Analysis of the existing methods for GNSS integrity: how local effects can be characterized and included in the PL evaluation in specific land applications?

**Sabrina Ugazio and Letizia Lo Presti**

Department of Electronics e Telecommunications
Politecnico di Torino
• Motivations

• **Local effects**: an outline

• Local effects *detection and mitigation*: some *possible approaches*

• **Local effects**: how can they be included in the *PL* evaluation?

• Conclusions
Motivations

• **Reliability critical** applications (E.g. congestion management, GNSS-based road tolling, pay-as-you-drive insurance) increasing importance

→ **Integrity** requirements

• Need of **low-cost/autonomous** methods for integrity monitoring in **harsh environment** (such as urban canyon), in the presence of:
  - LOS signal affected by **multipath**
  - NLOS signals
  - unintentional interference
  - spoofing
Motivations

• **GNSS integrity** is an issue involving a wide gamma of problems that may occur in the GNSS, including:

  - GNSS signal errors and distortions
  - Atmospheric effects (ionosphere, troposphere) and bit errors
  - Local effects
    - environmental effects (multipath and NLOS)
    - unintentional interference
    - spoofing
  - Input data errors (antenna phase centers, earth orientation parameters, satellite maneuver descriptions)
  - Operator and maintainer errors
  - Software design flaws (data corruption) and algorithm inadequacies
  - User receiver and antenna faults and errors (hardware, and software):
    - antenna bias, “unobservable” or partially observable measurement biases, memory faults, data corruption, cycle slips
Local effects and possible countermeasures: an outline

• Multipath and NLOS signals (depend on the satellite)
  → signal quality monitoring
  → consistency check between different sets of satellites
• Interference (affects all the satellites)
• Intentional attacks: spoofing and jamming (affects all the satellites, fake position or blinded receiver)

Moreover:

• Receiver failures
  → Consistency check between different receivers
Local effects detection and mitigation: methods overview

- Signal quality monitoring
  - multi-correlator techniques
  - strobe correlator
  - the double-delta correlator
  - Multipath Estimating Delay Lock Loop (MEDLL)
  - ...

- RAIM
  - Integrity monitoring at the position level

→ satellite exclusion
Local effects detection and mitigation: examples of some possible approaches:

- Linear Adaptive Filters (LAFs) applied to MP and NLOS detection
- Multipath Distance Detection Algorithm (MDDA)
- NLOS propagation model and detection threshold

Goal: characterize and include local effects in the PL evaluation, properly for different land applications
Multipath: a dominant error source in Global Navigation Satellite System (GNSS)

- Multipath channel: weighted sum of signal delayed replicas

→ FIR, Linear Adaptive Filters (LAFs) look suitable

- Post-correlation signal → computational simplification

BUT

- LAFs hypothesis: Additive White Gaussian Noise (AWGN)
- Post correlation GNSS signal: affected by correlated noise
Focus: multipath channel

Land users → multipath is a major issue, in particular in urban environment

**Multipath channel**: can be modeled as a FIR filter: the received signal is the sum of replicas of the transmitted signal, with different delay and power.

Multipath channel model in the **discrete-time domain**:

\[ h_c[n] = h_c(nT_s) = \sum_{k=0}^{M-1} \beta_k \delta[n - k] \]

where only multipath delays of type \( \tau_k = kT_s \) can be represented.
• Delay Lock Loop (DLL): close loop system – **null seeker**

Hypothesis: **correlation peak symmetry**

Used to refine the delay estimate performed in the acquisition stage.

The correlation evaluated by a DLL is, in presence of noise and multipath:

\[
R_{DLL}(mT_s) = \sum_{k=0}^{M-1} \beta_k R(mT_s + kT_s) + w_R(mT_s)
\]

**IDEAL CORRELATION FUNCTION**

Ideally zero outside the time interval \((-T_C, T_C)\) around the peak

**NOISE COMPONENT**

Resulting from the correlation between the noisy incoming signal (after carrier wipe-off) and the local code
Linear Adaptive Filters [1]

A measured signal $d[n]$ is estimated as weighted sum of delayed replicas of an ideal input signal. A Linear Adaptive Filter **adapts the coefficients** of a **FIR** filter to **minimize** the residual error $e[n]$.

Basic principles

FIR coefficients
\[ \hat{w} = \phi^{-1} \Theta \]

Simulation:
- Ideal case NO NOISE
- 1 MP
  - delay = 0.2 T\(_C\)
  - \( P_{MP\,db} = P_{LOS\,db} - 6\,dB \)

As an effect of the sampling resolution, a multipath contribution may be estimated as the sum of two lower contributions around the true multipath delay.
LAF threshold method for multipath detection

Given the possible scenarios some conditions can be applied in order to detect the LOS delay:

- The FIR coefficient corresponding to the LOS has same sign as the correlation function $d[n]$ (or $y[n]$):
  \[
  \text{sign}(\hat{w}_{LOS}) = \text{sign}(y[n])
  \]

- LOS is in a limited interval around the peak of $d[n]$ (or $y[n]$):
  \[
  |\hat{\tau}_{LOS}| < \tau_{th}
  \]

- LOS corresponds to a coefficient which absolute value is above a fixed threshold
  \[
  |\hat{w}_{LOS}| > th_w
  \]

Simulation results

\[ \tau_{TRUE} = 0.2T_C \]

- 1 MP
  - \( \tau_{MP} = \tau_{LOS} + 0.2T_C \)
  - \( P_{MP} = P_{LOS} \)
  - NO NOISE

Contribution to \( y \)

FIR coefficients \( \hat{w} \)
Simulation results

- $\tau_{\text{TRUE}} = 0.2 T_C$
- 1 MP
- $\tau_{\text{MP}} = \tau_{\text{LOS}} + 0.2 T_C$
- $P_{\text{MP}} = P_{\text{LOS}}$
- $C/N_0 = 50 \text{ d BHHz}$
Multipath Distance Detector (MPDD) algorithm

- The length of the filter is $M$, so there are $M$ basis signals.

- The idea is to work at level of the tracking stage, after the demodulation, when the correlation between local signal and incoming one is computed.

- Basis signals are a set of ideal correlations delayed from 0 to $M-1$ samples. They are weighted, summed to represent the measured correlation.

- The presence of the noise may significantly change the behavior of the coefficients of the filter.

Multipath Distance Detector (MPDD) algorithm

- The correlation are collected in time and a moving average filter is implemented and applied in order to reduce the noise.
- The output of moving average filter is decomposed by the LAF.
- A dictionary of possible vectors containing several scenarios is created, included LOS case ($w_{LOS} = [1 \ 0 \ ... \ 0 \ 0]$).
- We calculate the distance between $w$ and the sample vectors in a dictionary and find which one is at minimum distance $d_{min}$.
- NO multipath $\rightarrow$ means $d_{min} = \|w - w_{LOS}\|^2$. 
### Multipath Distance Detector (MPDD) algorithm

**Multicorrelator**
- Great time resolution

**Moving average filter**
- Reduced noise and computational load

**LAF**
- \( \hat{w} \) estimated with the LAF

**Decision Metric**
- \( E_{LOS} = \| \hat{w} - w_{LOS} \|^2 \)

- \( E_k = \| \hat{w} - w_k \|^2 \) where \( k = 1, 2, \ldots, N_v - 1 \)

- \( \min_k (E_k, E_{LOS}) \neq E_{LOS} \)
LAFs applied to MP and NLOS detection

final remarks

- LS filter applied to GNSS **multipath detection**
- Scenario with **no strict conditions** on multipath
- **Noise effects mitigation**

Possible developments:

- Analysis with Doppler frequency effects (**fading channel**)
- Simulation campaign and **statistical analysis** of the results
- Application to Receiver Autonomous Integrity Monitoring (**RAIM**)

Challenges for PL evaluation applications

- In order to get a less conservative solution, in very harsh environment (urban canyon) $\rightarrow$ satellite exclusion, multipath detection and mitigation
- Estimate of the bigger not detectable MP and set of a protection level
- Inclusion of the event probability in the fault tree
In very harsh environment, such as urban canyon, it is not unusual to get from a satellite only NLOS signals, being the LOS obstructed

• NLOS propagation model and detection threshold
• Hard to distinguish Non-Line Of Sight (NLOS) from Line Of Sight (LOS) GNSS signals

Fundamental to recognize NLOS signals for safety/reliability critical applications
NLOS propagation model

Focus: study of the probability that the received energy $E_s$ is above a detection threshold $\lambda$, being NLOS state. Such a situation is critical and is defined here as False Alarm Event:

$$P_{FA} = P(E_s > \lambda | \text{NLOS state})$$

The mathematical analysis was done in 2 steps:

- $P_{FA}$ study considering deterministic signal amplitude
- $P_{FA}$ study considering the signal amplitude statistical distribution

OBJECTIVE:

- applying the channel model
  
  $\Rightarrow$
  
  find $\lambda$ that gives the desired $P_{FA}$
In the blocked case, defining the Loo distribution as $f_{Loo,B}$, the average $P_{FA}$ for a value of signal amplitude is computed, from the PDF of $\nu$, as:

$$P_{FA} = \int_{\nu} Q_u \left( \sqrt{\frac{\nu^2 E_S}{\sigma^2}}, \sqrt{\frac{\nu}{\sigma^2}} \right) f_{Loo,B}(\nu) d\nu$$
The **multipath channel** can be modeled as a **FIR filter**: the received signal is the **sum of replicas** of the transmitted signal, with different **delay** and **power**.

In the **discrete-time domain**:

\[
    h_c[n] = h_c(nT_s) = \sum_{k=0}^{M-1} \beta_k \delta[n - k]
\]

where multipath delays of type \( \tau_k = kT_s \) are represented.

**In absence of LOS (NLOS)**, all the components are **multipath** signals.
Receiver Operative Curves (ROCs) varying $q = \frac{V_{LOS}}{V_{MP}}$ in the interval $[1.25: 0.05: 1.5]$
Method to detect the presence of NLOS signals based on:
- analytical derivation of a detection threshold $\lambda$ given a desired $P_{FA}$
- applying a propagation channel model

- **Challenge**: properly setting the model parameters
- **Simulation** results proved the model to be effective

Possible developments:
- Study of channel models for different particular environments
- **Real time** (applying math approximations, already studied)

Challenges for PL evaluation applications
- Include the channel model evaluation in the PL definition
Thank you for your attention!

sabrina.ugazio@polito.it