Indoor Positioning Based on LTE Carrier Phase Measurements and an Inertial Measurement Unit

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BIOGRAPHIES
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ABSTRACT
A tightly-coupled inertial navigation system (INS) with cellular long-term evolution (LTE) signal aiding for indoor positioning is developed. The navigation approach is based on a carrier phase-based software-defined receiver (SDR), which tracks LTE signals and provides aiding corrections to an inertial measurement unit (IMU) in a tightly-coupled fashion via an extended Kalman filter (EKF). The indoor positioning framework employs an outdoor receiver, referred to as the base, which estimates the unknown clock biases of LTE eNodeBs and shares these estimates with the indoor navigating receiver. The availability and strength of received LTE signals indoors is evaluated in different conditions: different floor levels and in rooms with and without windows. It is demonstrated that the received carrier-to-noise ratio $\frac{C}{N_0}$ in all such conditions is $48$-$80$ dB-Hz. The performance of the developed system is evaluated in an indoor environment over a trajectory of $109$ m using a tactical-grade IMU. The two-dimensional position root mean-squared error (RMSE) for the proposed LTE-IMU system is demonstrated to be $3.52$ m with a standard deviation of $3.85$ m and a maximum error of $8.1$ m. In contrast, the IMU-only system provided an RMSE of $9.91$ m with a standard deviation of $9.67$ m and a maximum error of $22.53$ m.

I. INTRODUCTION
The records by the Federal Communications Commission (FCC) have shown an ongoing dramatic increase in the number of emergency calls originating indoors, making indoor positioning even more important to provide first responders the ability to perform search and rescue missions, while ensuring their safety [1]. Although global navigation satellite system (GNSS) provides a highly accurate navigation solution outdoors, it is practically unusable indoors due to severe attenuation of the GNSS weak signals. Many approaches have been developed to enable indoor positioning: visible light communication [2, 3], active radio frequency identifications (RFIDs) [4, 5], ultra wideband signals [6], and WiFi signals [7, 8].

Wi-Fi signals are among the most studied signals for indoor positioning due to their abundance and high received power [9]. Most existing approaches for WiFi positioning are based on received signal strength (RSS), which yields a coarse estimate of the position. In emergency situations, WiFi signals may be unavailable indoors. Moreover, the
geometric diversity of WiFi access points may be poor, which limits their usefulness in time-of-arrival (TOA)-based approaches. In contrast to WiFi, cellular signals do not suffer from such limitations. Cellular towers are abundant and available in favorable geometric configurations by construction of the cellular infrastructure. Moreover, cellular long-term evolution (LTE) signals possess a large bandwidth (up to 20 MHz), which would yield accurate TOA estimates [10]. Furthermore, the availability of these signals is not hindered by the emergency situation indoors (e.g., loss of power, fire, smoke, etc.). Cellular LTE and code-division multiple-access (CDMA) signals have been demonstrated in the recent literature to produce a meter-level-accurate navigation solution outdoors on ground-based receivers [11–14] and a centimeter-level-accurate navigation solution on outdoors aerial-based receivers [15, 16].

Indoor positioning with cellular LTE signals has been studied in the recent literature. In [17], a super resolution algorithm was used to estimate the TOA of LTE signals indoors, and the position error distribution showed a 95% confidence interval of 12.9 m. In [18], a particle filter was used with laboratory-emulated LTE signals, assuming synchronized LTE transmitters which yielded a position root mean-squared error (RMSE) of 5.35 m.

To use LTE signals for accurate positioning in indoor environments, two main challenges must be addressed. The first challenge is the multipath-induced errors. In particular, short delay multipath is significantly high indoors, which introduces large errors in the code phase measurements. The second challenge is the unknown clock biases of the LTE transmitters (also known as evolved Node Bs or eNodeBs). This paper addresses these two challenges as follows. First, it develops a carrier phase-based receiver for obtaining pseudorange measurements. Second, it proposed a base/navigator framework in which a base with access to GNSS is placed outdoors. Using GNSS signals, the base can estimate its own position. The base makes pseudorange measurements on ambient LTE eNodeBs whose locations are known (e.g., via signal mapping [19–21]) and estimates the clock biases of the LTE eNodeBs. The base shares these estimates with the indoor navigating receiver.

This paper makes three contributions. First, a software-defined receiver (SDR) is developed to track the carrier phase of LTE signals. Second, a base/navigator framework is proposed to estimate the clock biases of the eNodeBs. Third, a framework is developed that fuses LTE pseudoranges with an inertial measurement unit (IMU) in a tightly-coupled fashion using an extended Kalman filter (EKF). Experimental results are presented evaluating: (1) the carrier-to-noise ratio (C/N) of received LTE signals in different indoor environments and (2) the performance of the proposed indoor positioning framework. It is demonstrated that the proposed framework yields a two dimensional (2-D) position RMSE of 3.52 m with a standard deviation of 3.85 m and a maximum error of 8.1 m over an indoor trajectory of 109 m, with a tactical-grade IMU and using 5 LTE eNodeBs.

The remainder of this paper is organized as follows. Section II describes the LTE signal structure. Section III discusses the receiver structure. Section IV describes the IMU kinematics model, receiver’s clock error state dynamics model, and pseudorange measurement model. Section V presents the proposed base/navigator framework. Section VI presents experimental results with the proposed framework in an indoor environment. Concluding remarks are given in Section VII.

II. LTE SIGNAL STRUCTURE

The LTE signal is modulated using orthogonal frequency division multiplexing (OFDM) before transmission. In OFDM, the transmitted data symbols are mapped onto multiple carrier frequencies called subcarriers. The serial data symbols \{S_1, \ldots, S_{N_r}\} are first parallelized in groups of length \(N_r\), where \(N_r\) is the number of subcarriers carrying the data. Then, each group is extended from \(N_r\) subcarriers to \(N_c\) subcarriers by zero-padding both sides of the signal. The total number of subcarriers \(N_c\) is chosen to be greater than \(N_r\) in order to provide a guard band in the frequency-domain [22]. An inverse fast Fourier transform (IFFT) is taken at this level. Then, the last \(L_{CP}\) elements are added at the beginning of the data, which are called the cyclic prefix (CP). The CP is used to increase the reliability of communication and protect the OFDM signals from inter-symbol interference (ISI). At an LTE receiver, these steps should be executed in reverse in order to decode the transmitted serial data symbols. There are two types of transmission for LTE: (1) frequency division duplexing (FDD) and (2) time division duplexing (TDD). Due to the superior performance of FDD in terms of latency and transmission range, most cellular providers use FDD for LTE transmission. Hence, FDD LTE signals are considered in this paper.

The LTE signal bandwidth is scalable from 1.4 MHz to 20 MHz with a symbol period \(T_{symb} = 1/\Delta f = 66.67\) µs, which corresponds to a subcarrier spacing \(\Delta f = 15\) kHz. The bandwidth could take specific values among the
mentioned range depending on the values of $N_r$ and $N_c$. The LTE frame is composed $T_f = 10$ ms data as shown in Fig. 1, which is divided into 10 subframes with a duration of 1 ms, where each subframe consists of 2 slots with a duration of $T_{\text{slot}} = 0.5$ ms each. A slot can be decomposed into multiple resource grids (RGs), where each RG consists of a large number of resource blocks (RBs). Then, an RB is broken down into the smallest elements of the frame, called resource elements (REs). Thus, the subcarrier and symbol are the frequency and time indices of an RE, respectively. When a UE receives the LTE signal, it must first convert the signal into the frame structure to be able to extract the transmitted information. This is achieved by first identifying the frame start time. Then, the receiver can remove the CPs and take a fast Fourier transform (FFT) of each $N_c$ symbols. The duration of a normal CP is 5.21 $\mu$s for the first symbol of each slot and 4.69 $\mu$s for the rest of the symbols.

![LTE Frame Structure](image)

Fig. 1 shows different reference signals that are transmitted in LTE system: (1) primary synchronization signal (PSS), (2) secondary synchronization signal (SSS), (3) cell-specific reference signal (CRS), and (4) positioning reference signal (PRS). The PSS and SSS are transmitted to provide the frame start time and the eNodeB’s cell ID to the UE. The PSS is a length-62 Zadoff-Chu sequence, which is located in the 62 middle subcarriers of the bandwidth, excluding the DC subcarriers. It is transmitted on the last symbol of slot 0 and is repeated on slot 10. The PSS sequence can take only one of the three possible sequences, each of which corresponds to an integer number $N_{ID}^{(2)} \in \{0, 1, 2\}$ representing the sector ID of the eNodeB. The SSS is an orthogonal length-62 sequence, which is transmitted in either slot 0 or 10 in the symbol preceding the PSS and on the same subcarriers as the PSS. The SSS is obtained by concatenating two maximal-length sequences scrambled by a third orthogonal sequence based on $N_{ID}^{(2)}$. There are 168 possible sequences for the SSS that are mapped to an integer number $N_{ID}^{(1)} \in \{0, \ldots, 167\}$ called the cell group identifier. Thus, the eNodeB’s physical cell ID can be calculated according to [22]

$$N_{\text{Cell}}^{ID} = 3N_{ID}^{(1)} + N_{ID}^{(2)}.$$  

The CRS signal is an orthogonal sequence that is scattered in time and bandwidth. It is mainly transmitted to estimate the channel frequency response (CFR). Mapping the CRS REs depends directly on the cell ID, the allocated symbol number, the slot number, and the transmission antenna port number [23]. The transmitted OFDM signal from the $u$-th eNodeB at the $k$-th subcarrier and on the $i$-th symbol can be expressed as

$$Y_i^{(u)}(k) = \begin{cases} S_i^{(u)}(k), & \text{if } k = m\Delta_{\text{CRS}} + \nu_i, N_{\text{Cell}}^{ID}, \\ D_i^{(u)}(k), & \text{otherwise}, \end{cases}$$  

(1)

where $S_i^{(u)}(k)$ represents the CRS sequence; $m = 0, \cdots, M - 1$; $M = \lfloor N_r/\Delta_{\text{CRS}} \rfloor$; $\Delta_{\text{CRS}} = 6$; $\nu_i, N_{\text{Cell}}^{ID}$ is a constant shift that depends on the cell ID and $i$; and $D_i^{(u)}(k)$ represents some other data signals.
In general, there is a mismatch between the estimated received symbol timing and the actual one, which can be due to imperfect synchronization, clock drift, Doppler frequency, and/or carrier frequency offset. Assuming that the time mismatch is less than the CP duration, the received signal at the $i$-th symbol can be written as \[ R_i(k) = e^{j\pi e_f} e^{j2\pi(iN_c+L_{CP})e_f/N_c} e^{j2\pi e_f k/N_c} \sqrt{C_Y}(k)H_i(k) + W_i(k), \quad k = 0, \cdots, N_c - 1, \] where $N_t = N_c + L_{CP}$; $e_f = f_D/\Delta f$; $f_D$ is the total carrier frequency offset due to the Doppler frequency, clock drift, and oscillators’ mismatch; $e_\theta = \hat{\theta} - \theta$ is the symbol timing error normalized by the sampling interval $T_s = T_{symb}/N_c$; and $\hat{\theta}$ and $\theta$ are the normalized estimated and true symbol timings, respectively; $H_i(k)$ represents the channel frequency response; and $W_i(k) \sim \mathcal{CN}(0, \sigma^2)$, where $\mathcal{CN}(a, b)$ denotes the complex Gaussian distribution with mean $a$ and variance $b$.

### III. LTE RECEIVER ARCHITECTURE

Several code phase-based receivers have been proposed to obtain the pseudorange measurements from LTE signals [13, 26–28]. Analytical and experimental results have shown that the performance of these receivers significantly degrades in multipath environments, making them practically unusable in indoor environments [14, 17, 29]. In this section, a receiver structure is proposed, which exploits the carrier phase measurements of LTE signals. Fig. 2 shows the block diagram of the proposed receiver.

![Fig. 2. Block diagram of proposed carrier phase-based LTE receiver](image)

This receiver is adapted from the receiver developed in [14], which used a phase-locked loop (PLL)-aided delay-locked loop (DLL). Here, only phase tracking is performed (i.e., code tracking is not utilized) since it was observed experimentally that such tracking indoors degrades the receiver’s performance. The receiver has three main stages, where in each stage the nodes A, B, and C are connected to nodes 1, 2, or 3. In the first stage, where the nodes A, B, and C are connected to 1, the receiver acquires a coarse estimate of the frame start time by correlating the received signal with the locally generated PSS and SSS. In the second stage, where the nodes A, B, and C are connected to 2, the estimation of signal parameters by rotational invariance techniques (ESPRIT) algorithm is used to estimate the channel impulse response. In the third stage, where the nodes A, B, and C are connected to 3, the receiver tracks the signal and produces a fine estimate of the TOA.

### IV. IMU KINEMATICS, RECEIVER CLOCK ERROR DYNAMICS, AND MEASUREMENT MODEL

#### A. IMU Kinematics

The altitude of the navigating receiver is assumed to be obtained using an external sensor (e.g., a barometer). Therefore, only the 2-D position $\mathbf{r}$, velocity $\dot{\mathbf{r}}$, and orientation with respect to the $z$-axis $\theta_z$ is considered. These
states are assumed to evolve according to
\[
\begin{align*}
\theta_z(k+1) &= \theta_z(k) + T \dot{\theta}_z(k) \\
G\dot{r}(k+1) &= G\dot{r}(k) + T G\dot{r}(k) \\
G_r(k+1) &= G_r(k) + T G_r(k)
\end{align*}
\]  
(3-5)

where \( T \) is the sampling interval, \( \dot{\theta}_z \) is the angular rate with respect to \( z \)-axis, \( G\dot{r} \) is the 2-D acceleration of the IMU in the global frame \( G \). The IMU produces measurement \( \mathbf{z}_{imu} \triangleq [\mathbf{\theta}_{imu}, \mathbf{\dot{r}}_{imu}]^T \) of the angular rate around the \( z \)-axis and the specific forces along \( x \)- and \( y \)-axes, which are modeled according to
\[
\begin{align*}
\dot{\mathbf{\theta}}_{imu} &= \mathbf{\dot{\theta}} + \mathbf{b}_g + \mathbf{n}_g \\
\mathbf{\dot{r}}_{imu} &= \mathbf{R}(\mathbf{\theta}) G\mathbf{\dot{r}} + \mathbf{b}_r + \mathbf{n}_r
\end{align*}
\]

where \( \mathbf{R}(\mathbf{\theta}) \) is the rotation matrix representing the orientation of the body frame with respect to the global frame and is defined as
\[
\mathbf{R}(\mathbf{\theta}) = \begin{bmatrix} \cos \theta_z & \sin \theta_z \\ -\sin \theta_z & \cos \theta_z \end{bmatrix};
\]

\( \mathbf{b}_r \) represents the biases in the two accelerometers (\( x \)- and \( y \)-axes); \( n_g \) and \( \mathbf{n}_r \) are the gyroscope’s and accelerometer’s measurement noise, which are modeled as zero-mean white noise sequences with covariances \( \sigma^2_{g} \) and \( \sigma^2_{r} I_{2 \times 2} \), respectively.

The evolution of \( b_g \) and \( \mathbf{b}_r \) are modeled as random walk processes, i.e., \( \dot{b}_g = w_{g} \) and \( \dot{\mathbf{b}}_r = \mathbf{w}_r \) with \( \mathbb{E}[w_{g}] = 0 \), \( \mathbb{E}[\mathbf{w}_r] = 0 \), \( \text{cov}[w_{g}] = \sigma^2_{w_g} I_{2 \times 2} \), and \( \text{cov}[\mathbf{w}_r] = \sigma^2_{w_r} I_{2 \times 2} \).

**B. Receiver Clock State Dynamics Model**

The base/navigator’s framework for indoor positioning relies on estimating the clock error states (bias and drift) corresponding to the difference between the base and navigator. This will be discussed in Section V. The \( i \)-th receiver clock error state will be modeled as
\[
\mathbf{x}_{clk}(k+1) = \mathbf{F}_{clk} \mathbf{x}_{clk}(k) + \mathbf{w}_{clk}(k), \quad \text{for } i \in \{\text{nav, base}\},
\]

(6)

where, \( \mathbf{x}_{clk} \triangleq [c \delta t_{i}, c \dot{\delta} t_{i}]^T \), \( \mathbf{F}_{clk} \triangleq \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \), and \( \mathbf{w}_{clk} \) is modeled as a discrete-time zero-mean white random sequence with covariance \( \mathbf{Q}_{clk} \) given by
\[
\begin{bmatrix} S_{\delta t_{i}, T} + S_{\dot{\delta} t_{i}, \frac{T^3}{3}} & S_{\delta t_{i}, \frac{T^2}{2}} \\ S_{\dot{\delta} t_{i}, \frac{T^2}{2}} & S_{\dot{\delta} t_{i}, T} \end{bmatrix}
\]

where \( S_{\delta t_{i}, T} \) and \( S_{\dot{\delta} t_{i}, T} \) are the power spectra of the continuous-time process noise \( w_{\delta t_{i}} \) and \( w_{\dot{\delta} t_{i}} \) driving the clock bias and clock drift, respectively. The values of \( S_{\delta t_{i}, T} \) and \( S_{\dot{\delta} t_{i}, T} \) depend on the clock’s quality [19].

**C. Pseudorange Model**

The pseudorange observation made by the base or navigator on the \( u \)-th LTE eNodeB can be shown after mild approximations discussed in [30] to be
\[
\rho_{i,u}(k) = ||\mathbf{r}_i(k) - \mathbf{r}_{su}||_2 + c[\delta t_i(k) - \delta t_{su}(k)] + \nu_{i,u}(k), \quad u = 1, \ldots, U, \text{ and } i \in \{\text{nav, base}\},
\]

(7)

where \( U \) is the number of eNodeBs; \( \mathbf{r}_i \triangleq [x_i, y_i]^T \) is the 2-D position of the receiver (base or navigator); \( \mathbf{r}_{su} \triangleq [x_{su}, y_{su}]^T \) is the 2-D position of the \( u \)-th eNodeB; \( \delta t_i \) and \( \delta t_{su} \) are the receiver and \( u \)-th eNodeB clock biases, respectively; and \( \nu_{i,u} \) is the measurement noise, which is modeled as a discrete-time zero-mean white Gaussian sequence with variance \( \sigma^2_{\nu_{i,u}} \).
VI. BASE/NAVIGATOR NAVIGATION FRAMEWORK

A. Base/Navigator Description

the proposed framework is composed of two receivers. The first receiver is referred to as the base, which gets placed outdoors. The base is assumed to have access to GPS signals and can estimate its position. The base makes pseudorange measurements to nearby LTE eNodeBs according to the model (7). The second receiver is referred to as the navigator, which navigates indoors, while receiving signals from the same LTE eNodeBs as the ones the base is tracking. The navigator makes pseudorange measurements to these eNodeBs according to the model (7). Next the effect of the eNodeBs’ clock biases can be removed by subtracting the pseudorange measurements of the base and navigator and adding the known range $\|r_{\text{base}} - r_s\|$ to generate the pseudo-measurement $z_u$ defined as

$$z_u \triangleq \rho_{\text{nav}_u} - \rho_{\text{base}_u} + \|r_{\text{base}} - r_s\|_2$$

$$= \|r_{\text{nav}} - r_s\|_2 + c\Delta \delta t + v_u$$

where $\Delta \delta t \triangleq (\delta t_{\text{nav}} - \delta t_{\text{base}})$ and $v_u \triangleq v_{\text{nav}_u} - v_{\text{base}_u} \sim \mathcal{N}(0, \sigma^2 v_u \triangleq \sigma^2_{\text{nav}, u} + \sigma^2_{\text{base}, u})$. These pseudo-measurements to all $U$ eNodeBs are augmented into the measurement vector $z \triangleq [z_1, \ldots, z_U]^T$.

B. Extended Kalman Filter

An EKF is used to fuse the IMU measurements with the LTE pseudo-measurements in a tightly-coupled fashion. The EKF estimates the vector $\mathbf{x}$ defined as

$$\mathbf{x} = [\mathbf{x}_{\text{IMU}}^T, \mathbf{x}_{\text{clk}}^T]^T,$$

where $\mathbf{x}_{\text{IMU}} \triangleq [\theta_{\text{z}}, \mathbf{r}^T, \mathbf{r}_{\dot{}}^T, \mathbf{b}_{\mathbf{r}}^T, \mathbf{b}_{\mathbf{g}z}]^T$ and $\mathbf{x}_{\text{clk}} \triangleq [c\Delta \delta t, c\Delta \delta t]^T$.

VI. EXPERIMENTAL RESULTS

This section presents experimental results of the proposed indoor positioning framework. First, the experimental setup is discussed. Next, received LTE signal in different indoor conditions is evaluated. Finally, results for an indoor navigating receiver are presented.

A. Experimental Setup

In this experiment, the base and navigator were placed outside and inside the Winston Chung Hall (WCH) building, respectively, at the University of California, Riverside. The base was equipped with 4 consumer-grade 800/1900 MHz cellular omnidirectional Laird antennas. The antennas were used to receive LTE signals at 4 different carrier frequencies: 2145 MHz, 1955 MHz, 751 MHz, and 739 MHz, which were used by three U.S. LTE cellular providers: T-Mobile, Verizon, and AT&T. Four single-channel National Instruments (NI) universal software radio peripherals (USRPs)-2920 were connected by a multiple-input multiple-output (MIMO) cable to each other to simultaneously down-mix and synchronously sample LTE signals at 10 Msps. The signals were recorded on a laptop, which was connected to the USRPs through an ethernet cable. The base could estimate its own position from GPS signals. The navigator hardware setup was similar to the base except for the USRP configuration, which was a USRP-2954R and two 2920 USRPs, which simultaneously down-mixed and synchronously sampled LTE signals at 20 Msps. The navigator was equipped with a tactical-grade IMU (Septentrio AsteRx-i V [31]). The signals were processed in a post-processing fashion using MATLAB. Fig. 3 shows the base and navigator experimental hardware setup.

Fig. 4 shows the environmental layout in which the experiment was performed and the location of the eNodeBs to which the base and navigator were listening. The characteristics of the eNodeBs are shown in Table I.
B. Evaluation of Received LTE Signal’s $C/N_0$ Indoors

Several experiments were conducted to evaluate the received LTE signals in different indoor conditions. In the first experiment, the navigator was placed in different floors, but at the same location in each floor. The navigator was also placed on the roof for comparison purposes. Fig. 5 shows the location of the navigator in each floor. The LTE signals were recorded at each location and evaluated using the proposed receiver. Fig. 6 shows the $C/N_0$ of received LTE signals in each floor and from eNodeBs 1–4 over 20 s for a stationary receiver. Table II summarizes the average $C/N_0$ for different eNodeBs at different floors.
TABLE I
LTE ENodeBs’ Characteristics

<table>
<thead>
<tr>
<th>eNodeB</th>
<th>Carrier frequency (MHz)</th>
<th>$N_{\text{Cell}}^{\text{TD}}$</th>
<th>Bandwidth (MHz)</th>
<th>Cellular provider</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>739</td>
<td>144</td>
<td>10</td>
<td>AT&amp;T</td>
</tr>
<tr>
<td>2</td>
<td>2145</td>
<td>490</td>
<td>20</td>
<td>T-Mobile</td>
</tr>
<tr>
<td>3</td>
<td>1955</td>
<td>262</td>
<td>20</td>
<td>AT&amp;T</td>
</tr>
<tr>
<td>4</td>
<td>2145</td>
<td>383</td>
<td>20</td>
<td>T-Mobile</td>
</tr>
<tr>
<td>5</td>
<td>751</td>
<td>156</td>
<td>10</td>
<td>Verizon</td>
</tr>
</tbody>
</table>

Fig. 6. $C/N_0$ of received signals in floor 1–4 and the roof of the WCH building. (a)–(d) show the results for eNodeBs 1–4, respectively.

TABLE II
Average $C/N_0$ for different eNodeBs at different floors

<table>
<thead>
<tr>
<th>eNodeB</th>
<th>Floor 1</th>
<th>Floor 2</th>
<th>Floor 3</th>
<th>Floor 4</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>65.06</td>
<td>64.44</td>
<td>61.36</td>
<td>69.55</td>
<td>66.63</td>
</tr>
<tr>
<td>2</td>
<td>67.32</td>
<td>77.85</td>
<td>77.31</td>
<td>72.52</td>
<td>68.44</td>
</tr>
<tr>
<td>3</td>
<td>63.15</td>
<td>56.61</td>
<td>58.22</td>
<td>53.10</td>
<td>61.74</td>
</tr>
<tr>
<td>4</td>
<td>59.21</td>
<td>62.63</td>
<td>65.39</td>
<td>68.05</td>
<td>71.82</td>
</tr>
</tbody>
</table>

Next, the effect of the room structure on the received power and availability of LTE signals is evaluated. For this purpose, the LTE signals were recorded in two different rooms of the WCH building: (1) with windows access and (2) without windows access. Fig. 7 shows the environmental layout of the rooms in which the experiment was performed.

Fig. 7. Environmental layout of the rooms in which the experiment was performed

Remarks: From the results presented in Fig. 6, Fig. 8, and Table II, the following can be concluded:
Table II shows that the received signal $C/N_0$ in different floor levels ranged between 53.10 dB-Hz and 77.85 dB-Hz, which is significantly higher than received GPS signals outdoors, which is typically 38–45 dB-Hz.

It was expected to measure lower $C/N_0$ for lower floors. However, the results shown in Fig. 6 suggest otherwise. This could be attributed to all obstructions that influence the propagation channel between the eNodeB and the receiver (e.g., building structure and material, constructive/destructive interference, etc.).

It was expected to measure lower $C/N_0$ when the room has no access to windows. However, the results presented in Fig. 8 suggest otherwise. Similar to the remark above, this could be attributed to the complicated propagation channel characteristics between the eNodeB and the receiver.

C. Navigation Solution

In this subsection, the performance of the proposed navigation framework is evaluated. For this purpose, the base was placed on the roof of the WCH building, while the navigator was moved in the corridor of the third floor of same building. The navigator traversed a total trajectory of 109 m. Several tags with known locations were placed on the ground to be used as the ground truth. A camera was used to record the tags while the navigator was moving. The LTE signals received by both the base and navigator and the ground truth recorded by the camera were processed off-line. The EKF presented in Subsection V-B was used to obtain the navigation solution.

The gyroscope’s and accelerator’s biases were initialized by taking the mean of 30 seconds of IMU data while the receiver was stationary. The receiver’s orientation, position, and velocity, and their covariances were initialized using the output of the AsteRx-i Vs GNSS-INS. The receiver’s initial position and orientation are considered as the origin and orientation of a local frame in which the receiver’s motion state is estimated. The receiver’s clock bias and drift were initialized using the receiver’s initial’s position and two consecutive prior measurements. The initial clock bias and drift uncertainties were set to 1 m$^2$ and 0.1 (m/s)$^2$, respectively. The values of $\sigma_{w_{gt,1}}^2$, $\sigma_{w_{gt,1}}^2$, $\sigma_{w_{gt,1}}^2$, and $\sigma_{w_{gt,1}}^2$ were determined empirically using 30 seconds of IMU data while the receiver was stationary. It is assumed that the receiver is equipped with a temperature-compensated crystal oscillator (TCXO); hence, the values of $S_{w_{gt,1}}$ and $S_{w_{gt,1}}$ are set to be $4.7 \times 10^{-20}$ and $7.5 \times 10^{-20}$ [19]. The measurement noise variance $\{\sigma^2_{v_u}\}_{u=1}^U$ were set to $\{\sigma^2_{(C/N_0)_u}\}_{u=1}^U$, respectively, where $(C/N_0)_u$ is the received carrier-to-noise ratio for the $u$-th eNodeB and $\{\alpha_u > 0\}_{u=1}^U$ are tuning parameters that were chosen to be $\{5.56, 7.78, 3.33, 3.1, 3.78\} \times 10^{-12}$ in this paper.

Table III summarizes the experimental settings. Fig. 9 compares the navigator’s ground truth trajectory versus the navigation solution from: (1) IMU only, (2) LTE only, and (3) LTE-IMU framework developed in this paper.
TABLE III
EXPERIMENTAL SETTINGS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r(0</td>
<td>0)$</td>
<td>Navigator’s initial position estimate</td>
</tr>
<tr>
<td>$U$</td>
<td>Number of eNodeBs</td>
<td>5</td>
</tr>
<tr>
<td>$T$</td>
<td>Sampling time</td>
<td>0.01 s</td>
</tr>
<tr>
<td>$r_{s1}$</td>
<td>eNodeB 1 location</td>
<td>$[-1753.2, -955.7]^T$ m</td>
</tr>
<tr>
<td>$r_{s2}$</td>
<td>eNodeB 2 location</td>
<td>$[-467.5, -1516.15]^T$ m</td>
</tr>
<tr>
<td>$r_{s3}$</td>
<td>eNodeB 3 location</td>
<td>$[-381.3, -277.1]^T$ m</td>
</tr>
<tr>
<td>$r_{s4}$</td>
<td>eNodeB 4 location</td>
<td>$[246.4, 243.9]^T$ m</td>
</tr>
<tr>
<td>$r_{s5}$</td>
<td>eNodeB 5 location</td>
<td>$[464.8, -277.1]^T$ m</td>
</tr>
</tbody>
</table>

VII. CONCLUSION

This paper presented a tightly-coupled IMU-LTE framework for indoor positioning. A carrier phase-based SDR was presented to track LTE signals indoors and a base/navigator framework was proposed to eliminate the eNodeBs’ clock biases. Experimental results were presented an average $C/N_0$ to be between 53.10 dB-Hz and 77.85 dB-Hz. Experimental results were presented for a receiver that navigated indoor over a 109 m trajectory, showing a position RMSE of 3.52 m with a standard deviation of 3.85 m and a maximum error of 8.1 m.

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TABLE IV
INDOOR POSITIONING PERFORMANCE COMPARISON

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>IMU Only</th>
<th>LTE Only</th>
<th>LTE-IMU</th>
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</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>9.91</td>
<td>5.64</td>
<td>3.52 m</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>9.67</td>
<td>5.66</td>
<td>3.85 m</td>
</tr>
<tr>
<td>Maximum error</td>
<td>22.53</td>
<td>14.24</td>
<td>8.1 m</td>
</tr>
</tbody>
</table>
References


[23] 3GPP, “Evolved universal terrestrial radio access (E-UTRA); requirements for support of radio resource management,” 3rd Generation Partnership Project (3GPP), TS 36.133, April.


