cell search times in heterogeneous networks with the same frequency spectrum.

Keywords—cell search; LTE; synchronization signal; heterogeneous networks; outdoor small cell

I. INTRODUCTION

In the Long Term Evolution (LTE) and LTE-Advanced downlinks, orthogonal frequency division multiple access (OFDMA) is adopted [1]. At the beginning of communications, i.e., physical channel setup, a set of user equipment (UE) must perform a cell search. During the cell search, the UE acquires the cell ID in addition to the received subframe and radio frame timings in the downlink. The cell search process must also be performed periodically in order to update the cell to be connected and to find a candidate cell for handover. In LTE, a hierarchical synchronization signal structure that comprises a primary synchronization signal (PSS) and secondary synchronization signal (SSS) is adopted to achieve fast cell search [1],[2].

Heterogeneous networks have recently drawn attention in which a macrocell is overlaid onto small cells or local cells including micro and picocells [3],[4]. Small cells including picocells are effectively installed in local areas that have high traffic density such as hotspots, large halls, and underground shopping malls. The small cells mainly accommodate users that demand high-speed data services and are under low mobility conditions. On the other hand, macrocells support users with high mobility. In a 3rd generation partnership project (3GPP) technical report, the deployment scenarios of heterogeneous networks using the same or separate frequency spectra between a macrocell and small cells are specified [4]. In the scenario using separate frequency spectra, flexible deployment of small cells is achieved since no co-channel interference occurs between the macrocell and small cells. Meanwhile, in the deployment with the same frequency spectrum, the deployment of small cells in a local area with high traffic density is achieved efficiently without employing additional frequency spectrum. In this scenario however, the co-channel interference, particularly from a macrocell to an outdoor small cell degrades the achievable block error rate performance. This is also true for the initial cell search to find the best cell accurately. In the paper, we focus on the effect of transmit diversity on the initial cell search time performance by mitigating the mutual co-channel interference for heterogeneous networks with the same frequency spectrum.

This paper presents the initial cell search time performance using the PSS and SSS based on the LTE radio interface by applying precoding vector switching (PVS) transmit diversity in heterogeneous networks with the same frequency spectrum. Since the PSS and SSS are physical channels that a UE acquires first in the downlink, the applied transmit diversity scheme should be transparent to the UE. Hence, PVS transmit diversity is adopted for the PSS and SSS [1]. Through system-level simulations, we investigate the initial cell search time performance in heterogeneous networks for the various inter-cell site synchronization modes. The rest of the paper is organized as follows. In Section II, we describe the structures and sequences of the PSS and SSS based on the LTE radio interface. Then in Section III, we describe the initial cell search method. After explaining the system-level simulation model focusing on the outdoor small cell configuration in Section IV, we present the computer simulation results in Section V. We give our concluding statements in Section VI.

II. SEQUENCES AND STRUCTURES OF PSS AND SSS BASED ON LTE RADIO INTERFACE

A. PSS and SSS Sequences

1) PSS sequence

The constant amplitude zero auto-correlation (CAZAC) sequence has a constant amplitude both in the time and frequency domains and provides a low auto-correlation property for a non-zero time shift. Thus, the Zadoff-Chu sequence has a constant amplitude both in the time and frequency domains. In heterogeneous networks using the same or separate frequency spectra between a macrocell and small cells are specified [4].

In the scenario using separate frequency spectra, flexible deployment of small cells is achieved since no co-channel interference occurs between the macrocell and small cells. Meanwhile, in the deployment with the same frequency spectrum, the deployment of small cells in a local area with high traffic density is achieved efficiently without employing additional frequency spectrum. In this scenario however, the co-channel interference, particularly from a macrocell to an outdoor small cell degrades the achievable block error rate performance. This is also true for the initial cell search to find the best cell accurately. In the paper, we focus on the effect of transmit diversity on the initial cell search time performance by mitigating the mutual co-channel interference for heterogeneous networks with the same frequency spectrum.

This paper presents the initial cell search time performance using the PSS and SSS based on the LTE radio interface by applying precoding vector switching (PVS) transmit diversity in heterogeneous networks with the same frequency spectrum. Since the PSS and SSS are physical channels that a UE acquires first in the downlink, the applied transmit diversity scheme should be transparent to the UE. Hence, PVS transmit diversity is adopted for the PSS and SSS [1]. Through system-level simulations, we investigate the initial cell search time performance in heterogeneous networks for the various inter-cell site synchronization modes. The rest of the paper is organized as follows. In Section II, we describe the structures and sequences of the PSS and SSS based on the LTE radio interface. Then in Section III, we describe the initial cell search method. After explaining the system-level simulation model focusing on the outdoor small cell configuration in Section IV, we present the computer simulation results in Section V. We give our concluding statements in Section VI.
The SSS sequence corresponds to a cell ID group. By assigning different cell ID group-specific sequences to two SSS symbols within a radio frame, the radio frame timing can be detected simultaneously along with the cell ID group. We assign different PSS sequences to the three cells within the same cell site for a macrocell according to the conventional PSS assignment [2]. Moreover, a PSS sequence is assigned to the small cell cluster that is different from that assigned to the macrocell [6].

### 2) SSS sequence

The SSS sequence corresponds to a cell ID group. By assigning different cell ID group-specific sequences to two SSS symbols within a radio frame, the radio frame timing can be detected simultaneously along with the cell ID group. The two M-sequences that take +1 or -1, \( \tilde{s}(\text{n}_{\text{SSS}}) \) and \( \tilde{z}(\text{n}_{\text{SSS}}) \), are generated from the two M-sequences based on different generator polynomials with a length of 31 sequences. Here, sequence index \( n_{\text{SSS}} \) is given as \( 0 \leq n_{\text{SSS}} \leq 30 \). We generate two sequences, \( s_{\text{SSS}}^{(n_{\text{SSS}})}(\text{m}_{\text{SSS}}) \) and \( s_{\text{SSS}}^{(n_{\text{SSS}})}(\text{m}_{\text{SSS}}) \), by adding the first and second cyclic shifts to the first M-sequence, \( \tilde{s}(\text{n}_{\text{SSS}}) \). The two sequences are given as:

\[
\begin{align*}
&n_{\text{SSS}} = 0, \ldots, 30, \quad (1) \\
&s_{\text{SSS}}^{(n_{\text{SSS}})}(\text{m}_{\text{SSS}}) = \tilde{s}(\text{n}_{\text{SSS}} + \text{m}_{\text{SSS}})_{\text{mod}31}, \quad n_{\text{SSS}} = 0, \ldots, 30 \\
&s_{\text{SSS}}^{(n_{\text{SSS}})}(\text{m}_{\text{SSS}}) = \tilde{z}(\text{n}_{\text{SSS}} + \text{m}_{\text{SSS}})_{\text{mod}31}, \quad n_{\text{SSS}} = 31, \ldots, 61
\end{align*}
\]

In (1), parameter \( M \) is the root value that takes 25, 29, and 34 for cell ID indices \( N_{\text{ID}}(=l) = 0, 1, 2 \), respectively [1]. In the LTE radio interface, 504 cell IDs are divided into 168 cell ID groups. Hence, one cell ID group contains three cell IDs. The three PSS sequences correspond to three cell IDs within the same cell ID group. We assign different PSS sequences to the three cells within the same cell site for a macrocell according to the conventional PSS assignment [2]. Moreover, a PSS sequence is assigned to the small cell cluster that is different from that assigned to the macrocell [6].
\(\kappa = 0^\text{th} \text{ or } 1^\text{st} \) set of PSS and SSS alternately over the one radio frame.

\[
S^{\text{PSS}}_h = \frac{1}{\sqrt{2}} \begin{bmatrix} a_{0,h} & a_{1,h} \\ a_{0,h} & -a_{1,h} \end{bmatrix}
\]  

In (3), \(a_{\kappa,h} \) represents \(a'_{\kappa,\text{PSS}} \) or \(a'_{\kappa,\text{SSS}} \). We used precoding vectors \((+1, +1)\) and \((+1, -1)\) for \(\kappa = 0 \) and 1, respectively, for all the subcarrier components of the PSS and SSS without using frequency-selective precoding. By applying different precoding vectors for the two sets of the PSS and SSS in the same radio frame, the received signal levels of the two sets are randomized in the time domain. The same precoding vector is multiplied to both the PSS and SSS in the same slot. Hence, the PSS at each subcarrier position is used as a reference signal for coherent computation of the SSS correlation.

### III. CELL SEARCH METHOD

At a UE receiver, we apply two-antenna receiver diversity with uncorrelated fading variation between the antennas. Fig. 3 shows the initial cell search procedure for the same frequency spectrum between a macrocell and an outdoor small cell. We assume a single-path model to simplify the explanation. The received sampled signal in the time domain for FFT processing.

\[
r^{(i)}(n) = \sum_{\tau=1}^{N_{\text{FFT}}} h^{(i)}(n - \tau) + w^{(i)}(n) e^{-j2\pi n \Delta h^{(i)}}
\]  

In (4), \(n\) denotes the sample index that corresponds to the sampling timing index for FFT processing. Moreover, \(I\) denotes the number of cells and \(\phi(n)\) represents the transmitted signals including the PSS and SSS that are transmitted from cell \(i\). Term \(h^{(i)}(n)\) represents a channel response of the received signal from cell \(i\) including distance-dependent path loss, log-normal shadowing, and instantaneous fading; \(\bar{\tau}_{i}\) denotes the total delay time from cell site \(i\) to the target UE; \(\Delta f^{(i)}\) is the frequency offset; \(w^{(i)}(n)\) is background noise with zero mean. We assume that \(\bar{\tau}_{i}\) and \(\Delta f^{(i)}\) are identical between the two receiver branches.

#### A. First Step: Detection of Received Timing and Sequence for PSS

In the first step, a UE computes the correlation between the received signal and PSS sequence replica with a \(N_{\text{FFT}}\)-chip length in the time domain and simultaneously generates a power delay profile for all the sample positions over a 10-ms duration for the three PSS sequences. Two correlations at intervals of 5 ms are summed in squared form. Here, the 5-ms interval corresponds to the difference in the received timings of the two PSSs within a 10-ms radio frame. The correlations at the two receiver branches are further summed in squared form to avoid the influence of instantaneous fading variation. The received PSS timing from a cell with the minimum path loss for the assigned UE location is estimated from the sample timing that yields the maximum correlation peak as shown in the equation below. We simultaneously estimate the PSS sequence among the three candidates.

\[
\hat{\mu}, \hat{t} = \arg \max_{\mu, k} \sum_{n=0}^{N_{\text{FFT}}-1} \left[ \sum_{\kappa=0}^{1} r^{(i)}(n + \mu N_{\text{FFT}} + k) \phi^{(i)}(n) \right]^2
\]  

In (5), \(\phi^{(i)}(n)\) denotes the PSS sequence in the time domain for \(N_{\text{FFT}} = 1\) (\(\phi^{(i)}\) denotes the complex conjugate). The IFFT generates the PSS sequence in the time domain, \(\phi^{(i)}(n)\), from the PSS sequence with a length of 62 sequences in the frequency domain, \(d_{\text{PSS}}(n)\), after padding zeros into the remaining subcarriers at both ends. Expression \(N_{\text{FFT}} = (N_{\text{FFT}} + N_{\text{CP}}) \times 14 \times 5\) indicates samples in the interval in which two consecutive PSSs are multiplexed. The UE detects the received FFT timing, \(\mu\), that provides the maximum correlation signal and the cell ID within the same cell ID group. Based on the estimated PSS received timing, \(\mu\), we compute the respective correlations between the former half or latter half of the PSS sequence and the received signal over a \(N_{\text{FFT}}/2\)-sample duration as

\[
c^{(i)}_0 = \sum_{n=0}^{N_{\text{FFT}}/2} r^{(i)}(n + \mu) \phi^{(i)}(n)
\]

and

\[
c^{(i)}_1 = \sum_{n=0}^{N_{\text{FFT}}/2} r^{(i)}(n + N_{\text{FFT}}/2 + \mu) \phi^{(i)}(n + N_{\text{FFT}}/2)
\]

From the correlation values from (6a) and (6b), we compute the phase rotation due to the frequency offset of a temperature compensated crystal oscillator (TCXO) of a UE between the center of the former half and that of the latter half for the FFT block. The PSS is multiplexed as

\[
\Delta f^{(i)} = \tan^{-1} \left( \frac{\sum_{n=0}^{N_{\text{FFT}}/2} c^{(i)}_1}{\sum_{n=0}^{N_{\text{FFT}}/2} c^{(i)}_0} \right)
\]

Since Zadoff-Chu sequences yield a high autocorrelation peak when the frequency offset is small, the estimated frequency offset value in (7) is estimated accurately. Then, the estimated frequency offset is given as

\[
\Delta f^{(i)} = \frac{\Delta f^{(i)} - f_{\text{TCXO}}}{N_{\text{FFT}}}
\]

#### B. Second Step: Detection of SSS Sequence and Radio Frame Timing

Before the second step, we compensate for the frequency offset component by multiplying the complex conjugate of the estimated frequency offset, \(e^{-j2\pi \Delta f^{(i)}/N_{\text{FFT}}}\), to the received PSS and SSS. Subsequently, a UE converts the FFT blocks including the PSS and SSS into the frequency domain signal using the FFT based on the received PSS timing, \(\mu\), which is estimated in the first step.

In the second step, using the detected SSS symbol timing, a UE performs FFT for both the PSS and SSS symbols. The channel gain at each subcarrier position is computed by coherently averaging the channel gains of the PSS over a nine subcarrier spacing with the target subcarrier as the center. The FFT output of the SSS is maximal-ratio-combined over the two SSS symbols within the one radio frame and two receiver antennas. Let \(P_{\text{SSS}}(k)\) be the received signal of the FFT block including the SSS in the frequency domain at the \(k\)-th subcarrier at the \(h\)-th receiver branch for the \(v\)-th slot. The complex conjugate of the estimated channel response at each subcarrier position and that of the SSS sequence replica are multiplied to the corresponding received SSS. The correlation signals for the SSS sequences, \(d_{\text{SSS}}(2\pi_{\text{SSS}})\) and \(d_{\text{SSS}}(2\pi_{\text{SSS}} + 1)\), which are interleave, are individually
generated by coherently accumulating the computed signal at each subcarrier position every other subcarrier over 31 subcarriers. The computed correlation signals of the first and eleventh slots within one radio frame at the two receiver branches are further coherently averaged. Then, the cell ID group and the radio frame timing are simultaneously detected from the combination of the SSS sequences that yield the maximum correlation power level as shown in the equation below.

$$\hat{d}_{SSS}^{(k)} = \arg \max_{d_{SSS}} \left\{ \sum_{n=1}^{N_{SSS}} \sum_{c=1}^{N_{c}} \left[ R_{SSS}^{(c)}(2k)^{n} \tilde{d}_{SSS}^{(c)}(2n_{SSS} + 1) \right] \right\}$$

In (8), $$E^{(c)}_{SSS}(k)$$ represents the channel response that is estimated by using the PSS at the $$k$$-th subcarrier position of the $$h$$-th receiver branch for the $$v$$-th slot. In this paper, the time for one cycle comprising the first and second steps in the cell search is 20 ms, since the averaging interval in each step is 10 ms. The UE repeats the processing of the first and second steps until the correct cell ID is detected.

IV. SYSTEM-LEVEL SIMULATION MODEL

Table I gives the major simulation parameters including the outdoor small cell deployment based on [4]. We assume a 19-hexagonal cell-site model where each cell comprises three cells. The inter-site distance is assumed to be 1732 m. One small cell cluster is placed in each of the three cells. The radius of a small cell cluster is 100 m and the distance between the macrocell site and the center of the small cell cluster is 700 m. The $$N_{Small} = 4$$ small cells are placed in a small cell cluster. We assume that all the small cells in the same small cell cluster are time-synchronized. We assume both inter-macrocell synchronous and asynchronous operations and investigate the effect of the inter-macrocell synchronization mode on the initial cell search time performance. In this evaluation, the UE locations are randomly selected and the cell search time to detect the correct cell is measured. Two thirds of the UEs are dropped within the small cell clusters and 1/3 of the UEs are dropped in the macro geographical area including small cell clusters. By repeating this process, the cumulative distribution function (CDF) of the cell search time is derived. Focusing on the initial cell search, we set the frequency offset to be +/- 6 kHz assuming the frequency error of the standard oscillator of 3 ppm at a UE assuming the carrier frequency of 2 GHz. In the evaluations, we define the correct cell to be detected as the cell in which the average received signal power is within 3 dB compared to the highest average received signal power.

| Table I. Major Simulation Parameters |
|------------------------------|-----------------|
|                              | Maccell          | Small cell       |
| Cell structure               | 19 cell sites, 5 cells per site | 4 cells per small cell cluster |
| System bandwidth             | 5 MHz            | 2.0 GHz          |
| Carrier frequency            | 2.0 GHz          |                  |
| RSS transmission power       | 43 dBm           | 27 dBm           |
| BS antenna gain              | 17 dBi           | 5 dBi            |
| Inter-cell site synchronization mode | (1) Inter-macrocell site synchron | (2) Inter-macrocell site synch |
| Inter-site distance (ISD)    | 1732 m           | Approximately 100 m |
| Distance between macrocell site and center of small cell cluster | 700 m          |
| Distance-dependent path loss | 128.1 + 37.6 log[rms] dB | 140.7 + 36.7 log[rms] dB |
| Shadowing                    | 8.0 dB           | 4.0 dB           |
| Standard deviation           |                  |                  |
| Correlation                  |                  |                  |
| Inter-cell / intra-cell      | 0.5 / 1.0        |
| Maximum Doppler frequency    | 5.55 Hz          |                  |
| Maximum frequency offset     | +/- 6.0 kHz      |                  |
| Transmit/receiver diversity  | $$N_{Rx} \times N_{Tx} = 1 \times 2, 2 \times 2, 2 \times 4$$ |

V. COMPUTER SIMULATION RESULTS

Fig. 4 shows the CDF for the PSS detection time for the heterogeneous networks when using PVS transmit diversity. In the figure, we represent a combination of $$N_{Rx} = 2$$ transmit antennas and $$N_{Rx} = 2$$ receive antennas as 2 x 2. We also show the performance for only the macrocell configuration. We assume inter-macrocell asynchronous operation. Fig. 4 shows that the PVS transmit diversity without receive diversity achieves almost the same PSS detection probability as that for $$N_{Rx} = 1$$ and receive diversity with $$N_{Rx} = 2$$ antennas. Hence, we confirm the diversity effect of PVS transmit diversity. When using receive diversity with $$N_{Rx} = 2$$ antennas, the search time satisfying the PSS detection probability of 98% by using PVS transmit diversity is decreased by approximately 20 ms compared to that for $$N_{Rx} = 1$$ antenna transmission.

Next, Fig. 5 shows the CDF of the cell ID detection time, i.e., initial cell search time using the PVS transmit diversity in heterogeneous networks. Fig. 5 shows that the PVS transmit diversity without receive diversity achieves almost the same initial cell search time as the 1-antenna transmission associated with $$N_{Rx} = 2$$ receive diversity. We find that the PVS transmit diversity is effective in shortening the initial cell search time in the region where the correct cell ID detection probability is higher than approximately 95%, i.e., near the cell edge. The figure shows that when assuming receive diversity with $$N_{Rx} = 2$$ antennas, the initial cell search time at the detection probability of 98% for the PVS transmit diversity is decreased by approximately 20 ms compared to that for the 1-antenna transmission. With 1-antenna transmission, the PSS detection probability in heterogeneous networks becomes higher compared to that for a macrocell only due to the decrease in the false detection. We find that the improvement in the cell ID detection probability of the PVS transmit diversity from the 1-antenna transmission is decreased slightly compared to that for the macrocell only configuration. However, we confirm a distinct reduction effect in the initial cell search time of PVS transmit diversity. Fig. 5 also shows that the $$N_{Rx} = 4$$ receive
diversity is effective in improving the correct cell ID detection probability even with the PVS transmit diversity.

![Fig. 4. CDF of PSS detection time using PVS transmit diversity for heterogeneous networks.](image1)

![Fig. 5. CDF of initial cell search time using PVS transmit diversity for heterogeneous networks.](image2)

Finally, Fig. 6 shows comparisons of the CDFs of the initial cell search time using PVS for inter-macrocell site asynchronous and synchronous operations. Fig. 6 shows that the cell ID detection probability for the inter-macrocell synchronous operation is lower than that for the inter-macrocell asynchronous operation for the 1-antenna transmission. This cause is explained as follows. As we described previously, the correlation between the received signal and SSS sequence replica is computed coherently in the frequency domain. In this case, the PSS at each subcarrier position is used as a reference signal to estimate the channel response for the corresponding SSS. In the inter-macrocell synchronous operation, the time-aligned interference of the PSS with the same sequence from other macrocells degrades the channel estimation accuracy for the SSS correlation computation. By using PVS transmit diversity however, the cell ID detection probability for the inter-macrocell synchronous operation is significantly improved and it is close to that for the inter-macrocell asynchronous operation. This is due to the improving channel estimation accuracy using the PSS from the cell with the minimum path loss.

![Fig. 6. CDF of initial cell search time using PVS transmit diversity for heterogeneous networks for inter-macrocell asynchronous and synchronous operations.](image3)

VI. CONCLUSION

This paper presented the initial cell search time performance when applying PVS transmit diversity to the PSS and SSS in heterogeneous networks with the same frequency spectrum. System-level simulation results showed that PVS transmit diversity is effective in shortening the initial cell search time for the correct cell ID detection probability of greater than approximately 95% although the improvement from one-antenna transmission is smaller compared to that for the macrocell-only deployment. We also showed that when using 2-antenna receive diversity, the cell search time at the cell ID detection probability of 98% using PVS transmit diversity is decreased by approximately 20 ms compared to that for one-antenna transmission. Moreover, we showed that the PVS transmit diversity effect is more effective for inter-macrocell synchronous operation compared to that for inter-macrocell asynchronous operation due to the greater improvement in the channel estimation accuracy for coherently computing the SSS correlation in the second step. In conclusion, we showed that PVS transmit diversity is beneficial in achieving fast initial cell search times in heterogeneous networks with the same frequency spectrum up to $N_{Rx}=4$ receive diversity.

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