Enhanced GNSS Indoor Signal Detectability Using Polarization Diversity

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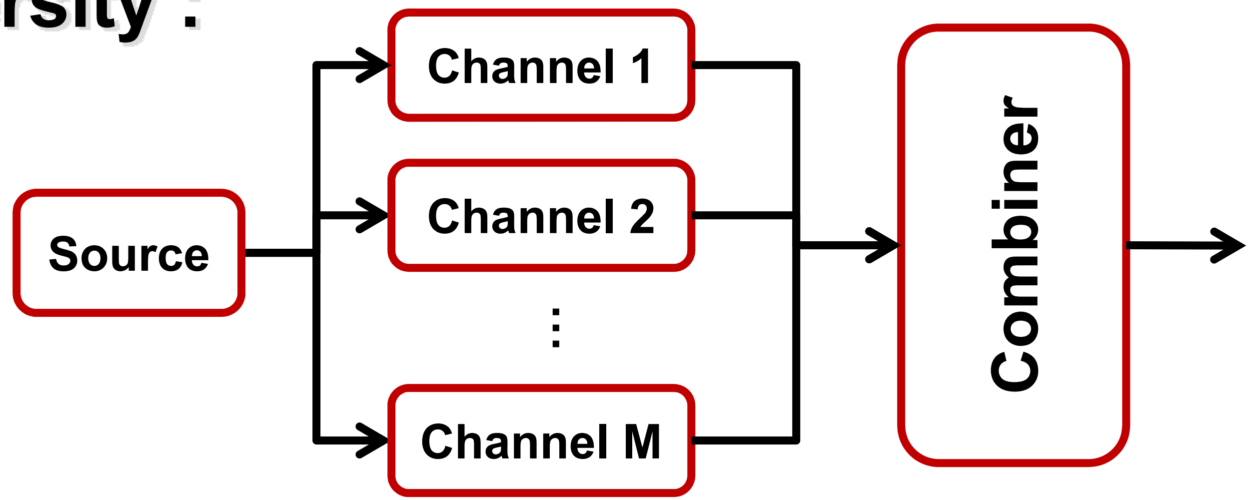
Motivation

- Indoor positioning with GNSS signals poses many challenges
  - Attenuation – up to 30 dB or more – difficult to *detect* signals
  - Multipath and fading – significant errors in range measurements
- Can energy from extra paths be used to enhance detectability?
- Diversity schemes utilize multiple independent channels to enhance performance
  - Detectability, bit-error rate, etc

Diversity

- When information reaches a receiver through multiple transmission channels:
  - Can combine information from each channel to improve system performance
  - Improvement is maximised when channels are independent
- Forms of diversity :
  - Frequency
  - Spatial
  - Multipath
  - Polarization

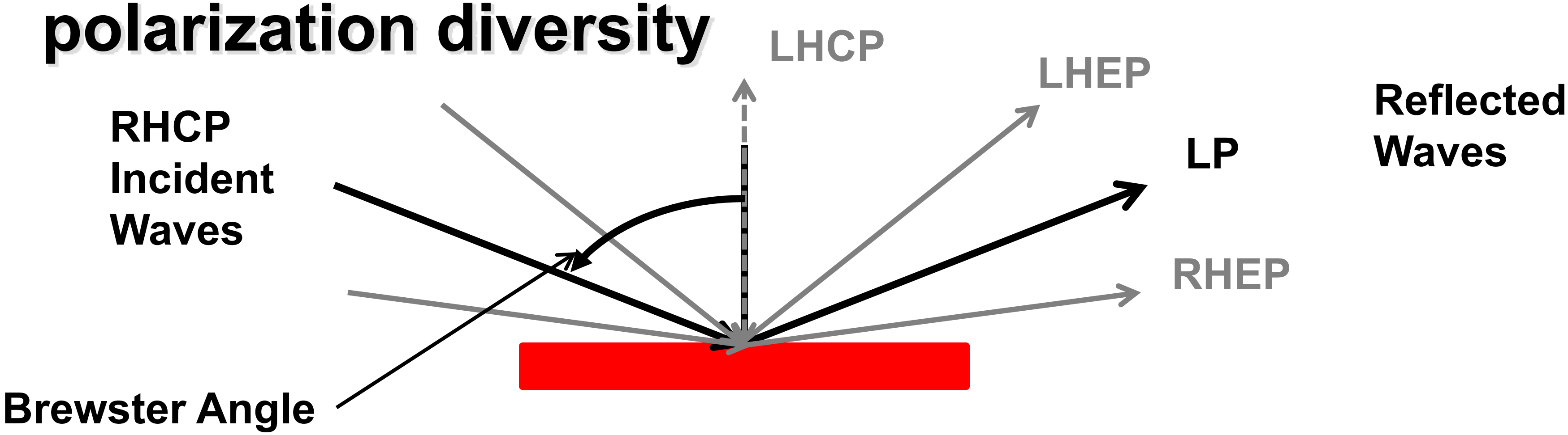


Combining Schemes

- Diversity gives us multiple sources of information
  - How to combine these sources ?
- For optimal detection – optimal combining implements the Likelihood Ratio Test (LRT)
  - May be computationally expensive
  - May not be obtainable in closed form
- Sub-optimal combining
  - Equal gain combining – weight all sources equally
  - Selection Combining – Choose “best” source in each epoch

GNSS Signal Polarization

- GNSS signals are Right Hand Circularly Polarized (RHCP) at transmission
- Polarization changes upon reflection
  - Reflected signals contain both RHCP and Left Hand Circularly Polarized (LHCP) components
  - Elliptical Polarization (RHEP, LHEP)
- Reflections introduce both multipath and polarization diversity



Polarization Diversity

- Requires a dual polarized antenna
  - Same form factor as typical RHCP antenna – advantage with respect to spatial diversity
  - Increased processing load due to second data stream
- Requires multipath
  - No benefit in LOS only conditions
- Does not require any modifications at transmission

Indoor Channel Model

- **Indoor channel is modelled as consisting of many reflectors**
- **Received signal is the complex sum of all reflections**
  - **With sufficiently large number of reflectors – invoke central limit theorem to model signal as Gaussian**

$$x \sim N(\mu_s, \sigma_s^2)$$

  - **The RHCP and LHCP signals are modeled as jointly Gaussian**

$$\mathbf{x} = \left[x_{RHCP}, x_{LHCP}\right]^T \sim N\left(\boldsymbol{\mu}_s, \mathbf{C}_s\right)$$

Signal Envelopes

- **If the signal is zero mean the envelope will have a Rayleigh distribution**

$$p_{|x|}(r) = \frac{r}{\sigma_s^2} \exp\left(-\frac{r^2}{2\sigma_s^2}\right)$$

- **For a non-zero mean signal the envelope is Rician**

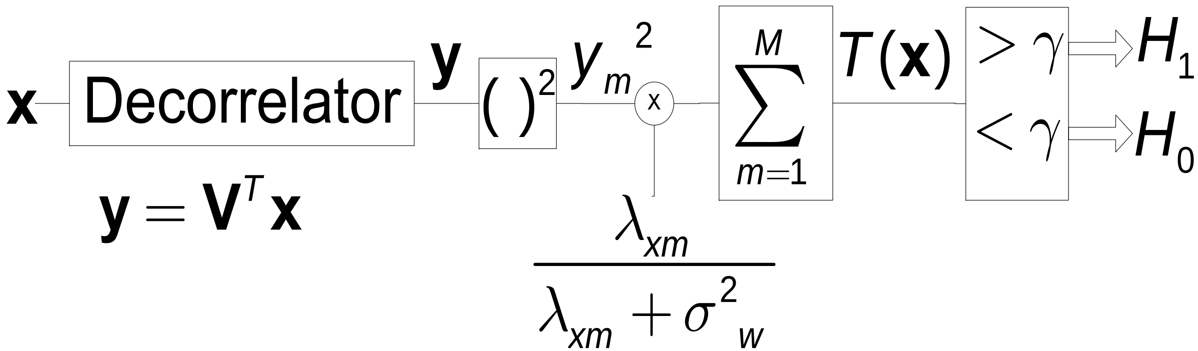
$$p_{|x|}(r) = \frac{r}{\sigma_s^2} \exp\left(-\frac{r^2 + |\mu_s|^2}{2\sigma_s^2}\right) I_0\left(\frac{r|\mu_s|}{\sigma_s^2}\right)$$

- **The K Factor is a measure of the “Rician-ness” of the distribution**

$$K = 10\log\frac{|\mu_s|^2}{2\sigma_s^2} dB$$

Optimal Combining

- **Zero-mean case (Rayleigh envelope) → LRT takes form of Estimator Correlator (EC)**

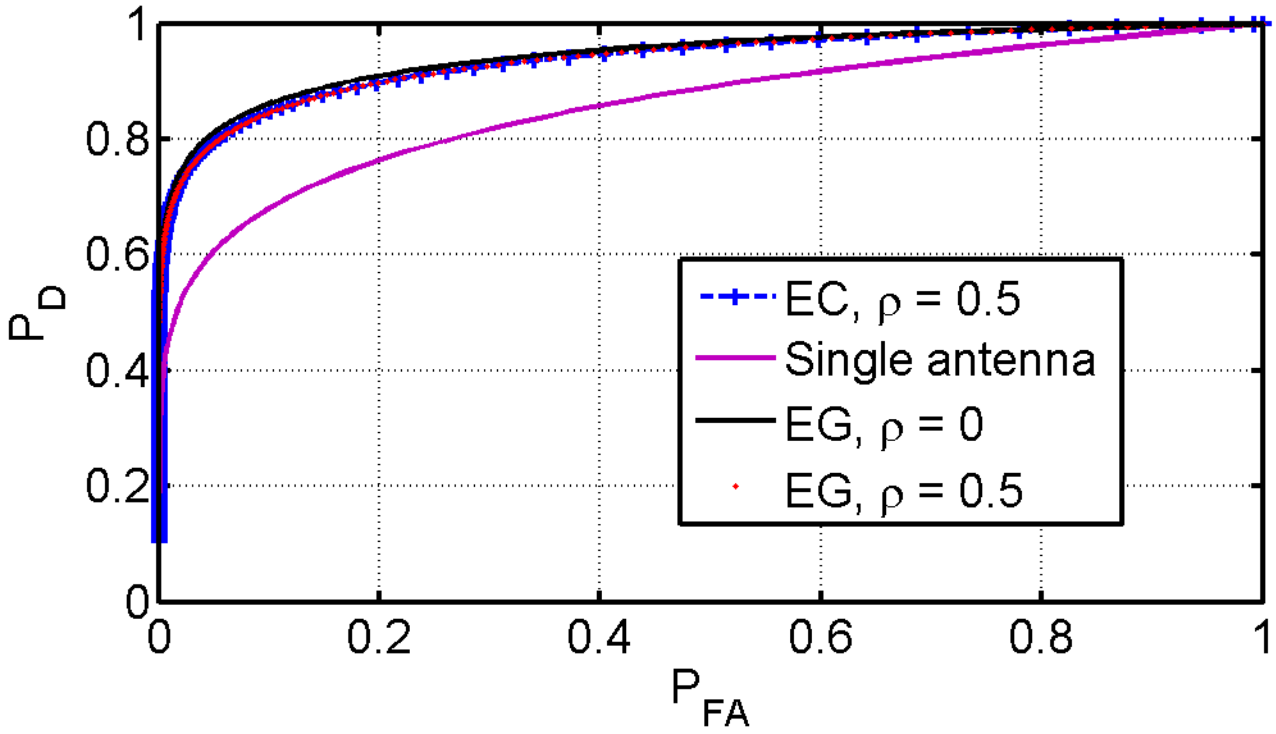


- **For independent channels – this becomes the Equal Gain Combiner (EGC)**

$$T(x) = \left|x_{LHCP}\right|^2 + \left|x_{RHCP}\right|^2$$

Impact of Channel Correlation

- Gaussian Signal : Correlation ⇔ Dependence
- Impact of non-zero correlation RHCP & LHCP?

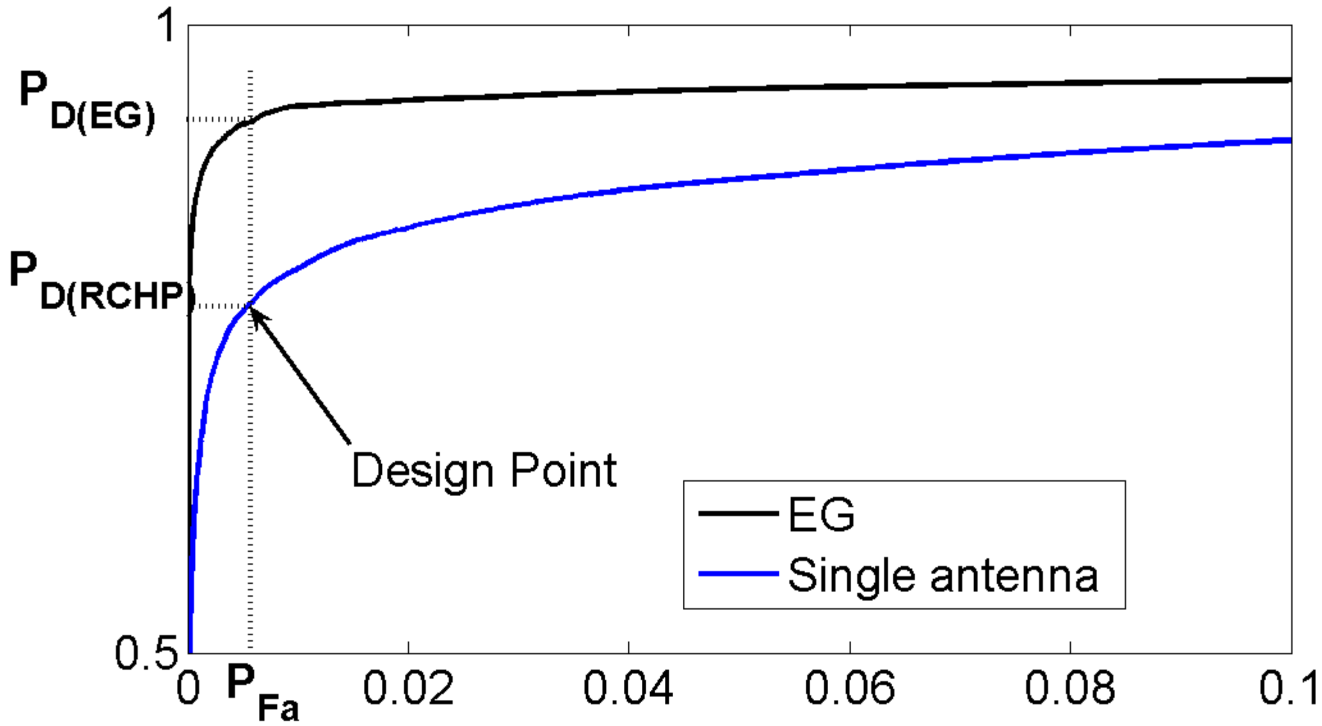


- Correlation has little impact

Quantifying Diversity Gain

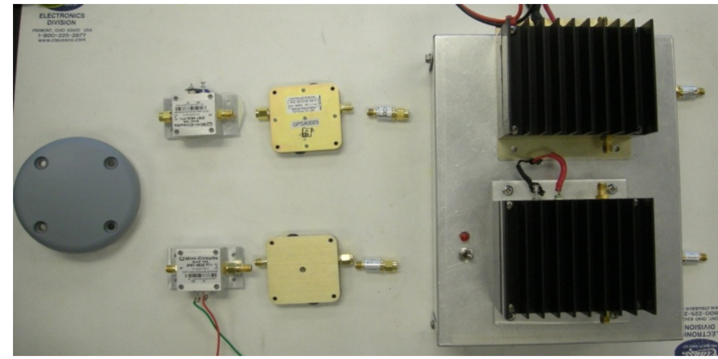
- **<u>Definition:</u> Diversity Gain – Ratio of input SNRs required to achieve same design point**

$$G = \frac{SNR_{RHCP}}{SNR_{EG}}$$

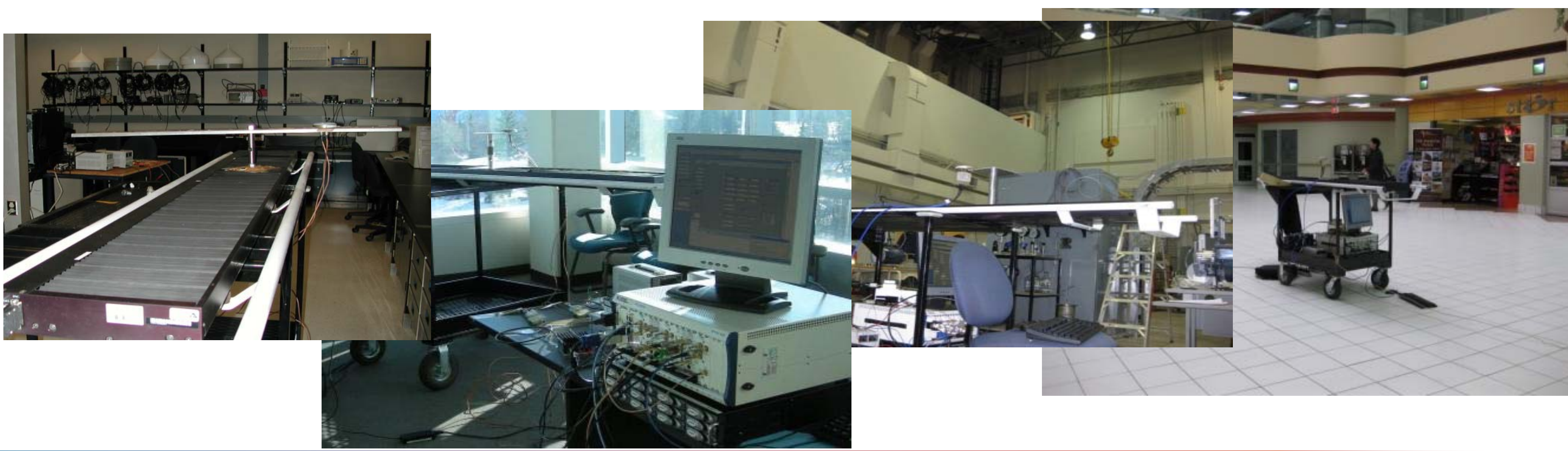


Experimental Setup

- Raw IF data collected in 4 indoor environments
  - Research Lab
  - Meeting room
  - Engineering high bay
  - Student centre



- Antenna mounted on linear motion table



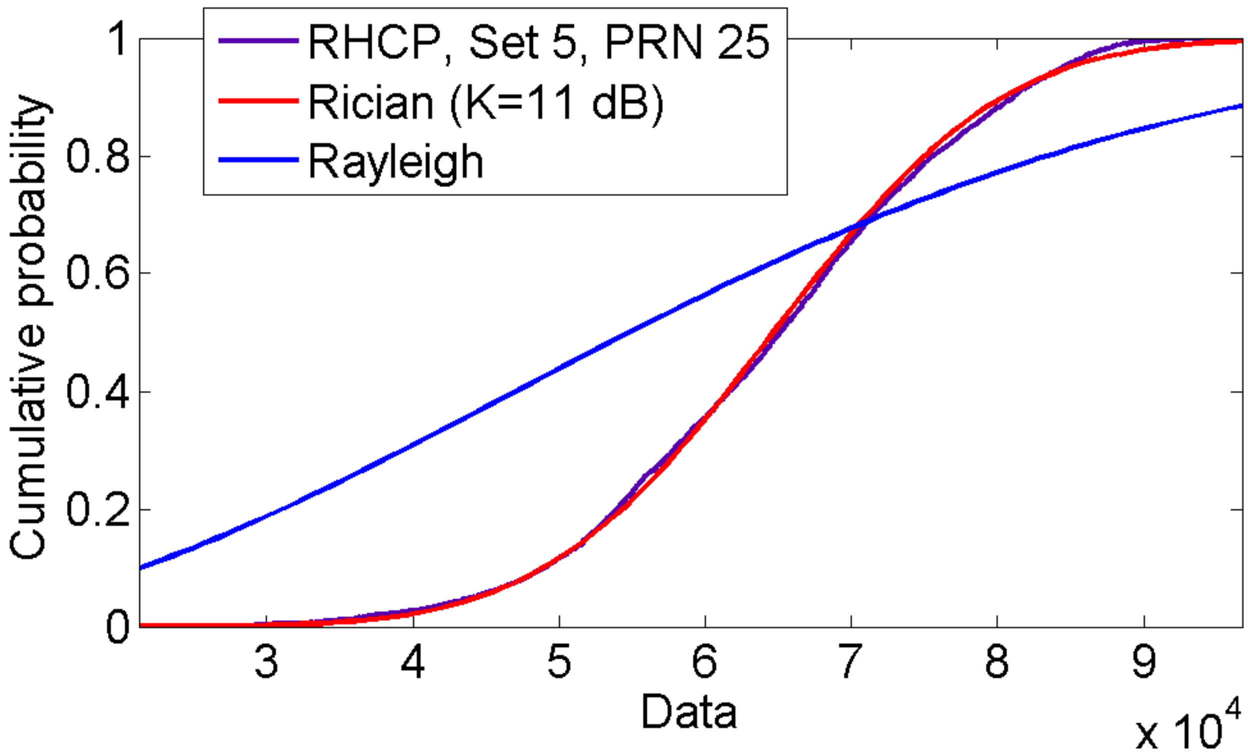
Processing Strategy

- Reference antenna used to provide aiding
  - Doppler, data bits, code phase
- Raw measurement vector given by correlator outputs with 100 ms coherent integration
- Reference used to determine signal parameters (H_1 bin) – extraction of statistics
- Both single antenna and EGC strategies implemented

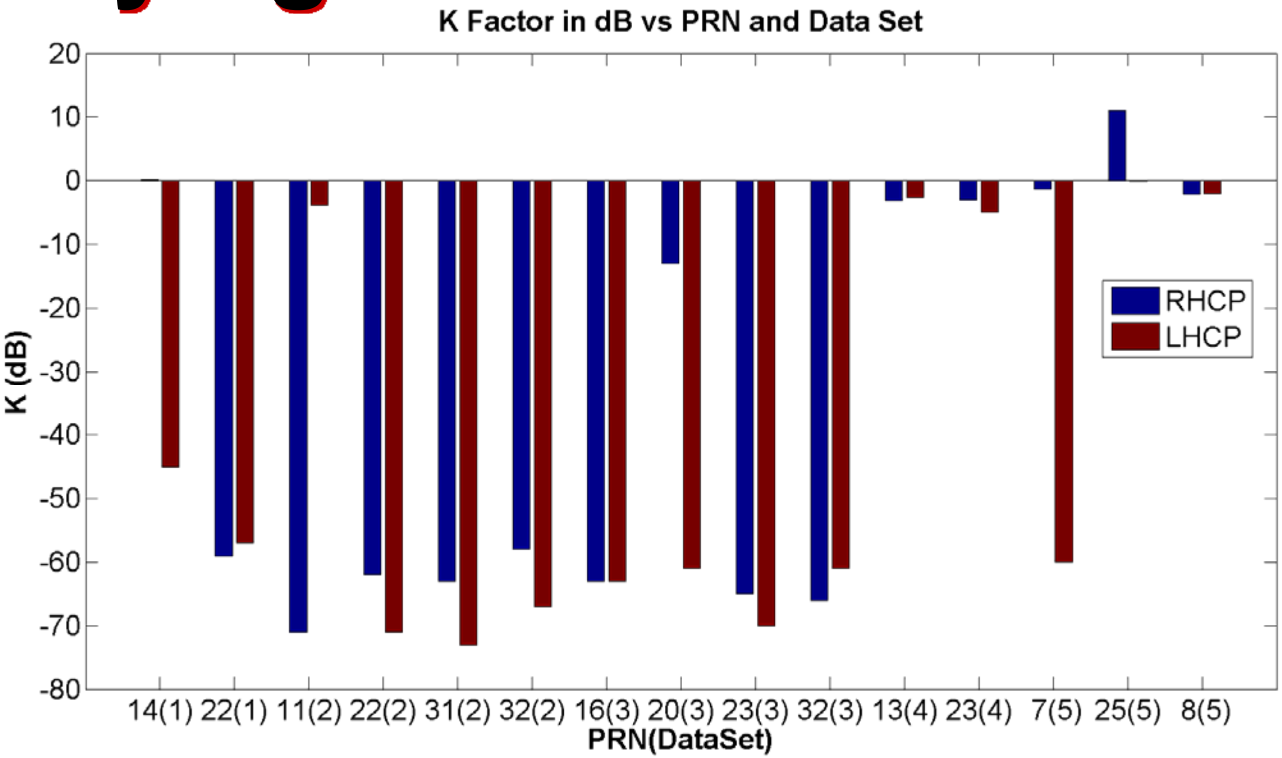
PLAN

Verifying the Channel Model I/II

- **Empirical distributions of H_1 correlator output for two different PRNs shown below**

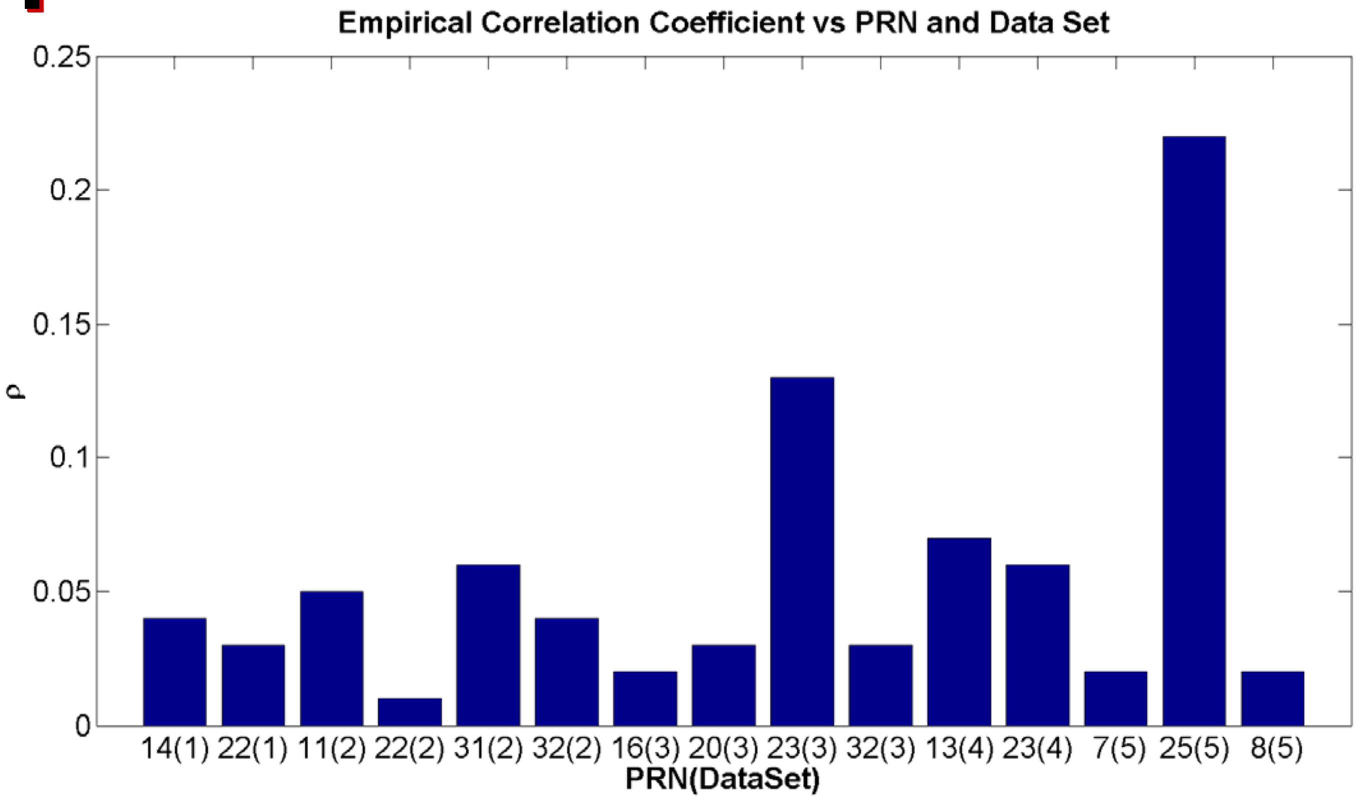


Verifying the Channel Model II/II



- Rayleigh fading model holds in majority of cases
- Some cases are Rician – dominant component
- PRN 25 in set 5 is most striking example
  - Illustrated on previous slide

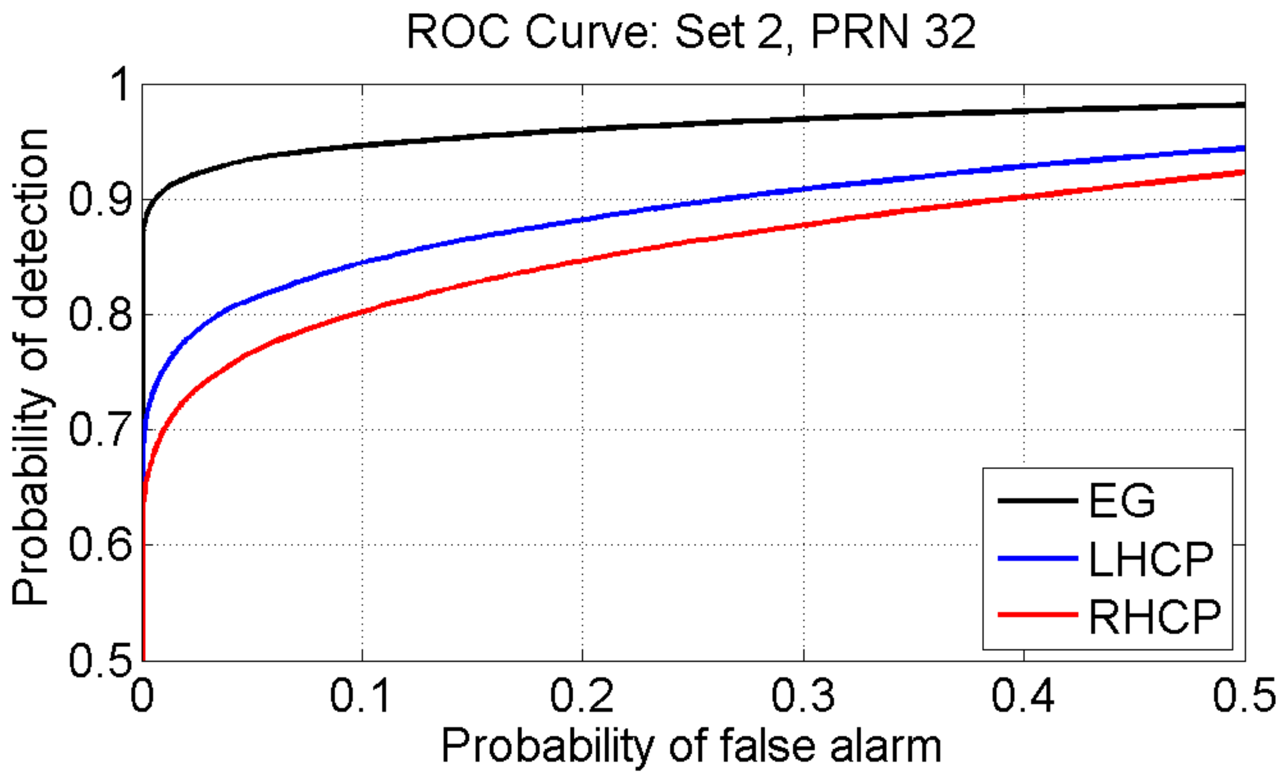
Empirical Correlation Coefficients



- **Correlation coefficients low in general**
- **Maximum of 0.22**
  - **PRN 25, set 5 again**
- **Indicates that EGC should work well**

Empirical ROC Curves

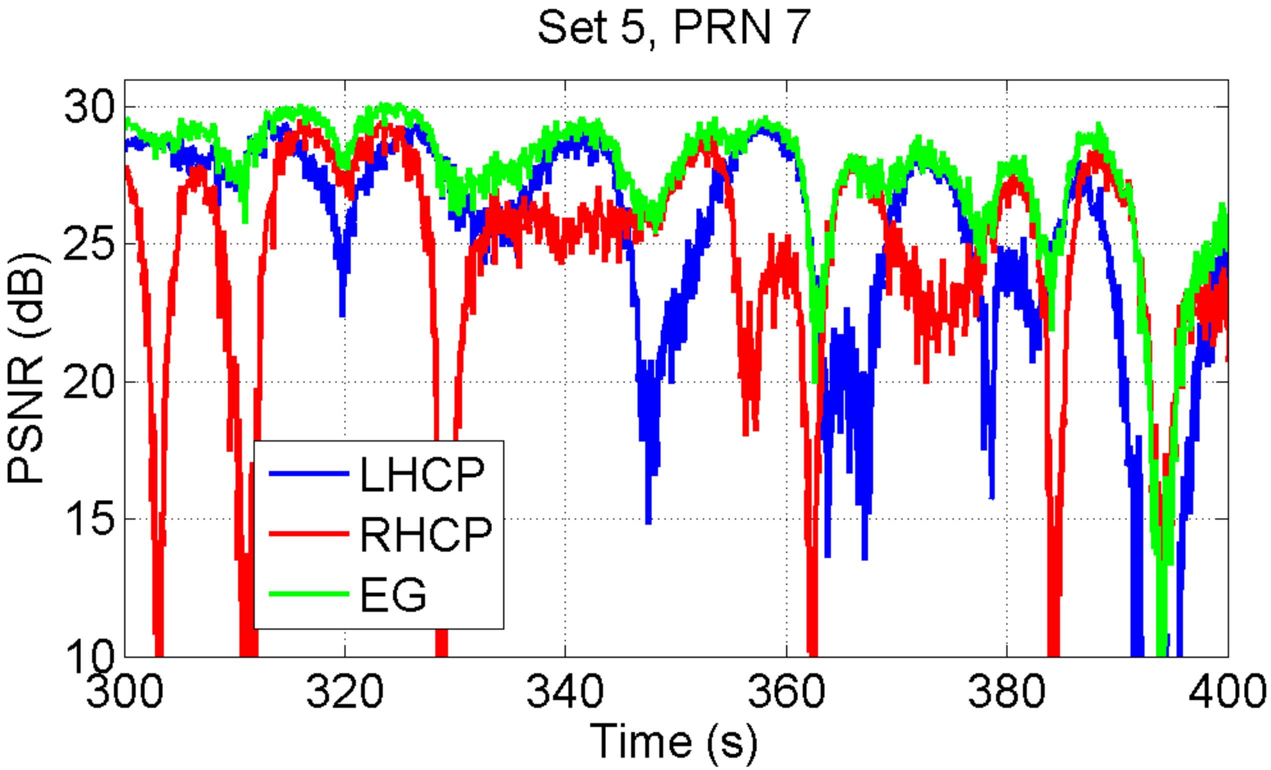
- Receiver Operating Characteristic (ROC) Curve
  - P_d vs P_{FA} – completely determines performance



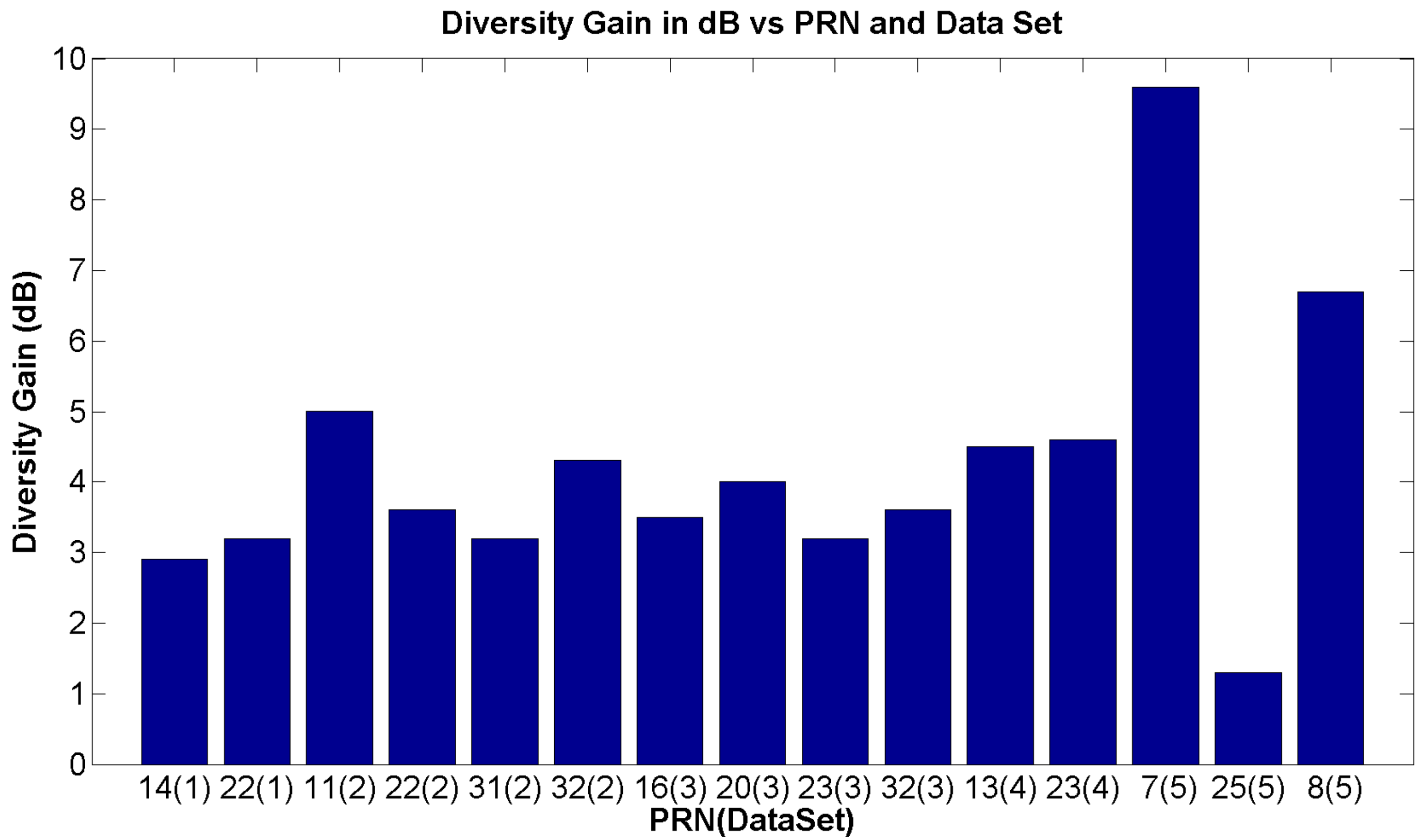
Fading and the Decision Statistic

- **Post-Detection SNR : good indicator of impact of fading**

$$\text{PSNR} = \frac{\left(E[T;H_1] - E[T;H_0]\right)^2}{\text{var}[T;H_0]}$$



Empirical Diversity Gain



- **Diversity gain in the region of 1 – 10 dB**
- **Caveat: a single number is not sufficient to describe benefits of combining**

Conclusions and Future Work

- The dynamic indoor GNSS channel can be modelled by Rayleigh fading
- Left and Right hand circularly polarized signals provide a form of reception diversity
- Equal gain combining is sufficient to provide increased detection performance
  - Simple structure – works reasonably well even when underlying assumptions are not exactly met

- Future work :
  - Investigation of impact on navigation – pseudorange error modelling