ABSTRACT

GNSS is excellent in open-sky conditions, but in many everyday situations such as traveling in urban canyons or being inside buildings, too few GNSS space vehicles (SV) are visible to get a position fix. An alternative is then desirable, and can be provided by positioning using the signals from cellular base stations. Of particular interest are the new signals and positioning possibilities from LTE cellular network operators, since the LTE coverage is expected to be high in cities and other well-populated areas. Furthermore, to accommodate the need for increasing data rates network operators are configuring their LTE downlink bandwidth to be as wide as possible, providing good resolution of different multipath components, which also assists positioning.

A portable experimental setup was built to perform measurements and to gather knowledge about the overall performance of positioning with LTE signals. It consists of a universal software radio peripheral (USRP) N210 that is synchronized to a GPS-locked Rubidium frequency standard. A personal computer (PC) acts as an overall system controller and as a recording unit, storing LTE data samples together with GNSS sentences from a u-blox LEA-6T module. A Matlab-based algorithm does the complete post-processing, extracting pseudoranges for the LTE BS, and calculating the position solution.

The results of determining the position of a car driven on a route around the town of Rapperswil, Switzerland show the potential of the positioning approach, using only available LTE signals. Even with the basic system the root mean square (RMS) value of the absolute error in a position using LTE compared to the actual position using GPS is 43 m, demonstrating that the CRS signal of the LTE standard is well suited as a fall-back alternative to GNSS in environmentally challenging situations.

LTE SIGNALS SUITABLE FOR RANGING

The LTE standard defines two signals that are considered suitable for range measurements, namely the Positioning Reference Signal (PRS) and the Cell-Specific Reference Signal (CRS)[1]. As the name suggests, the PRS was specifically designed for positioning purposes, while the CRS is actually used to determine the phase reference for coherent demodulation of the downlink data. The two signals are generated in the same way and therefore exhibit identical auto- and cross-correlation properties.

The PRS is transmitted in up to 6 consecutive subframes, which repeat every 160 ms – 1280 ms, with the number and interval depending on the higher-layer configuration. To increase the quality of the range measurements, the non-PRS subcarriers do not bear any data in OFDM symbols containing the PRS. As a result the available transmit power is
Table 1: List of possible downlink bandwidth configurations

<table>
<thead>
<tr>
<th>Bandwidth</th>
<th>1.4 MHz</th>
<th>3 MHz</th>
<th>5 MHz</th>
<th>10 MHz</th>
<th>15 MHz</th>
<th>20 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Blocks (RB)</td>
<td>6</td>
<td>15</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>Subcarriers</td>
<td>72</td>
<td>180</td>
<td>300</td>
<td>600</td>
<td>900</td>
<td>1200</td>
</tr>
</tbody>
</table>

distributed on the PRS subcarriers. To reduce inter-cell interference, neighboring cells usually apply a shift of 0 – 5 subcarriers when allocating resources for the PRS. In contrast to the CRS, which is a central part of the LTE system design, the transmission of the PRS is optional. It was not present in any of the data sets collected in this experiment.

The CRS is transmitted in every slot. Due to the CRS’ intended purpose of channel estimation, its bandwidth is that of the transmission bandwidth of the respective cell. The range measurements do therefore benefit from base stations transmitting with a large bandwidth. Fig. 1 shows the auto-correlation properties of the CRS.

**LTE PHYSICAL LAYER**

The modulation and channel-access scheme used in LTE is OFDMA and the radio resources are organized in a time-frequency grid as illustrated in Fig. 2. One subcarrier for the duration of one OFDM symbol is called a Resource Element (RE), which is the smallest resource unit. A Resource Block (RB) consists of 12 subcarriers for the duration of one slot. A RB is sometimes also used to specify the bandwidth of a cell and the possible configurations are listed in Table 1 [1]. The CRS is transmitted once or twice per slot as illustrated in Fig. 2 (depending on the port number of the base station antenna). Detailed information on the LTE concept of antenna ports can be found in [1]. As a consequence of the antenna-port concept an individual CRS is transmitted for every antenna port on which the cell transmits. In the frequency domain the CRS occupies two out of 12 subcarriers of a RB and therefore a sixth of all subcarriers. The subcarrier mapping varies depending on the cell configuration, the cells physical cell identity, and the antenna-port number. For LTE, there are 504 different Physical Cell Identities, grouped into 168 cell-ID groups denoted $N_{\text{ID}}^{(1)}(0...167)$ with 3 identities per group denoted $N_{\text{ID}}^{(2)}$. Usually the identities of one group are assigned to cells that are controlled by the same evolvedNodeB (eNodeB), i.e. base station controller (and are therefore presumably on the same antenna site). The physical cell ID for a given cell is

$$N_{\text{cell}}^{\text{ID}} = 3 \cdot N_{\text{ID}}^{(1)} + N_{\text{ID}}^{(2)} \quad (1)$$

![Fig. 1: Correlation function of the LTE CRS signal for different bandwidth configurations](image1)

![Fig. 2: Reference signal (CRS) pattern within a resource block (normal cyclic prefix), [1, Fig. 6.10.1.2-1]. $R_p$ denotes the reference signal sent over antenna port $p \in \{0,1,2,3\}$, $k$ is the subcarrier index and $l$ is the OFDM symbol number within the slot.](image2)
Table 2: Downlink configuration of the different operators.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Operator 1</th>
<th>Operator 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency DL</td>
<td>1815.1 MHz</td>
<td>1869 MHz</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>1200</td>
<td>900</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>15 kHz</td>
<td>15 kHz</td>
</tr>
<tr>
<td>Bandwidth DL</td>
<td>20 MHz</td>
<td>15 MHz</td>
</tr>
</tbody>
</table>

The relation between the physical-cell-ID and the transmitted CRS allows the signals from different antenna sites to be distinguished.

EXPERIMENTAL DATA COLLECTION

A set of experiments were performed with live LTE signal data, collected in Rapperswil SG, Switzerland. In this area the deployment of LTE started very early and began by the end of 2012. The data was collected by car, employing a mobile data-recording setup, recording a 10 ms block of raw data every second. The recording setup consisted of two Universal Software Radio Peripheral (USRP) N210 Software Defined Radios (SDR)[2], a u-blox LEA-6T GPS receiver, and a desktop computer to store the recorded data of the SDR and the messages of the GPS receiver. Two USRP N210s were used since the signals from two LTE operators were recorded on different center frequencies in parallel. The USRP clock is generated by a rubidium frequency standard, which is itself connected to the 1 Pulse-Per-Second (1 PPS) output of the GPS receiver which also provided a reference track of position during the experimental data gathering. The program to perform configuration and capture the raw data was written in C++ to give highest flexibility. Fig. 3 gives a schematic overview of the live-data capturing system. The live-data capturing setup was installed in a van with the magnetic antennas mounted on the roof. The raw data was recorded on a 8 km long circuit around the town of Rapperswil SG, in Switzerland. Fig. 4 shows the base station situation in the Rapperswil area at the time of data collection, and Table 2 shows the downlink configuration used by the measured operators.

DETERMINING THE TIME-OF-ARRIVAL (TOA)

As the PRS was not being transmitted, the CRS was used in this experiment to measure the time of arrival. To obtain a TOA estimate for a given cell, a local copy of its CRS was used to estimate the channel transfer function (CTF). Strictly speaking if a given cell transmits more than one antenna port, the CRS of any transmitted antenna port can be used to find the TOA for that cell. The CTF is then transformed into the time domain and the TOA is extracted from the resulting channel impulse response (CIR). To limit the number of multipath-caused outliers a simple yet effective criterion was...
used. In the CIR the N highest peaks above a certain threshold were searched, and from the found peaks the earliest was used as LOS measurement only if it is also the highest as illustrated in Fig. 5.

MULTI NETWORK OPERATION

The reception, demodulation, and measurement of the CRS signal does not require the receiver to be registered on the network of the respective base station (BS) operator. This allows TOA measurements of signals from BS belonging to other and indeed multiple network operators to be made and used in combination. The result of using measurements from multiple network operators, at the current LTE deployment stage, is a significantly increased coverage with respect to positioning. Figures 6 a and b show the coverage when using each operator independently and Fig. 6 c when combining measurements from both operators. In the single-operator case the coverage with respect to positioning, defined as locations where at least 3 BS are received, is 8.4 % for Operator 1 and 7.3 % for Operator 2. These figures increase to 71.0 % when measurements to both operators are used. Combining operators does provide coverage benefits, but it also increases the hardware complexity, as the receiver needs to be able to cover the different channel frequencies used by each operator.

DETERMINATION OF ROVER POSITION

Base Station Position

In a practical application the location is known to the network operator, or is established by a prior survey. For this study the calculations were performed with the base station coordinates provided by the Swiss federal office of communication [3]. Additionally the cell IDs of the base stations to be measured are assumed to be known in advance and were recorded for the experiment.

Base Station Timing

In a practical application the timing may be controlled by the network operator, or monitored by a Location Measurement Unit (LMU) [4], which measures the timing of the base station signals at a known location, corrects for the time of flight from the base station, and so estimates the relative timing of the signals from the base stations [5]. For this study the calculations were performed with an estimation of the timing of the signals from the base stations derived from the measurements over the period, once the whole live-data capturing has been finished. The pseudoranges for each base station \( n \) measured consist of the following components:

\[
pseudorange^n_t = \text{GPS-based range}^n_t + c_0 \cdot \left[ \text{bias}^n_{t_0} + \text{drift}^n_{t-t_0} \right], \quad n = 0..N_t - 1,
\]
where $t - t_0$ is the elapsed time since start $t_0$ and $c_0$ is the speed of light. $N$ corresponds to the total number of base stations visible in the recorded block at time $t$. The GPS-based ranges are the calculated ranges from the measurement location to the base station $n$. They can be determined by using the known base station location $\text{BS}_n = \left[ \text{BS}_n^{\text{East}} \text{BS}_n^{\text{North}} \text{BS}_n^{\text{Up}} \right]^T$ and the GPS-measured rover position $\text{GMP} = \left[ \text{GMP}^{\text{East}} \text{GMP}^{\text{North}} \text{GMP}^{\text{Up}} \right]^T$ at time $t$. Both are measured in local east-north-up (ENU) coordinates [7].

$$\text{GPS-based range}_n^t = \| \text{BS}_n^t - \text{GMP}_t \|$$

This finally leads to:

$$\text{bias}_n^t + \text{drift}_{t - t_0} = \frac{\text{pseudorange}_n^t - \| \text{BS}_n^t - \text{GMP}_t \|}{c_0}.$$

Hence, only the bias and drift of each base station remain unknown. Once the live-data capturing has finished, the bias and drift can be estimated individually for each base station. Assuming that these two unknowns are constants, a first degree polynomial can be fitted, using an ordinary least-square method [6]. Note that multipath effects were not taken into consideration. Multipath occurrences were mostly fast time-varying effects during this experiment, and they do not affect the overall dataset estimate of bias and drift significantly. Fig. 7 shows the bias and drift corrected pseudoranges plotted against the GPS-based ranges and the measured pseudorange for a typical base station. Compared to the pseudorange, the bias and drift are well estimated and so provide good matching between the corrected pseudorange and the GPS-based range. The spikes and temporary biases, visible in the two pseudorange curves, are due to multipath.
Rover Positioning

The rover position is determined with an extended Kalman filter (EKF) [8]. Looking at the problem geometry shows that, although base station heights differ slightly, the overall situation is close to all base stations lying in one plane. The rover position is therefore solved for in two dimensions only. To conveniently constrain the problem space to two dimensions, local east-north-up (ENU) coordinates are used, with the up component set to zero. The state vector of the Kalman filter is \( \hat{\zeta} = [x \ y \ \dot{x} \ \dot{y}]^T \) where \( x \) (east) and \( y \) (north) are the estimated rover coordinates and \( \dot{x} \) and \( \dot{y} \) the corresponding estimated rover speeds. A measurement update is performed if range measurements to at least two base stations are available in a block. As the states already show, a linear motion with constant velocity is assumed that leads to the following state transition model.

\[
F_{t-1} = \begin{bmatrix}
1 & \Delta t & 0 & 0 \\
0 & 1 & 0 & \Delta t \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(5)

\( \Delta t \) is the elapsed time since the last position estimate at \( t - 1 \). The non-linear observation model is:

\[
h_n(\hat{\zeta}_{t|t-1}) = ||BS^n - \hat{\zeta}_{t-1}[1, 2]||, \quad n = 0..N_t - 1.
\]

(6)

The observation model matrix

\[
H_t = \begin{bmatrix}
BS^n[1] - \hat{\zeta}_{t-1}[1] & BS^n[2] - \hat{\zeta}_{t-1}[2] & 0 & 0 \\
||BS^n[1, 2] - \hat{\zeta}_{t-1}[1, 2]|| & ||BS^n[1, 2] - \hat{\zeta}_{t-1}[1, 2]|| & 0 & 0 \\
||BS^n[1, 2] - \hat{\zeta}_{t-1}[1, 2]|| & ||BS^n[1, 2] - \hat{\zeta}_{t-1}[1, 2]|| & 0 & 0 \\
||BS^n[1, 2] - \hat{\zeta}_{t-1}[1, 2]|| & ||BS^n[1, 2] - \hat{\zeta}_{t-1}[1, 2]|| & 0 & 0 \\
... & ... & ... & ...
\end{bmatrix}
\]

(7)

is the Jacobian of the non-linear observation model. The process noise \( Q \) and the measurement uncertainty \( R \) were tuned manually.

Fig. 8 shows the result of the 2 dimensional (2D) LTE Track. Additionally the GPS track is plotted as a reference, with the blue arrows indicating the direction of travel. The root mean square (RMS) error in position using LTE compared to the actual position using GPS is 43.08 m.

MULTIPATH ANALYSIS USING SUPER RESOLUTION ALGORITHMS

In order to assess whether the positioning errors that can be noted in Fig. 8 are effectively due to multipath, an in-depth analysis of the collected data was performed by applying super resolution algorithms (SRAs) to the measured LTE raw samples. SRAs were originally designed for frequency estimation in discrete-time harmonic models. However, SRAs may be exploited also for TOA estimation of signals transmitted in multipath fading channels [9]. Indeed, the CIR of a multipath channel comprising \( L \) paths, which is given by \( h(t) = \sum_{l=0}^{L-1} \delta(t - \tau_l) \), corresponds, in the frequency domain, to the channel frequency response \( H(f) = \sum_{l=0}^{L-1} e^{j2\pi f \tau_l} \), which actually is an harmonic model. Hence, SRAs can be
For the CTF sampling $X[k]$ acquired using each CRS, the estimation of signal parameters via rotational invariance technique (ESPRIT) was applied for the calculation of the multipath delays $\tau_l$ [10]. Briefly, the ESPRIT relies on the eigendecomposition of the matrix $R_X = XX^H$, where $X \in \mathbb{C}^{M \times N}$ is obtained by conveniently arranging the samples $X[k]$, and $M, N$ are design parameters that have to be carefully chosen [9]. Since the SRA requires the number of multipath components $L$ to be known, this is also estimated, by using the minimum descriptive length criterion on the eigenvalues of $R_X$ [9]. This algorithm was applied to the recorded signal samples to generate a set of $\hat{L}$ estimated delays $\hat{\tau}_0, \ldots, \hat{\tau}_{L-1}$ for all the CRS detected in each received block for each cell ID $N_{\text{ID}}$.

To assess the practical impact of multipath, two test positions were considered, A and B, which correspond to cases where a relatively poor and a good position fix are obtained, respectively (see Fig. 8). For the two test positions, the multipath delays estimated by the ESPRIT SRA are compared to the corresponding IFFT based CIR estimation used for ranging in the positioning algorithm. The results are shown by the two plots of Fig. 9. Fig. 9a represents the result of the pseudorange measured in test position A using the CRS of cell ID $N_{\text{ID}} = 53$. The effect of the multipath can be seen clearly. Indeed, the direct path is weaker than the higher-order paths, and the multipath delays are too close to each other, compared to the system bandwidth, for being distinguished in the CIR. This causes an offset of 66 m between the main peak of the CIR and the direct path detected by the ESPRIT SRA, that is an error consistent with the 77 m error in the position fix. Meanwhile, consider Fig. 9b, where the result of the pseudorange measured in test position B using the CRS corresponding to cell ID $N_{\text{ID}} = 53$ is depicted. Here, despite multipath still present, the direct path is correctly detected by the IFFT based CIR estimation, resulting in a ranging error of 5 m and ultimately in a relatively good position fix, with an error of 14 m.

**CONCLUSION**

The results of positioning using real LTE signals have been presented. It has been shown that the LTE CRS signal is well suited for ranging purposes as a fallback to GNSS, since it has useful signal properties and is becoming widely available. Furthermore it has been shown that, since CRS TOA measurements do not require the registration on a specific network, signals from base stations belonging to different network operators can be combined, resulting in a considerably increased positioning coverage. In this test case, even with the early deployment of the networks, the positioning coverage reached 71% when using the signals from the base stations of both operators simultaneously. The influence of multipath
Fig. 9: Comparison between the ESPRIT TOA estimates and the corresponding IFFT estimated CIR.

propagation on TOA estimates obtained by means of the CIR has been illustrated, and compared with analysis results from the use of Super Resolution Algorithms. SRAs give much improved TOA estimation in the difficult urban multipath environments encountered. Using the CIR to obtain pseudoranges for positioning, the rover position can be tracked with an error of 43 m RMS. This error is substantially due to the multipath experienced by the LTE signals. The tracking performance demonstrated would be useful for many applications, and keeping in mind that this is a first positioning solution, with more advanced signal processing, a better navigation filter, and the wider deployment of LTE base stations, the practical performance will further improve.

References


