1. INTRODUCTION

The global navigation satellite system (GNSS) [1-3] is considered the most popular positioning and navigation system today, owing to its accurate positioning and timing information, as well as its convenience. However, performance issues can occur with the GNSS when its signals become unavailable. The performance of GNSS can be degraded by anomalous ionospheric conditions [4-7], signal reflection/blockage [8, 9], and can also be affected by interference and obstruction owing to the low strength of GNSS signals [10-13].

Recently, signals of opportunity (SOPs) have drawn significant attention for use in organizing a new form of positioning system [14-17]. SOPs are radio frequency (RF) signals that are not originally provided for positioning purposes, including Wi-Fi, TV, radio, and mobile phone signals. SOPs have the advantages of transmission power and coverage compared to GNSS signals, thus they could be used as complementary positioning signals when GNSS signals are unavailable. Among various kinds of SOPs, long-term evolution (LTE) signals are considered one of the most suitable candidates for use as positioning system signals owing to its high bandwidth and data rates [18, 19].

To utilize LTE signals for positioning purposes, special algorithms are needed to identify which base transceiver station, also known as eNodeB, transmitted the signal and the time of arrival (TOA) of the signal [20]. In an LTE system, signals from baseband data can be distinguished from each other by detecting a system-information parameter called cell identity (cell ID). Cell ID can be used to identify the eNodeB that transmitted the signal. Cell ID is determined from two kinds of reference signal sequences inserted in the time-frequency grid: the Primary Synchronization Sequence (PSS) and the Secondary Synchronization Sequence (SSS). The detection of a correct cell ID directly leads to the reliability of an LTE-based positioning system [21-23]. To organize a high-reliability positioning system, an analysis of the correlation peak value of reference signals and reference signal received quality (RSRQ) must be provided, because these are considered useful criteria by which to evaluate the reliability of a determined LTE cell ID. This paper shows the analyzed results of real LTE signals acquired in commercial frequency bands and sampled. The correlation peak value and RSRQ are measured and compared at different spectral and sampling frequencies.

2. LTE FRAME STRUCTURE AND CELL ID ACQUISITION

In this section, first, the structure of an LTE frame is discussed. Then, a method to acquire the LTE cell ID and parameters that are related to the cell ID estimation accuracy (i.e., maximum correlation peak values and RSRQ) are explained.

2.1 LTE frame structure

In an LTE downlink transmission, by which an eNodeB transmits an LTE signal to user equipment (UE), data transmission is organized in the form of multiple radio frames. As shown in Fig. 1, each radio frame has a length of 10 ms; furthermore, each radio frame is divided into 10 subframes each of which has equal length (1 ms).
Each subframe is divided into two slots, each of which also has equal length (0.5 ms). For coherent demodulation of the LTE signal at the UE, the PSS and SSS are inserted in the fixed timing of a frame structure to provide symbol timing. PSS is transmitted on the last symbol of slot 0 and repeated on slot 10. PSS is based on a frequency-domain Zadoff-Chu sequence, which has the property of having zero cyclic autocorrelation at all nonzero lags. PSS is transmitted in three possible sequences that are mapped into an integer value $N_{ID}^{(1)} \in \{0, 1, 2\}$. SSS is transmitted in slot 0 or 10, in the symbol preceding PSS. SSS is based on maximum length sequence ($m$-sequence), which is a pseudorandom binary sequence that can be created by cycling through every possible state of a shift register of length $m$ resulting in a sequence of length $2^m - 1$. SSS has 168 possible sequences, which are mapped into an integer value $N_{ID}^{(2)} \in \{0, 1, ..., 167\}$.

![Fig. 1 LTE frame and slot structure in the time domain.](image)

2.2 Cell ID acquisition

Fig. 2 shows the LTE cell ID acquisition process. Because there are 168 possible sequences for SSS, it is efficient to first find the PSS location by correlating the three possible PSSs in a frame and predicting the SSS location.

![Fig. 2 LTE Cell ID acquisition block diagram.](image)

To detect a PSS, the UE generates the different PSSs and correlates the received signal.

$$
\text{Corr}(r, s_{PSS})[n] = \sum_{m=0}^{N-1} r[m] s_{PSS}[((n + m) \mod N)]
$$

$$
= r[m] \otimes_N s_{PSS}^*[-m],
$$

where $r$ is the received signal, $s_{PSS}$ is the UE-generated PSS in time-domain, $N$ is the number of samples in a single frame of LTE signal, $(\cdot)^*$ denotes the complex conjugate, $(\cdot)_N$ represents the modulo $N$ operation, and $\otimes_N$ denotes the $N$-point circular convolution. To operate the process in frequency-domain, we take a fast Fourier transform (FFT) and an inverse fast Fourier transform (IFFT) of (1) which yields

$$
\text{Corr}(r, s_{PSS}) = \text{IFFT} \{ R^*_{\text{PSS}} \},
$$

where $R \triangleq \text{FFT}(r)$ and $S^*_{\text{PSS}} \triangleq \text{FFT}(s^*_{\text{PSS}})$. Fig. 3 shows an example of Corr$(r, s_{PSS})$ obtained from the real LTE signals.

![Fig. 3 Example of correlation values of PSS.](image)

A PSS can be detected by finding the maximum correlation peak value, and the same method is applicable to detect an SSS. The maximum correlation peak value for PSS and SSS (i.e., $N_{PSS}$ and $N_{SSS}$, respectively) is defined as follows.

$$
N_{PSS} = \text{Max} \{ \text{Corr}(r, s_{PSS}) \},
$$

$$
N_{SSS} = \text{Max} \{ \text{Corr}(r, s_{SSS}) \},
$$

After detecting the PSS and SSS, the sequences are translated into the fixed integer value, $N_{ID}^{(1)}$ and $N_{ID}^{(2)}$, respectively. The cell ID is calculated by

$$
N_{CID} = N_{ID}^{(1)} + 3N_{ID}^{(2)},
$$

where $N_{CID} \in \{0, 1, ..., 503\}$ is an integer representing the cell ID. During the process, RSRQ is calculated and collected. RSRQ is the ratio of the received reference signal power to the received signal power, defined as

$$
N_{\text{RSRQ}} = \frac{N_{\text{RSSP}}}{N_{\text{RSSI}}},
$$

where $N_{\text{RSSP}}$ is the reference signal received power (RSRP) and $N_{\text{RSSI}}$ is a received signal strength indicator (RSSI). A multipath propagation causes intersymbol interference (ISI) in the LTE signal and the influence of ISI can be identified better with RSRQ than with RSRP or RSSI [27].
3. EXPERIMENTAL RESULTS

3.1 Received signal acquisition

The Analog Device ADI AD9361 System-on-Module (SOM) SDR, connected with a consumer-grade antenna shown in Fig. 4, was used to receive LTE signals at a center frequency of 879, 1820, or 2665 MHz, which is used (in South Korea) by SKT (an LTE network provider). The signal was received on the rooftop of the Veritas Hall C building (Yonsei University, Incheon). Among the cell IDs we received, we focused on cell ID 25 and 499 in this experiment, considered the most consistent signals received. Then the recorded signals were processed to acquire the cell ID, maximum correlation peak values, and RSRQ with a code implemented in MATLAB. The signals were sampled at a frequency of 15.36 MHz for all the center frequencies, and additionally at 30.72 MHz for the 2665 MHz center frequency where the bandwidth was wide enough to process both sampling frequencies.

![Fig. 4 Experimental setup showing Analog Device ADI AD9361 connected with an antenna.](image)

3.2 Experimental results

Table 1 shows the maximum correlation peak values, $N_{PSS}$ and $N_{SSS}$, and RSRQ value, $N_{RSRQ}$, at different center frequencies in (a) cell ID 25 and (b) cell ID 499, respectively. By comparing Tables 1(a) and 1(b), it is clear that the $N_{PSS}$, $N_{SSS}$, and $N_{RSRQ}$ values are relatively higher for cell ID 25 than for cell ID 499 in each frequency band, denoting that the cell ID 25 signal is more reliable for positioning. Moreover, $N_{PSS}$ and $N_{SSS}$ are noticeably higher in both cell IDs at 1820 MHz compared to other frequencies. Knowing that the signals with the same cell ID came from the same eNodeB, these should be due to different frequency channel characteristics. This result shows that the threshold values of $N_{PSS}$, $N_{SSS}$, and $N_{RSRQ}$ for selecting reliable signals for positioning need to be set in accordance with frequency channel characteristics.

![Table 1 Maximum correlation peak values, $N_{PSS}$ and $N_{SSS}$, and RSRQ value, $N_{RSRQ}$, at different center frequencies in (a) cell ID 25 and (b) cell ID 499](image)

Table 2 shows the maximum correlation peak values and the RSRQ value at the center frequency of 2665 MHz with two different sampling frequencies for the same cell ID 25 signal. It can be seen that $N_{PSS}$, $N_{SSS}$, and $N_{RSRQ}$ values are smaller when sampled at higher frequencies, indicating that the correlation results are relatively lower and the multipath effects are relatively higher when sampled at higher frequency. Because each sample indicates a time epoch in a time domain, it is necessary to sample the signal at a higher frequency to achieve higher timing resolution and thus higher positioning accuracy, but this also provides lower reliability when estimating the cell ID.

![Table 2 Maximum correlation peak values, $N_{PSS}$ and $N_{SSS}$, and RSRQ value, $N_{RSRQ}$, at different sampling frequencies in cell ID 25](image)

4. CONCLUSIONS

This paper presents the results of an analysis of real LTE signals acquired in different frequency bands and with different sampling frequency for LTE-based positioning. The maximum correlation peak values of PSS and SSS and the RSRQ value are compared, because these values can be used as criteria for evaluating the reliability of LTE signals for positioning purposes. We showed that the maximum correlation peak values and the RSRQ can vary differently in each frequency channel. Thus, the thresholds of these values for selecting reliable signals for positioning need to be set separately for each frequency channel. We also showed that sampling the signal at a higher frequency can raise a reliability issue for cell ID estimation, even though it can provide a higher positioning accuracy.
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