Hybrid Navigation Filters Performances Between GPS, Galileo and 5G TOA Measurements in Multipath Environment

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Session D1: Alternative Technologies for GNSS-Denied Environments 1

Introduction – Context

- The need for positioning in constrained environment is in constant growth.
- **GNSS positioning solution in harsh environment is degraded** and challenging for urban applications due to multipath and lack of Line-of-Sight (LOS) satellite visibility
- Due to GNSS limitations, several alternatives are already developed:
  - **Hybridization with additional sensors** ([10], [11])
  - **Usage of Signal of Opportunity**: mobile communication signals such as 4G LTE or 5G ([1], [2], [3], [5]),…

- **The objective is to generate a positioning module using 5G and GNSS signals in a realistic multipath environment**.
- 5G systems use OFDM signals, **OFDM signal-type ranging modules are already developed** in the literature [2]-[6]
- These modules were derived by assuming a **constant propagation channel over the duration of an OFDM symbol**. An analysis conducted on QuaDRiGa ([7]) has shown that these models can be refined.

- Objectives:
  - To realistically characterize GNSS and 5G pseudo range measurement mathematical models
  - To develop hybrid navigation modules exploiting/adapted to the previously derived pseudo range measurements mathematical models.

Outline

1. Propagation channel
2. Correlator output mathematical models
3. Characterization of pseudo range error distributions
4. Hybrid filters
5. Simulator overview
6. Results
7. Conclusion

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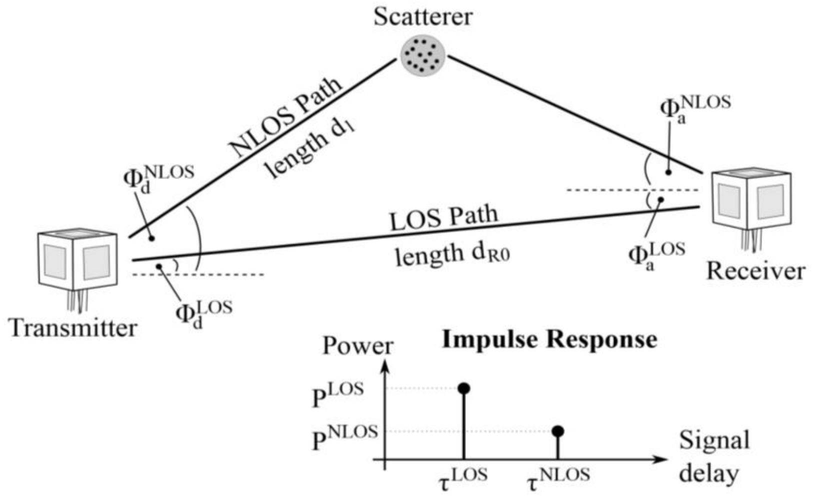
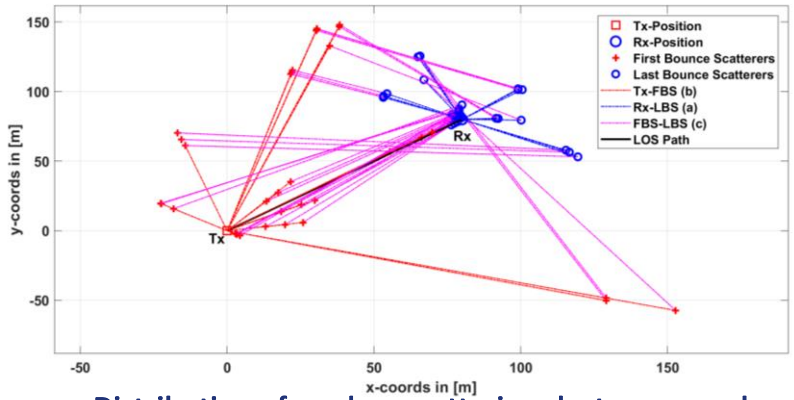
1. Propagation channel (1/2)

- **5G propagation channel: QuaDRiGa [7]**
  - **New innovations** require an evolved propagation channel model:
    - Technologies: massive Multiple Input Multiple Output antenna, denser network, or millimetre waves
    - Case studies: wide variety of case study envisioned for 5G
  - QuaDRiGa: QUAsi Deterministic RadIo channel GenerAtor
    - Developed at the Fraunhofer Heinrich Hertz Institute
    - **Enable the modeling of MIMO radio channels** for specific network configurations: indoor, satellite or heterogeneous configurations.
  - The QuaDRiGa approach is a **"statistical ray-tracing model"**. It does not use an exact geometric representation of the environment but distributes the positions of the scattering clusters (the sources of indirect signals such as buildings or trees) randomly.



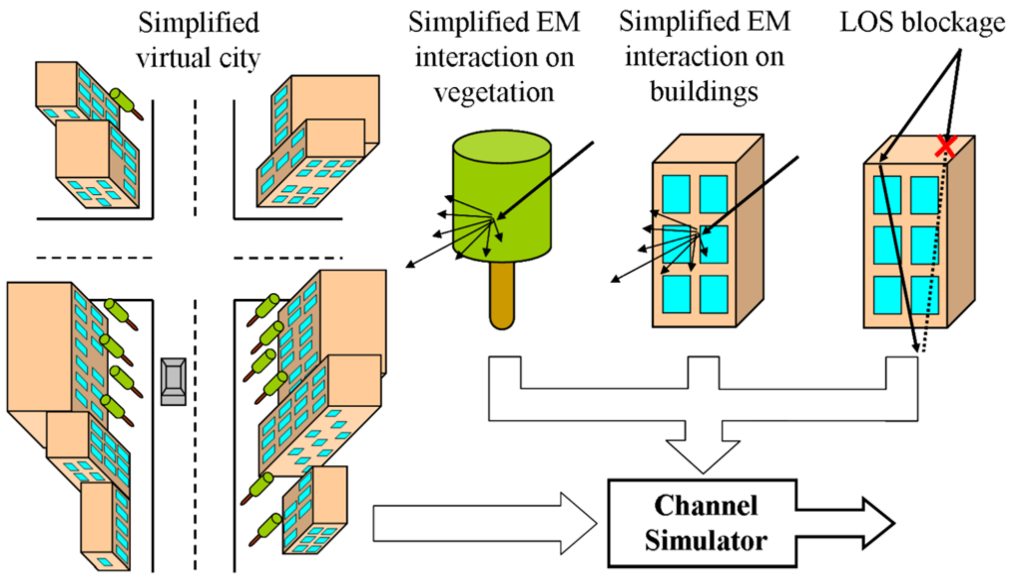
Simplified overview of the modelling approach in QuaDRiGa – source [7]



Distribution of random scattering clusters example

1. Propagation channel (2/2)

- **GNSS propagation channel: SCHUN [12]**
  - SCHUN: Simplified Channel for Urban Navigation; it is a hybrid physical-statistical Land Mobile Satellite propagation channel
  - SCHUN:
    - generates the environment by using a virtual city approach (statistic aspect).
    - models the interactions between impinging signals and the environment by using simple Electromagnetic (EM) interaction models (deterministic aspect)



SCHUN macro architecture – source [12]

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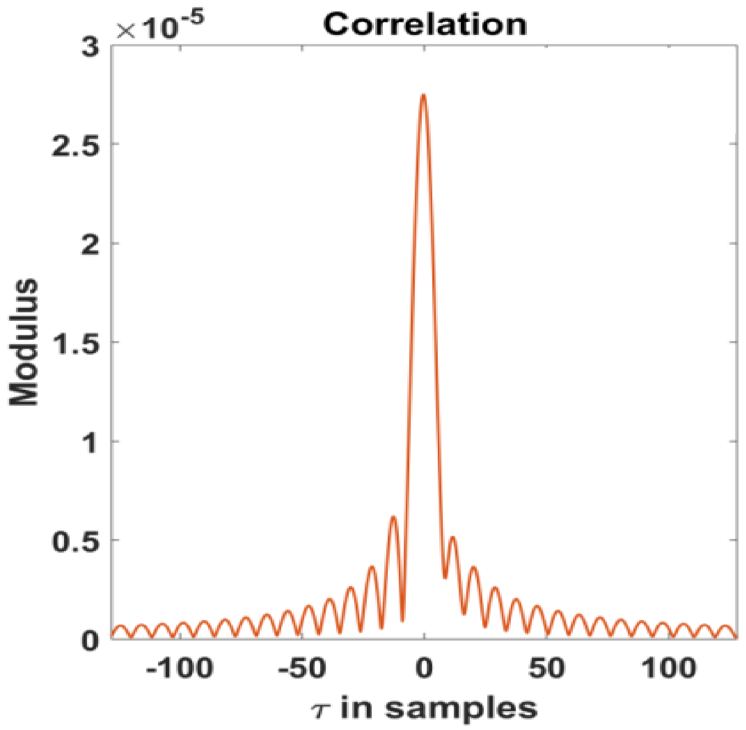
2. Correlator output models (1/2)

- **5G correlator output mathematical model:**
  - QuaDRiGa propagation channel is not constant over the OFDM symbol duration, classical models are insufficient
  - The OFDM signal-type correlator output mathematical model considering an evolving propagation channel have been derived in [13] and [14].

$$\boldsymbol{R(\varepsilon_\tau) = R_{useful}(\varepsilon_\tau) + R_{interf_{data}}(\varepsilon_\tau) + R_{interf_{pilot}}(\varepsilon_\tau) + R_{noise}(\varepsilon_\tau)}$$

- $R_{useful}(\varepsilon_\tau) = \sum_{l=0}^{L-1} \frac{A_l^k(0)}{N_{FFT}} R_l(\varepsilon_{\tau_l})$ correlation part non linked to interferences
- $A_l^k(0) = \sum_{n=0}^{N_{FFT}-1} \alpha_l^k(n)$: evolution of the propagation channel over one symbol
- L: number of paths
- $R_{interf_{pilot}}$: interference term due to the pilots (ICI = Inter Carrier Interference – du to the evolution of the propagation channel)
- $R_{interf_{data}}$: interference term due to the data present in the OFDM symbol (ICI)
- R_{noise}: correlator output noise contribution.



Correlation operation for 5G signal

  - In [14], studies have proved that in targeted scenario: $\boldsymbol{R(\varepsilon_\tau) \cong R_{useful}(\varepsilon_\tau) + R_{noise}(\varepsilon_\tau)}$

2. Correlator output models (2/2)

- **GNSS correlator output model:**
  - Models are known, mastered and well defined in [11]
  - Assuming the SCHUN propagation model

$$g(t,\tau) = \sum_{l=0}^{N_{multi}-1} \gamma_l(t) e^{-i\Phi_l(t)} \delta(t - \tau_l(t))$$

- N_{multi} is the number of path
- $\Phi_l(t)$ is the phase of the l^{th} path
- τ is the convolution variable
- $\gamma_l(t)$ is the amplitude (real) of the l^{th} path
- $\tau_l(t)$is the delay of the l^{th} path

  - The correlator output mathematical model is

$$I(k) = \sum_{l=0}^{N_{multi}-1} \frac{\gamma_{l_k} A d_k}{2} K_{c,c_l}(\varepsilon_{\tau_l}) \cos(\pi \varepsilon_{f_l} T_I + \varepsilon_{\theta_l})\, sinc(\pi \varepsilon_{f_l} T_I) + n_I(k)$$

- $\varepsilon_\tau = \tau - \hat{\tau}$ the code delay estimation error
- $\varepsilon_f = f_D - \widehat{f_D}$ the carrier frequency estimation error
- $\varepsilon_\theta = \theta_0 - \hat{\theta}$ the carrier phase estimation error

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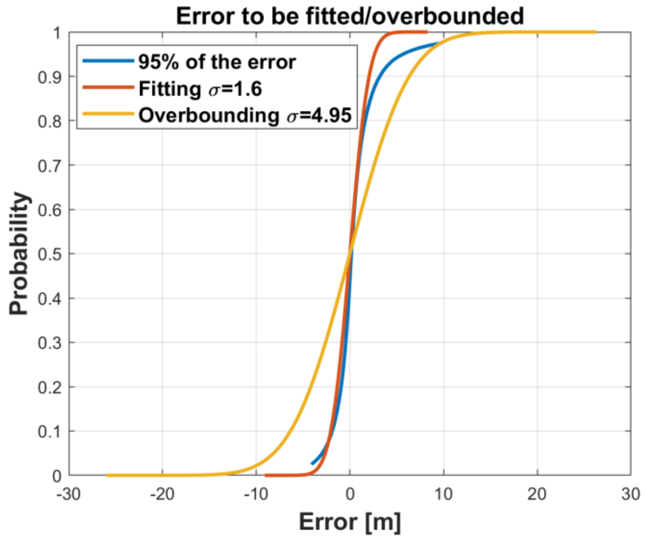
3. Pseudorange characterization (1/4)

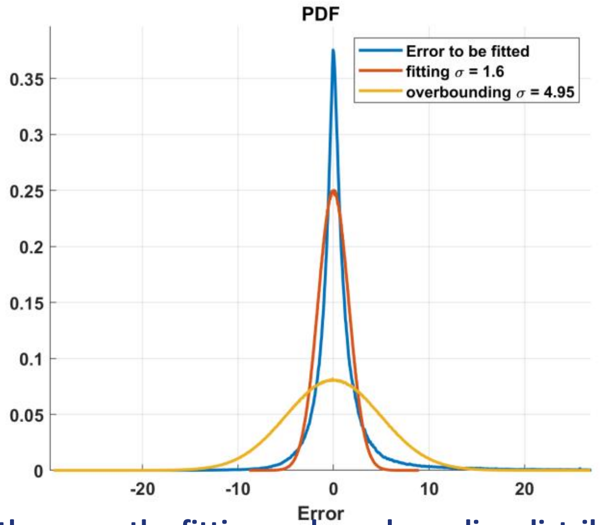
- **Problematic:**
  - The propagation channels SCHUN and QuaDRiGa and the thermal noise introduce errors on the pseudo range measurements.
  - Kalman Filters assume that these errors follow a Gaussian distribution; this assumption may be too restrictive in urban environments and may degrade the positioning performances by over-bounding the measurement error.
  - Monte Carlo simulations will permit to characterize accurately in terms of mean, variance and probability density functions (PDF) these errors.
  - Methods have been derived to overbound and to fit the PDFs, the final choice depends on the envisioned applications

3. Pseudorange characterization (2/4)

- **Targeted solution**
  - Overbounding and fitting methods have been designed and are described in the article
  - The overbounding distribution is such that the overbounding CDF always envelop the error CDF
  - The fitting distribution is such that the norm of the error between the CDF of the error and the CDF of the fitting distribution is minimal
  - The fitting distribution allows a better characterization of small errors while the overbounding distribution will cover the tails of the error characterized
  - Example with a 25m radius circular trajectory is provided



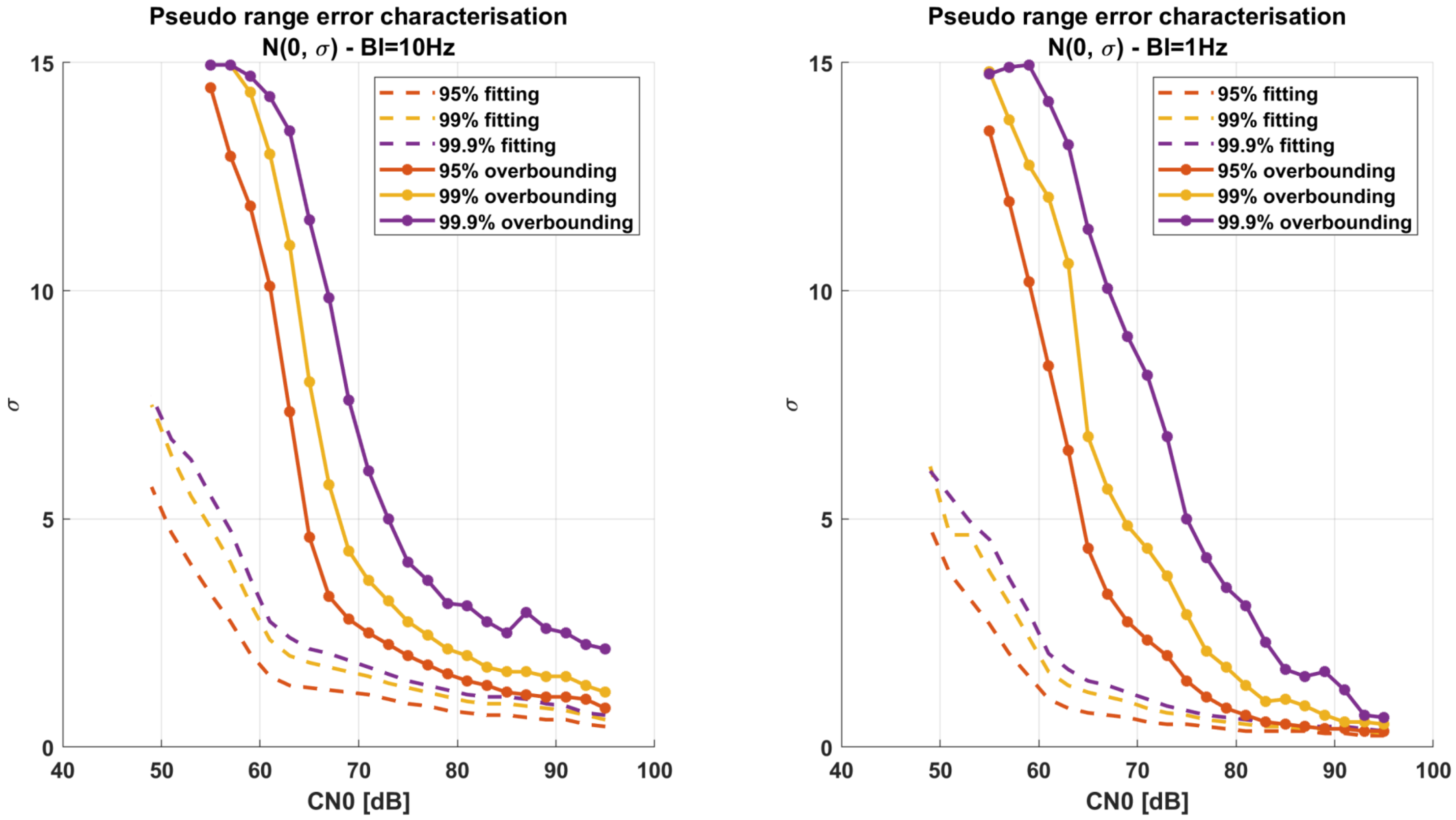
CDF of the error, the fitting and overbounding distributions



PDF of the error, the fitting and overbounding distributions

3. Pseudorange characterization (3/4)

- **QuaDRiGa characterization:**
  - Characterisation for a LOS pico cell scenario
  - Several characterization have been made:
    - $N(0, \sigma)$
    - $N(\mu, \sigma)$ where μ is the mean of the distribution
    - $N(max, \sigma)$ where max is the index of the maximum of the distribution
  - 3 confidence bounds have been studied: 95%, 99%, 99.9%

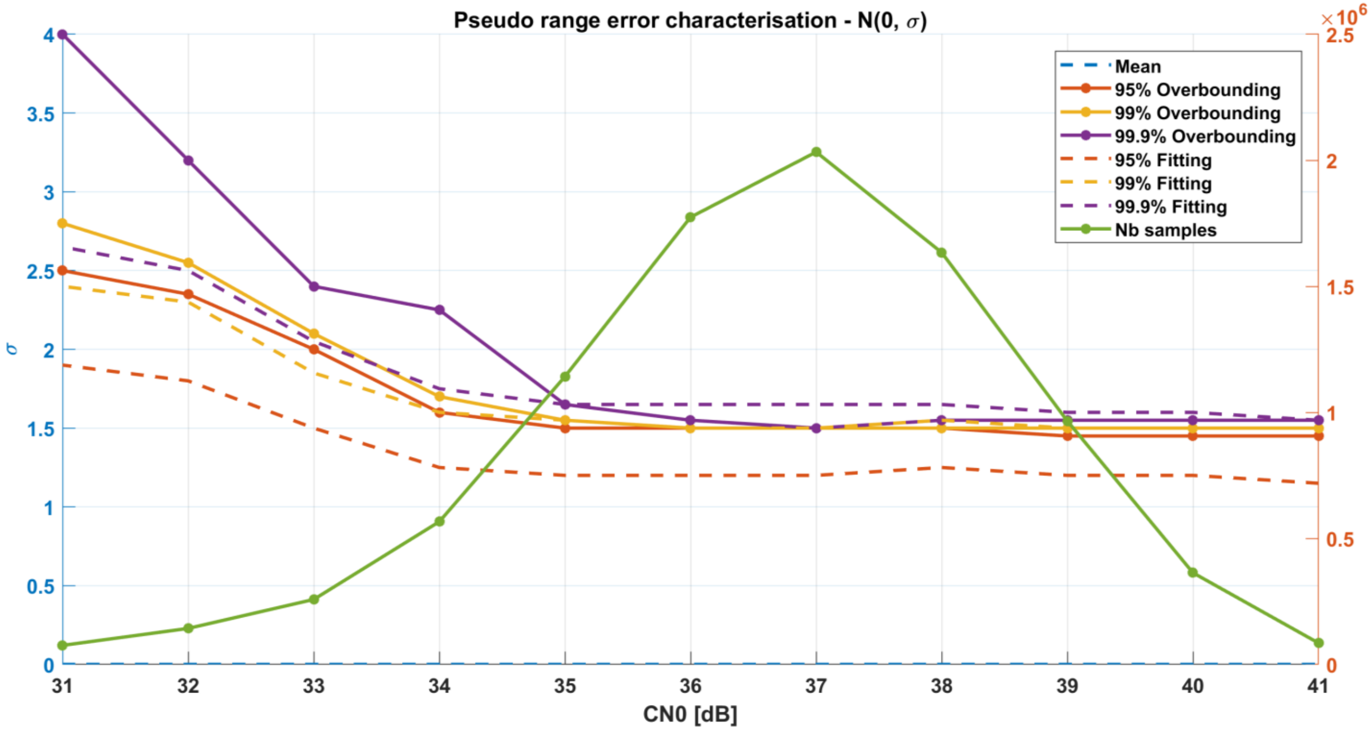


QuaDRiGa pseudo range errors characterization

3. Pseudorange characterization (4/4)

- **SCHUN characterization:**
  – Characterisation based on LOS signal
  – Several characterization have been made:
    - $N(0,\sigma)$
    - $N(\mu,\sigma)$ where μ is the mean of the distribution
    - $N(max,\sigma)$ where max is the index of the maximum of the distribution

  – 3 confidence bounds have been studied: 95%, 99%, 99.9%



SCHUN pseudo range errors characterization

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4. Hybrid navigation filters (1/3)

- **Pseudo range definition and time frame considerations**

$$\begin{cases} \rho_{GPS_j} = r_{GPS_j} + c \cdot \Delta t_{GPS/user} - c \cdot \Delta t_{GPS/sat_{j,GPS}} & j = 1 \dots N_{GPS} \\ \rho_{Gal_j} = r_{Gal_j} + c \cdot \Delta t_{GPS/user} - c \cdot \Delta t_{GPS/Gal} - c \cdot \Delta t_{Gal/sat_{j,Gal}} & j = 1 \dots N_{Gal} \\ \rho_{5G_j} = r_{5G_j} + c \cdot \Delta t_{GPS/user} - c \cdot \Delta t_{GPS/5G} - c \cdot \Delta t_{5G/BS_j} & j = 1 \dots N_{5G} \end{cases}$$

  - $r_{GPS_j}, r_{Gal_j}, r_{5G_j}$: geometric distance between the j^{th} GPS/Galileo/5G BS and the receiver
  - $\Delta t_{GPS/user}, \Delta t_{GPS/5G}, \Delta t_{GPS/Gal}$ time shifts of the receiver clock, the 5G clock and the Galileo clock with respect to the GPS clock time frame respectively
  - $\Delta t_{GPS/sat_{j,GPS}}$ time shift of the j^{th} GPS satellite clock with respect to the GPS clock time frame
  - $\Delta t_{Gal/sat_{j,Gal}}$ time shift of the j^{th} Galileo satellite clock with respect to the Galileo clock time frame
  - $\Delta t_{5G/BS_j}$ the time shift of the j^{th} 5G base station clock with respect to the 5G clock time frame

4. Hybrid navigation filters (2/3)

- **State model:**

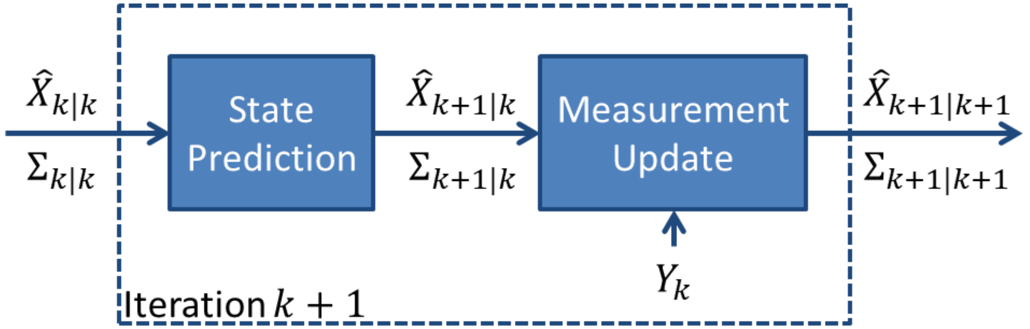
$$X_k = \begin{bmatrix} X & V_X & Y & V_Y & Z & V_Z & c \cdot \Delta t_{GPS/user} & c \cdot \dot{\Delta t}_{GPS/user} & c \cdot \Delta t_{GPS/Gal} & c \cdot \Delta t_{GPS/5G} \end{bmatrix}$$

- **Measurement model:** $\boldsymbol{Y_k = h(X_k) + V_k}$
  - $h(X_k)$ is observation matrix $h(X_k) = \begin{bmatrix} h^{(GPS)}(X_k) \\ h^{(Gal)}(X_k) \\ h^{(5G)}(X_k) \\ \dot{h}^{(GPS)}(X_k) \\ \dot{h}^{(Gal)}(X_k) \end{bmatrix}$
  - $h^{(X)}$ are pseudo range code measurements
  - $\dot{h}^{(X)}$ are pseudo range rate measurements
  - V_k measurement noise vector

- **Navigation filters: EKF and UKF**

4. Hybrid navigation filters (3/3)

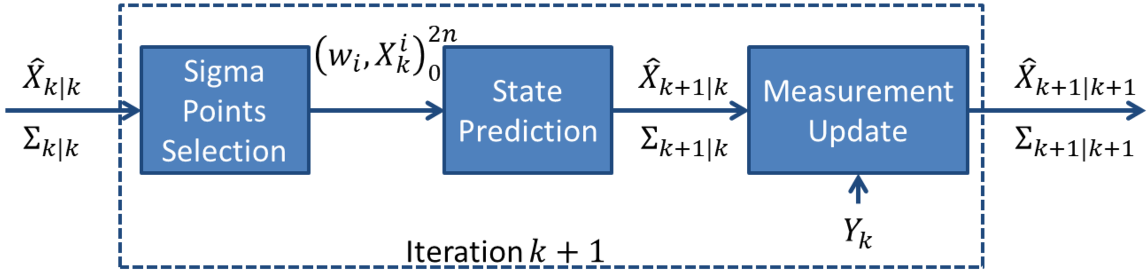
- **EKF Filter:**
  - A classical navigation filter
  - It is a Bayesian estimation technique where all probability density functions are supposed Gaussian.
  - The **analytical** method for the evaluation of the integrals over the Gaussian weighted non-linear functions consists in using Taylor polynomial expansion about a single point.
  - It gives reasonable estimation results if the nonlinearities are not severe.



EKF processing

$\hat{X}$: *state vector*
Σ: *covariance matrix*
n: *state vector dimension*
w_i: *weight*
X_k^i: *sigma point i*

- **UKF Filter:**
  - It is based on a **statistical** linearization technique
  - It consists in the linearization of a nonlinear function of a random variable through a linear regression between n points drawn from the prior distribution of the random variable.
  - The state distribution is represented using a minimal set of carefully chosen sample points called sigma points.



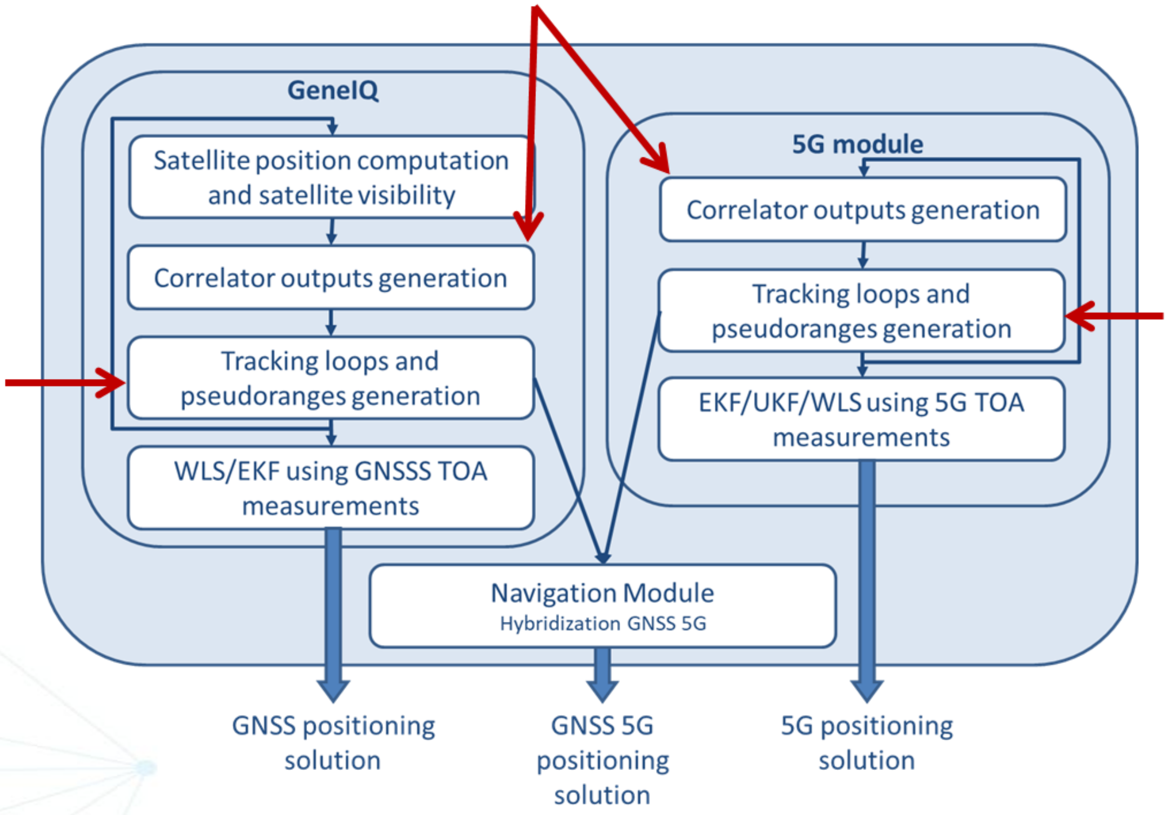
UKF processing

Outline

5. Simulator overview

Generation of correlator outputs: to simplify the simulator and to remove computationally-heavy signal processing stages

Tracking loops: code and phase



Tracking loop: code

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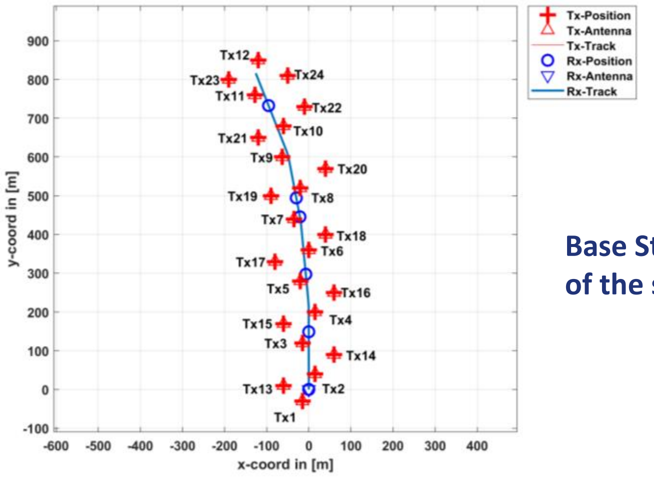
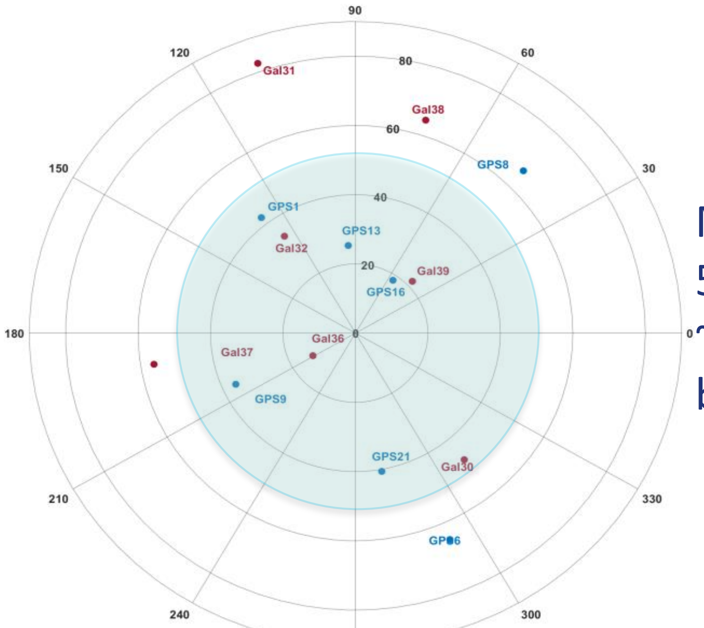
6. Results

- **Objective:**
  - To determine the positioning performances obtained using the previously describe navigation filters
- **Scenario**
  - SCHUN and QuaDRiGa have been used to generate realistic propagation channel
  - Ultra Dense Network envisioned
  - High mask angle value implying few satellites in vue
- **Navigation solution**
  - 5G standalone and GNSS (GPS+Galileo) standalone navigation solution
  - hybrid navigation solution
- **Figure of merit**
  - Root Mean Square Error (RMSE)



Base Station localization of the simulated scenario

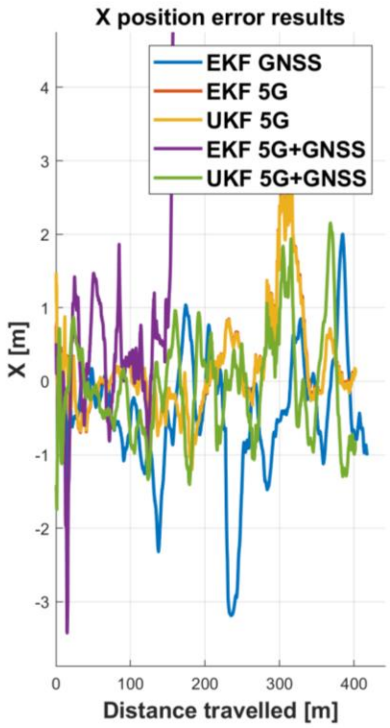


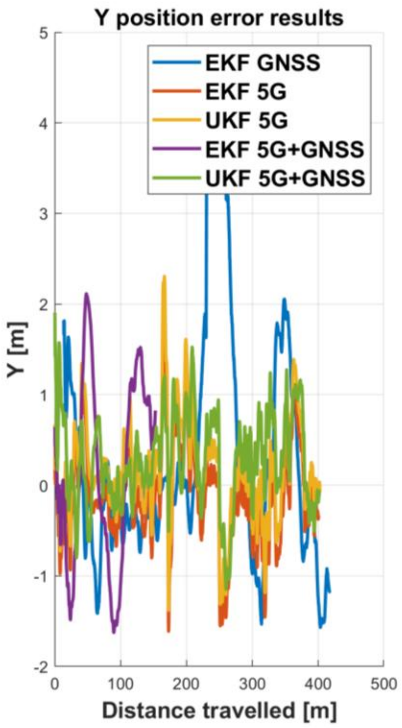
Skyplot of the simulated scenario

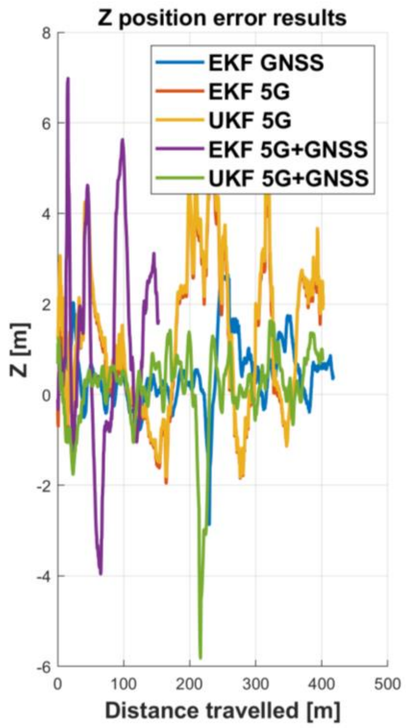
Mask angle 50°
~4 floors building

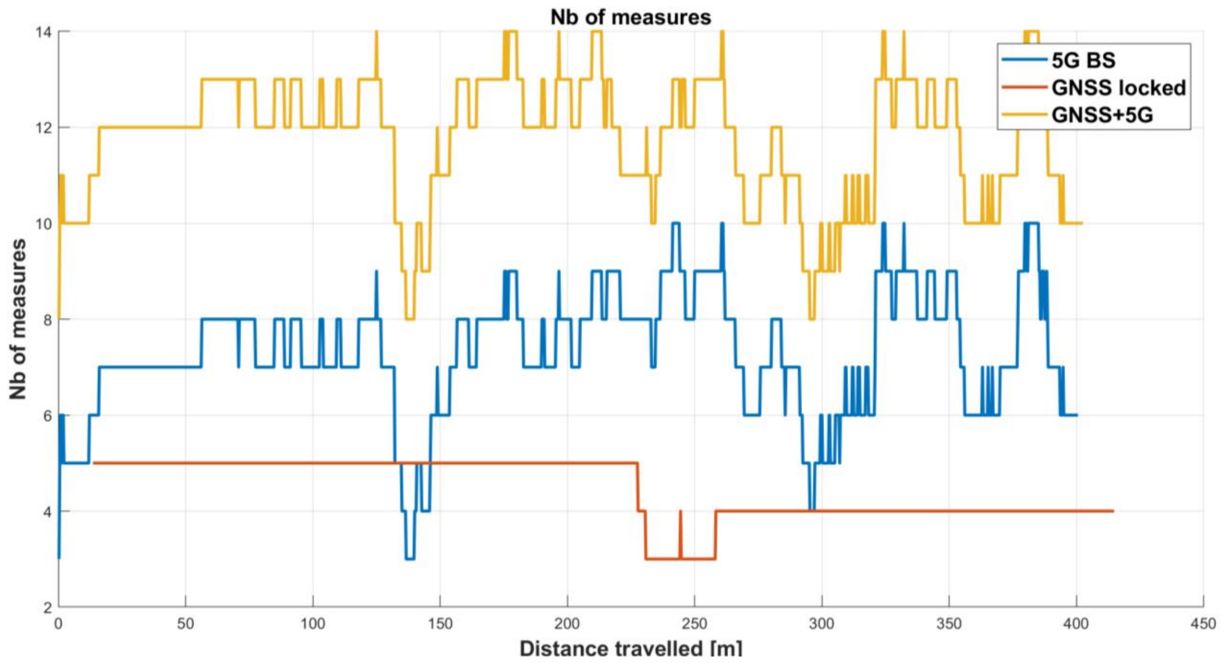
6. Results

- The position error in the ENU coordinate frame on each axis









6. Results

- The figure of merit selected is the RMSE
- As expected, the 5G standalone position solution over Z is worst, due to the base stations geometry

RMSE	Systems	X	Y	Z
Position [m]	EKF GNSS	0.9715	1.3520	0.8660
	EKF 5G	0.7289	0.5688	2.0788
	EKF 5G+GNSS	0.7204	0.5886	2.2075
	UKF 5G	0.7922	1.0586	2.6064
	UKF 5G+GNSS	0.7164	0.5758	0.9556

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7. Conclusions and Future work

- The pseudo range measurements mathematical models have been derived from a realistic simulator which integrates a typical GNSS receiver processing module and a typical 5G signal processing module proposition.
- In order to achieve a realistic characterization, the simulator implements highly realistic propagation channels for GNSS, SCHUN [8], and for 5G, QuaDRiGa [9].
- A realistically characterization of GNSS and 5G pseudo range measurement mathematical models have been presented
- Hybrid navigation modules exploiting/adapted to the derived pseudo range measurements mathematical models have been studied and compared
- The pseudo range error distributions have been overbounded and fitted by Gaussian distribution future work can consists in finding a distribution more adapted to the actual distribution and to implement new filters such as Particle Filters.
- Particle Filters main advantage is that they do not rely on a Gaussian PDF approximation contrary to Kalman Filters; nevertheless an a-priori information on the distributions must be provided.

Thank you!
Any questions?

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