Comparing Detection Performance of Polarization and Spatial Diversity for Indoor GNSS Applications

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Abstract**—GPS signal detection is limited in indoor areas due to signal attenuation and multipath fading. Considering diversity systems can provide two major benefits: increasing overall average received signal power and decreasing signal fading margins by combining independent signal sources. In this paper, detection performance of spatial and polarization diversity systems applied to the received GPS signals in indoor environments is investigated. Herein, the polarization diversity is formed using two different combinations of orthogonal polarized antennas: one with Right Hand Circular Polarized (RHCP) and Left Hand Circular Polarized (LHCP) antennas and another one by vertical and horizontal antennas. Theoretical comparison of these antenna diversity structures is investigated along with real GPS signal collection in different indoor locations to evaluate their performance experimentally. The diversity gain metric has been introduced to quantify the performance of the combining method theoretically and experimentally. Since diversity gain is a function of correlation coefficient and average signal input, these parameters are measured and compared as well for the target diversity systems.**

Keywords- Antenna diversity, indoor GNSS, detection performance

I. INTRODUCTION

Global Navigation Satellite System (GNSS) signal suffers from attenuation and deep fading in dense multipath environments such as indoor and urban areas due to propagation through building materials and interference between multiple reflected signals. In order to overcome these problems and improve position estimation under weak GNSS signal conditions, several techniques including High-sensitivity GPS (HSGPS), assisted GPS (AGPS), and diversity techniques have been utilized. There are various techniques to implement a diversity system such as antenna, time and frequency diversity [1]. In the antenna diversity technique, a receiver utilizes multiple antennas known as diversity branches to capture independent copies of the transmitted signal. Different techniques including spatial, polarization and pattern diversities have been implemented and analyzed in the literature (see [2] and references therein). Among them, spatial diversity and polarization diversity are widely utilized in communication systems.

The spatial diversity system is developed based on the fact that in a multipath fading environment the received signals on different antenna elements decorrelate spatially [3]. In [4] an optimum spatial post-correlation signal processing and detection algorithm for two-antenna array GPS receivers is proposed. Reference [5] analyzes theoretically and experimentally the processing gain achievable through spatial combining of a pair of antennas. The spatial diversity performance of three different antenna configurations in indoor 902-928 MHz propagation channel is evaluated in [6]. In this work, it has been shown that the indoor propagation channel has either Rician or Rayleigh models and the fading distribution characteristics are discussed. Reference [7] has recently proposed a new spatial diversity structure based on the synthetic array concept to enhance the detectability of GPS signal in indoor locations.

In the polarization diversity system, antennas with orthogonal polarization can be considered as diversity structure branches. In indoor environments, since the signal path is cluttered by multiple scatters the received signal polarization changes randomly. The polarization diversity and channel characteristics at 1800 MHz are extensively analyzed in [8]. The effect of correlation between two polarization branches on diversity gain has been discussed in [8] as well. In addition, the performance of polarization diversity using different antenna configurations in both Rayleigh and Rician environments was evaluated. The concept that the received GNSS signal in high multipath environments is no longer circularly polarized has been used by [9] with introducing GNSS signal detectability enhancement approach using circular polarization diversity by a dual-polarized RHCP and LHCP antennas. Using real GPS signal in various environments, it has been shown that up to 5 dB diversity gain can be achieved by a dual-polarized antenna in dense multipath environments. In addition to the circular polarization diversity, the enhancement of GNSS signal detection performance utilizing dual linear polarized antenna is considered herein.

The paper is organized as follows. Second II describes indoor fading channel and its corresponding considerations. In Section III, the spatial and polarization diversity systems are introduced. The important factors leading to higher detection performance and diversity gain in a diversity system are discussed in Section IV. In continue the test setup and experimental results are explained and analyzed in Section V. Conclusions are given in Section VI.

II. FADING CHANNEL MODEL:

Since in indoor environments the receiver antenna receives multiple signals from many reflections and different directions, the received signal becomes a complex vectorial sum of the signals reflected from various obstacles with different amplitude and phase characteristics. This phenomenon results in random variations in the received signal amplitude known as multipath fading [10].

As discussed in [9], the final envelope leads to either Rayleigh or Rician distribution depending on the existence of a dominant signal source which can be quantified by the *K* factor as below [6]:

$$K = 10\log\frac{r_s^2}{2\sigma^2}dB \qquad (1)$$

where $r_s^2/2$ is the dominant component power and σ^2 is the mean signal power. Considering the Cumulative Distribution Function (CDF) of the Rician and Rayleigh functions illustrates that for small *K* factors, less than 0 dB, the propagation channel can be considered as a Rayleigh fading channel. The optimum combining method is defined according to the propagation channel characteristics. As will be discussed latter, here, the detection structure leads to the Likelihood Ratio Test (LRT) and it reduces to the Estimator Correlator (EC). The EC is an optimum detector when the input signals carry zero mean Gaussian distribution and, hence, the signal envelope is Rayleigh distributed. The channel measurement for the objective diversity structures is presented in this paper.

III. ANTENNA DIVERSITY SYSTEMS

A. Spatial Diversity

In a spatial diversity system, an array of spaced apart antennas is utilized to achieve independent fading paths. The arrangement of multiple antennas to receive multiple signals with uncorrelated fading is the most important issue in spatial diversity, since the spatial correlation and signal Angle of Arrival (AoA) statistics are strongly related. The statistics of how the electromagnetic waves arrive from different directions on antennas are defined as AoA statistics. Assumptions of different signal distributions result in different correlation values [11]. In fact, the spatial signal covariance matrix is a function of both the array geometry and AoA statistics of the incoming signals. Reference [7] has quantified the spatial correlation coefficients as a function of antenna space for a uniform AoA distribution with the angel of spread of φ, as shown in Fig. 1, where θ is the mean of incident signal direction. It is obvious that the correlation coefficient between received signals in spatial diversity systems depends on the reflectors angle spread and environment specifications.

B. Polarization Diversity

In polarization diversity systems, antennas with orthogonal polarization are employed to form a diversity system [1]. Using polarization diversity in indoor locations is based on the concept that in high multipath environments the signal polarization is subject to change due to diffraction, refraction and reflection. Compared to spatial diversity, a compact dual polarized antenna can be utilized to create a polarization diversity structure.

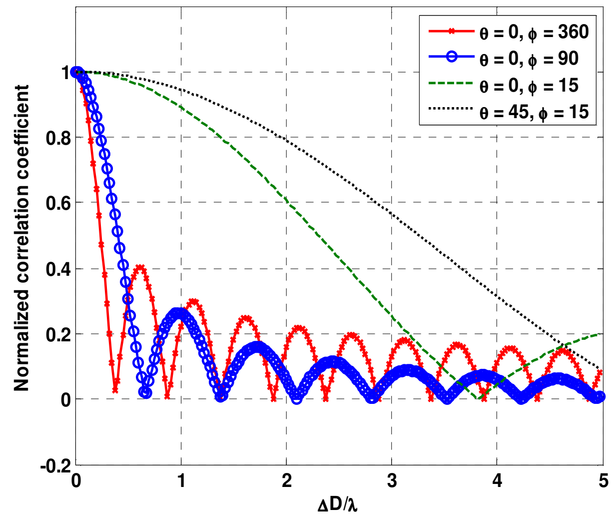

Figure 1. Spatial correlation coefficient for various angel of spread

In fact in this approach the receiver antennas are not required to be physically spaced apart to receive independent signals which are practically more suitable for handheld and small GNSS devices. In this work both combination of RHCP-LHCP and Vertical-Horizontal antenna are examined.

Although, the transmitted GNSS signals are right hand circularly polarized (RHCP), the reflected GNSS waves polarization may change to either left or right hand elliptical polarization depending on the reflector type and the grazing angle (the angle at which the signal impinges on the reflector) [12]. In indoor environments, since different reflected signals received by the antenna carry various polarizations, the final received signal can be assumed to be elliptically polarized including both RHCP and LHCP components. However, the received signals components in the orthogonal antennas should be adequately discriminated to achieve sufficiently low correlation coefficient between received signals. To accomplish this, the part-to-part isolation of the antennas should be at least -30 dB and their cross polarization ratio should be less than -20 dB [13].

Another employed structure for polarization diversity is the combination of received signals from linear polarized antennas. This is based on the principle that the amplitude and phase of vertical and horizontal components in reflected GNSS signals are varying independently since the parallel and perpendicular components of reflection coefficients for any reflector are independent [1]. These antennas are simpler in term of design and implementation which leads to lower overall cost of the mobile devices. However, lower average SNR is expected in this structure since the orthogonal components of a circular polarization signal carry almost 3dB power less than the original wave.

IV. SIGNAL MODEL AND DETECTION PROCEDURE

The received complex baseband GNSS signal at the output of the *i*th diversity branch can be denoted as below:

$$r_i(t) = h_i(t)s_0(t) + w_i(t) \tag{2}$$

where *h(t)* is the complex channel gain as a function of antenna time *t* and *w(t)* is complex additive white Gaussian noise and $s_0(t)$ is the transmitted signal from satellite, where

$$s_0(t) = \mathrm{d}(t-\tau)c(t-\tau)e^{j(2\pi\Delta f t+\psi)}\,. \tag{3}$$

d(t) is the navigation data modulation, *c(t)* is the Pseudo Random Noise (PRN) code, τ represents the code phase, Δf stands for the carrier frequency offset (due to the Doppler effect and frequency offset of the receiver local oscillator), ψ is the initial phase offset. $s_0(t)$ parameters are known to the receiver except for the navigation data, the code phase, the carrier frequency offset and the initial phase offset. In un-resolvable Rayleigh faded multipath environments, *h(p,t)* can be approximated as a Complex Normal (CN) random variable [10]. For indoor GNSS applications it can be shown that $s_0(t)$ is sufficiently narrowband such that a flat fading model can be assumed [1]. It is also assumed that during signal snapshots *T*, the channel is temporally static in which case coherent integration results in processing gain. The optimal detection process is then a matched filter based on correlation with $s_o(t)^*$, where * is the conjugate operator, followed by a magnitude squared as shown in Fig. 2 where the processed output of the *i*th diversity branch is given by

$$x_i = \int_0^T r_i(t)s_o(t)^* dt\,. \tag{4}$$

In the detection procedure for the GNSS signals as the hypotheses are tested with orthogonal despreading functions, the performance can be assessed by considering an individual binary hypothesis testing defined as H_0 and H_1 [19]. H_0 represents the case when the incoming signal does not correspond to the hypothesis associated with $s_0(t)$ and H_1 represents the case when the incoming signal corresponds to the hypothesis associated with $s_0(t)$. Therefore, under H_1 state, it is assumed that the frequency and code phase of the incident signal is synchronized with the locally generated signal. The detection structure for such binary hypothesis test leads to the Likelihood Ratio Test (LRT) when the additive noise is zero mean Gaussian one [14].

In antenna diversity combining, *M* input signal after despreading denoted as x_i (*i*=1 to *M*) received via *M* diversity branches are considered. The LRT for an antenna diversity structure including *M* branches can be considered as received signal estimator followed by a correlator. This detector is called the Estimator Correlator (EC) and can be simplified to Equal Gain (EG) combiner for uncorrelated signals as [9]

$$T(x) = x_{EG} = \sum_{i=1}^{M} |x_i|^2 \tag{5}$$

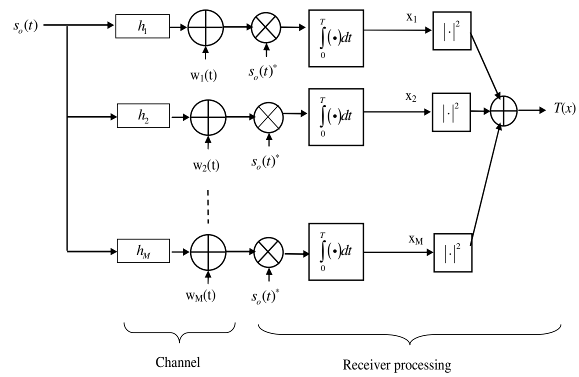

Figure 2. The LRT detector for a diversity scheme

The EG combiner is considered as a sub-optimum detector for correlated signals [15]. The detection performance of a detector can be quantified by the probability of false alarm (P_{fa}) and the probability of detection (P_d). P_{fa} is defined as deciding H_1 hypothesis where H_0 is true while P_d corresponds to deciding H_1 when the signal is present. The Receiver Operating Characteristic (ROC) curve, which plot P_d as a function of P_{fa}, can be employed to present and compare the detection performance of various detectors while higher probability of detection for a given probability of false alarm is desired.

The detection performance of EG combiner and EC are analyzed in [9] and concluded that they carry almost the same performance when the correlation coefficient between received signals in various branches is less than 0.5. In this work, the equal gain combiner is utilized to combine received signals through different branches in each diversity systems.

V. DIVERSITY GAIN

The effectiveness of a diversity system is usually evaluated by a quantity known as diversity gain. The diversity gain is defined as the excess in required input SNR for a single antenna scheme to achieve the same probability of detection as the combining scheme, for a specific probability of false alarm. The most significant effective factor which characterizes the performance of each diversity structure is the correlation coefficient between the received signals in different diversity branches. In fact, the efficiency of a diversity technique depends on the independent occurrence of deep fading in diversity branches [8]. Another important factor is the average Signal-to-Noise Ratio (SNR) in each diversity branch. It is shown in [16] that the imbalance power in diversity branches leads to lower overall diversity gain. Another important factor is the combining method by which the signals in the two branches are combined. A wide and comprehensive analysis of different diversity schemes including selection, equal gain and maximal ratio is accomplished in [17] by 924 measurements. It derives an experimental equation for diversity gain for equal gain combiner as a function of input power difference and signals cross correlation, as below:

$$G = -8.98 + 15.22\exp(-0.2\rho - 0.04\Delta) \tag{6}$$

where *G* stands for the diversity gain and Δ represents the mean input signal level difference and ρ is the cross correlation coefficient between input signals. The diversity gain for equal gain combiner as a function of correlation coefficient and signal power differences has been shown in Fig. 3. This plot shows an equal gain combiner can achieve up to 5.5 dB diversity gain when the mean levels of the signals from the two branches are equal and the correlation between them is zero. In the case of high correlated input with equal power, the system reaches 3 dB gain. However, when the amplitude of one channel is much lower than other one, diversity gain falls to less than -2 dB even in case of uncorrelated inputs. This shows that a low power branch can corrupt the performance of a higher one.

In this paper, the correlation coefficient between received signals in each diversity branches along with their average SNR are measured to evaluate their combination performance. In addition, the final diversity gain achieved in each structure is quantified.

VI. TEST SETUP AND EXPERIMENTAL RESULTS

In order to achieve the objectives of this work, three data sets in two different indoor locations were collected. The data collection specification is addressed in Table I. Each data set consisted of three consecutive data collection with different diversity schemes including spatial, circular polarization (CP) and linear polarization (LP) structures. In each case, the diversity branches output along with a reference antenna were connected to a synchronized triple port down-converter/digitizer to collect synchronous raw IF samples in GPS L1 band for all inputs.

The reference antenna was located in an un-obstructed view of the sky and within 30 m of the indoor diversity structures. It has been used to remove the navigation data bit from the received signal to increase the coherent integration time up to 100 ms. The spatial diversity scheme were consisted of two RHCP GPS L1 antenna spaced apart 1.5 wavelength (30 cm). Commercial dual polarized antennas were utilized to create polarization diversity structures. One of them includes RHCP and LHCP GPS L1 signal antenna and the other one consists of two orthogonal linear GPS L1 antennas named horizontal and vertical.

TABLE I. THE DATA SETS AND SELECTED VEHICLE SATELLITES FOR EACH OF THEM

Set#	Date	Location	Diversity scheme	Start time	Selected SV's
1	22Oct2009	Energy high Bay	CP	3:27 p.m.	2, 4, 12
			LP	3:42 p.m.	2, 4, 12
			Spatial	4:05 p.m.	2, 4, 12
2	4Dec2009	ICT corridor	CP	9:20 p.m.	31
			Spatial	9:29 p.m.	31
			LP	9:37 p.m.	31
3	7Dec2009	Energy high Bay	CP	11:43 a.m.	2, 12, 30
			LP	11:56 a.m.	2, 12, 30
			Spatial	12:08 p.m.	2, 12, 30

The indoor antennas were mounted on a linear motion table to model moving scatters in an indoor GNSS channel. The table traversed a 2.8 m (2x1.4 m) distance in each lap. The table speed was chosen 2 cm/s for 100 ms pre-integration time to guarantee that more than 99% of the signal remains unaliased or within the Nyquist interval [18].

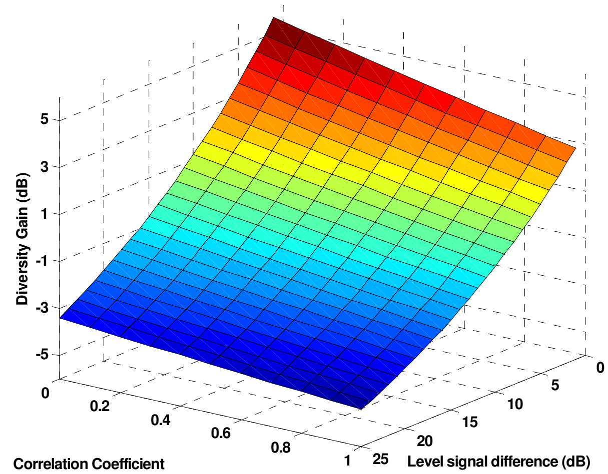

Figure 3. Diversity gain as a function of input signals cross correlation and difference in mean power

Figure 4. Energy High Bay in CCIT building, University of Calgary

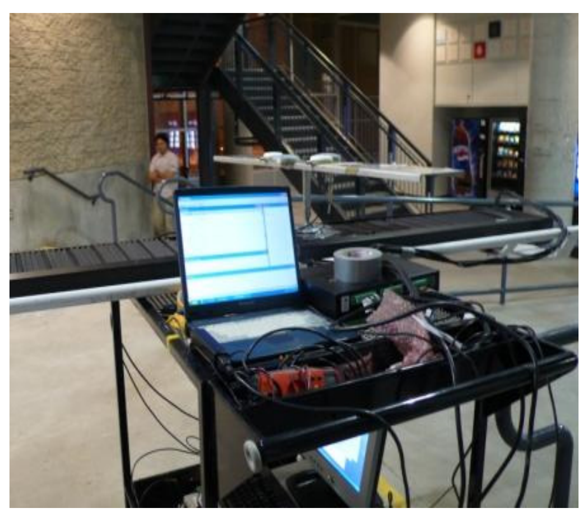

Figure 5. ICT corridor, spatial diversity structure

The first and third data set collections were performed in a laboratory with a high metallic ceiling called Energy High Bay at the CCIT building in the University of Calgary shown in Fig. 4. The former one was started at 3:20 p.m. on 22 October 2009 and the latter one collected at 11:40 a.m. on 7 December 2009. The second data set was carried out in corridor of a building encompassed with large window pans in both south and north direction and concrete ceiling as shown in Fig. 5. This one has been performed at 4:10 p.m. on 4 December 2009. These data collections last roughly 45 minutes and were consisted of three consecutive data collection with various diversity structures. According to their corresponding sky-plots, appropriate GPS satellite vehicles are selected from each data collection tabulated in Table I.

A. *Experimental results*

1) Channel Measurement: In Fig. 6 fitted Rician and Rayleigh distributions on measured signal amplitudes for linear polarized antennas (vertical and horizontal) are plotted. In this figures, the *K* factor for Rician distributions are close to zero and it can be seen that the Ricin distribution roughly overlap the Rayleigh one. In addition, TableII shows the estimated *K* factors for all selected satellites. As discussed, the small *K* factor represents Rayleigh fading distribution and, hence, the estimator correlator combining method can be considered as an optimum detection approach.

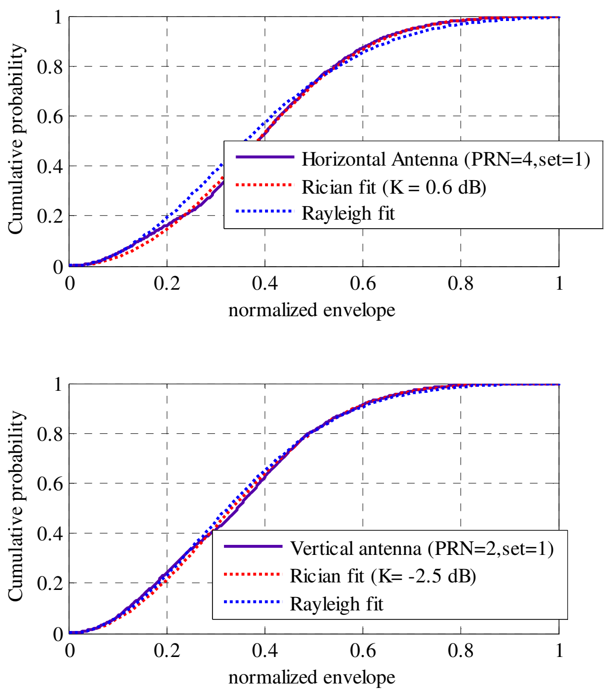

Figure 6. Cumulative probability of received signals and fitted Rician Rayleigh distribution on them

TABLE II. THE K FACTOR FOR RECEIVED SIGNALS IN INDOOR SITUATION

PRN# (set#)	K factor (dB)					
	RHCP	*LHCP*	*Vertical*	*Horizontal*	*RHCP1*	*RHCP2*
2(1)	-66	-9.6	-2.4	-62	-64	-60
4(1)	-3.8	-0.64	-42	0.64	-3.8	-1.4
12(1)	-60	-4.7	-44	-52	-11	-3.7
31(2)	-3	-2.2	-61	-57	-67	1.88
2(3)	-59	-63	-6	-59	-60	-58
12(3)	-63	-48	-5	-58	-60	-52
30(3)	-14	0	0.5	-0.46	-7.7	-17

2) Correlation Coefficient: Herein complex correlation coefficient between received signals in each diversity branches is considered and empiricaly evaluated. Fig. 7 shows the absolute value of complex correlation coefficient quantified as below:

$$\rho_c = \left| \frac{E\left[V_1 V_2^*\right]}{\sqrt{E\left[V_1 V_1^*\right] E\left[V_2 V_2^*\right]}} \right| \tag{7}$$

where $E[]$ stands for the expected value operator, * is complex conjugate operator and V_1 and V_2 are zero mean complex values of the correlator output of each branch.

As shown in Fig. 7, in the spatial diversity case the correlation coefficient value may lead up to 0.35 under some circumstances. However, the polarization diversity structures, both circular and linear one, hold very low correlation coefficients (less than 0.1). Higher correlation coefficient in spatial diversity may result in lower diversity gain. However, for correlation coefficients lower than 0.5 the processing loss of utilizing Equal Gain (EG) over estimator correlator is negligible.

3) Average input SNR: As discussed, the average input SNR play a crucial role in the efficiency of a diversity system. Here, the average input SNR is quantified as below [15]:

$$SNR_{ave} = \frac{E\left[x^2\right]\Big|_{H_1}}{E\left[x^2\right]\Big|_{H_0}} - 1 \tag{8}$$

where x is the input signal envelope and H_1 and H_0 stands for the binary hypothesis test conditions in the design of the detection algorithm.

The average input SNR for different diversity structures are shown in the Fig. 8. According to these plots, the circular polarization and spatial diversity systems comprise of equal input powers in different branches, whereas the linear polarization diversity carries the highest level of SNR difference among the rest of the systems. As disscused earlier, the unequal average power in received signals by two orthogonal linear antennas can lead to lower diversity gain in this structure rather than the spatial and circular polarization systems.

4) Detection performance: Having analysed the probability distribution function (PDF) of each individual branch and the combined signal under H_0 and H_1, the ROC curves can be plotted using a threshold as an intermediate variable [14].

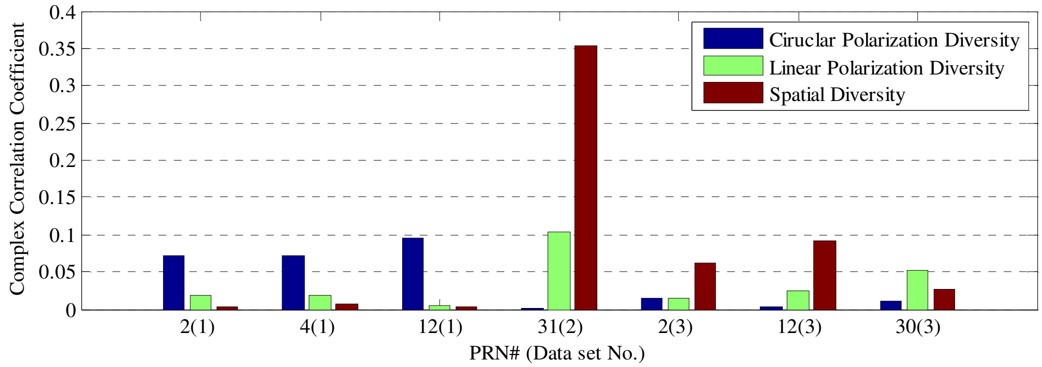

Figure 7. The correlation coefficient between received signals

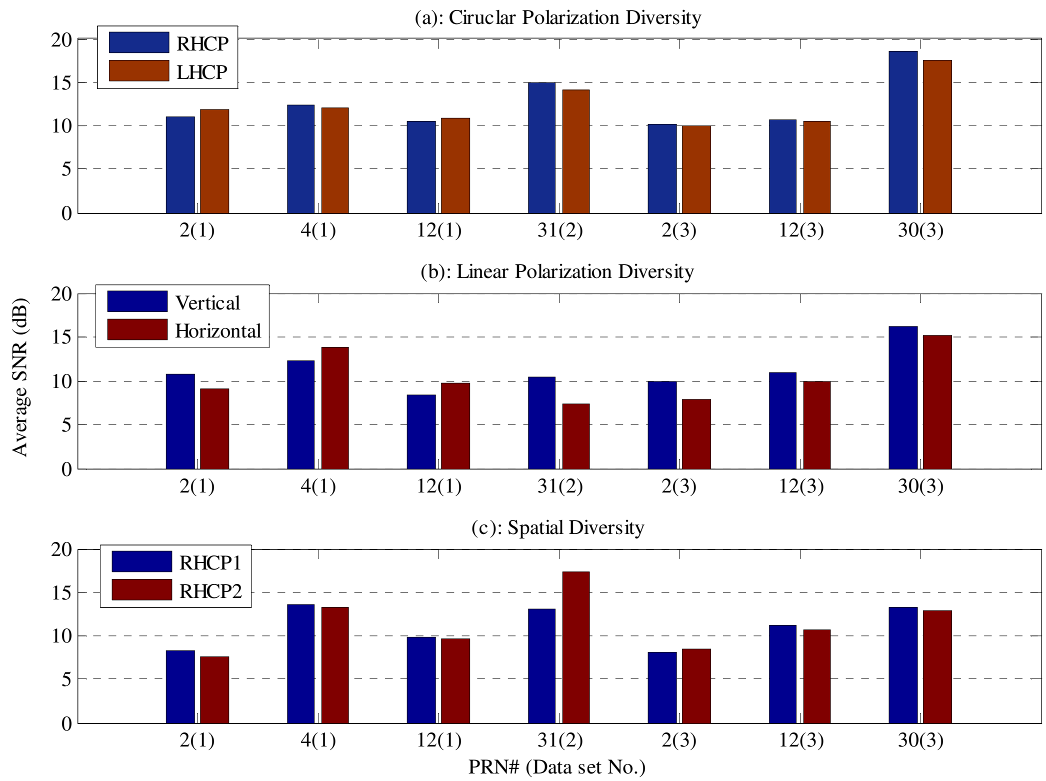

Figure 8. Average input SNR

Fig. 9 shows the probability of detection of all selected satellites for each diversity system at a specific probability of false alarm (P_{fa}=0.01). The probability of detection specifies the input branches efficiency. As shown, the polarization and the spatial diversity systems utilizing circular polarized antenna have higher detection perfronace than the polarization diversity utilizing the linear polarized antenna. This is due to the existance of unequal received signal power at different diversity branches of linear polarized system and it can lead to lower overal diversity gain in this structure.

5) Diversity Gain: The diversity gain for a specific design point is quantified as reduction in the input average SNR utilizing a diversity system based on discussions in [9]. The measured diversity gains for different diversity systems are plotted in Fig. 10. Here, the diversity gain is measured for the probability of false alarm equals to 0.01. The average diversity gain for CP, LP and spatial structure is 4.3 dB, 2.6 dB and 3.25 dB respectively. As seen from the graph, the circular polarization leads to higher diversity gain (up to 6.3 dB) and consequently higher performance in overall. According to the provided analyses, the lower correlation coefficient between two RHCP and LHCP received signal rather than two RHCP ones in spatial diversity can justify the higher performance in circular polarization diversity. In addition, since in indoor environments the GNSS signal is reshaped to a elliptically polarized wave, a circular polarization diversity employes the advantages of LHCP waves to improve the detectability of GNSS signals.

On the other hand, power level difference in linear polarization system branches, caused lower overal diversity gain in such system. The interesting observation is the negetive diversity gain for PRN 31 in third data set. As it can be seen from Fig. 9 as well, a very low performance brach (horizontal antenna one) in this structure has led to a lower probability of detection for combined signal compared to the received signal via vertical antenna.

VII. CONCLUSION

This paper examined and compared the detection performance of the spatial and the polarization diversity structures in the same environment for indoor GPS signal. According to the experimental results, the correlation coefficient between received signals in polarization diversity systems was sufficiently low, while this value for spatial diversity was considerable under some circumstances. In addition, received signal power level for different diversity systems was measured. Experimental results showed that the signal level difference received by two antennas in a diversity system utilizing the circular polarized antenna is negligible whereas, these values are significant in a polarization diversity system using a dual linear polarized antenna. By combing signals using the equal gain combiner, the diversity gain was quantified. In overall, all of the diversity formations led to a significant diversity gain; however, as expected from the provided correlation coefficient and the average input SNR analyses, the circular polarization diversity resulted in highest diversity gain among other structures.

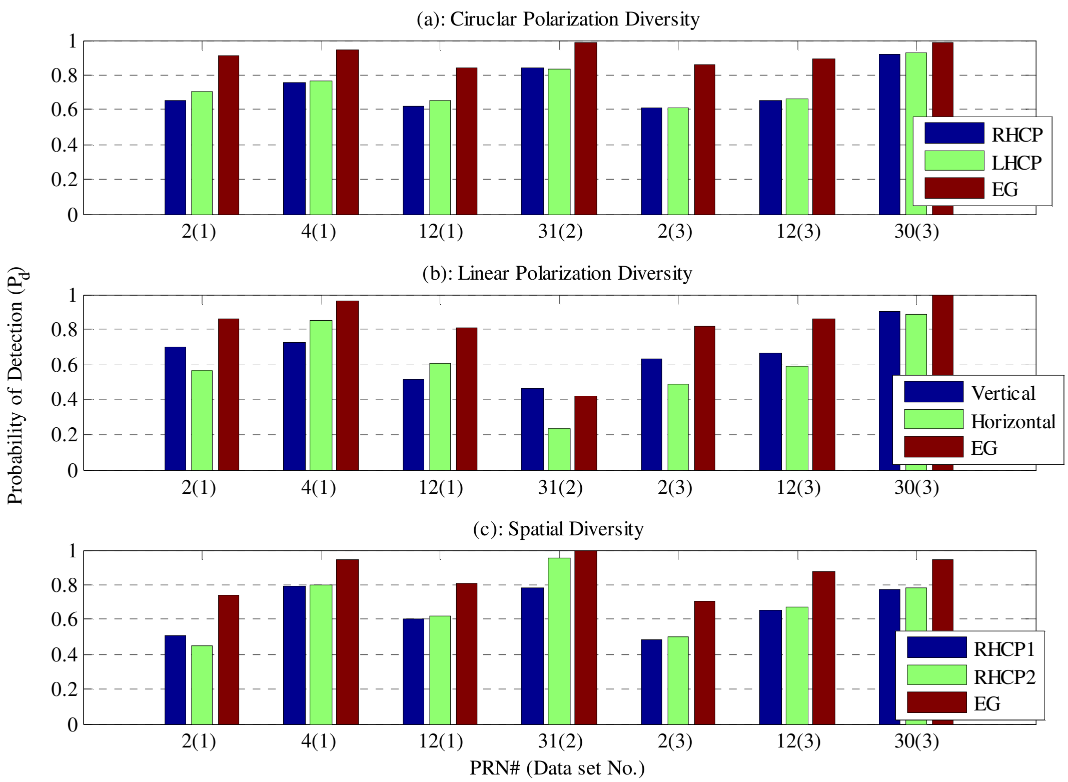

Figure 9. Probability of detection for various diversity schemes in P_{fa}=0.01

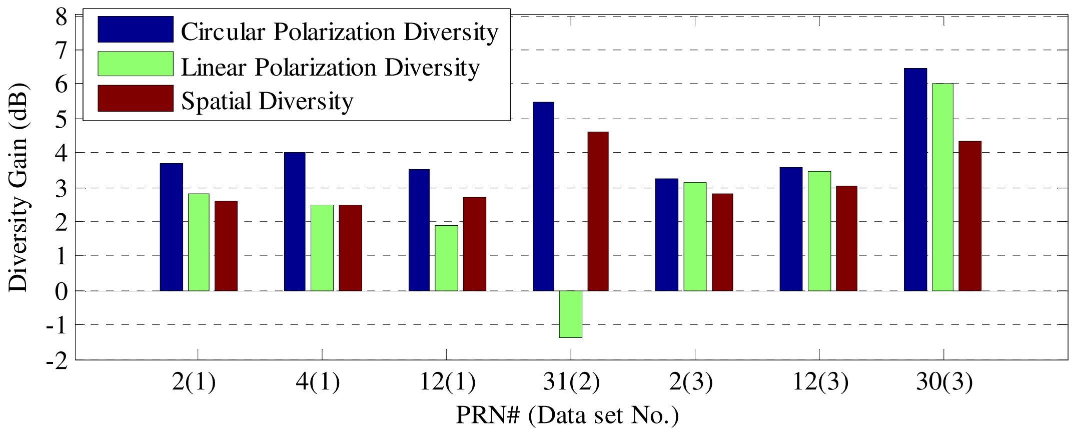

Figure 10. Diversity gain for various diversity schemes

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