Use of Diversity Techniques for Weak GNSS Signal Tracking in Fading Environments

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Abstract—This research focuses on improving the GNSS signal measurement performance in harsh multipath environments. The nature of GNSS signal propagation in typical signal impeding wireless channels such as indoors and urban environments is studied. The signal power distribution, delay spread, and Doppler spread characteristics of real GNSS signals in such environments are investigated. Based on the observations obtained from this characterization, a closed-loop tracking architecture based on spatial diversity reception is proposed. The proposed algorithm is tested on real data collected using two antennas in indoor static and urban kinematic scenarios. The carrier loop tracking, code loop tracking, and pseudorange errors are compared between single antenna reception and dual antenna spatial diversity reception for different scenarios. Results show that the proposed tracking method improves the Doppler measurement by more than 50% and pseudorange measurements by 2-5 m compared to a single antenna receiver.

Keywords—GNSS, tracking, fading, antenna diversity, Doppler spread, urban canyon, weak signal, spatial combining

I. INTRODUCTION

Commercial GNSS receivers are often confronted with the challenges posed by harsh environment conditions such as indoors and urban canyons where they are most frequently used. Such environments undermine the GNSS signal, not only by attenuation, but also by decreasing the effective signal-to-noise ratio (SNR) resulting in the fading effect. Furthermore, direct visibility to satellites is impeded because of reflection, refraction, diffraction, and scattering effects [1]. Processing such impaired signals using traditional algorithms often leads to inaccurate range measurements, resulting in inaccurate navigation solutions. In addition, when a receiver is moving in a wireless channel, it experiences a spread in the observed Doppler frequency in the form of multiple correlation peaks as opposed to a distinct peak [2],[3]. The main reasons for this effect are the appearance of multiple replicas of the same signal from different directions with different delays, Doppler frequencies and amplitude coefficients at the receiver antenna. Because of the broadened Doppler spectrum, synchronization of the receiver’s local replica carrier with the direct signal is difficult. Also, since different code delays are associated with each Doppler frequency in a broadened Doppler spectrum [4], performance of time of arrival estimation techniques such as narrow and strobe correlators is limited in severe multipath conditions.

It has been previously demonstrated that improving the processing gain of the receiver increases the SNR, which eventually enhances positioning accuracy [5]. In recent years, Mahfuz [6] and Sadrieh [7] have corroborated that spatial antenna diversity theory can be utilized in the GNSS context to enhance the processing gain. The signals received from multiple antennas that are arranged in spatial diversity form can be combined to combat the fading effect, thereby improving the processing gain. Most of the research has been limited to the signal detection stage that focuses on acquisition of the signal from a specific satellite. However, limited research has been carried out to design and evaluate the performance of spatial antenna diversity based receiver at the tracking stage.

The first objective of this research is to examine the nature of GNSS signal propagation in the following two harsh environment conditions, namely high scattering indoor environments, and dense multipath urban navigation environments such as those consisting of tall buildings. In the latter case, vehicular dynamics will be considered. Major characterization metrics are the signal power distribution over space and time, the delay spread, and the Doppler spread as experienced by an antenna. The Doppler spread is a situation where the Line-of-Sight (LOS) component and non-LOS (NLOS) components appearing at the receiver antenna have different Doppler values, thereby producing multiple peaks in the signal’s Cross Ambiguity Function (CAF). Hence the Doppler spectrum appears to be broadened. Code spread has a similar effect that occurs in the code delay domain. The level of spread depends on the speed and heading of the receiver with respect to (w.r.t.) the transmitter and on the structure of fading environment [3]. GNSS signal propagation is typically characterized by temporal and spatial variations of signal power [8]. For spatial analysis, a second antenna (Antenna-B/Channel-B) spatially separated by 2λ from the first antenna (Antenna-A/Channel-A) was used to collect a synchronized data in the second channel. Carrier-to-Noise density Ratio (C/N₀) independency, Doppler spread independency, and delay spread independency between the signals collected in two channels is investigated to demonstrate the spatial diversity. Empirical statistics are obtained for each of these metrics under different test scenarios.

Secondly, this work strives to design and implement a closed-loop tracking method using different diversity reception and combination techniques. As it will be shown in the following sections, the received signal decorrelates in the space-time and space domains. Utilizing this space-time and space diversity nature, signals from two antennas are combined after de-spreading. Three types of combinations are implemented, namely selection combining, Equal Gain Combining (EGC) and Maximum Ratio Combining (MRC). A single closed loop tracking is implemented to track carrier and code for the combined composite signal instead of.
separate loops for two channels. There exists a phase difference between the signals received at two unique points in space [9]. In dense multipath environments, signal samples from two separate antennas become highly independent. Because of this non-coherency the in-phase ($I$) and quadrature phase ($Q$) correlation values obtained from two channels cannot be combined coherently. Instead, their absolute correlation powers can be combined. Hence due to the loss of phase information, the Phase Lock Loop (PLL) cannot be implemented in the carrier tracking loop. In this research, the Frequency Lock Loop (FLL) is implemented using the Power Difference (PD) discriminator and the Delay Lock Loop (DLL) is implemented using the Early-Minus-Late Power (EMLP) discriminator. Implementation details are explained in later sections. The level of improvement in carrier tracking and code tracking is assessed between single channel receivers and the combined two-channel receiver. Here two channels correspond to the two separate hardware chains involved in front-end operation starting from the antenna to the Analog-to-Digital Converter (ADC). Two separate software correlator blocks are implemented. However, a single tracking loop is implemented. Improvement in pseudorange (PR) measurements is also compared to the one obtained from a single-channel receiver.

II. CHARACTERIZATION

In this section, GNSS signal propagation in typical fading environments is characterized, mainly in terms of the signal power variation, delay spread and the Doppler spread. Spatial decorrelation of these metrics is evaluated experimentally at different locations and for different visibility conditions.

A. Signal model

A GNSS signal propagating in a typical wireless channel such as urban areas, indoors, or any environment that includes objects of size larger than or comparable to the signal’s wavelength, is generally characterized by temporal and spatial variations of its power. This is known as signal fading. In the presence of solid objects, the LOS signal is diffracted, reflected, and scattered producing several replicas having different amplitude, delay and Doppler components. Interference of these replicas on original signal forms the constructive and/or destructive composite multipath signal. The received signal at $m^{th}$ antenna from a given satellite can be written as shown below. A similar formulation for the signal received at a single antenna is given by Satyanarayana [10]:

$$y_m(t) = r_m(t) + n_m(t)$$

where $n_m(t)$ is the additive white Gaussian noise (AWGN) and $r_m(t)$ is the useful signal, which can be expressed as

$$r_m(t) = \mathbb{R} \left\{ \sum_{k=0}^{K(t)} a_k(t) \sqrt{2E_d} d(t - \tau_k(t)) \right\} c(t - \tau_k(t)) e^{j2\pi f_D(t)(t - \tau_k(t))}$$

where $d(*)$ and $c(*)$ are the data and the modulating code respectively, and $a_k(t)$, $\tau_k(t)$ and $f_D(t)$ are the time varying amplitude, delay, Doppler frequency components associated with the $k^{th}$ multipath component. $K(t)$ is the total number of multipath components available at time $t$. At a given time, these values would not be the same for two antennas unless their phase centers coincide. In the above equation, $k=0$ corresponds to the LOS component (if available). In the characterization, the following metrics are evaluated in the signals $y_I(t)$ and $y_Q(t)$ with the knowledge of true Doppler $f_{D,I}(t)$ and true delay $\tau_0(t)$:

1. Temporal signal amplitude distribution and spatial amplitude correlation coefficient.
2. Temporal delay spread and spatial delay spread correlation coefficient.
3. Temporal Doppler spread and spatial Doppler spread correlation coefficient.

B. Correlation coefficient and spread statistics

The correlation coefficient is a metric that quantifies the similarities between two random variables. In this research, the independent signal reception in fading environments is evaluated empirically by computing the correlation coefficients of the measurements obtained from two antennas separated by $2\lambda$. The correlation coefficient is given by

$$\rho = \frac{\mathbb{E}[x_i x_j^*]}{\sqrt{\mathbb{E}[x_i^2] \mathbb{E}[x_j^2]}}$$

where $x_i$ and $x_j$ are zero mean complex random variables. To compute amplitude correlation coefficient, $x_i = I + jQ_i$ and $x_j = I + jQ_j$, where $I$ and $Q$ are the in-phase and quadrature phase correlator outputs obtained when the local signal with true code delay $\tau_0(t)$ and true Doppler $f_{D,I}(t)$ is correlated with the incoming signal. For random variables $(I, Q)$ to be zero mean, it is assumed that the number of logic high bits (ones) and logic low bits (zeros) are equally distributed in the collected data set. To compute spatial correlation coefficient for the delay spread and the Doppler spread, the random variable $x_i$ is the respective delay and Doppler error that produces maximum correlation power. That is, to compute the delay spread correlation coefficient, $x_i$ or $x_j$ is computed as

$$x_i(t) = x_{i,d} = \tau_0(t) - \tau_i(t), k \neq 0$$

such that the correlation operation expressed below produces maximum power among all $k \in \{1, 2, ..., K\}$:

$$\tau_i \left\{ \int_{(\omega-1)T_c}^{\omega T_c} y_m(t) c_L(t - \tau_0(t)) e^{j2\pi (f_c + f_{D,L}(t))(t - \tau_k(t))} \right\} dt$$

where the suffix $L$ stands for local code and carrier replica, and $T_c$ is the coherent integration time. Similarly, to compute the

Doppler spread correlation coefficient, $x_i$ or $x_j$ is computed as,

$$x_i(t) = x_{i,d} = f_{D,0}(t) - f_{D,k}(t), k \neq 0$$

such that the correlation operation expressed below produces maximum power among all $k \in \{1, 2, ..., K\}$.

$$\tau_j \left\{ \int_{(\omega-1)T_c}^{\omega T_c} y_m(t) c_L(t - \tau_0(t)) e^{j2\pi (f_c + f_{D,L}(t))(t - \tau_0(t))} \right\} dt$$
In this research, the true delay $\tau_d(t)$ and Doppler $f_d(t)$ were obtained from a reference trajectory using Novatel-SPAN™ receiver coupled with tactical grade IMU-LCT™ [11]. More details about data processing are given in the next section.

Delay and Doppler spread statistics are obtained from $x(t)$ in (4) and (6) respectively. Empirical Probability Density Functions (PDFs) of these spreads are shown in the results section.

C. Data collection

Real GPS L1 C/A code signal was collected using two Novatel GPS-701-GG antennas. The spatial correlation is function of antenna separation and signal distribution. The larger the separation, the lower the correlation. GNSS data collected in similar environments [6], [7] have shown that a fairly independent reception can be expected with a separation of $2\lambda$, which is used in this research as well. Antennas were firmly mounted on a mobile cart (used for indoor tests)/vehicle top (used for downtown tests). Figure 1 shows the test set-up, environment and sky plot for the indoor data collection in McEwan Hall at the University of Calgary (UofC) campus (Data set-I and Data set-II). Figure 2 shows the test set-up, downtown environment with tall buildings and sky plot for the urban canyon data collection (Data set-III). All the characterization metrics are investigated in these scenarios as listed in Table 1.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Antenna motion</th>
<th>Signal visibility, PRN, and (Elevation°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data set - I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shopping mall (Indoor):</td>
<td></td>
<td>LOS + NLOS: PRN23 (85°)</td>
</tr>
<tr>
<td>McEwan Hall, UofC,</td>
<td></td>
<td>NLOS: PRN16(50°), PRN13(45°), PRN20(40°), PRN10(25°), PRN07(10°)</td>
</tr>
<tr>
<td>1st Feb 2014, 5.40 pm local time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data set - II</td>
<td></td>
<td>LOS + NLOS: PRN13(85°)</td>
</tr>
<tr>
<td>Shopping mall (Indoor):</td>
<td></td>
<td>NLOS: PRN23(70°), PRN16(60°), PRN10(35°), PRN07(35°)</td>
</tr>
<tr>
<td>McEwan Hall, UofC,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st Feb 2014, 6.40 pm local time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data set - III</td>
<td></td>
<td>LOS + NLOS: PRN17(75°)</td>
</tr>
<tr>
<td>Urban canyon:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Downtown Calgary,</td>
<td></td>
<td>NLOS: PRN28(60°), PRN01(35°), PRN09(30°), PRN15(30°), PRN24(30°), PRN11(25°), PRN26(25°), PRN08(25°),</td>
</tr>
<tr>
<td>25th March 2014, 9.30 pm local time</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NLOS PRNs listed for Data set-III in Table 1 are not strictly NLOS always. Signal from these PRNs is shadowed by the buildings in most part of the data as the antennas are moved through the urban canyon. Only those portions of the data where the signal is above the noise floor are considered for the characterization.

D. Characterization results

First, the temporal signal envelope distribution for the indoor static case is shown for two selected PRNs, one with the mixed LOS and NLOS visibility (PRN23) w.r.t. the antenna set-up and the other with NLOS only visibility (PRN13). Data set-I is chosen for this purpose. Signals with dominant LOS (PRN23) have a Rician distribution and NLOS signals (PRN13) have a Rayleigh distribution as shown in Figure 3. Most of the samples follow the theoretical fit, however, because of the non-stationary nature of the channel (due to satellite motion); PRN23 also contains some samples that are deeply faded (Rayleigh) rather than just the Rician components. Likewise, PRN13 also contains some samples with Rayleigh fading.
Figure 2 Downtown data collection: test set-up (top) and 3D sky plot (bottom) for Data set-III. True trajectory is shown in red color. ‘S’ mark is the starting point. Center of the sky plot is placed at a convenient point to visualize the approximate location of satellites as the vehicle moves along the trajectory.

Figure 3 Signal envelope distribution in Data set-I for (a) LOS + NLOS case - PRN23, (b) NLOS only case - PRN13

Figure 4 shows the temporal C/N, variation for Channel-A (Ch-A) and Channel-B (Ch-B) in Data set-I. Constructive and destructive multipath fading can be observed. Although individual branches experience significant fading, both, or at least one of the antennas receive fairly good signals in most part of the data. This complementary behavior is significant for NLOS PRNs.

Independent signal reception is investigated by computing the correlation coefficient (ρ) of the metrics as discussed earlier. These values are specific to 2λ separation. In all the following figures, PRNs are arranged in decreasing order of elevation angle (refer Table 1) so that the reader can visualize the influence of C/N₀ and signal visibility on the characterization metrics. It is recommended to refer to the sky plots of various scenarios. Figure 5-b shows ρ for different signal visibility conditions (PRNs). In both the static and dynamic case, the correlation coefficient decreases with decreasing elevation. The signal decorrelation is more for low elevation satellites in the dynamic case compared to the static case, and it is complementary for high elevation satellites. Figure 5-a also shows the maximum C/N₀ and Minimum C/N₀ observed by Ch-A and Ch-B antennas. Although it does not provide temporal signal variations, it gives an idea about the absolute C/N₀ envelope variation in the elevation dimension. Figure 5-c shows a similar plot for Data set-III along with the correlation coefficient. It is quite interesting to note that the signal decorrelation is not significant as it is in the indoor scenario. It stays almost constant for any elevation. Unlike indoors, antennas in the downtown test are exposed to dominant LOS signals in some portion of the data irrespective of elevation angle. Both antennas experience dominant LOS equally.
The standard deviations of the delay and Doppler spread for three data sets are shown in Table 2 and Table 3 respectively. Indoors, the delay and Doppler spread increases with a decrease in signal availability (elevation angle). Same is the case for the downtown scenario. Both delay and Doppler spread are large in the downtown test compared to indoors, due to the distance of reflecting objects from the antennas.

### Table 2 Delay spread standard deviation in meters

<table>
<thead>
<tr>
<th>Data set</th>
<th>PRN</th>
<th>Ch-A [m]</th>
<th>Ch-B [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>23</td>
<td>03</td>
<td>02</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>II</td>
<td>13</td>
<td>11</td>
<td>09</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>08</td>
<td>06</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>III</td>
<td>17</td>
<td>06</td>
<td>06</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>30</td>
<td>31</td>
</tr>
</tbody>
</table>

### Table 3 Doppler spread standard deviation in Hz

<table>
<thead>
<tr>
<th>Data set</th>
<th>PRN</th>
<th>Ch-A [Hz]</th>
<th>Ch-B [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>13</td>
<td>0.41</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.53</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.61</td>
<td>0.50</td>
</tr>
<tr>
<td>III</td>
<td>17</td>
<td>0.56</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>1.73</td>
<td>1.79</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>2.50</td>
<td>2.50</td>
</tr>
</tbody>
</table>
In order to investigate the independence in Doppler and delay spread as experienced by antennas, the correlation coefficients of the delay and Doppler spread errors are computed. Table 4 lists the correlation coefficient values for different scenarios. In Data set-I, the delay spread experienced by two spatially separated antennas is highly independent at low elevations. In Data set-II, this decorrelation is large even at high elevation. This is an important observation because, although the signal power is not quite independent for high elevation PRNs in indoor dynamic scenario (refer Figure 5-b), the delay spread is fairly independent in nature. Hence benefit from diversity combination can be expected even in such cases. Conversely, Table 4 shows that for Data set-III, the delay spread is highly independent at higher elevation only. Signals from low elevation satellites seem to be spread equally in two antennas. This may happen because for given dynamics in downtown, the fast fading behavior is poorer than indoors. Most low elevation satellites are mostly shadowed by buildings, while high elevation PRNs undergo reasonable amount of fast fading. This behavior is also evident from the plot showing signal amplitude correlation coefficient; observe Figure 5-c, where high elevation satellites have lower signal correlation.

Table 4 Correlation coefficient for delay and Doppler spread between Ch-A and Ch-B

<table>
<thead>
<tr>
<th>Data set</th>
<th>PRN</th>
<th>Delay spread</th>
<th>Doppler spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>0.59</td>
<td></td>
<td></td>
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<tr>
<td>13</td>
<td>0.21</td>
<td></td>
<td></td>
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<tr>
<td>10</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.22</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.17</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.11</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>0.25</td>
<td>0.33</td>
<td></td>
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<tr>
<td>28</td>
<td>0.61</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>0.79</td>
<td>0.37</td>
<td></td>
</tr>
</tbody>
</table>

III. TRACKING METHODOLOGY

Based on the observations made from characterization, it is now evident that the signals received at two different locations separated by sufficient spacing in a fading environment behave differently, especially in terms of C/N0 level, Delay, and Doppler measurements. Hence utilizing this diversity nature, a tracking loop is designed and implemented. A carrier tracking loop of a single-channel (antenna) receiver operating in open-sky conditions generally includes a PLL. PLLs cannot be implemented in situations that demand non-coherent combination where the phase information will be lost. Instead, PLLs such as ATAN2, cross*sign(dot), are normally implemented [12]. However, when multiple antennas are used for signal reception and combination, owing to the phase differences between the signals received at multiple antennas, coherent combination of I or Q values is not possible.

The PLL implemented in the modified tracking architecture uses a Power Difference (PD) discriminator and the DLL uses an Early-Minus-Late Power (EMLP) discriminator. The PD PLL discriminator uses correlation values from three frequency bins: one set from the frequency bin being tracked (sync), and two sets from the adjacent fast and slow frequency bins. The sync, fast, and slow correlation values for m\textsuperscript{th} antenna are expressed as

\[
P_{\text{sync}}^m = \sum_{k=1}^{K} \sqrt{C^2 R(t_{m,k})} \sin^{2}\left(\frac{\delta\theta_{m,k} - \Delta\theta}{2} T \right) \exp\left(j\delta\vartheta_{m,k}\right) + n_{m}^{\text{sync}} \tag{8}
\]

\[
P_{\text{fast}}^m = \sum_{k=1}^{K} \sqrt{C^2 R(t_{m,k})} \sin^{2}\left(\frac{\delta\theta_{m,k} + \Delta\theta}{2} T \right) \exp\left(j\delta\vartheta_{m,k}\right) + n_{m}^{\text{fast}} \tag{9}
\]

\[
P_{\text{slow}}^m = \sum_{k=1}^{K} \sqrt{C^2 R(t_{m,k})} \sin^{2}\left(\delta\theta_{m,k} - \Delta\theta \right) \exp\left(j\delta\vartheta_{m,k}\right) + n_{m}^{\text{slow}} \tag{10}
\]

where \(\Delta\theta = 2\pi\Delta f\) is the frequency spacing (in rad/sec) between the correlators. \(\Delta f\) is set as 38 Hz for \(T_f = 0.02\ s\), such that \(\Delta f_{\text{TSS}}\) is between 4 to 5 radians in order to maintain linear region of operation for C/N, ranging between 25 dB-Hz to 35 dB-Hz as shown by Curran [13].

A. Discriminators

1. The Power Difference (PD) discriminator for FLL is expressed as

\[
\hat{f}_{PD} = \frac{\left(S_{\text{fast}} - S_{\text{slow}}\right)\left(\Delta f_{\text{TSS}}\right)^3}{T_{\text{P}}S_{\text{sync}}\left(1 - \cos \left(\Delta f_{\text{TSS}}\right) - \frac{\Delta f_{\text{TSS}}}{2} \sin \left(\Delta f_{\text{TSS}}\right)\right)} \tag{11}
\]

where

\[
S_{\text{fast}} = w_1\left|P_{\text{fast}}\right|^2 + w_2\left|P_{\text{slow}}\right|^2 \quad \text{is the fast power}
\]

\[
S_{\text{slow}} = w_1\left|P_{\text{slow}}\right|^2 + w_2\left|P_{\text{fast}}\right|^2 \quad \text{is the slow power}
\]

\[
S_{\text{sync}} = w_1\left|P_{\text{sync}}\right|^2 + w_2\left|P_{\text{sync}}\right|^2 \quad \text{is the sync power}
\]

\(P_{\text{m}}\) is a coherent accumulation of complex correlator outputs from fast/sync/slow frequency bins for the \(m\text{th}\) antenna. Weights \(w_1\) and \(w_2\) decide the type of combination: selection, Equal Gain Combination (EGC), or Maximum Ratio Combination (MRC). In the selection combination, only one signal with maximum power is selected with its weight equal to 1. The weights of the other signals are zero. In EGC, \(w_1 = w_2 = 1\). Weights for MRC are computed based on the SNR of signals as formulated in [14].

2. Early Minus Late Power (EMLP) discriminator for DLL

The DLL uses a traditional EMLP discriminator, whose inputs are the early and late powers from sync frequency bin:

\[
\hat{c} = \left(1 - \frac{C_{\text{EL}}}{2}\right) \left(\frac{S_{\text{sync}} - S_{\text{sync}}^2}{S_{\text{sync}}^2 + S_{\text{sync}}^2}\right) \tag{12}
\]
where \(c_{SE2}\) is the early-late chip spacing. \(S^{\text{sync}}\) early and late powers are obtained by combining respective powers from two antennas with appropriate weights \(w_1\) and \(w_2\).

B. Architecture

The proposed tracking architecture is shown in Figure 8. Blocks indicated in blue color are used in a generic single antenna receiver. Additional blocks required for the proposed architecture are shown in purple color.

![Figure 8 Proposed tracking architecture to track combined signal from multiple antennas](image)

C. Data bit decoding

Pseudorange measurement performance can be accessed only if ephemeris bits are decoded properly. In PLL, data bit transition is generally decoded by the change in sign of the \(I\) accumulator as it assumes in-phase component becomes maximum and quadrature-phase component becomes minimum. However, in FLL, the phasor (vector sum of \(I\) and \(Q\) from an antenna) always makes an angle w.r.t \(I\)-axis. This angle may be different for other antenna. In the presence of noise, these phasors rotate at the rate of the frequency error. Due to rotating phasors in FLL, the data bits cannot be decoded based on the sign of the \(I\) accumulator. Hence the data bits are decoded by differential demodulation technique [11]. Relying on the phasor obtained from only one antenna for differential demodulation results in data bit errors due to fading. Hence, phasors from both the antennas are considered for data bit decoding and the one with the maximum power is selected.

IV. TEST DESCRIPTION AND EXPERIMENTAL RESULTS

To analyze the tracking performance of the proposed architecture, Data set-I and Data set-III were chosen. Similar to the process followed during characterization, the tracking algorithm is compared for different signal visibility conditions (LOS+NLOS or NLOS) which depend upon the elevation angle and the surrounding objects. Sample PRNs corresponding to High Elevation (HE), Medium Elevation (ME), and Low Elevation (LE) are chosen.

The GPS L1 signal was sampled by National Instrument’s data acquisition system. Sampling clocks of two channels were synchronized. As the Low Noise Amplifier (LNA), RF front-end, and subsequent ADC section used for two channels are separate, the noise floor in the two channels will be different. This is taken care by pre-processing scaling of the Intermediate Frequency (IF) samples for relative noise floor difference. Because of fading, acquisition may not be successful if the signal from only one antenna is used. Hence, EGC acquisition is performed.

After bit sync, 20 ms coherent integration is performed in FLL assisted DLL mode. All the following plots are shown after successful ephemeris decoding. No tracking plots or tracking measurement error values are shown for the epochs starting from acquisition to the bit sync. PRNs may lose lock at some point in tracking loop due to severe loss in \(C/N_0\). Hence, tracking measurement error values for a given PRN are computed up to the point of first loss of lock. The carrier Doppler measurement error, code Doppler measurement error and pseudorange measurement error for each scenario are compared between the single-channel tracking mode and the proposed method. EGC is chosen first to assess the improvements in combined tracking mode. Later, different combination techniques within the combined tracking mode are compared to each other. In all the following figures, ‘True’ plot corresponds to the reference Doppler obtained from a Novatel-SPAN™ receiver coupled with a tactical grade IMU-LCT™.

First, Data set-I was processed for all PRNs in different visibility conditions w.r.t. the antennas set-up. It was observed that an LOS+NLOS signal (PRN23) from both the antennas can be tracked independently with a certain error, without performing any spatial signal combination. However with the proposed tracking implemented in EGC mode, this signal can not only be tracked, but also the error in the observed Doppler is reduced. Similarly, the observed code Doppler error variance and PR error variance are also decreased. For NLOS PRN tracking, the proposed algorithm shows even more interesting results. Figure 9 shows carrier Doppler for PRN20 (NLOS, ME). Tracking the signal from only Ch-A results in loss of lock at GPS Time (GPST) 2250 when Ch-A \(C/N_0\) drops. Although Ch-B signal can be still tracked, it has a large variance as its power drops below 30 dB-Hz. Tracking the EGC signal from two antennas with a PD discriminator produces better results with a reduced Doppler error. Similar result is observed in the PR error plot shown in Figure 10, where Ch-B signal has a larger PR error than that of the EGC.

PRN16 and PRN07 never acquired the Ch-B signal, while losing Ch-A signal after a few epochs. Low elevation PRN13 and PRN10 acquired neither of the channels. However all the satellites were acquired and tracked with comparatively lower errors in the EGC tracking mode. It was also observed that low elevation PRNs lose lock faster and tracking errors increase with decrease in elevation. Figure 11 shows the trend of carrier and code Doppler errors for sample PRNs compared between single channel tracking and EGC tracking. As the elevation decreases (poorer \(C/N_0\)), the error variance increases. Nevertheless, combined tracking always results in a lower error variance for both code Doppler and carrier Doppler tracking for any elevation.
However, this trend is not always linked to the elevation angle alone. It also depends on the azimuth of the satellite w.r.t. the receiver in a given fading environment. However, one exceptional observation is that PRN07 (10° elevation) sustains EGC tracking for more than 500 s, while PRN10 (25° elevation) loses EGC soon after 250 s. This behavior can be explained as follows: unlike PRN10, PRN07 is located in an azimuth such that its signal is reflected strongly inwards through the glass dome into the indoors where the antenna set-up is located (refer Figure 1). If the NLOS signal is stronger and if the loop bandwidth is able to accommodate the NLOS Doppler, the signal may not lose lock.

Tracking loop performance is also compared for Data set-III. Similar to the earlier observation, the variance of Code Doppler error, carrier Doppler error, and PR error decreases with EGC for all signal visibility conditions. Advantage of spatial diversity combining as proposed in this research is evident as shown in Figure 12. Here carrier Doppler of a sample low elevation PRN26 in downtown data is shown. The Doppler variation due to vehicle motion can be seen. If only Ch-A signal or Ch-B signal is used, loss of lock occurs at some point in time. However, if both signals are combined in EGC mode, the combined signal continues to track.

Notwithstanding improved performance with EGC tracking, two other diversity combination methods were also tested, namely selection and MRC. It was observed that for both Data set-I and Data set-III, selection combination resulted in increased tracking error compared to that in EGC. This is for the obvious reason that the signal from either of the two channels will be selected based on absolute power and as such no spatial signal combination will take place at any epoch. MRC, on the other hand, showed almost similar performance to that of EGC in Data set-III. Improvement observed in MRC is slightly better than EGC for some medium and high elevation PRNs in Data set-I. A noticeable advantage of MRC is observed in deep fading conditions. Figure 13 shows the Doppler tracking for PRN10 in Data set-I. EGC loses lock at GPST around 2275 when both Ch-A and Ch-B powers degrade almost simultaneously. MRC suffers from temporary Doppler in this instance but continues to track the signal thereafter.
A summary of tracking performance for Data set-I and Data set-III are shown in bar graphs in Figure 14 and Figure 15. RMS carrier Doppler errors and PR errors are shown for all Signal visibility conditions. PRNs are arranged in decreasing order of their elevation angle in the x-axis (Table 1). For each PRN, the Root Mean Square Error (RMSE) obtained from five different tracking modes, namely (1) tracking signal from Ch-A alone (channel A only), (2) tracking signal from Ch-B alone (channel B only), (3) EGC tracking, (4) MRC tracking, and (5) selection combination tracking. In order to maintain consistency in processing the IF data between different tracking modes, RMSE values are computed for a time window where all five modes are tracking the signal from a PRN. For example, for PRN20, this time window for all tracking modes is from GPST 2120 to GPST 2250 as ‘Ch-A-only’ mode loses lock at GPST 2250. If a certain mode does not acquire or track a PRN, its RMSE is not shown.

In the downtown test all channels are acquired and tracked unlike indoors for the reason that signal power is sufficiently high at the beginning of the data. The General trend in terms of improvement versus Signal availability (LOS/NLOS) is that Doppler and PR RMSE increases with decrease in elevation, however subject to direct Signal availability (azimuth) in some cases. For all the cases, spatial diversity combined tracking showed improvement in carrier and code tracking compared to single-channel tracking. Carrier Doppler RMSE improves by more than 50% for most of the PRNs in Data set-I and Data set-III. PR RMSE improves by more than 5 m in Data set-I, and by about 2-3 m in Data set-III. Although this improvement in PR is quite small compared to the large multipath errors of the order of tens of metres, it has to be noted that RMSE values for different tracking modes are computed for the same set of data for a time window when all modes are tracking the signals. Most importantly, a diversity combined signal is less prone to loss of lock as shown earlier.

Selection combining showed better results than single-channel tracking for the reason that discriminators are always input with the correlation values from a signal with high SNR. Still, its performance is poorer than EGC or MRC. Between EGC and MRC, the latter showed lower PR RMSE in Data set-I and almost the same performance in Data set-III. A reason for this behaviour could be because the signals received by different antennas is correlated in downtown environment.

The following conclusions are obtained from the characterization and tracking results:

V. CONCLUSIONS

The following conclusions are obtained from the characterization and tracking results:

A. Characterization

- Fading in shopping mall-like indoor environments is more diverse than in downtown environment.
- Spatial Signal decorrelation (channel power independency) for low elevation PRNs is higher in the indoor dynamic case (0.1 m/s) than the indoor static case. Decorrelation up to 0.1 is observed in the former case. On the other hand, this Signal decorrelation is almost constant in the downtown dynamic scenario.
• Similar to signal power, independence can be observed in the delay spread and Doppler spread in all scenarios and for all signal visibility conditions.

• The Doppler spread and delay spread error variances for different scenarios tested are in the following order:
  Downtown dynamic (~ 30 km/hr.) > Indoor dynamic (~ 0.1 m/s) > Indoor static, and
  High elevation > medium elevation > low elevation

B. Tracking

• Spatial diversity combined signal always produces better tracking performance compared to single-antenna signal irrespective of the scenario, or the signal visibility conditions.

• Combined tracking has a two-fold advantage. First, it produces less Doppler and pseudorange measurement errors compared to the single-antenna tracking. Second, it helps in sustaining the tracking even if either of the independent channels loses lock. For the dataset considered in this research, the carrier Doppler RMSE improved by more than 50% for all scenarios and PR RMSE improved by more than 5 m indoors and by 2-3 m in the downtown test.

• MRC shows a slight improvement compared to EGC in PR measurements for the indoor scenario and almost matching performance for the downtown scenario.

REFERENCES


