GNSS/5G Hybridization for Urban Navigation

Ph.D. Dissertation Defense by Anne-Marie TOBIE

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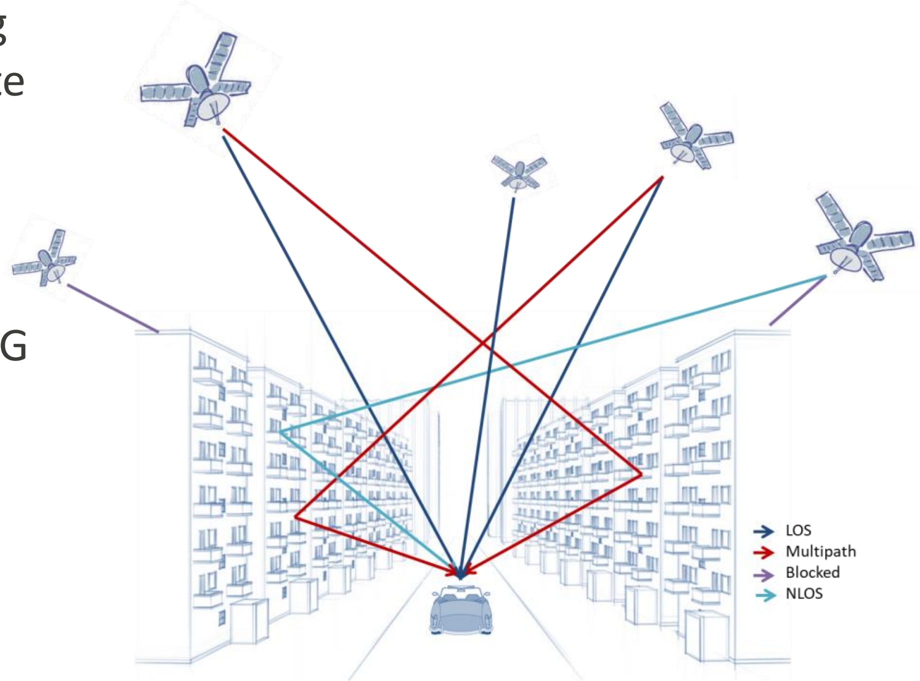
Introduction – Context (1/2)

- 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**
  - **Usage of Signal of Opportunity**: mobile communication signals such as 4G LTE or 5G,…

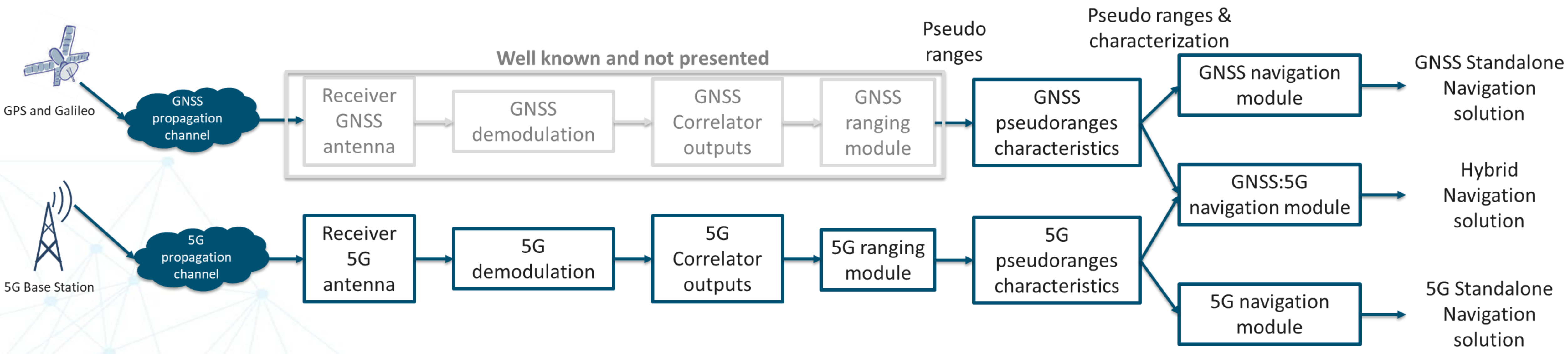


Introduction – Context (1/2)

- 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**
  - **Usage of Signal of Opportunity**: mobile communication signals such as 4G LTE or 5G,…
- 5G systems use Orthogonal Frequency Division Multiplexing (OFDM) signals, **OFDM signal-type ranging modules are already developed** in the literature
- These modules were derived by assuming a **constant propagation channel over the duration of an OFDM symbol**. An analysis conducted on QuaDRiGa has shown that these models must be refined.
- **Global objective: the design of hybrid navigation modules using both GNSS and 5G measurements in a realistic environment**.

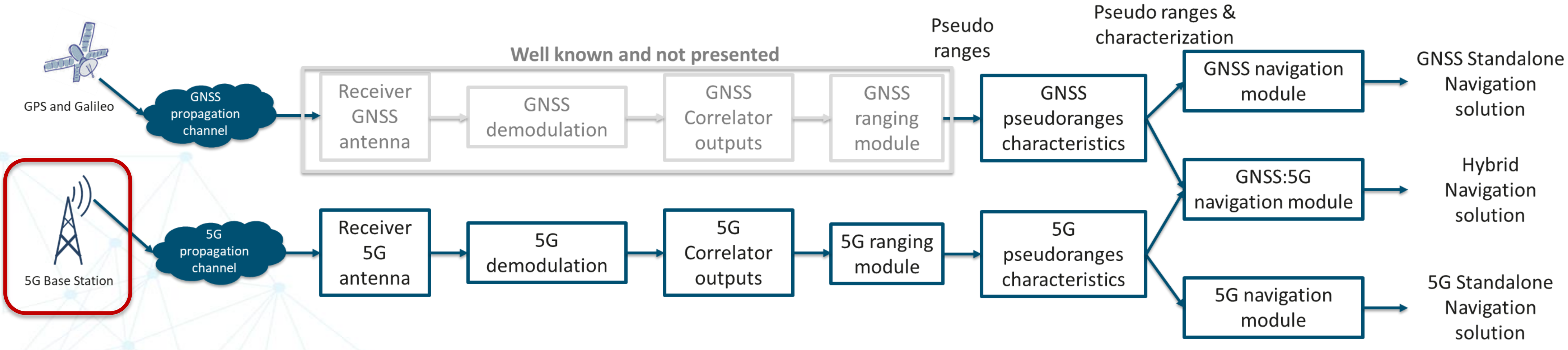
Introduction – Context (2/2)

Global objective: the design of hybrid navigation modules using both GNSS and 5G measurements in a realistic environment.



Introduction – Context (2/2)

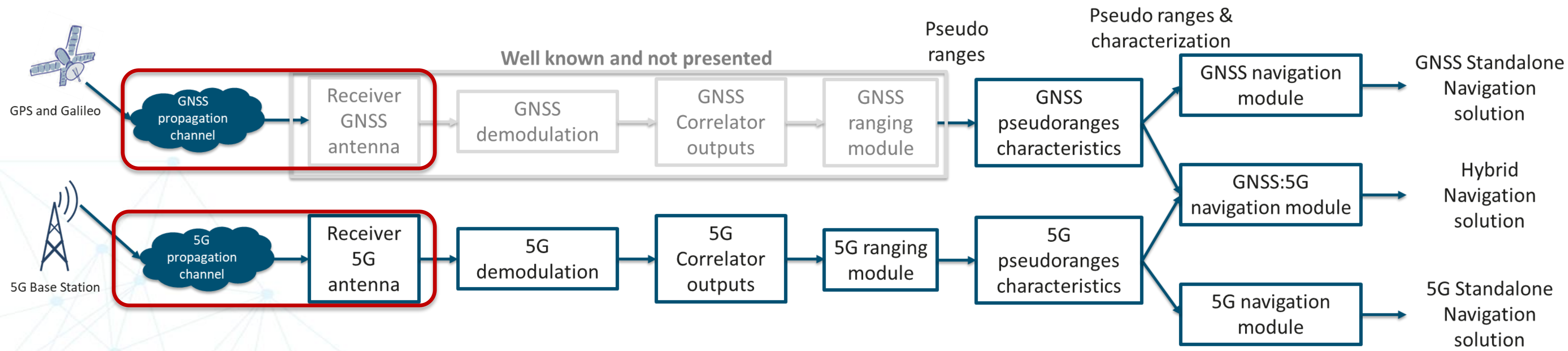
Global objective: the design of hybrid navigation modules using both GNSS and 5G measurements in a realistic environment.



- Detailed objective 1: The description the 5G physical layer

Introduction – Context (2/2)

Global objective: the design of hybrid navigation modules using both GNSS and 5G measurements in a realistic environment.



- Detailed objective 2: The selection GNSS and 5G compliant propagation channels

Introduction – Context (2/2)

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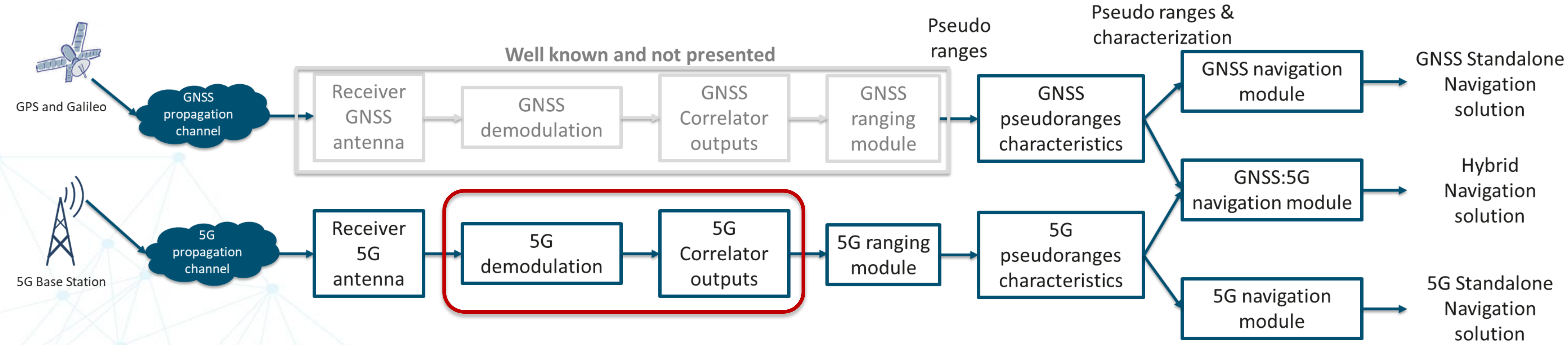
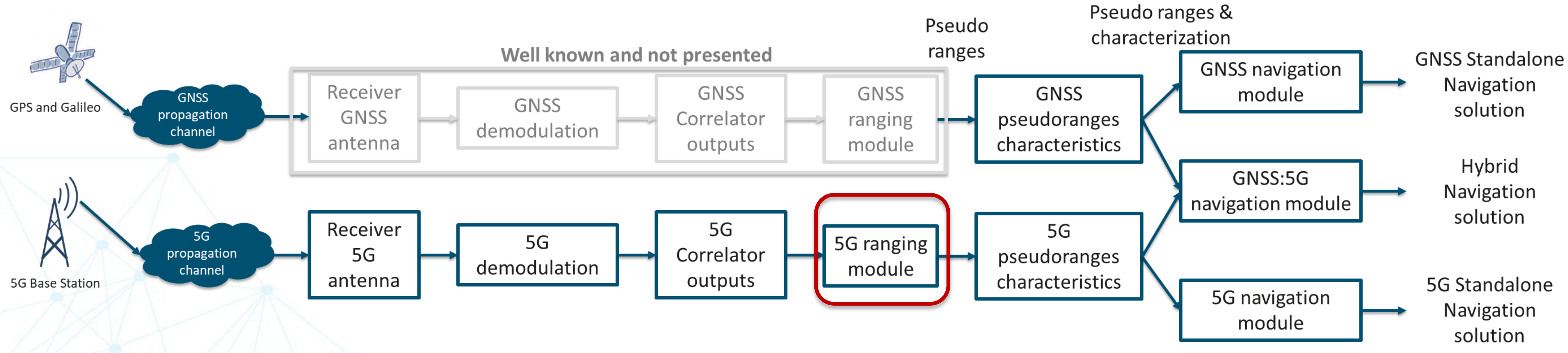


- Detailed objective 3: The development of **highly realistic 5G signals correlator outputs** for ranging based positioning considering a **realistic urban propagation channel**

Introduction – Context (2/2)

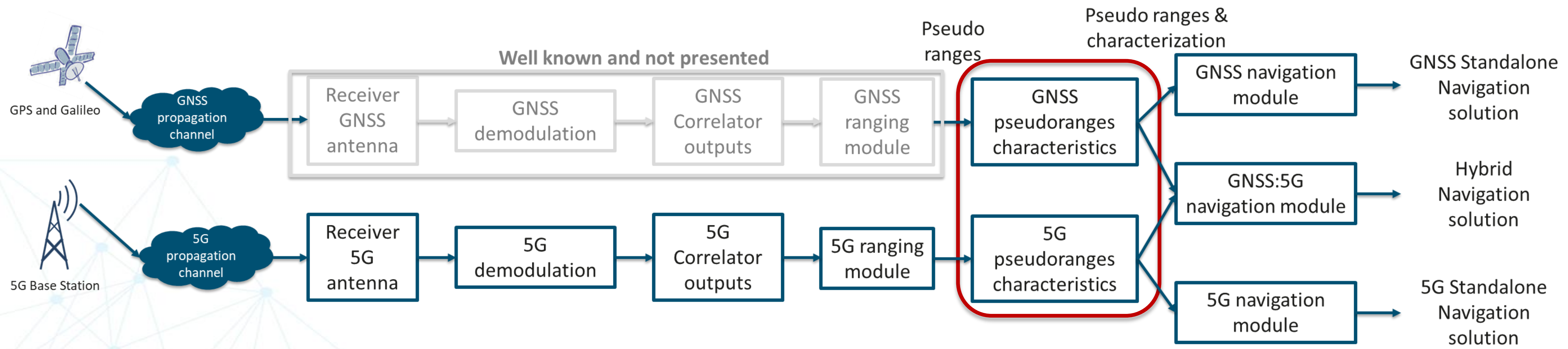
Global objective: the design of hybrid navigation modules using both GNSS and 5G measurements in a realistic environment.



- Detailed objective 4: The development of **5G ranging modules** to estimate the **time-of-arrival** (TOA) of the signal.

Introduction – Context (2/2)

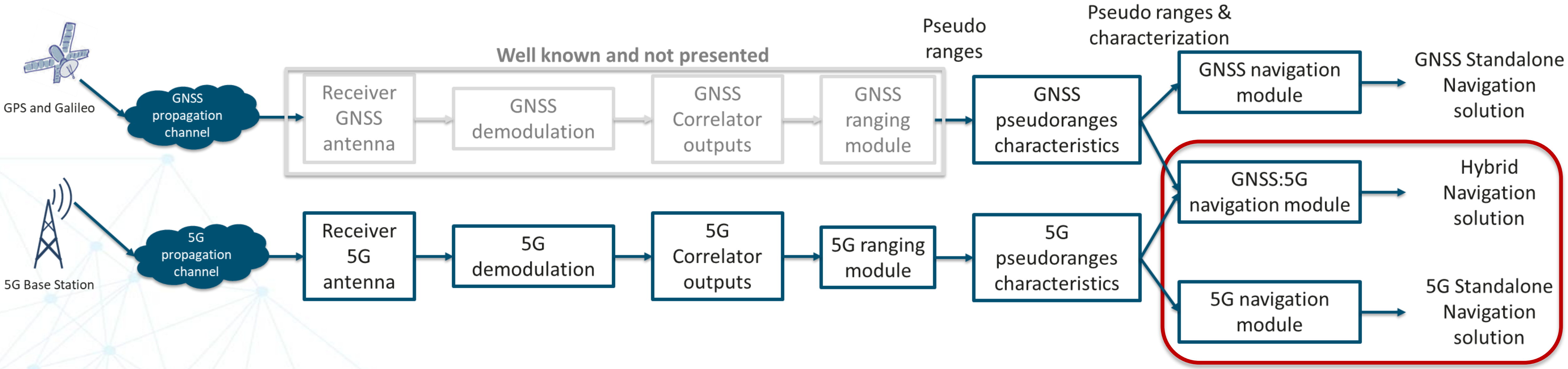
Global objective: the design of hybrid navigation modules using both GNSS and 5G measurements in a realistic environment.



- Detailed objective 5: The precise **Derivation of GNSS and 5G pseudo range errors** due to the propagation channels

Introduction – Context (2/2)

Global objective: the design of hybrid navigation modules using both GNSS and 5G measurements in a realistic environment.



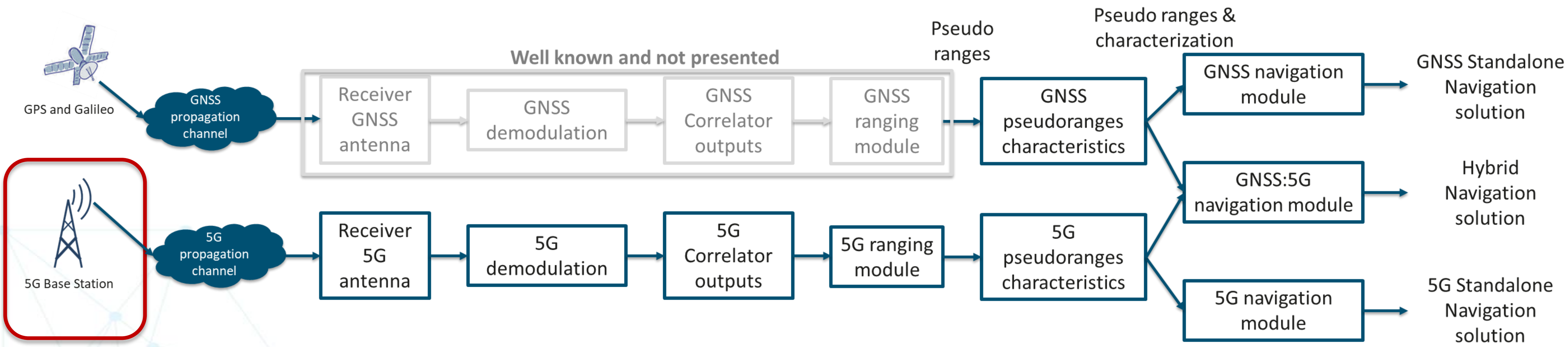
- Detailed objective 6: The development of **hybrid navigation modules** exploiting/adapted to the derived pseudo range measurements mathematical models.

Outline

Outline

1. **5G signal presentation**
2. Propagation channel
3. Correlator output mathematical models
4. 5G ranging module design
5. Derivation of pseudo range error distributions
6. Navigation modules and results
7. Conclusion

1. 5G signal presentation (1/4)



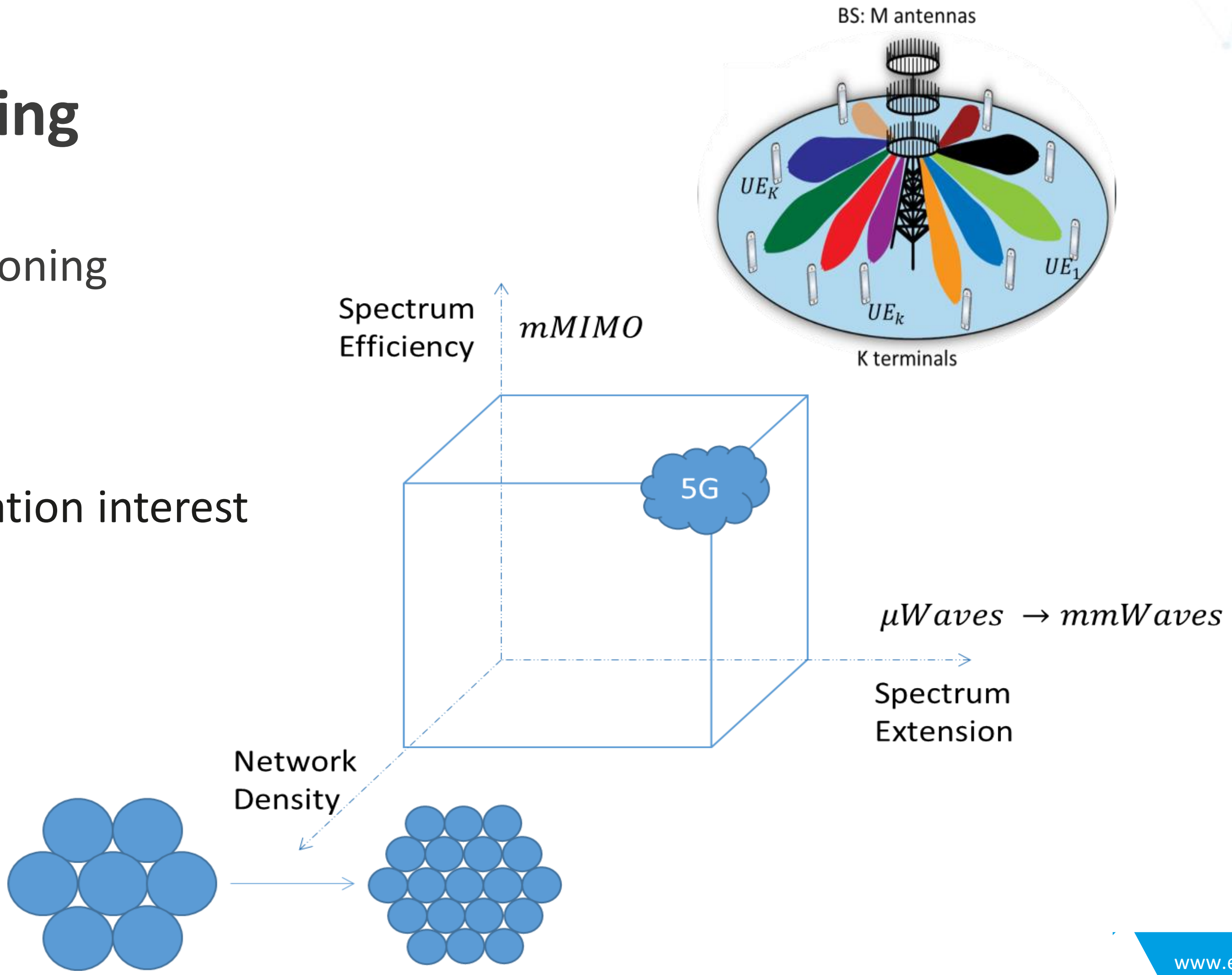
- **Objective 1**: The description the 5G physical layer
  - 1.1. The interest of 5G for positioning
  - 1.2. 5G transmitted signal
  - 1.3. 5G synchronization signal

1. 5G signal presentation (2/4)

1.1. The interest of 5G for positioning

- Objective:
  - To present the interest of 5G for positioning
- Approaches to address 5G requirements:
  - Denser Network
    - → Many more emitters
  - Millimetre Waves
    - → More bandwidth
  - Massive MIMO antenna
    - → Angle of Arrival measurements

$\left.\begin{array}{l}\text{Denser Network} \\ \text{Millimetre Waves}\end{array}\right\}$ Trilateration interest



5G requirements – source [15]

1. 5G signal presentation (2/4)

1.1. The interest of 5G for positioning

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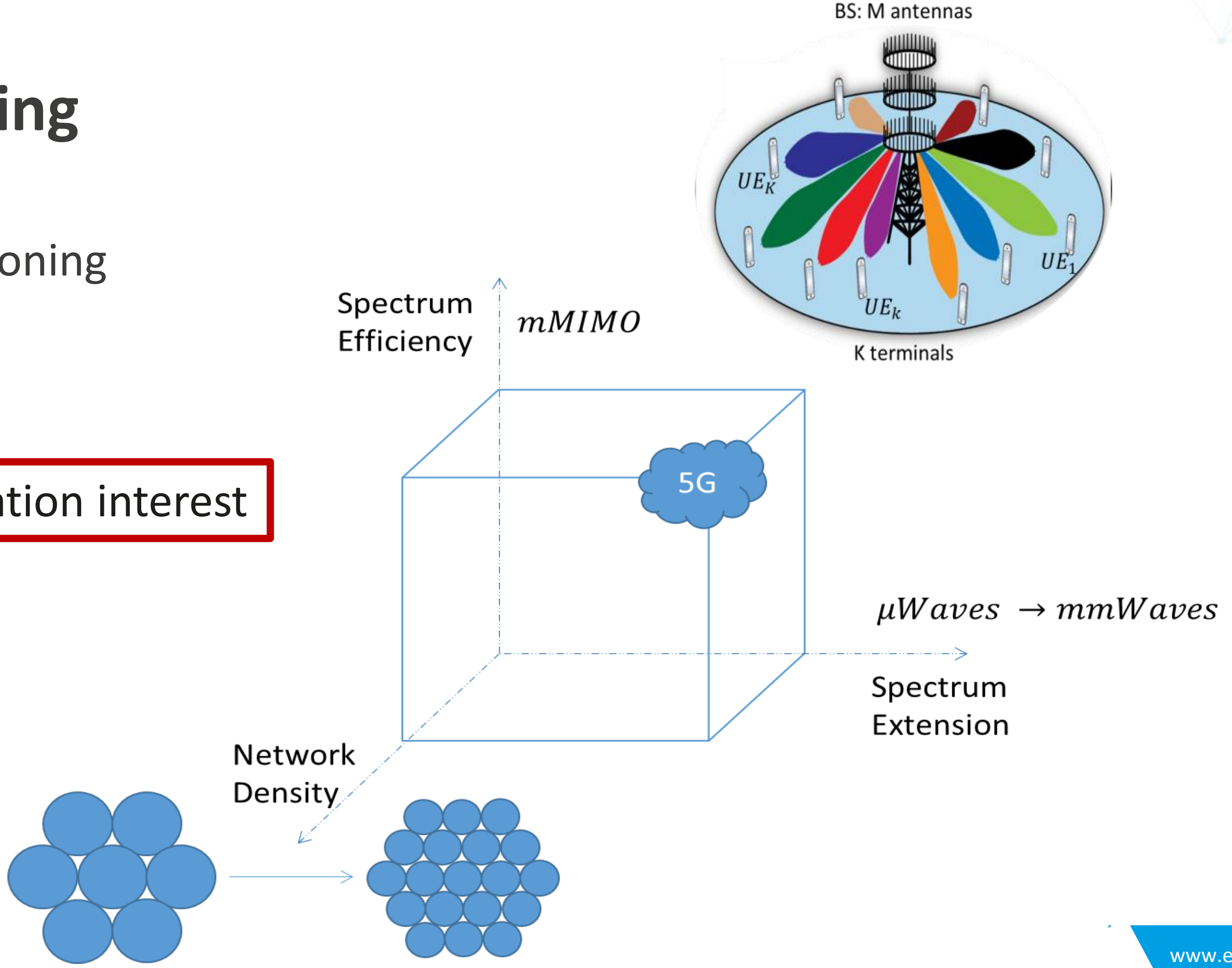
Trilateration interest

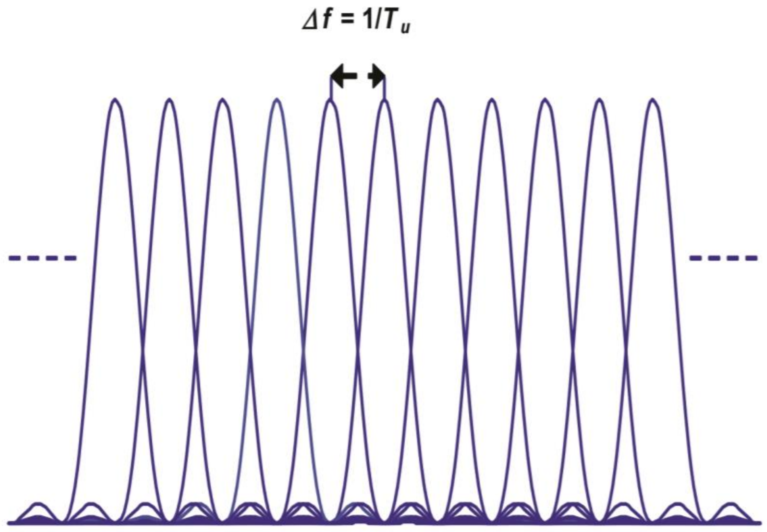


5G requirements – source [15]

1. 5G signal presentation (3/4)

1.2. 5G transmitted signal

- 5G uses **Orthogonal Frequency Division Multiplexing** (OFDM)
- Interest:
  - **Simple**:
    - modulation using an iFFT
    - demodulation using a FFT
  - **Robust in multipath environment**
    - Frequency selectivity
    - Time dispersity (cycle prefix)
- OFDM with a **scalable numerology**
- **Two frequency ranges** are identified:
  - FR1: 410 MHz – 7125 MHz (main focus)
  - FR2: 24250 MHz – 52600 MHz → mmW (partly analyzed)



OFDM modulation

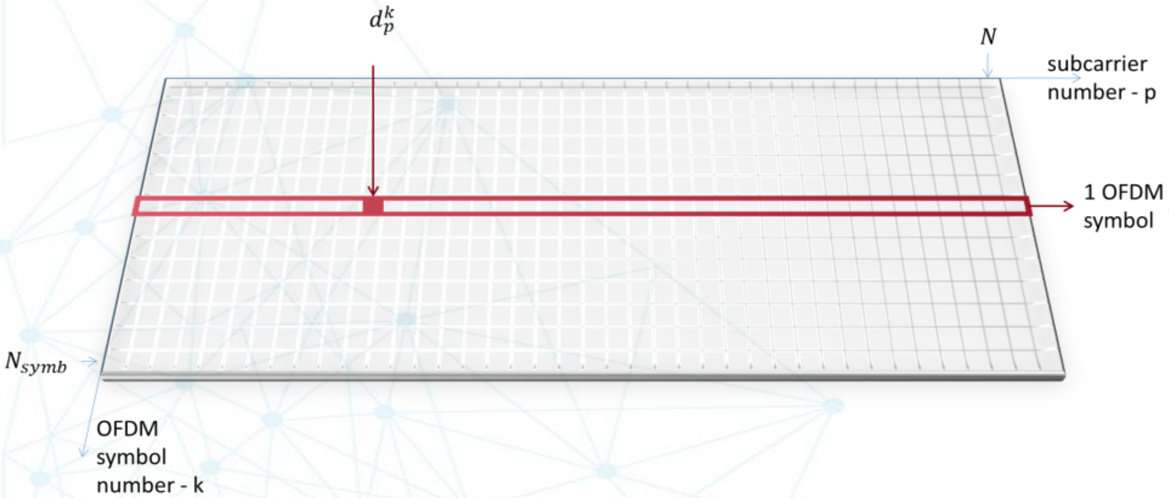
μ	$\Delta f\ [kHz]$	Cyclic prefix
0	15	Normal
1	30	Normal
2	60	Normal, Extended
3	120	Normal
4	240	Normal

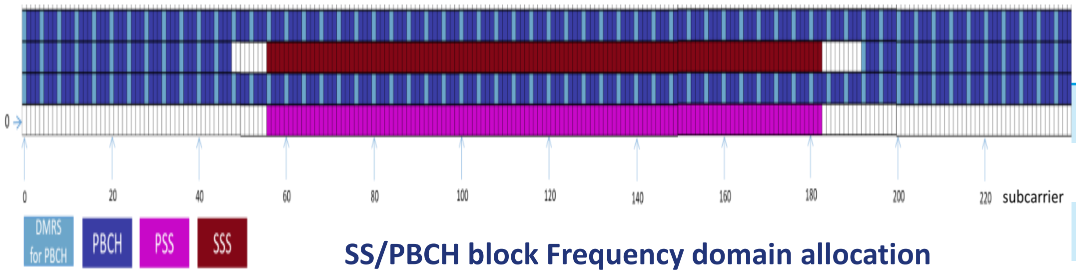
OFDM scalable numerology

1. 5G signal presentation (4/4)

1.3. Synchronization signals

- The definition of a 5G signal is made through the time/frequency allocation of resources in a resource grid:
  - A resource grid is composed of time-consecutive OFDM symbols
  - An OFDM symbol is composed of frequency-consecutive subcarriers carrying data or pilot symbols.
  - The data symbols correspond to the useful information transmitted to the 5G user – a-priori unknown.
  - The pilot symbols are known symbols in terms of time/frequency localization and value → **pilot symbols are used to compute the correlation**
- 3GPP standards has shown that the only set of pilots having a fixed position in the resource grid is the **SS/PBCH block**.





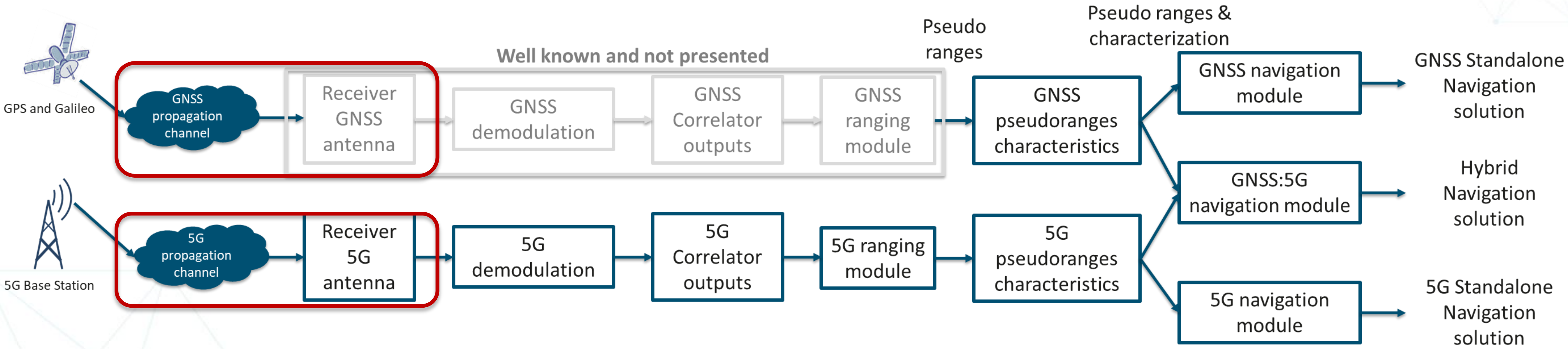
SS/PBCH block Frequency domain allocation

Δf $[kHz]$	B $[MHz]$
15	3.6
30	7.2
60	14.4
120	28.8
240	57.6

- A **simplified 5G frame** is considered, each symbol of the frame corresponds to the 2nd SS/PBCH symbol

Outline

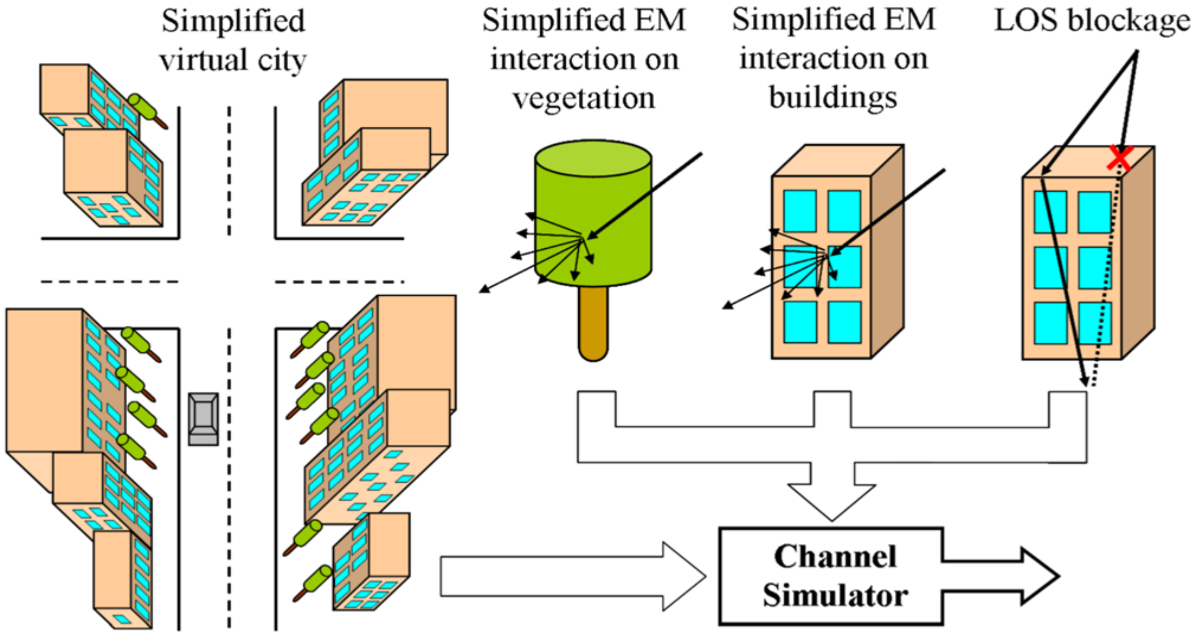
2. Propagation channel (1/3)



- **Objective 2:** The selection GNSS and 5G compliant propagation channels
  - Getting a **realistic and precise model** of the propagation channel is mandatory to develop signal processing techniques
  - The selection of an appropriate propagation channel is a trade off between **complexity** and **accuracy**
  - A **deep study of the literature** has been performed to find the best compromises

2. Propagation channel (2/3)

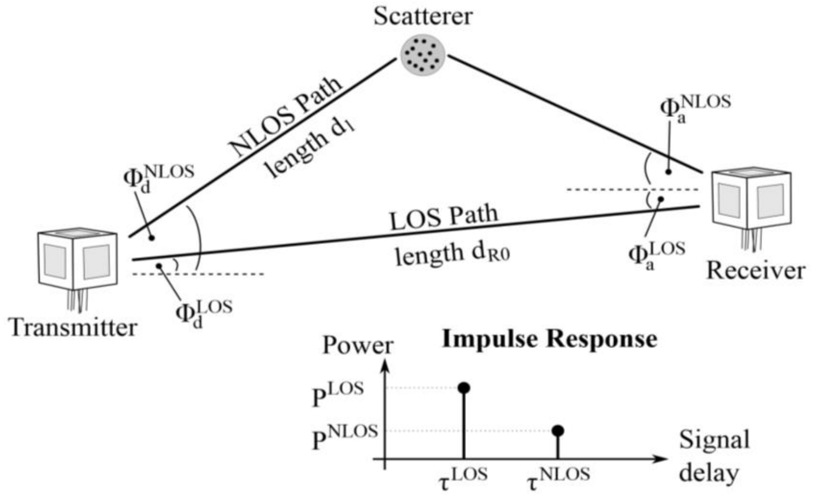
- **GNSS propagation channel: SCHUN [12]**
  - SCHUN: Simplified Channel for Urban Navigation; it is a hybrid physical-statistical Land Mobile Satellite propagation channel
  - SCHUN:
    - generates the environment by using a virtual city approach (statistic aspect).
    - models the interactions between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



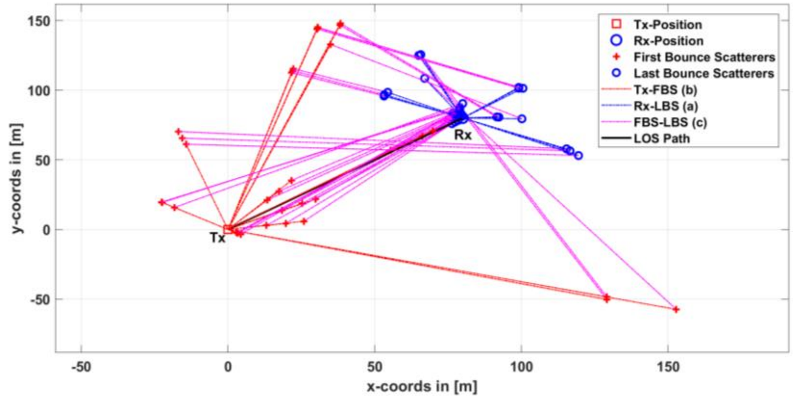
SCHUN macro architecture – source [12]

2. Propagation channel (3/3)

- **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 by 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

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1. 5G signal presentation
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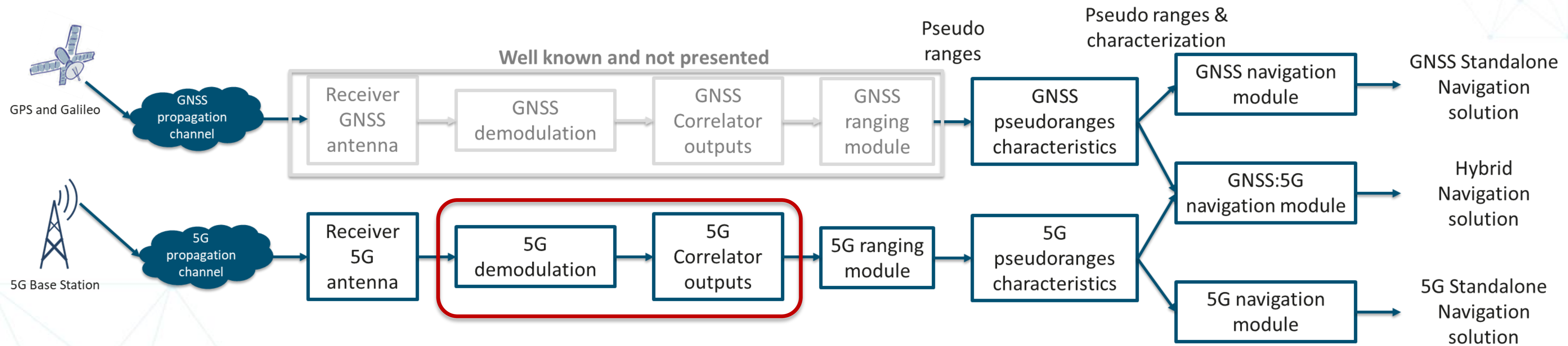
3. Correlator output models



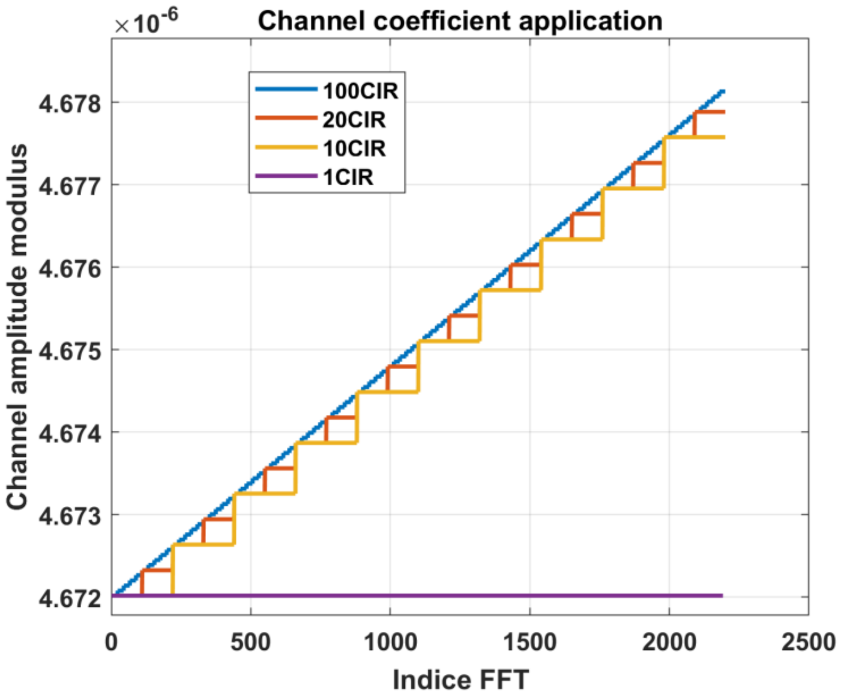
- **Objective 3**: The development of **highly realistic 5G signals correlator outputs model** for ranging based positioning considering a **realistic propagation channel**

  3.1. To correctly characterize the CIR propagation channel
  - To define the CIR sampling rate
  - To identify the significant time-varying channel parameters with respect to symbol duration
  - To select the appropriate CIR sampling rate

  3.2. To derive the correlator output mathematical model of a 5G signal for ranging purposes

3. Correlator output models

- **3.1. Impact of a time-evolving channel (1/2)**
  - High level Objective:
    - To correctly model the propagation channel and its parameters
  - Observation:
    - The CIR sampling rate is the number of CIR samples directly generated by the discrete propagation channel model over the duration of an OFDM symbol
    - 100 CIR per OFDM symbol is equivalent to a time continuous propagation channel → reference
    - The CIR sampling rate has consequences on the entire processing chain
    - The path delays evolution over an OFDM symbol is negligible but the propagation channel complex amplitude evolution is significant
  - Detailed objective
    - To select the appropriate CIR sampling rate to model the evolving propagation channel



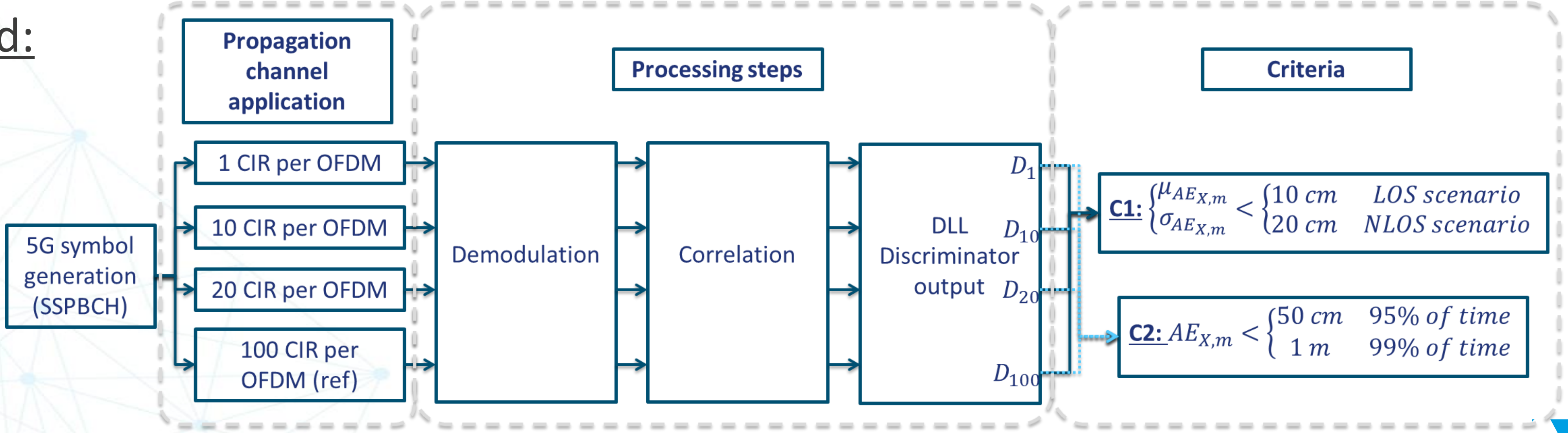
Channel coefficients modulus over the OFDM symbol

3. Correlator output models

3.1. Impact of a time-evolving channel (2/2)

– Objective:
  - To select the appropriate CIR sampling rate to model the evolving propagation channel
  - Appropriate = low enough to obtain a simple mathematical model while still able to accurately represent a true continuous CIR propagation channel

– Method:



$$AE_{X,m} = |D_{100} - D_X|_m$$

3. Correlator output models

3.1. Impact of a time-evolving channel (2/2)

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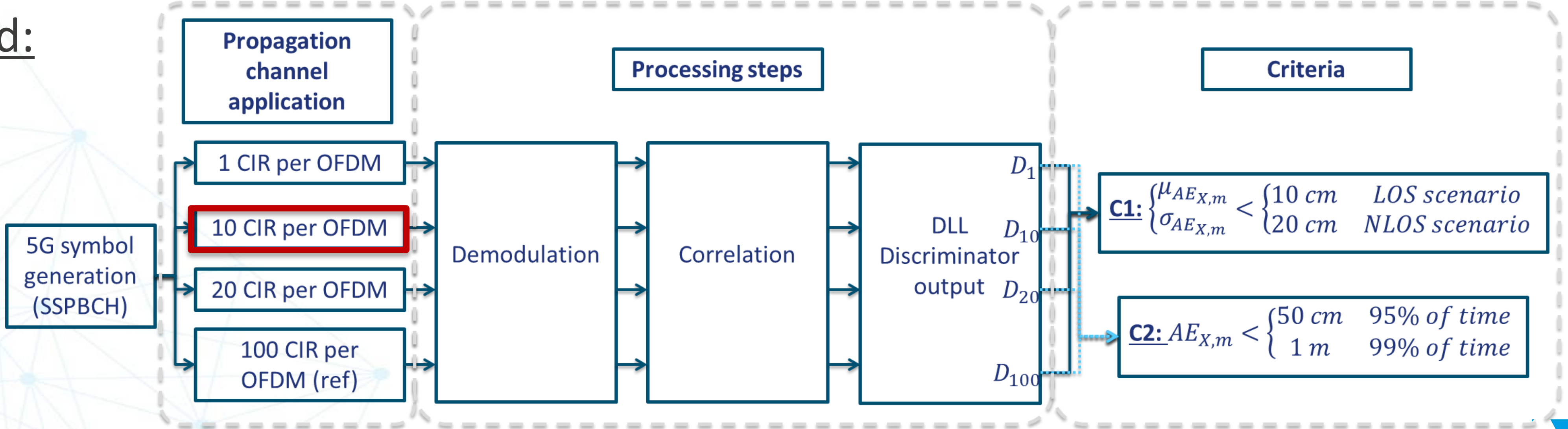


10 CIR per OFDM symbol is the appropriate CIR sampling rate for the majority of analyzed scenario

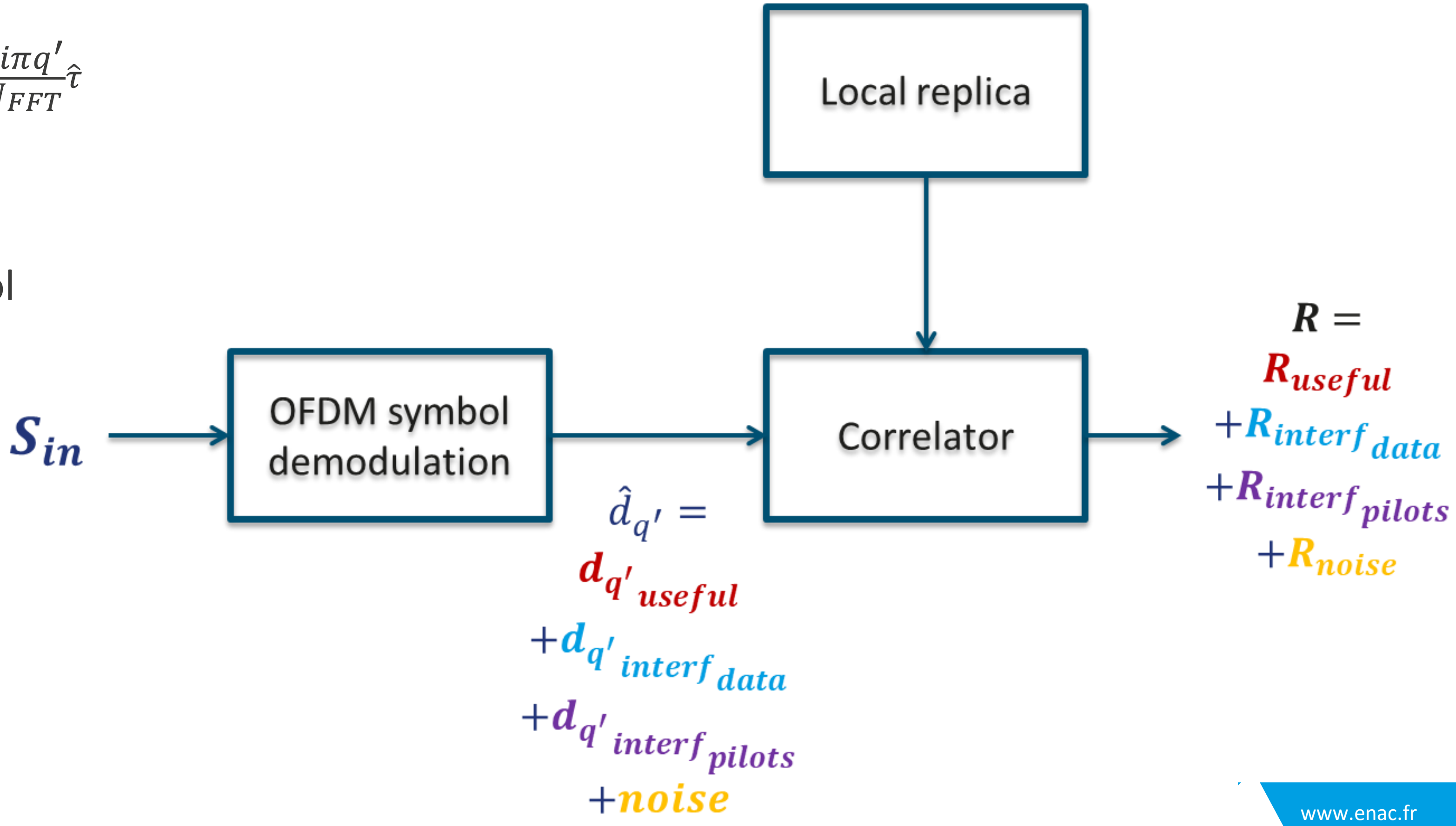
3. Correlator output models

3.2. Correlator output mathematical model (1/3)

- The general correlation formula is

$$R(\varepsilon_\tau) = \frac{1}{N_P} \sum_{q' \in P} \hat{d}_{q'} \cdot p_{q'} e^{-\frac{2i\pi q'}{N_{FFT}} \hat{\tau}}$$

- Where
  - $p_{q'}$ the locally generated pilot symbol localized in the q'^{th} subcarrier
  - N_p the number of pilot symbols,
  - $\hat{d}_{q'}$ the demodulated symbols
  - P set of pilots in the OFDM symbol

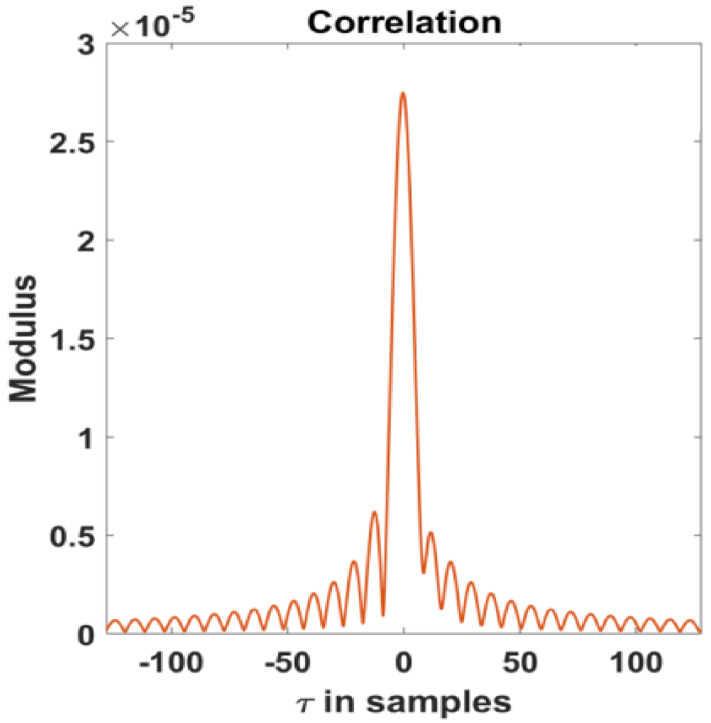


3. Correlator output models

3.2. Correlator output mathematical model (2/3)

– The OFDM signal-type correlator output mathematical model

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



Correlation operation for 5G signal

3. Correlator output models

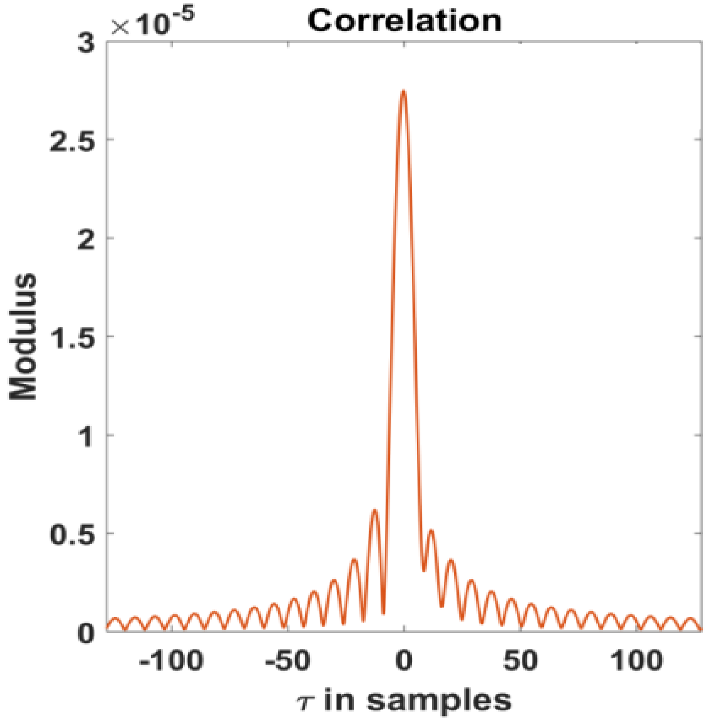
3.2. Correlator output mathematical model (2/3)

– The OFDM signal-type correlator output mathematical model

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

$$R_{useful}(\varepsilon_\tau) = \sum_{l=0}^{L-1} \frac{A_l^k(0)}{N_{FFT}} R_{nl,l}(\varepsilon_{\tau_l}) = \sum_{l=0}^{L-1} \frac{\sum_{n=0}^{N_{FFT}-1} \alpha_l^k(n)}{N_{FFT}} R_{nl,l}(\varepsilon_{\tau_l})$$

$$R_{nl,l}(\varepsilon_{\tau_l}) = \begin{cases} \frac{1}{N_P} e^{\frac{i\pi(2\beta+\gamma(N_P-1))\varepsilon_{\tau_l}}{N_{FFT}}} \frac{\sin\left(\frac{\pi\gamma\varepsilon_{\tau_l}N_P}{N_{FFT}}\right)}{\sin\left(\frac{\pi\gamma\varepsilon_{\tau_l}}{N_{FFT}}\right)} & \varepsilon_{\tau_l} \neq 0 \\ 1 & \varepsilon_{\tau_l} = 0 \end{cases}$$



Correlation operation for 5G signal

– Observation:
- The resulting complete model is still **quite complex**
- To derive a simplified model could be beneficial for **theoretical purposes and for practical purposes**

3. Correlator output models

3.2. Correlator output mathematical model (2/3)

– The OFDM signal-type correlator output mathematical model

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

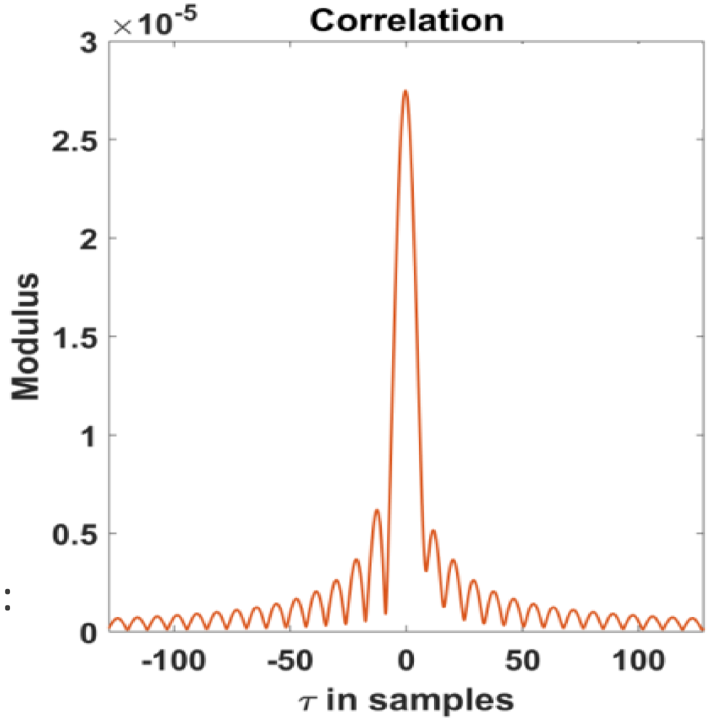
– Observation:

- This simplification would allow the **generation of only 1 CIR sample per OFDM symbol instead of 10 CIR samples**.

– Method: Simplification of the propagation channel contribution on the useful term: $A_l^k(0)$

$$\boxed{A_l^k(0) \cong \frac{|\alpha_l^k(0)| + |\alpha_l^{k+1}(0)|}{2} e^{i\theta_{0_l}} e^{i\pi\delta_{f_l}^k \cdot (N_{FFT}-1)} \frac{\sin\left(\pi\delta_{f_l}^k N_{FFT}\right)}{\sin\left(\pi\delta_{f_l}^k\right)}}$$

– Conclusion: The simplified model can be used instead of the initial one for the noiseless useful term for all scenarios since **the simplified model is statistically equivalent to the initial model using 10 CIR per OFDM symbol**.



Correlation operation for 5G signal

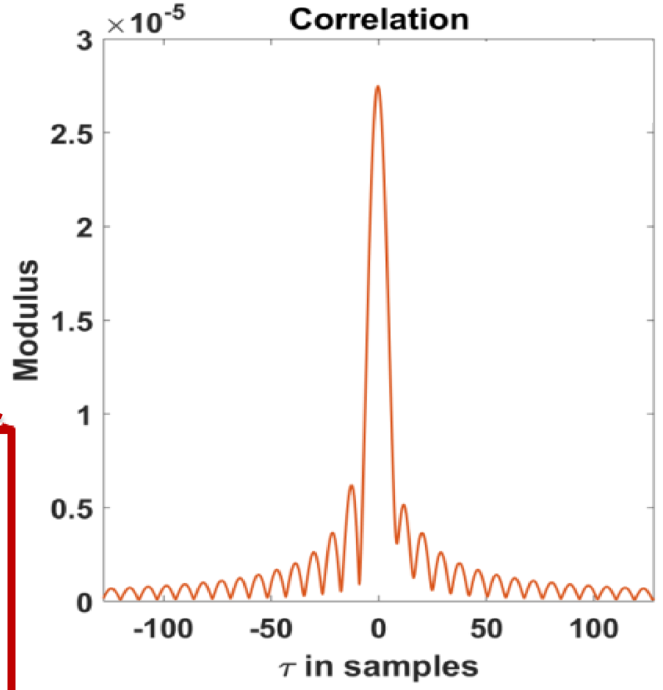
3. Correlator output models

3.2. Correlator output mathematical model (2/3)

– The OFDM signal-type correlator output mathematical model

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

$$\begin{cases} R_{interf\ pilot}(\varepsilon_\tau) = \dfrac{1}{N_P N_{FFT}} \displaystyle\sum_{l=0}^{L-1} \sum_{q'=0}^{N_P-1} \sum_{\substack{q=0 \\ q\neq q'}}^{N_P-1} e^{\frac{-2i\pi\gamma q\tilde{\tau}_l}{N_{FFT}}} p_q^k p_{q'}^{k*} e^{\frac{2i\pi\hat{\tau}\gamma q'}{N_{FFT}}} \sum_{n=0}^{N_{FFT}-1} \alpha_l^k(n) e^{\frac{2i\pi\gamma(q-q')n}{N_{FFT}}} \\ R_{interf\ data}(\varepsilon_\tau) = \dfrac{1}{N_P N_{FFT}} \displaystyle\sum_{l=0}^{L-1} \sum_{q'=0}^{N_P-1} \sum_{\substack{q=0 \\ q\neq\gamma q' \\ q \bmod \gamma\neq 0}}^{N_{FFT}-1} e^{\frac{-2i\pi q\tilde{\tau}_l}{N_{FFT}}} D_q^k p_{q'}^{k*} e^{\frac{2i\pi\hat{\tau}\gamma q'}{N_{FFT}}} \sum_{n=0}^{N_{FFT}-1} \alpha_l^k(n) e^{\frac{2i\pi(q-\gamma q')n}{N_{FFT}}} \end{cases}$$



Correlation operation for 5G signal

– The ICI term can be seen as a **degradation of the available SNR or C/N_0**

3. Correlator output models

3.2. Correlator output mathematical model (2/3)

– The OFDM signal-type correlator output mathematical model

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

– Model:

- The ICI can be, due to the Central Limit Theorem, modelled as a **Gaussian random variable** which statistics are dependent on the propagation channel generated and thus are **trajectory- and scenario-dependent.**

– Validation:

- The **Skewness** and **Kurtosis** statistics have been computed for 10000 Monte Carlo and over the Early, Prompt and Late correlator outputs.
- For a Gaussian distribution, the Skewness is equal to 0 and the Kurtosis to 3.

Skewness and Kurtosis measurements

Trajectory		1	3		
scenario		LOS	LOS	LOS	NLOS
Case		1	1	2	1
		Skewness measures			
$R(\varepsilon_\tau)$	Early	0.04	-0.03	-0.01	-0.01
	Prompt	0.02	-0.01	-0.04	-0.02
	Late	-0.01	-0.00	-0.01	-0.02
		Kurtosis measures			
$R(\varepsilon_\tau)$	Early	2.87	2.93	3.02	3.04
	Prompt	3.01	2.96	3.04	3.04
	Late	3.21	3.02	2.98	3.10

3. Correlator output models

3.2. Correlator output mathematical model (2/3)

– The OFDM signal-type correlator output mathematical model

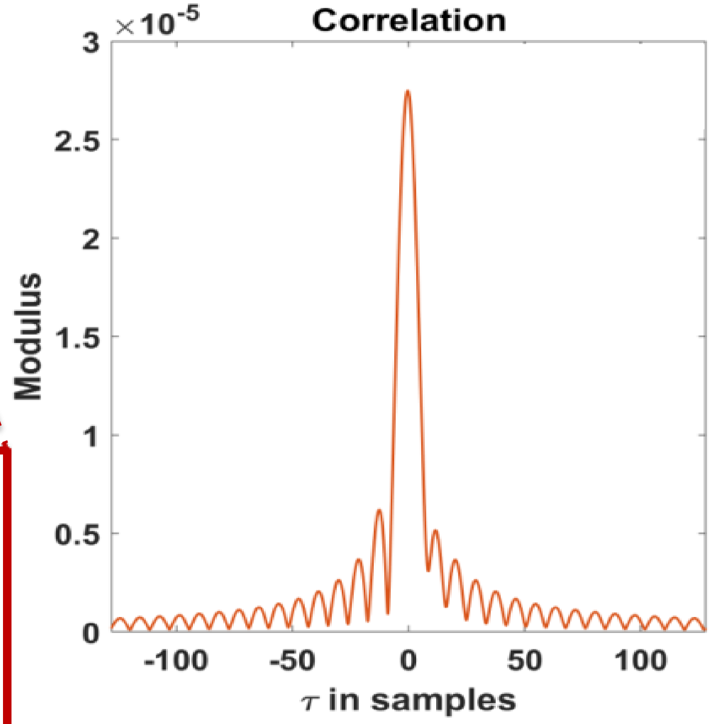
$$\boldsymbol{R(\varepsilon_\tau) = R_{useful}(\varepsilon_\tau) + R_{interf_{data}}(\varepsilon_\tau) + R_{interf_{pilot}}(\varepsilon_\tau) + \boxed{R_{noise}(\varepsilon_\tau)}}$$

$$E\left[b_q^k {b_{q'}^k}^*\right] = \begin{cases} 0 & if\ q \neq q' \\ \sigma_{noise}^2/N_{FFT} & if\ q = q' \end{cases}$$

$$E[R_{noise}(\hat{\tau})] = \frac{e^{\frac{2i\pi\hat{\tau}\beta}{N_{FFT}}}}{N_P}\sum_{q=0}^{N_P-1} E\left[b_q^k\right] p_q^{k*} e^{\frac{2i\pi\varepsilon_\tau\gamma q}{N_{FFT}}} = 0$$

$$Var[R_{noise}(\hat{\tau})] = \sigma_{noise}^2/(N_{FFT}N_P)$$

$$E[R_{noise}(\hat{\tau}){R_{noise}}^*(\hat{\tau}-\Delta\tau)] = \begin{cases} \frac{e^{\frac{i\pi\Delta\tau(2\beta+\gamma(N_P-1))}{N_{FFT}}}}{N_P^2}\frac{\sigma_{noise}^2}{N_{FFT}}\frac{\sin\left(\frac{\pi\Delta\tau\gamma N_P}{N_{FFT}}\right)}{\sin\left(\frac{\pi\Delta\tau\gamma}{N_{FFT}}\right)} & \Delta\tau \neq 0 \\ \frac{\sigma_{noise}^2}{N_{FFT}N_P} & \Delta\tau = 0 \end{cases}$$



Correlation operation for 5G signal

3. Correlator output models

3.2. Correlator output mathematical model (3/3)

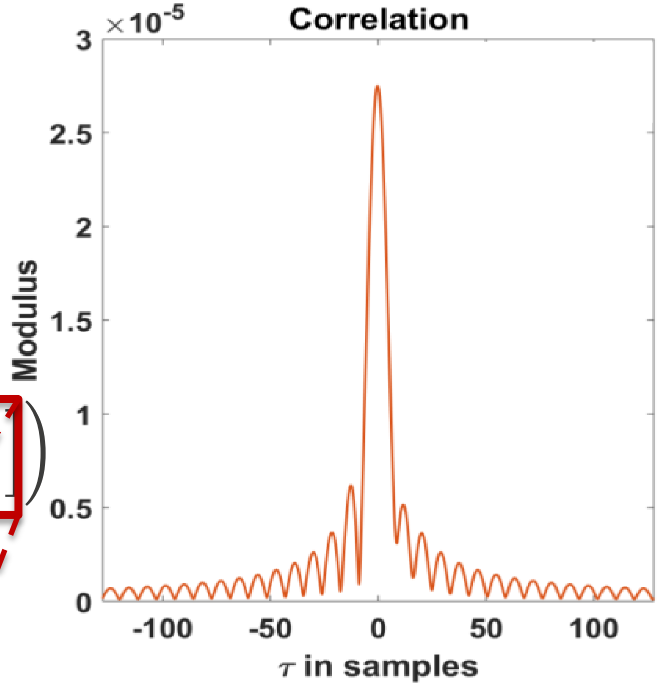
– Another model is therefore possible

$$\boxed{R(\varepsilon_\tau) = R_{useful}(\varepsilon_\tau) + R_{noise+interf}(\varepsilon_\tau)}$$

where

$$R_{noise+interf}(\varepsilon_\tau) \sim N\left(R_{interf_{pilot}}(\varepsilon_\tau), Var[R_{noise}(\hat{\tau})] + \boxed{Var\left[R_{interf_{data}}(\varepsilon_\tau)\right]}\right)$$

$$Var\left[R_{interf}(\varepsilon_\tau)\right] = \frac{1}{N_P^2 N_{FFT}^2} \sum_{\substack{q=0 \\ q \bmod \gamma \neq 0}}^{N_{FFT}-1} \left| \sum_{l=0}^{L-1} e^{\frac{-2i\pi q \tilde{\tau}_l}{N_{FFT}}} \sum_{\substack{q'=0 \\ q \neq \gamma q'}}^{N_P-1} p_{q'}^{k*} e^{\frac{2i\pi \hat{\tau} \gamma q'}{N_{FFT}}} \sum_{n=0}^{N_{FFT}-1} \alpha_l^k(n) e^{\frac{2i\pi (q-\gamma q')n}{N_{FFT}}} \right|^2$$



Correlation operation for 5G signal

3. Correlator output models

- **Conclusion**
  - CIR characterization
    - The propagation channel **complex amplitude significantly varying in time**
    - The CIR sampling rate selection is constrained by the **trade-off** between the **generation computing time** and the **realism of the modelling**.
    - Using **10 CIR samples** per OFDM is suitable to model the propagation channel variation
    - The time-evolution of the propagation channel creates a **spectral broadening e**ffect. This spectral broadening implies the **loss of the orthogonality among the OFDM signal subcarriers**.
  - Correlator output mathematical model

$$R(\varepsilon_\tau) = \boxed{R_{useful}(\varepsilon_\tau)} + \boxed{R_{noise+interf}(\varepsilon_\tau)}$$

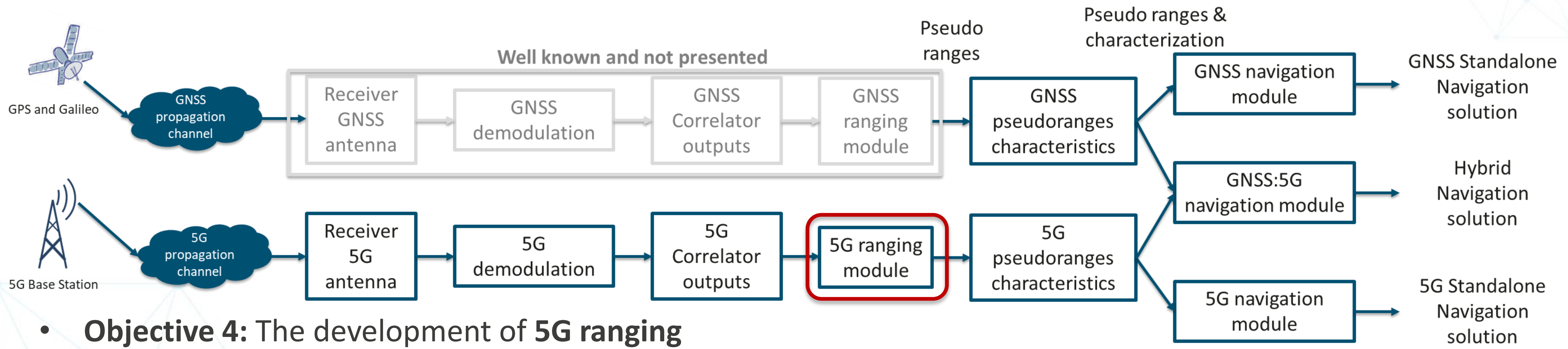
Simplified model available ← Noiseless useful part

Additive Gaussian variable: ~ enhanced noise power

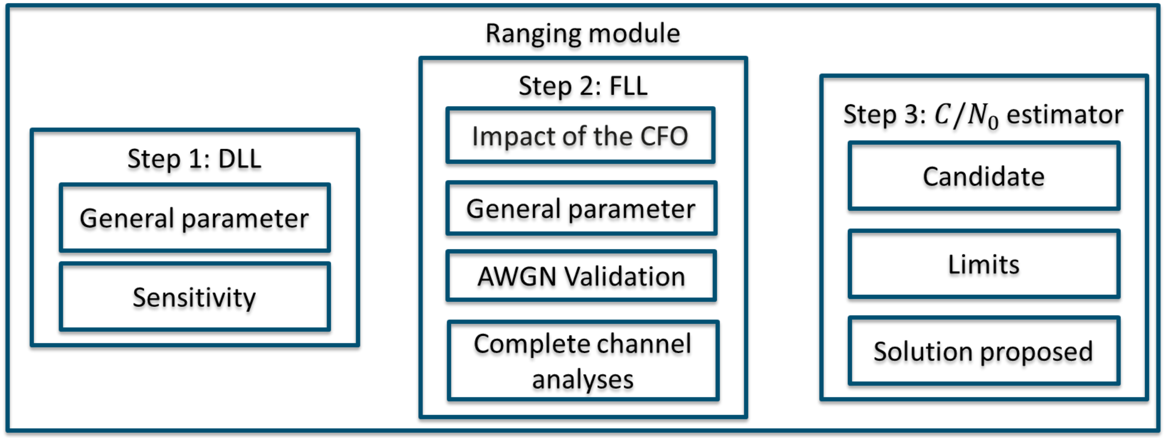
Outline

1. 5G signal presentation
2. Propagation channel
3. Correlator output mathematical models
4. **5G ranging module design**
5. Derivation of pseudo range error distributions
6. Navigation modules and results
7. Conclusion

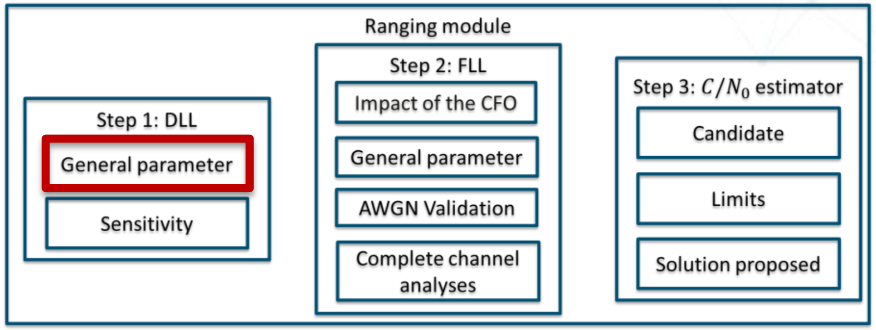
4. 5G ranging module design



- **Objective 4:** The development of **5G ranging modules** to estimate the **time-of-arrival** (TOA) of the signal.
  - 4.1. Description of the TOA estimator
  - 4.2. Necessity analysis of the FLL to improve the tracking performances
  - 4.3. Derivation of a C/N_0 estimator to state the lock condition of the tracking loops and to fill the filters measurement covariance matrix



4. 5G ranging module design

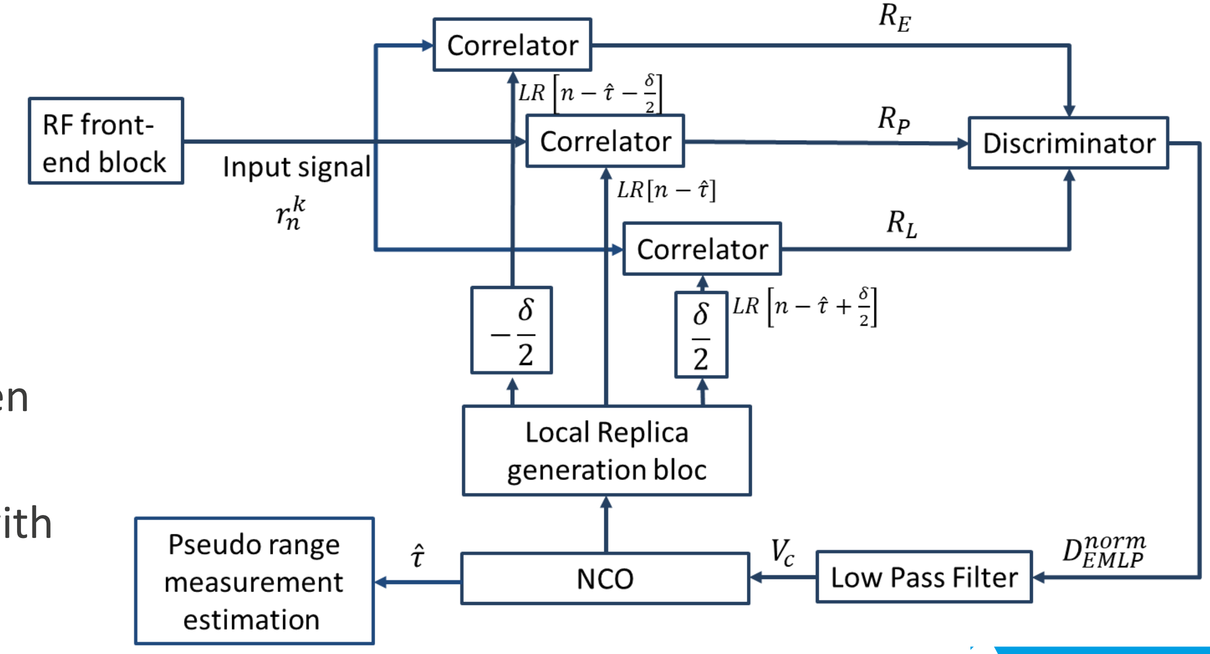


4.1.1. DLL Presentation (1/2)

- Objective:
  - To present the delay estimator

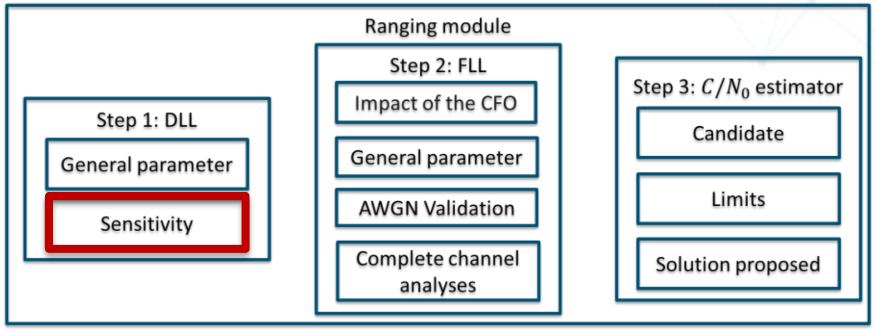
Update Rate	the OFDM symbol duration, $T_{symbol} = \frac{N_{FFT}+N_{CP}}{\Delta f N_{FFT}}$
Discriminator	Early Minus Late Power
Order	2^{nd} order
One-sided noise bandwidth	$B_l = 10\ Hz$ and $B_l = 1\ Hz$

- The proposed DLL is the result of an optimal derivation when assuming a constant AWGN propagation channel
- It can be re-used for the correlator output derived before with the same optimal solution status.
- The joint modelling of the noise and ICI terms as a Gaussian variable allows to select the proposed DLL



Delay Lock Loop architecture

4. 5G ranging module design



4.1.2. DLL Presentation (2/2)

– Sensitivity:

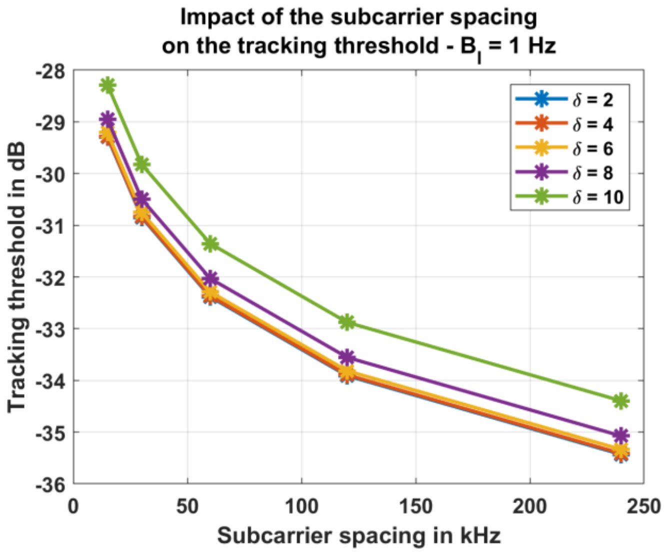
- The SNR at the RF front end output value below for which the loop can be considered to have **lost tracking**.
- The tracking loss criterion specifies that the **DLL has lost its lock** if the tracking error falls outside the linearity zone of the discriminator

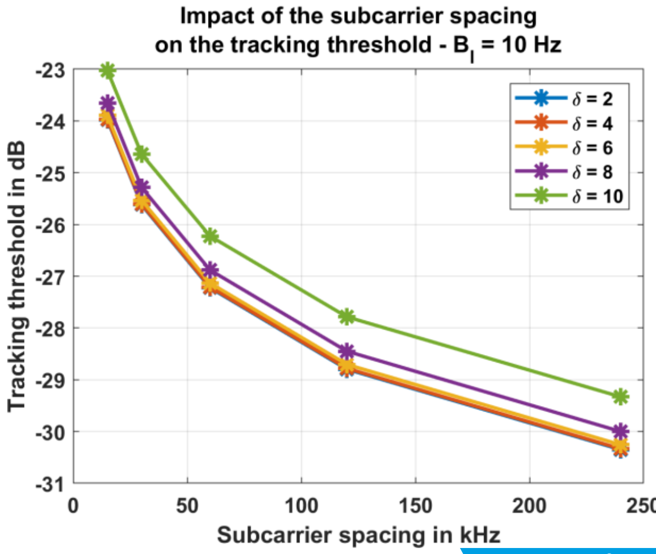
- Usual criterion:

$$3\sqrt{var[\varepsilon_\tau]} < D_{th}$$

- Where
  - $var[\varepsilon_\tau]$ variance of the tracking error estimate
  - D_{th} one-sided linearity zone of the discriminator

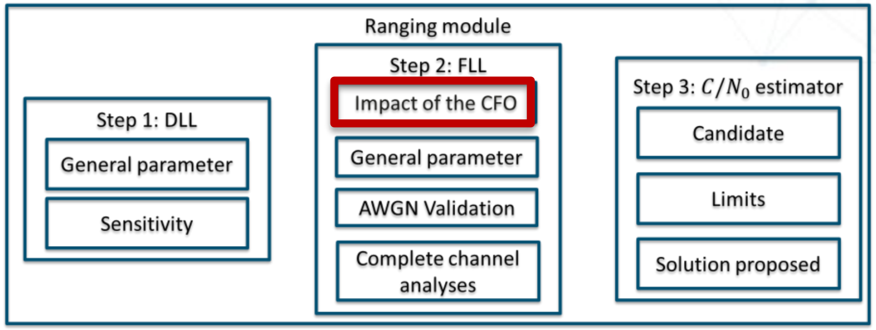
- $$SNR_{demodulator_{th}} = \frac{12^2}{7^2}\frac{B_l T_s K_1}{N_p}\left(1 + \sqrt{1 + \frac{2\cdot 7^2 K_2}{12^2 B_l T_s K_1}}\right)$$





DLL threshold ($SNR_{demodulation_{th}}$)

4. 5G ranging module design



4.2. Necessity to implement a carrier tracking loop

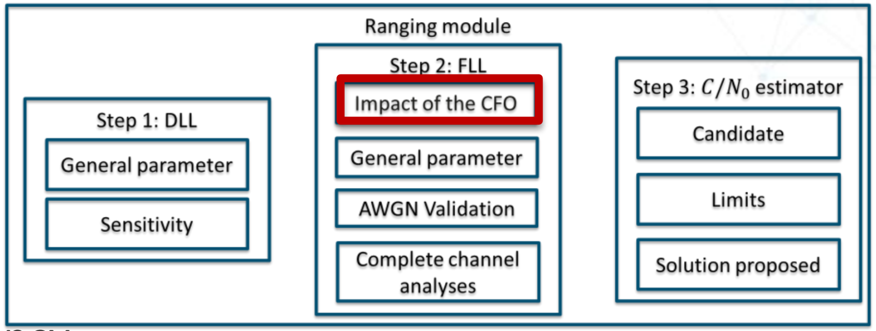
- Observation:
  - The DLL study assumed a perfect estimation of the 5G signals carrier frequency.
- Problematic
  - The baseband received signal is affected by a **residual carrier frequency offset** which impact must be **analyzed**, and **corrected** if necessary

Integer part ← $\delta_f = p_{f_l} + \delta_{f_l}$ → Fractional part $\delta_{f_l} \in [-0.5, 0.5]$

	p_{f_l}	δ_{f_l}
Impact	**Shift** on the demodulated symbol	**Attenuation + phase rotation** on the demodulated symbol and adds an **additional ICI** term
Correction	**Easily estimated/corrected** after the demodulation	**Cannot be corrected** after the demodulation
Study	Impact assumed corrected and **effect neglected**	**Requires to be estimated and corrected**

Which is the impact of the fractional CFO on the DLL tracking performance when applying the correlation integration for 1 OFDM symbol?

4. 5G ranging module design



4.2.2. Theoretical degradation due to CFO

- Objective:
  - To quantify the theoretical degradation of the SNR due to the CFO in order to infer the necessity of estimating the incoming signal carrier frequency
- Theoretical degradation of the SNR due to the CFO
  - $D = \frac{SNR}{SINR} = \frac{\frac{S}{N}}{\frac{A^2 S}{N+P_{ICI}}} = \frac{1}{A^2}\left(1 + \frac{7(\pi\delta_f)^2}{2N_P} SNR\right)$ where: $A = \frac{1}{N_{FFT}} \frac{\sin\left(\pi\delta_{f_l} N_{FFT}\right)}{\sin\left(\pi\delta_{f_l}\right)}$
  - Realistic SNR
    - A lower bound for the SNR can be set using the DLL sensitivity
  - Realistic doppler
    - A worst δ_f is derived when the receiver goes away from a base Station at high speed (50 km/h)
    - $\delta_{f,worst} = 2 f_d T_{sampling} = \frac{2 f_d}{\Delta f N_{FFT}} = \frac{2 f_c \cdot v}{N_{FFT} \cdot \Delta f \cdot c} \quad (cycle/sample)$

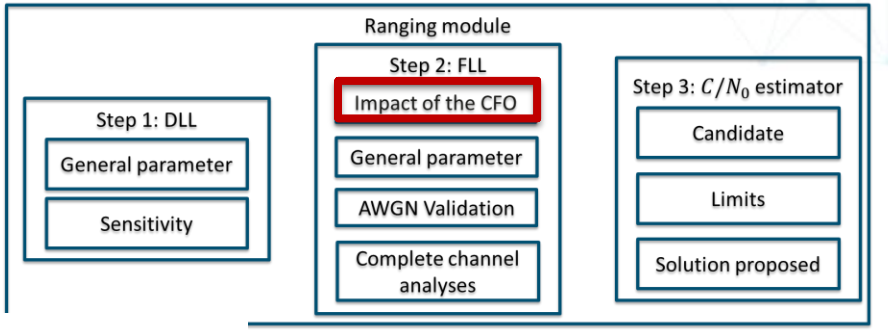
Case	Speed v	Carrier frequency f_c	Subcarrier spacing Δf
1	50 km/h	2 GHz	15 kHz
2		30 GHz	120 kHz
3		60 GHz	120 kHz

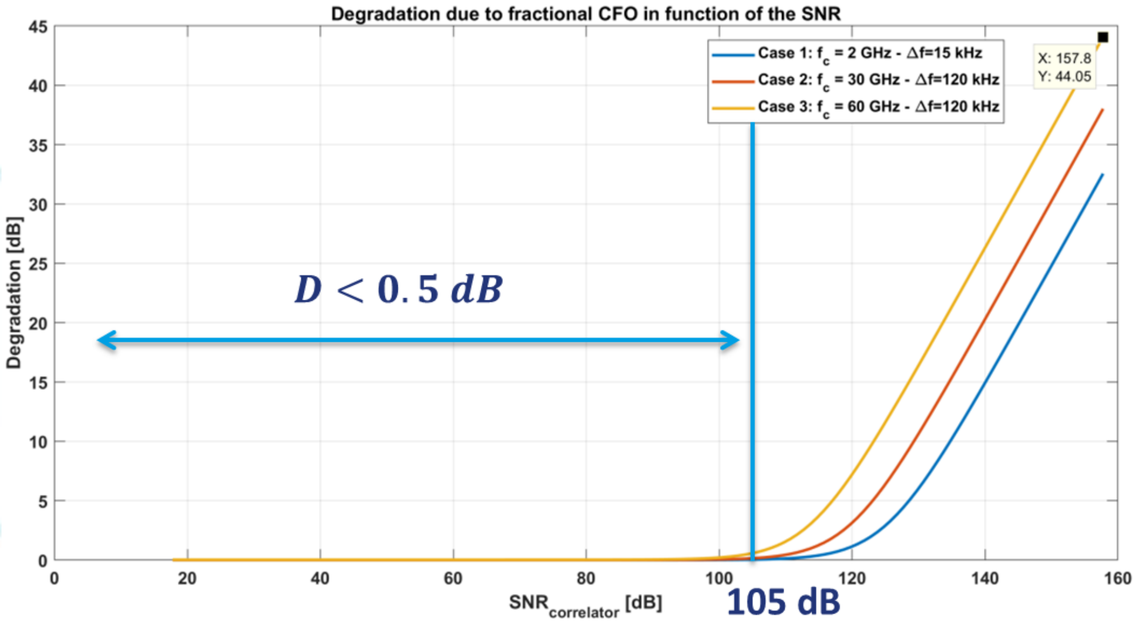
Determination of a realistic value of frequency error

4. 5G ranging module design

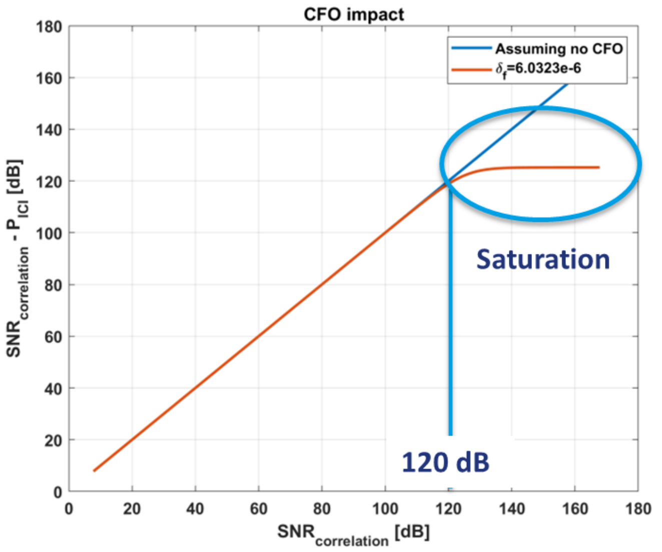
4.2.2. Theoretical degradation due to CFO

- Maximum BS emitted power provided in 3GPP standard: $P_{e_{max}} \cong -6\ dBW$.
- Assumptions: $P_e \cong -30\ dBW \Leftrightarrow SNR_{correlation} = 96\ dB$ → no saturation





Degradation due to a fractional CFO

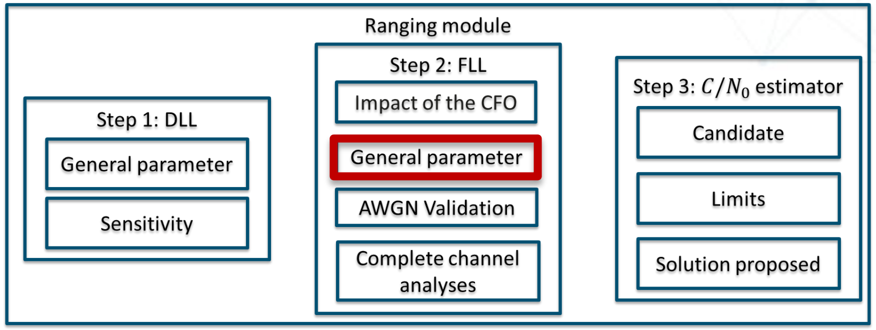


Impact of the Doppler on the $SNR_{correlation}$

$SNR_{correlation} = 120\ dB$
$\Leftrightarrow$
Base station emitted power
$P_e \cong -15\ dBW$

- **A carrier frequency estimator is theoretically not necessary in a AWGN channel for the considered conditions**

4. 5G ranging module design



4.2.1. FLL presentation

– Objective: To present the FLL candidate to lead the analyses

Update Rate	At half the symbol rate, or every $2 \cdot T_{symbol}$
Discriminator	computed at half symbol rate: $D_{FLL}= \frac{angle(R_P(k) \cdot R_P(k-1)^*)}{2\pi N_{FFT}}$
Order	2nd order
Loop bandwidth	$B_{l\,fll} = 10\ Hz$
Local replica phase	θ_{acc}, updated at symbol rate: $\theta_{acc}(k) = \theta_{acc}(k-1) + 2\pi V_c(k)$
VCO	$V_c(k)$, updated every two symbols

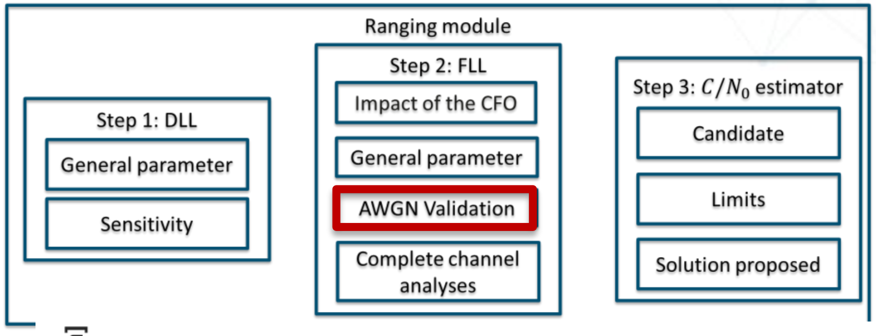
– The FLL outputs are used to correct the phase and Doppler of the incoming signal

$$r^k_{n\ nl,corrected} = r^k_{n\ nl} e^{-i(\boldsymbol{\theta}_{acc}(\boldsymbol{k}-\mathbf{1})+2\pi \boldsymbol{V}_C(\boldsymbol{k})n)}$$

– The contribution channel of the correlator output mathematical model is slightly modified as

$$A_l^k(0) \cong \frac{\left|\alpha_l^k(0)\right|+\left|\alpha_l^{k+1}(0)\right|}{2} e^{i\left(\theta_{0_l}^k-\boldsymbol{\theta}_{acc}(\boldsymbol{k})\right)} e^{i\pi\left(\delta_{f_l}^k-\boldsymbol{V}_c(\boldsymbol{k})\right)\cdot(N_{FFT}-1)} \frac{\sin\left(\pi\left(\delta_{f_l}^k-\boldsymbol{V}_c(\boldsymbol{k})\right)N_{FFT}\right)}{\sin\left(\pi\left(\delta_{f_l}^k-\boldsymbol{V}_c(\boldsymbol{k})\right)\right)}$$

4. 5G ranging module design

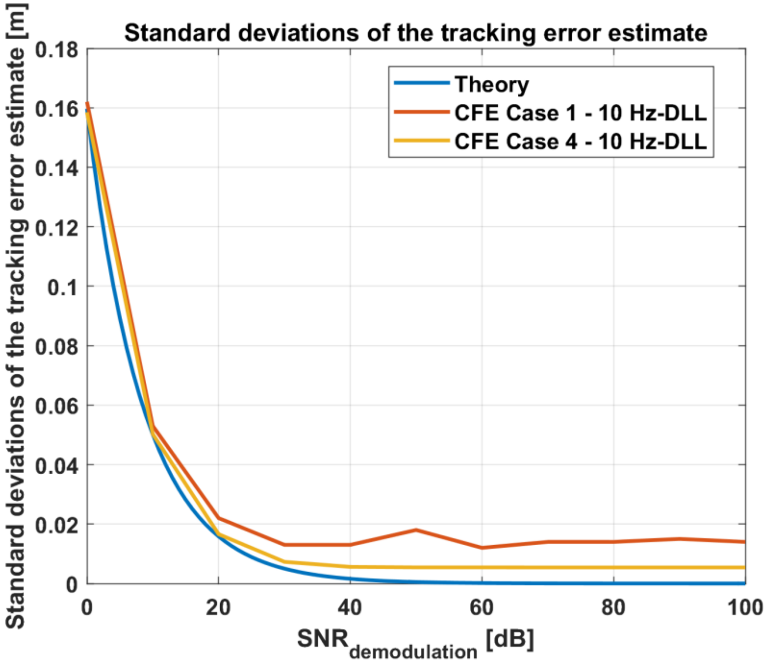


4.2.3. AWGN Validation

- Objective:
  - Validation of the theoretical results AWGN
- Presentation of the tested configurations

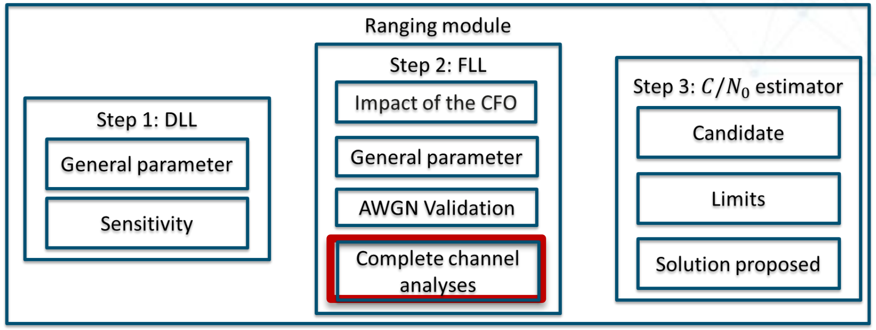
CFE	Case 1	Case 4
Fine frequency acquisition process	Not conducted	Conducted
Carrier frequency tracking process	Not implemented	FLL implemented

- Observations
  - Error approximately equal to 1.5 cm for SNR higher than 40 dB, it decreases to 3 mm for 0 dB
  - Error lower when a FLL is used
  - The differences at high SNR are mostly due to numerical issues.
- Conclusion:
  - Confirmation of the theoretical derivations: the implementation of a carrier frequency estimator is not mandatory for an AWGN propagation channel.



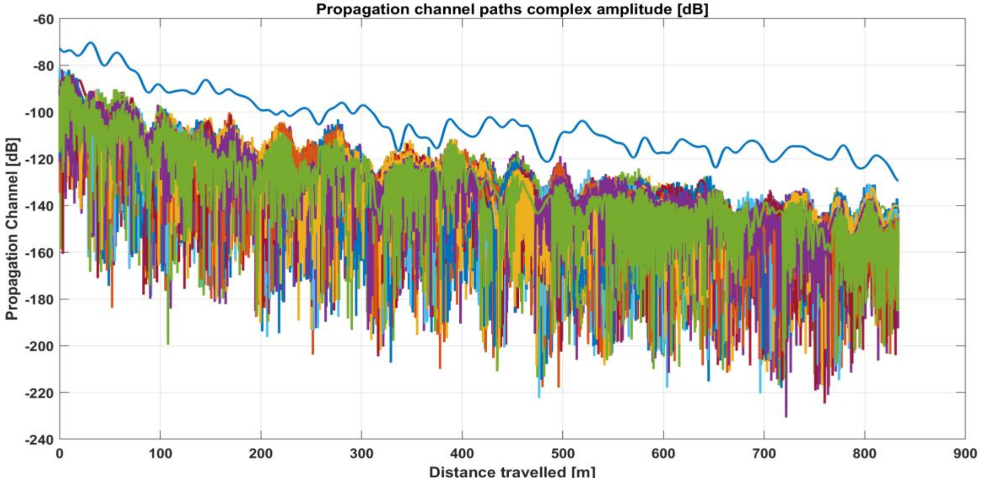
Standard deviations of the tracking error estimate

4. 5G ranging module design



4.2.4. Analyses for a complete (QuaDRiGa) channel

- Hypothesis:
  - Due to the degradation linked to the multipath, a carrier frequency estimator could improve the tracking performances
- Test case:
  - 4 CFE cases assuming a 10 Hz and a 1 Hz DLL loop bandwidth and for the first 300 m of the radial trajectory
- Observations:
  - FLL not required for a 10 Hz DLL loop bandwidth
  - the tracking performances improved for a 1 Hz DLL loop bandwidth when using a FLL
- Conclusion:
  - The FLL is not required but can improve the performances of the ranging module according to the DLL loop bandwidth chosen

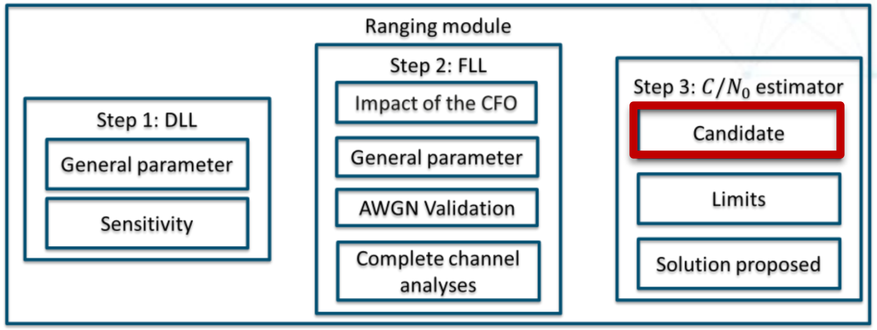


Propagation channel path power for the radial trajectory

Cases	10 Hz-DLL			1 Hz-DLL		
	μ [m]	σ [m]	RMSE [m]	μ [m]	σ [m]	RMSE [m]
CFE C1	0,63	4,74	4,78	-0,99	4,17	4,28
CFE C4	0,57	4,71	4,75	0,21	2,76	2,77

Pseudo range estimation error statistics

4. 5G ranging module design



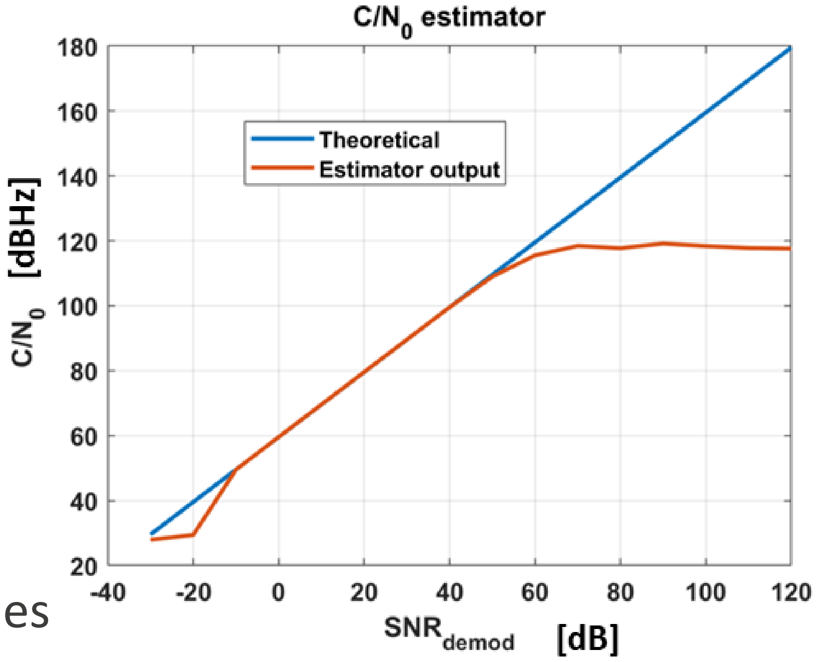
4.3.1. C/N_0 estimator implementation (1/3)

– C/N_0 estimator candidate: Narrow-to-Wideband-Power-Ratio

- The method is based on the comparison of total signal-plus-noise power in two different bandwidths

$\widehat{C/N_0} = 10 \cdot \log_{10}\left(\frac{1}{T}\frac{\hat{\mu}_{NP} - 1}{M - \hat{\mu}_{NP}}\right)$	$\hat{\mu}_{NP} = \frac{1}{K}\sum_{k=1}^{K}\frac{NBP_k}{WBP_k}$
$WBP_k = \left(\sum_{i=1}^{M}(I_i^2 + Q_i^2)\right)_k$	$\boldsymbol{NBP_k = \left(\sum_{i=1}^{M} I_i\right)_k^2 + \left(\sum_{i=1}^{M} Q_i\right)_k^2}$ **phase sensitive!**

- After simulations: $K = 50$ and $M = 10$ is the best found set of values

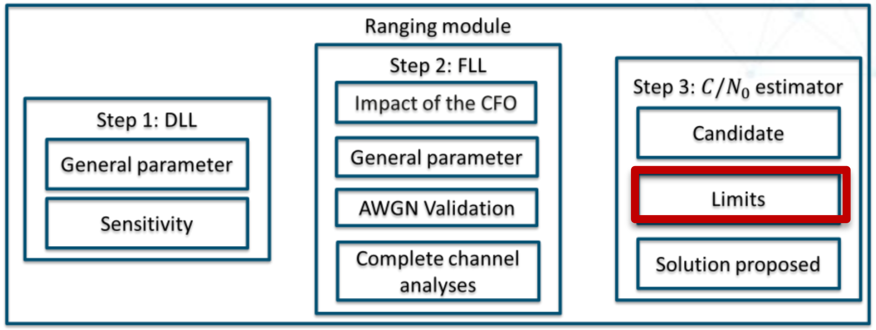


AWGN case C/N_0 estimator study

– Limits identification:

- In **AWGN, a saturation is observed**

4. 5G ranging module design

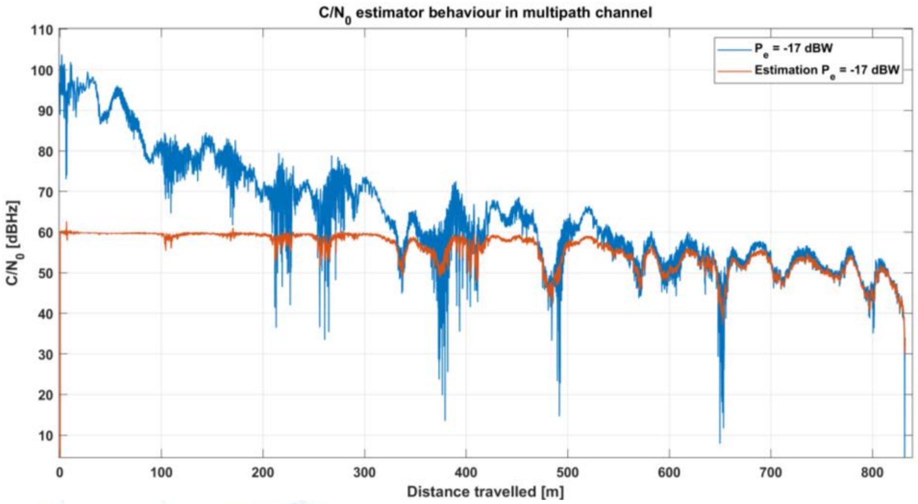


4.3.2. C/N_0 estimator implementation (2/3)

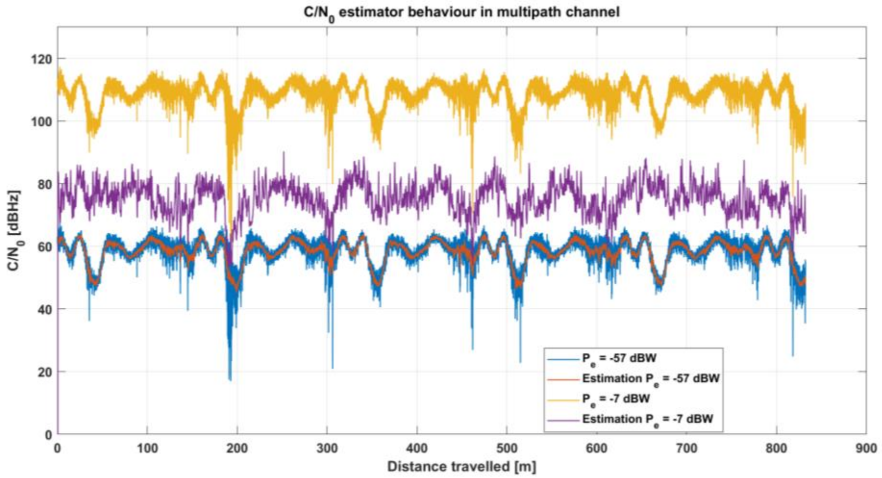
– Limits identification:

- For a complete QuaDRiGa channel

Saturation around $C/N_0 = 60\ dBHz$



Multipath case C/N_0 estimator study – Radial trajectory

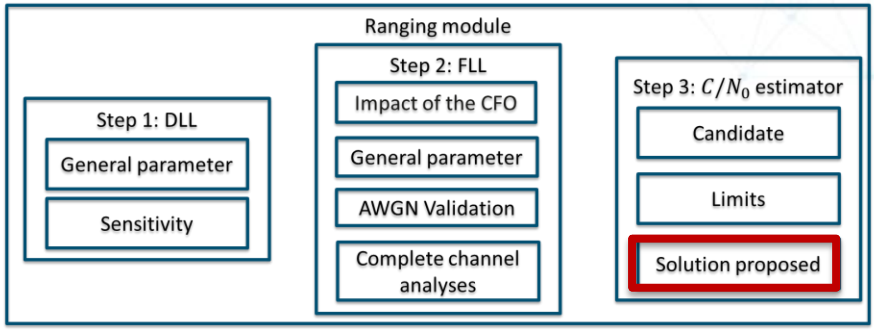


C/N_0 estimator behavior in multipath case for a circular trajectory

Saturation around $C/N_0 = 80\ dBHz$

- The NWPR- C/N_0 estimator works only for the circular trajectory in the LOS case where the LOS signal phase is constant → **the C/N_0 estimator is sensitive to phase variation**
- The evolution of the multipath phases for the radial trajectory is twice the evolution of the multipath phases for the circular trajectory → **the saturation threshold is linked to the phase variation amplitude**

4. 5G ranging module design



4.3.3. C/N_0 estimator implementation (3/3)

– Presentation of potential solutions:

C/N_0 estimator	Interest	Behaviour	Conclusion
Moment Method estimator	It is insensitive to the correlator outputs phase evolution	The estimation is working properly for $C/N_0 < 60\ dBHz$.	The estimation is not behaving as desired for higher C/N_0.
arctangent-NWPR C/N_0 phase-corrected	It corrects the phase in the initial NWPR C/N_0 estimator $R^{\mathrm{k}}_{\mathrm{P}\,corrected}(\varepsilon_\tau) = R^{\mathrm{k}}_{\mathrm{P}}(\varepsilon_\tau)e^{-i\cdot\hat{\phi}[k]}$ $\hat{\phi}[k] = \mathrm{atan}\left(\frac{Imag\left(R^{\mathrm{k}}_{\mathrm{P}}(\varepsilon_\tau)\right)}{Real\left(R^{\mathrm{k}}_{\mathrm{P}}(\varepsilon_\tau)\right)}\right)$	The estimation works well for $C/N_0 < 90/95\ dBHz$ but it is still erroneous for higher C/N_0 values	Both NWPR C/N_0 phase-corrected estimators are better than the NWPR- C/N_0 estimator. For $C/N_0 > 90/95\ dBHz$, the estimator is still not working optimally.
FLL-driven NWPR C/N_0 phase-corrected	$\hat{\phi}[k] = \hat{\phi}[k-1] + 2\pi V_{c,FLL}(k)$		

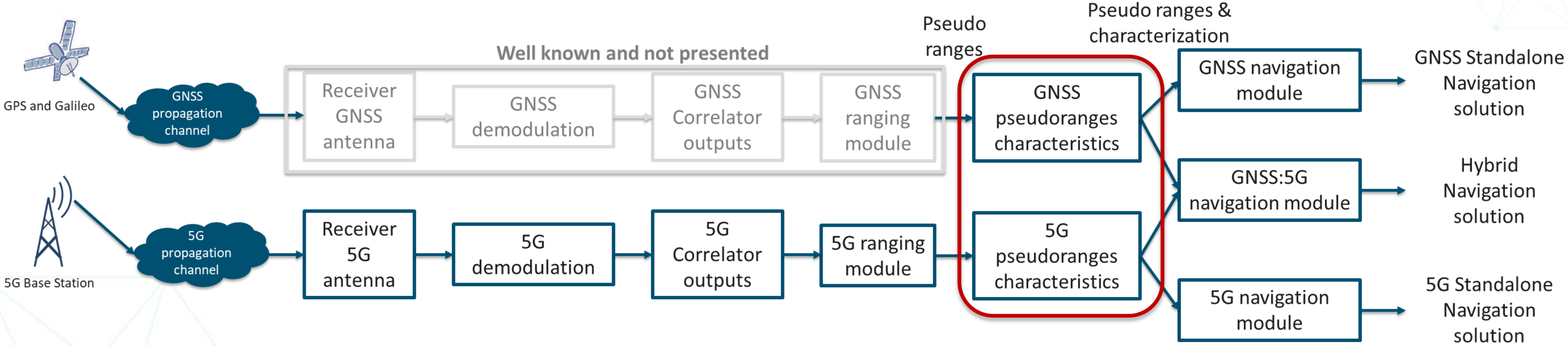
4. 5G ranging module design

- **Conclusion:**
  - ToA estimation:
    - Since the correlator output can be model as a Gaussian variable, the optimal DLL structure for a constant propagation channel can be reused for the evolving propagation channel
  - Carrier Frequency estimation:
    - In AWGN a carrier tracking loop is not necessary
    - For a complete propagation channel, the FLL is not required but can improve the performances of the ranging module according to the DLL loop bandwidth chosen
  - C/N_0 estimation:
    - C/N_0 is expected to be used as lock detector and to fill the measurement covariance matrix of the filter
    - The NWPR- C/N_0 estimator cannot correctly estimate high C/N_0 values since it saturates due to the phase evolution between symbols in the channel contribution term
    - The arctangent and FLL driven C/N_0 phase corrected NWPR estimator can be used instead but are still limited for high C/N_0

Outline

1. 5G signal presentation
2. Propagation channel
3. Correlator output mathematical models
4. 5G ranging module design
5. **Derivation of pseudo range error distributions**
6. Navigation modules and results
7. Conclusion

5. Pseudorange derivation (1/9)



- **Objective 5:** The precise **Derivation of GNSS and 5G pseudo range errors** due to the propagation channels
  - 5.1. Pseudo range definition and time frame considerations
  - 5.2. Problematic and method derivations:
  - 5.3. Presentation of the characterization step
  - 5.4. Presentation of the approximation step
  - 5.5. QuaDRiGa approximation
  - 5.6. SCHUN approximation

5. Pseudorange derivation (2/9)

5.1. Pseudo range definition and time frame considerations

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

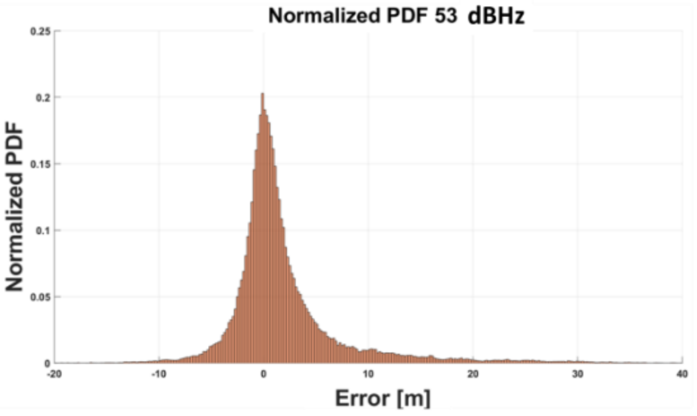
- $r_{GPS_j}, r_{Gal_j}, r_{5G_j}$: geometric distance between the j^{th} GPS/Galileo/5G BS and the receiver
- $\Delta t_{GPS/user}, \Delta t_{GPS/5G}, \Delta t_{GPS/Gal}$ time shifts of the receiver clock, the 5G clock and the Galileo clock with respect to the GPS clock time frame respectively
- $\Delta t_{SYSTEM/SYSTEM_j}$ time shift of the j^{th} SYSTEM clock with respect to the SYSTEM clock time frame (SYSTEM = GPS, Galileo or 5G)
- $\varepsilon_{multipath_{SYSTEM\,j}}$ the delay induced by the multipath effect
- $\varepsilon_{noise_{SYSTEM\,j}}$ The receiver's thermal noise

5. Pseudorange derivation (3/9)

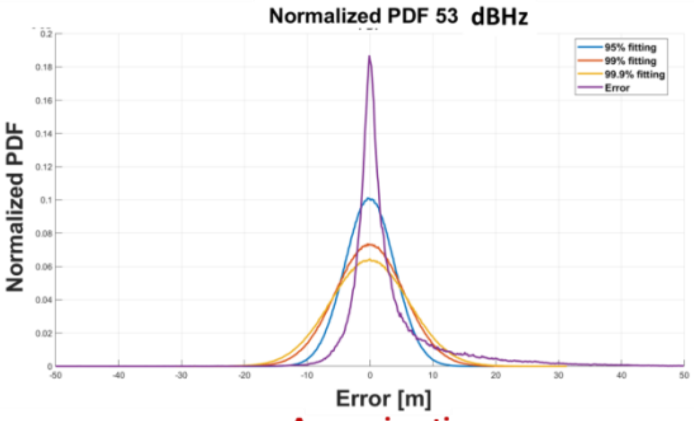
5.2. Problematic and method derivations:

- The propagation channels SCHUN and QuaDRiGa and the thermal noise introduce errors on the pseudo range measurements.
- The **derivation process** objective is to find the **Gaussian distribution which bests approximates a true distribution** (minimization of a cost function), that will allow **to maximize the performances of the navigation filters**
- In order to derive Gaussian distributions for the pseudo range measurements, a two-steps method has been developed:

1. To accurately **characterize** in terms of mean, variance and probability density functions (PDF) the pseudo range measurement errors.
2. To **approximate** these PDFs by Gaussian distributions. Two algorithms have been developed in this work: an over-bounding method and a fitting method.



Characterization



Approximation

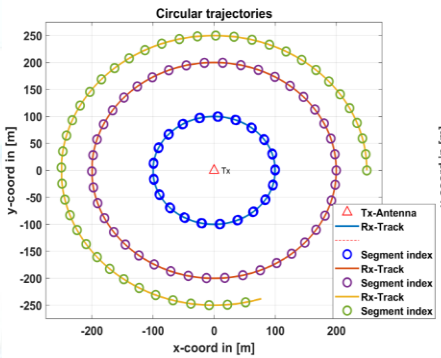
Description of the method

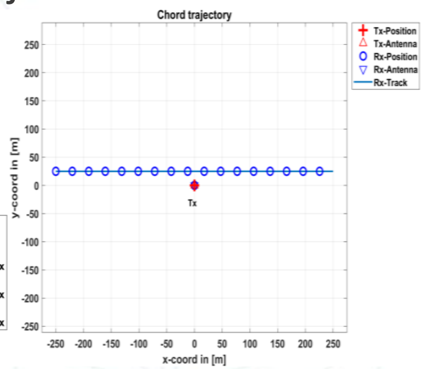
Derivation

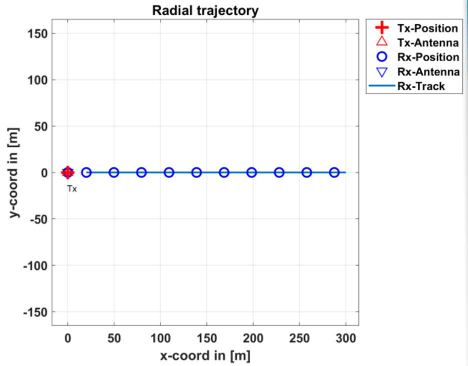
5. Pseudorange derivation (4/9)

5.3. Presentation of the characterization step

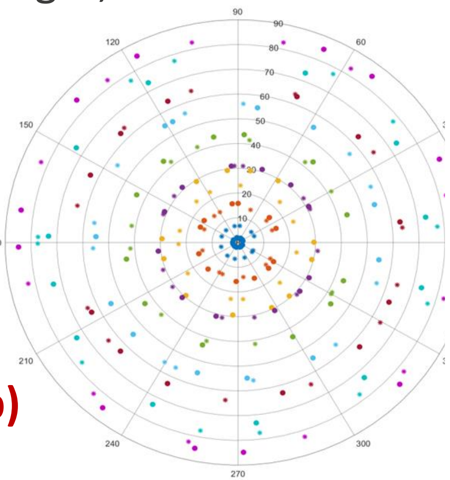
- QuaDRiGa scenario design:
  - high-level scenario
    - typical terrestrial pico-base stations deployed below rooftop in densely populated urban areas
  - signal/receiver characteristics
    - 15 kHz subcarrier spacing
    - 2 GHz carrier frequency.
  - receiver's trajectories

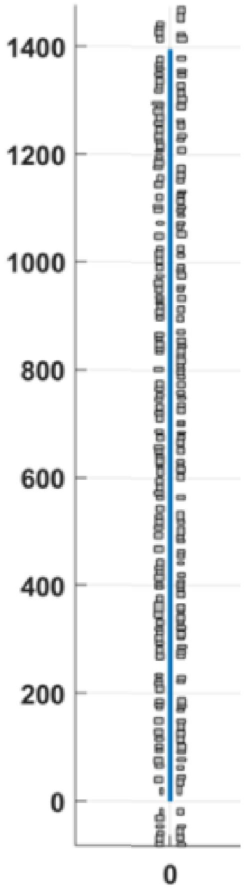






- SCHUN scenario design:
  - The trajectory of the receiver
    - Ensure constant relative azimuth
  - The satellites location in azimuth and elevation
    - Uniform distribution
  - The virtual city characterized by the building width, height, etc





From these scenarios, a PDF characterization is made for each value of true C/N_0 (2 dB step)

Step 2 is then applied to each PDF characterization

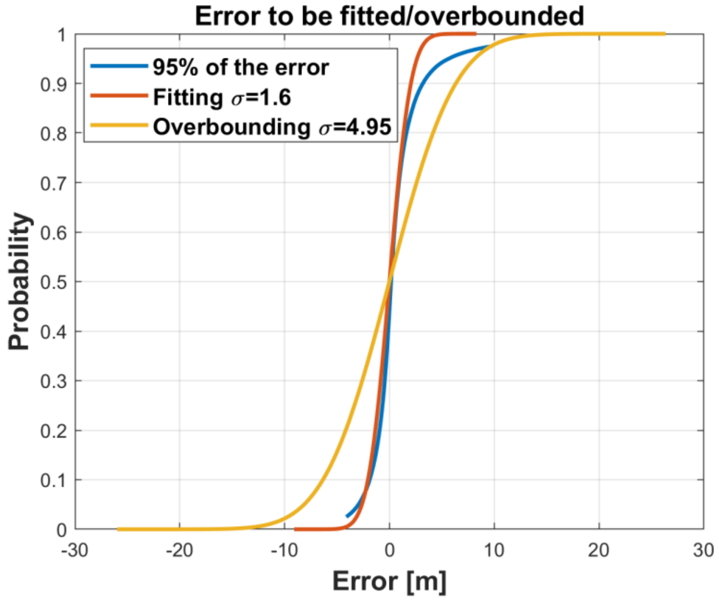
5. Pseudorange derivation (5/9)

5.4. Presentation of the approximation step

– Objective:
  - To select the Gaussian distribution which minimizes a given cost function, where the cost function depends on the Gaussian approximation method.

– Approximation parameters

Confidence bound	95%	99%	99.9%
Mean	$N(0,\sigma)$	$N(mean,\sigma)$	$N(max,\sigma)$



CDF of the error, the fitting and overbounding distributions

– Overbounding
  - To determine the minimal variance of the distribution that will permit to envelop the true distribution over the wanted confidence bound.
  - Cost function:

$$\min \sigma_{over\ bound} \ \ st \begin{cases} CDF_{overbounding}(Error) - CDF_{error}(Error) > 0 & for\ Error < \mu \\ CDF_{overbounding}(Error) - CDF_{error}(Error) < 0 & for\ Error > \mu \end{cases}$$

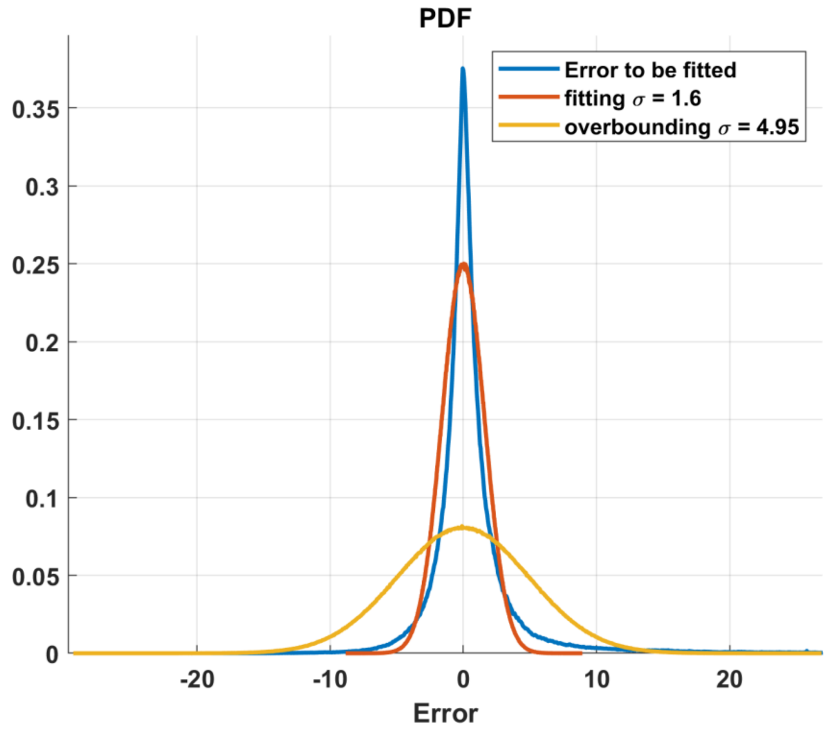
– Fitting
  - To find the variance such that the norm of the error over the abscises axis between the fitting CDF and the CDF of the error to be fitted is minimized.
  - Cost function:

$$\underset{\sigma}{Min} \left\| CDF_{error} - CDF_{fitting}(\sigma) \right\|$$
$$st\ the\ confidence\ bound\ interval$$

5. Pseudorange derivation (6/9)

5.4. Presentation of the approximation step

- Objective:
  - To select the Gaussian distribution which minimizes a given cost function, where the cost function depends on the Gaussian approximation method.
- Method comparison:
  - The fitting distribution allows a better derivation of small errors while the overbounding distribution will cover the tails of the error characterized

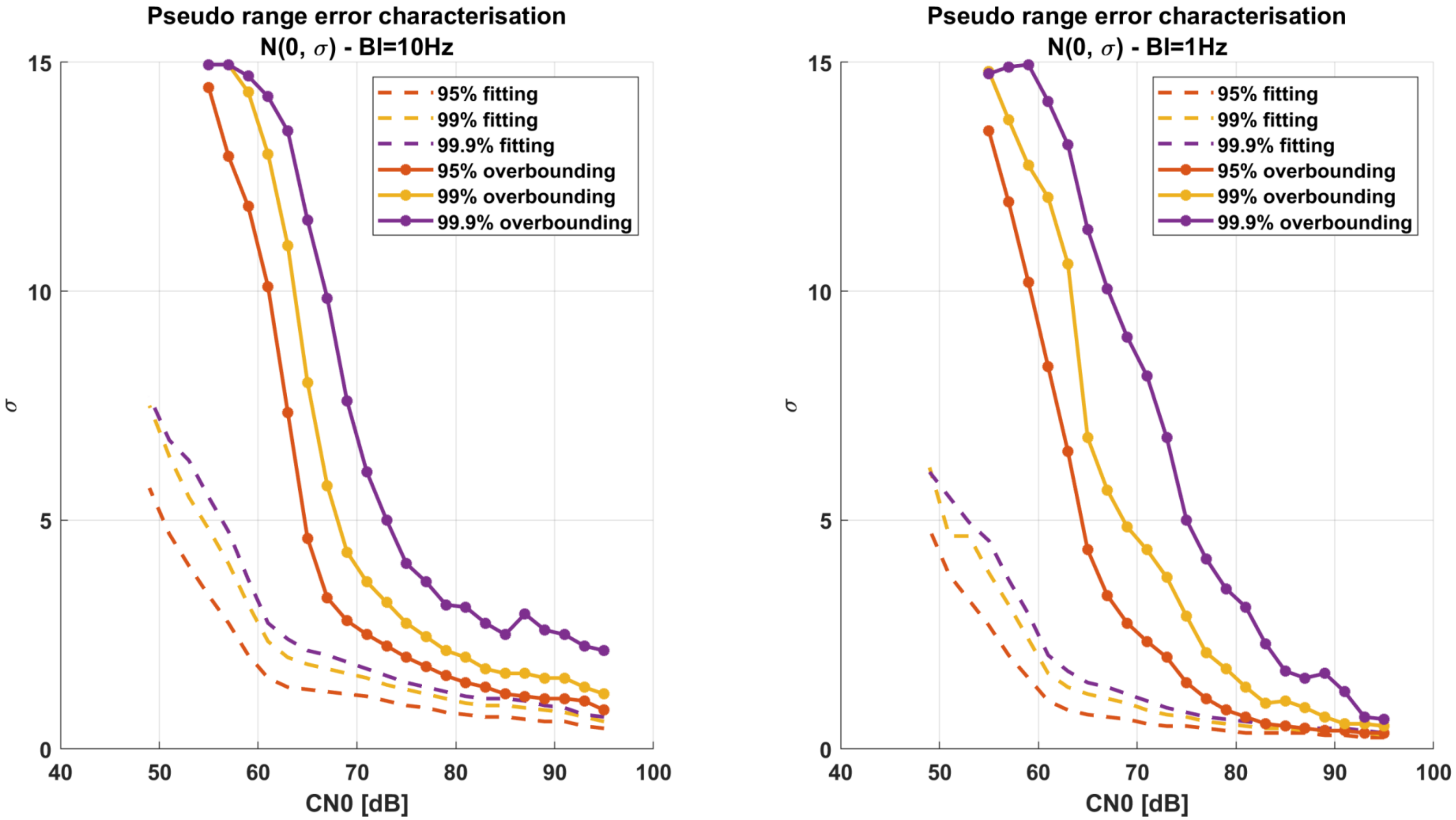


PDF of the error, the fitting and overbounding distributions

5. Pseudorange derivation (7/9)

5.5. QuaDRiGa approximation:

- Parameters:
  - Characterisation for a LOS picocell scenario
  - Generation of pseudo ranges for a set of trajectories to model different distance between the receiver and the BS
  - Characterization made for the true C/N_0



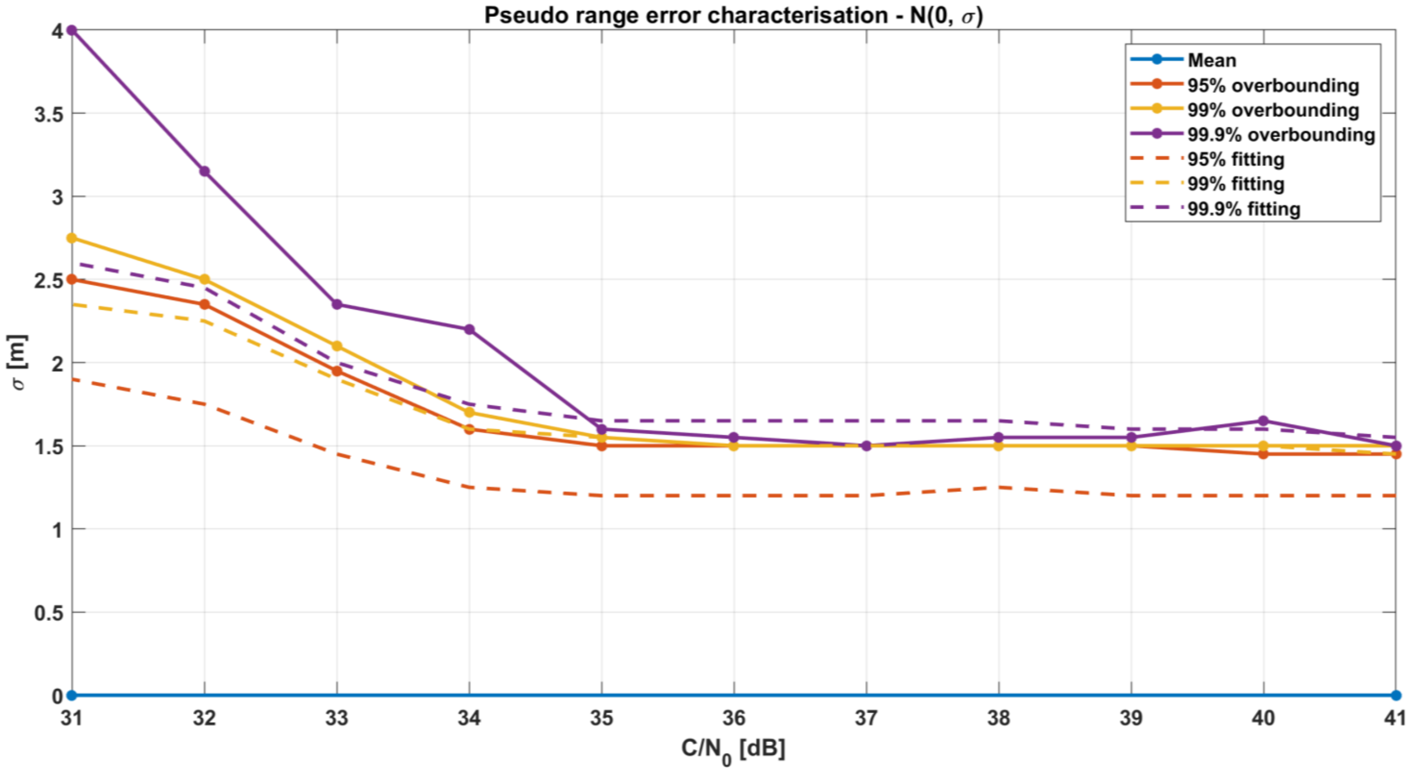
QuaDRiGa pseudo range errors characterization

5. Pseudorange derivation (8/9)

5.6. SCHUN characterization:

- Parameters:
  - Characterisation based on LOS signal with multipath
  - Generation of pseudo ranges for a uniform set of azimuth and elevation satellites
  - Characterization made with respect to the C/N_0

- Characterization made for GPS and used for Galileo as a higher bound characterization



SCHUN pseudo range errors characterization

5. Pseudorange derivation (9/9)

5.7. Conclusion

– The derivation of Gaussian distribution for the pseudo range measurement errors in presence of noise and multipath has been performed for both 5G and GNSS signal

QuaDRiGa conclusions	SCHUN conclusion
- The receiver tracking parameter has an impact. - The fitting and the over bounding methodologies yield very different results. - The distributions are not Gaussian, especially for 5G at low C/N_0, (positively skewed).	- A slight increase of the variances can be observed as the C/N_0 decreases - The distributions for $C/N_0 >$ 35 $dBHz$ are Gaussian

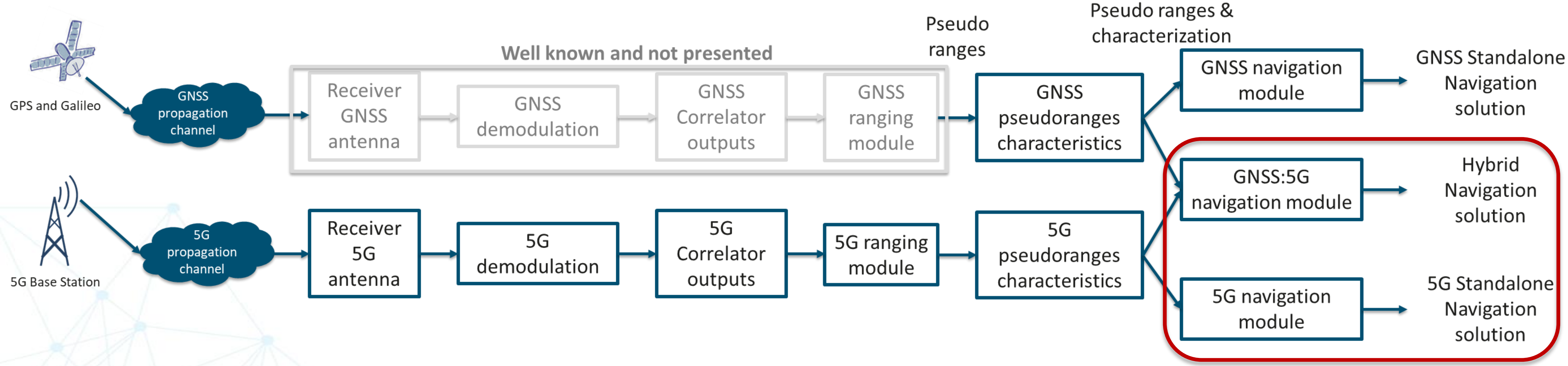
– The final outputs are look up tables obtained using the true C/N_0

C/N_0 $[dBHz]$	PR error σ [m]			
	Fitting (99.9%)		Over bounding (99.9%)	
	1 Hz	10 Hz	1 Hz	10 Hz
97	1.05	1.1	5.85	5.25
95	1.15	1.4	3.35	7.85
93	1.3	1.7	3.8	7.95
91	1.4	1.9	4.65	9.35
89	1.5	2.15	5.0	9.8
87	1.5	2.2	5.15	10.0
85	1.45	2.35	5.1	10.15
83	1.45	2.45	5.05	10.3
81	1.4	2.5	4.95	10.55
79	1.4	2.55	5.05	10.65
77	1.45	2.6	5.25	10.85
75	1.5	2.65	5.5	11.15
73	1.6	2.7	5.8	11.2
71	1.7	2.8	6.45	11.5
69	1.85	3.0	7.45	11.45
67	2.0	3.0	7.8	11.6
65	2.2	3.15	8.45	11.85
63	2.45	3.35	9.25	12.45
61	2.7	3.7	10.3	13.05
59	3.15	4.2	11.9	13.5
57	3.6	4.8	12.5	13.85
55	4.2	5.5	13.2	14.25
53	4.8	6.2	13.45	14.7
51	5.4	7.25	13.25	15.4
49	5.95	8.1	14.0	16.35
47	7.25	8.05	15.0	17.7
45	7.65	8.15	15.4	18.7
43	6.75	8.25	16.1	19.7
41	6.45	7.55	16.35	20.25
39	7.15	7.45	17.3	21.45

Look up table for QuaDRiGa

Outline

6. Navigation modules and results



- Objective 6: The development of **hybrid navigation modules** exploiting/adapted to the derived pseudo range measurements mathematical models.
  - 6.1. Navigation Filter Presentation
  - 6.2. Configurations
  - 6.3. Results

6. Navigation modules and results

6.1. Navigation filters presentation (1/2)

- **State model:**

$$X_k = [X \quad V_X \quad Y \quad V_Y \quad Z \quad V_Z \quad c\cdot\Delta t_{GPS/user} \quad c\cdot\dot{\Delta t}_{GPS/user} \quad c\cdot\Delta t_{GPS/Gal} \quad c\cdot\Delta t_{GPS/5G}]$$

- **Measurement model:** $Y_k = h(X_k) + V_k$

  - $h(X_k)$ is observation matrix $h(X_k) = \begin{bmatrix} \boxed{\begin{matrix} h^{(GPS)}(X_k) \\ h^{(Gal)}(X_k) \end{matrix}} \\ h^{(5G)}(X_k) \\ \dot{h}^{(GPS)}(X_k) \\ \dot{h}^{(Gal)}(X_k) \end{bmatrix}$

$$h^{(GPS)}(X_k) = \begin{bmatrix} d_{predicted_1}^{(GPS)} + c\cdot\widehat{\Delta t}_{GPS/user} - c\cdot\Delta t_{GPS/sat_{j,GPS}} \\ \cdots \\ d_{predicted_{N_{GPS}}}^{(GPS)} + c\cdot\widehat{\Delta t}_{GPS/user} - c\cdot\Delta t_{GPS/sat_{N_{GPS},GPS}} \end{bmatrix}$$

$$h^{(Gal)}(X_k) = \begin{bmatrix} d_{predicted_1}^{(Gal)} + c\cdot\widehat{\Delta t}_{GPS/user} - c\cdot\widehat{\Delta t}_{GPS/Gal} - c\cdot\Delta t_{Gal/sat_{1,Gal}} \\ \cdots \\ d_{predicted_{N_{Gal}}}^{(Gal)} + c\cdot\widehat{\Delta t}_{GPS/user} - c\cdot\widehat{\Delta t}_{GPS/Gal} - c\cdot\Delta t_{Gal/sat_{N_{Gal},Gal}} \end{bmatrix}$$

  - $h^{(X)}$ are pseudo range code measurements
  - $\dot{h}^{(X)}$ are pseudo range rate measurements
  - V_k measurement noise vector

- **Navigation filters: EKF and UKF**

6. Navigation modules and results

6.1. Navigation filters presentation (1/2)

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

$$h^{(GPS)}(X_k) = \begin{bmatrix} d_{predicted_1}^{(GPS)} + c\cdot\widehat{\Delta t}_{GPS/user} - c\cdot\cancel{\Delta t_{GPS/sat_{j,GPS}}} \\ \cdots \\ d_{predicted_{N_{GPS}}}^{(GPS)} + c\cdot\widehat{\Delta t}_{GPS/user} - c\cdot\cancel{\Delta t_{GPS/sat_{N_{GPS},GPS}}} \end{bmatrix}$$

$$h^{(Gal)}(X_k) = \begin{bmatrix} d_{predicted_1}^{(Gal)} + c\cdot\widehat{\Delta t}_{GPS/user} - c\cdot\widehat{\Delta t}_{GPS/Gal} - c\cdot\cancel{\Delta t_{Gal/sat_{1,Gal}}} \\ \cdots \\ d_{predicted_{N_{Gal}}}^{(Gal)} + c\cdot\widehat{\Delta t}_{GPS/user} - c\cdot\widehat{\Delta t}_{GPS/Gal} - c\cdot\cancel{\Delta t_{Gal/sat_{N_{Gal},Gal}}} \end{bmatrix}$$

Hypothesis: Perfectly known

6. Navigation modules and results

6.1. Navigation filters presentation (1/2)

- **State model:**

$$X_k = [X \quad V_X \quad Y \quad V_Y \quad Z \quad V_Z \quad c \cdot \Delta t_{GPS/user} \quad c \cdot \dot{\Delta t}_{GPS/user} \quad c \cdot \Delta t_{GPS/Gal} \quad c \cdot \Delta t_{GPS/5G}]$$

- **Measurement model: $Y_k = h(X_k) + V_k$**

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

$$h^{(5G)}(X_k) = \begin{bmatrix} d_{measure_1}^{(5G)} + c \cdot \Delta t_{GPS/user} - c \cdot \Delta t_{GPS/5G} - c \cdot \Delta t_{5G/BS_1} \\ \cdots \\ d_{measure_{N_{5G}}}^{(5G)} + c \cdot \Delta t_{GPS/user} - c \cdot \Delta t_{GPS/5G} - c \cdot \Delta t_{5G/BS_{N_{5G}}} \end{bmatrix}$$

Where

$$d_{predicted_j}^{(5G)} = \sqrt{\left(\hat{x}_k - x_{BS_j}\right)^2 + \left(\hat{y}_k - y_{BS_j}\right)^2 + \left(\hat{z}_k - z_{BS_j}\right)^2}$$

- **Navigation filters: EKF and UKF**

6. Navigation modules and results

6.1. Navigation filters presentation (1/2)

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

$$h^{(5G)}(X_k) = \begin{bmatrix} d_{measure_1}^{(5G)} + c\cdot\Delta t_{GPS/user} - c\cdot\Delta t_{GPS/5G} - c\cdot\cancel{\Delta t_{5G/BS_1}} \\ \dots \\ d_{measure_{N_{5G}}}^{(5G)} + c\cdot\Delta t_{GPS/user} - c\cdot\Delta t_{GPS/5G} - c\cdot\cancel{\Delta t_{5G/BS_{N_{5G}}}} \end{bmatrix}$$

Where

$$d_{predicted_j}^{(5G)} = \sqrt{\left(\hat{x}_k - x_{BS_j}\right)^2 + \left(\hat{y}_k - y_{BS_j}\right)^2 + \left(\hat{z}_k - z_{BS_j}\right)^2}$$

Hypothesis: BS perfectly synchronized among each others

6. Navigation modules and results

6.1. Navigation filters presentation (1/2)

- **State model:**
  $X_k = [X \quad V_X \quad Y \quad V_Y \quad Z \quad V_Z \quad c \cdot \Delta t_{GPS/user} \quad c \cdot \dot{\Delta t}_{GPS/user} \quad c \cdot \Delta t_{GPS/Gal} \quad c \cdot \Delta t_{GPS/5G}]$
- **Measurement model: $Y_k = h(X_k) + V_k$**
  - $h(X_k)$ 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**

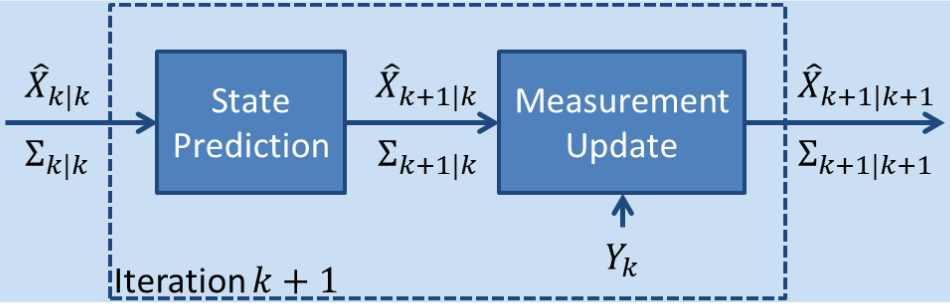
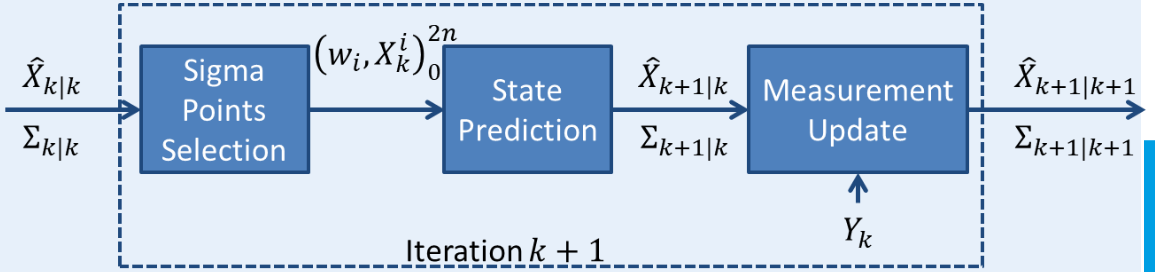
$$h^{(\dot{GPS})}(X_k) = \begin{bmatrix} h_1^{(\dot{GPS})}(X_k) \\ \dots \\ h_{N_{GPS}}^{(\dot{GPS})}(X_k) \end{bmatrix}$$

$$= \begin{bmatrix} \left(\widehat{v_x}_{k+1|k} - v_{xGPS_1}\right) \cdot \frac{\hat{x}_{k+1|k} - x_{GPS_1}}{d_{predicted_1}^{(GPS)}} + \left(\widehat{v_y}_{k+1|k} - v_{yGPS_1}\right) \cdot \frac{\hat{y}_{k+1|k} - y_{GPS_1}}{d_{predicted_1}^{(GPS)}} \\ + \left(\widehat{v_z}_{k+1|k} - v_{zGPS_1}\right) \cdot \frac{\hat{z}_{k+1|k} - z_{GPS_1}}{d_{predicted_1}^{(GPS)}} + c \cdot \Delta t_{GPS/user}^{\cdot} \\ \dots \\ \left(\widehat{v_x}_{k+1|k} - v_{xGPS_{N_{GPS}}}\right) \cdot \frac{\hat{x}_{k+1|k} - x_{GPS_{N_{GPS}}}}{d_{predicted_{N_{GPS}}}^{(GPS)}} + \left(\widehat{v_y}_{k+1|k} - v_{yGPS_{N_{GPS}}}\right) \cdot \frac{\hat{y}_{k+1|k} - y_{GPS_{N_{GPS}}}}{d_{predicted_{N_{GPS}}}^{(GPS)}} \\ + \left(\widehat{v_z}_{k+1|k} - v_{zGPS_{N_{GPS}}}\right) \cdot \frac{\hat{z}_{k+1|k} - z_{GPS_{N_{GPS}}}}{d_{predicted_{N_{GPS}}}^{(GPS)}} + c \cdot \Delta t_{GPS/user}^{\cdot} \end{bmatrix}$$

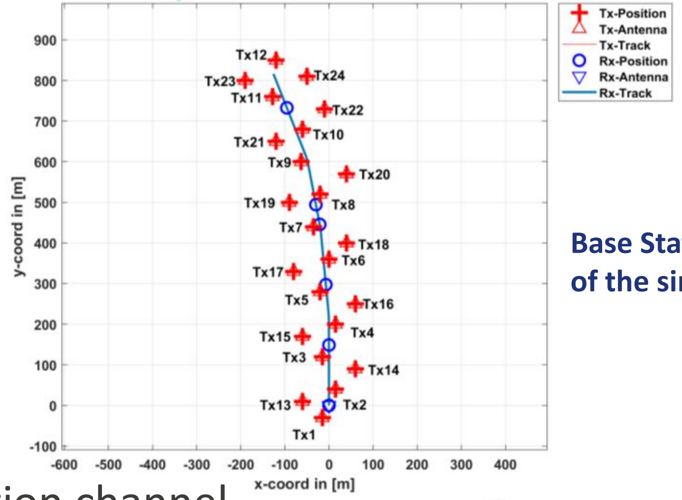
ENAC ThalesAlenia Space (a Thales / Leonardo company) cnes TéSA (Telecommunications for Space and Aeronautics) INP Toulouse

6. Navigation modules and results

6.1. Navigation filters presentation (2/2)

	Linearization techniques	Example: observation equation	Illustration
EKF	- Based on an **analytical** method - **Taylor polynomial expansion** about a single point	$\hat{Y}_{k+1\|k} = H_k\,\hat{X}_k$ $H_k = \frac{\partial h}{\partial X_k}_{\|X_k=\hat{X}_{k\|k-1}}$	
UKF	- Based on a **statistical** method - 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.	$\hat{Y}_{k+1\|k} \cong \sum_{j=0}^{2n} w_j h\left(X_k^j, V_k\right)$	$\hat{X}$: *state vector* Σ: *covariance matrix* n: *state vector dimension* w_i: *weight* X_k^i: *sigma point i* 

6. Navigation modules and results



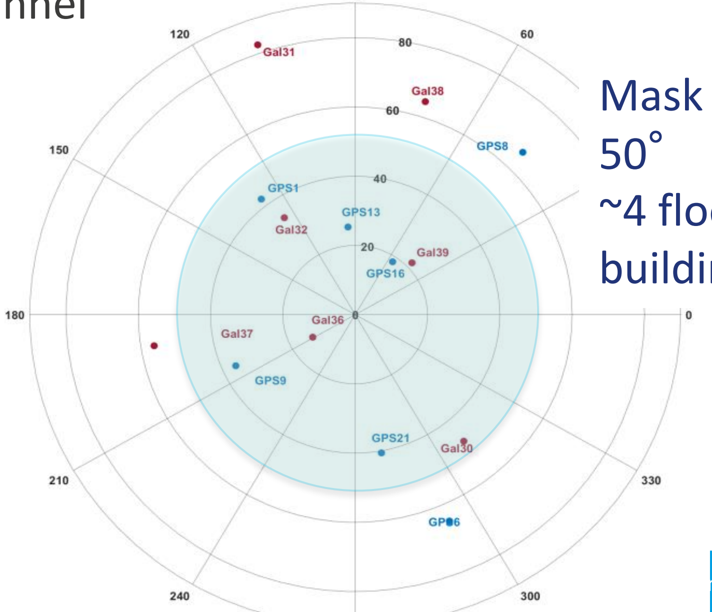
Base Station localization of the simulated scenario

6.2. Configurations

- **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 view
  - 60 s simulation duration
- **Figure of merit**
  - Root Mean Square Error (RMSE) of the positioning solution
    - Along the horizontal plane :

$$RMSE_H(t) = \sqrt{E[(X_{true}(t) - X_{estim}(t))^2 + (Y_{true}(t) - Y_{estim}(t))^2]}$$

    - Along the vertical axis: $RMSE_z(t) = \sqrt{E[(Z_{true}(t) - Z_{estim}(t))^2]}$



Mask angle 50°
~4 floors building

Skyplot of the simulated scenario

6.3. Results (1/4)

– Objectives:

- To study the performances of the EKF and UKF navigation solutions in order to define the more appropriate tuning in term of characterization, synchronization module parameterization.
- To study the impact of the navigation filter, of the measurement covariance matrix and C/N_0 estimator over the best solution defined in the previous section.

– Method:

- Step 1: EKF and UKF tuning based on the study of:
  - Confidence bound impact
  - Approximation method impact
  - Synchronization module impact
- Step 2: Impact analysis over the best identified solution
  - Navigation filter
  - Measurement error characterization
  - C/N_0 estimator

6. Navigation modules and results

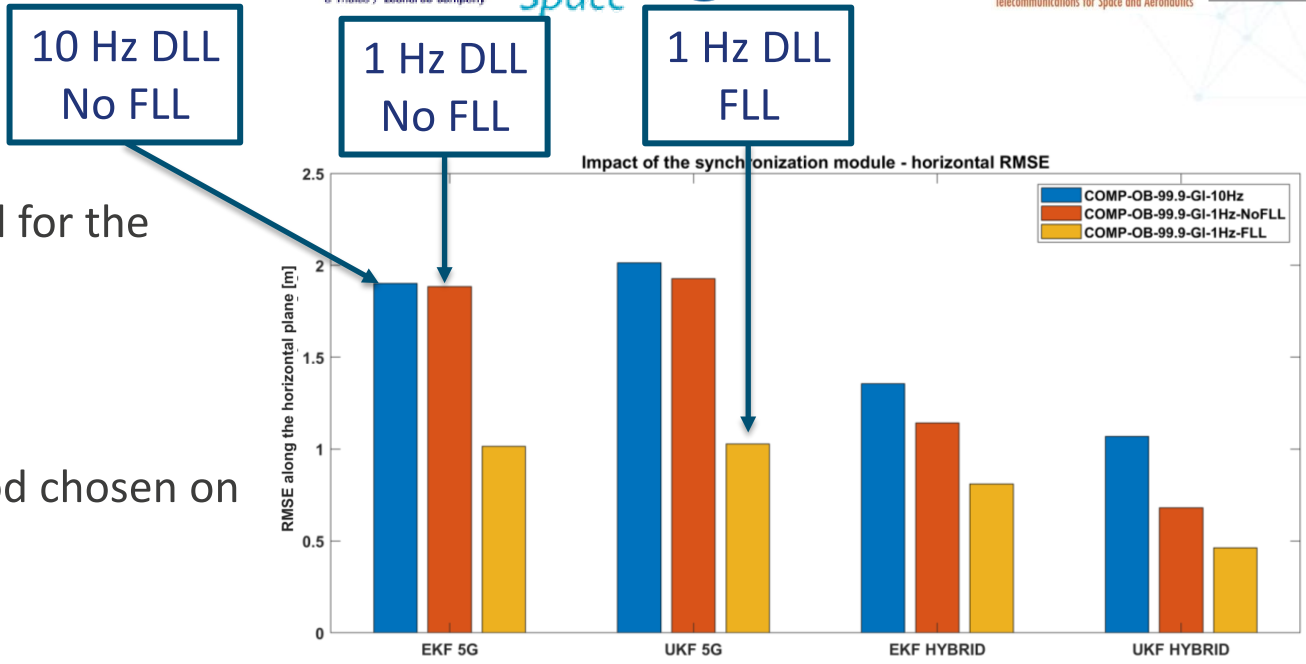
6.3. Step 1: EKF and UKF tuning (2/4)

- Confidence bound impact
  - To study the impact of the confidence bound used for the characterization on the filter performances

  → 99.9% confidence bound recommended
- Approximation method impact
  - To study the impact of the characterization method chosen on the filter performances

  → Overbounding method recommended
- Synchronization module impact
  - To study the impact of the DLL loop bandwidth: 10 Hz or 1 Hz when no FLL is considered
  - To study the impact of the FLL for a 1 Hz DLL loop bandwidth

  → 1 Hz DLL loop bandwidth and a FLL is recommended
- Best tuning:
  - **99.9% overbounding characterization with a 1 Hz DLL loop bandwidth and a FLL**



Synchronization module impact – horizontal RMSE

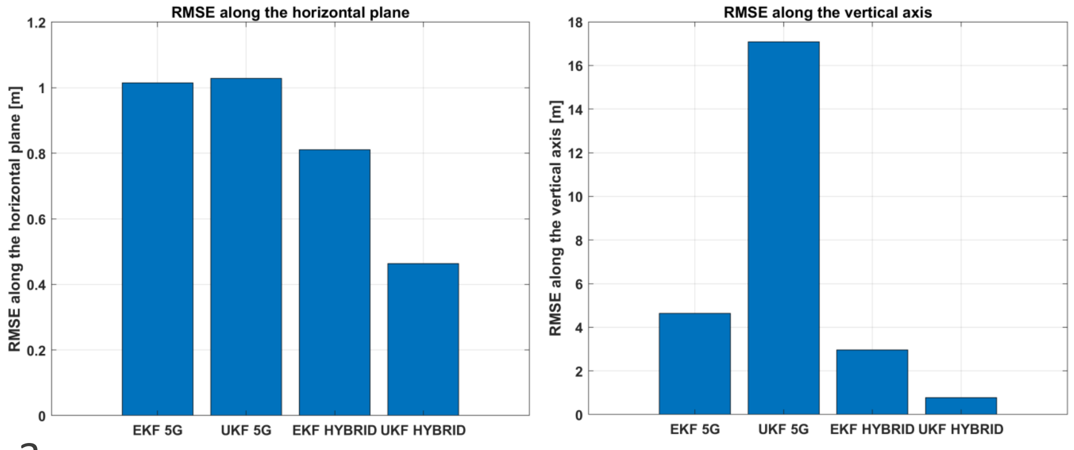
RMSE (m)	X	Y	Z	X^2+Y^2
EKF GNSS	0.47	1.10	2.66	1.20
EKF 5G	0.61	0.81	4.64	1.01
UKF 5G	0.67	0.78	17.09	1.03
EKF HYBRID	0.49	0.64	2.96	0.81
UKF HYBRID	0.43	0.38	0.75	0.58

Optimal solution performances

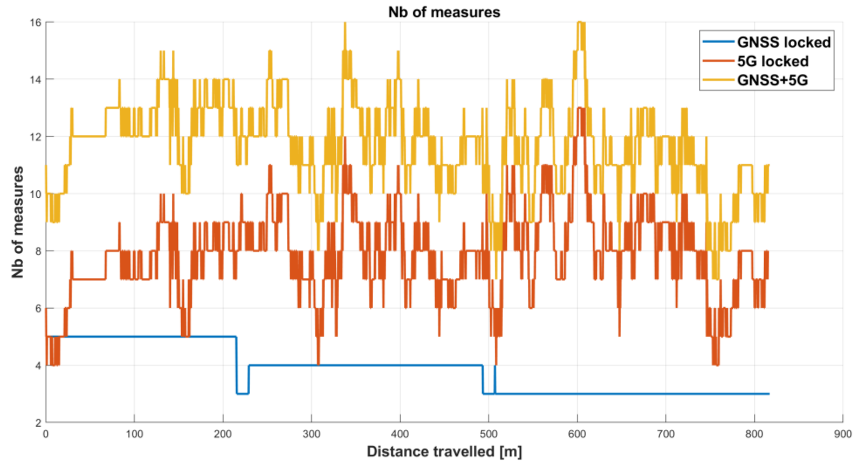
6. Navigation modules and results

6.3. Step 2: Impact analysis over the best solution (3/4)

- Impact of the navigation filter
  - *Observation:*
    - For 5G standalone solution, there are no significant differences between the UKF and the EKF
    - The vertical RMSE is much higher than the horizontal RMSE, a predictable behavior since all BSs are at the same height (bad Z axis geometry)
    - The hybrid navigation solution provides better solution than the standalone navigation solutions.
  - *Conclusion:*
    - The use of the hybrid navigation solution is recommended
    - The use of the UKF is recommended compared to the EKF.



Impact of the navigation filters used over the optimal solution



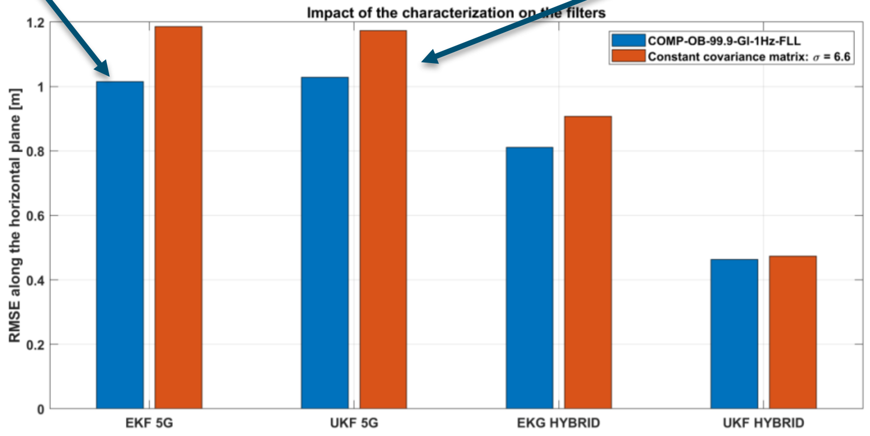
Number of measures

6. Navigation modules and results

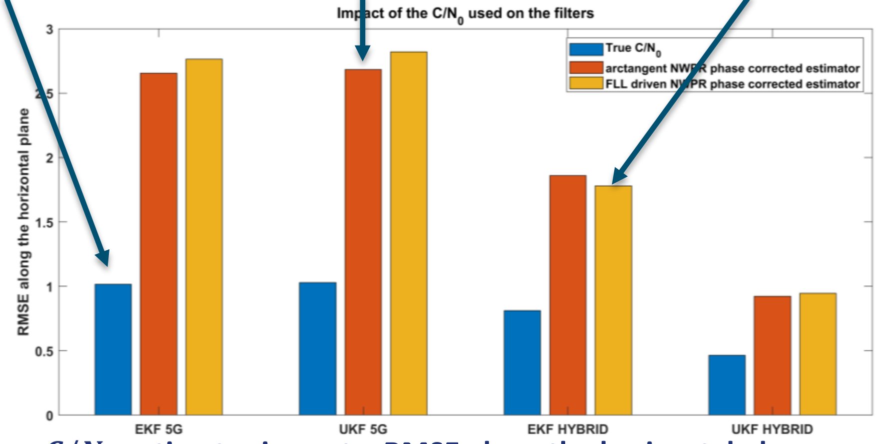
6.3. Step 2: Impact analysis over the best solution (4/4)

- Impact of the measurement error characterization
  - To determine the improvements brought by an accurate measurement covariance matrix
- Impact of the C/N_0 estimator
  - To determine the impact of an estimation of the C/N_0

- Observations:
  - An accurate measurement covariance matrix improves the filter performances
  - A estimation of the C/N_0 degrades the filter performances
  - The improvements brought by the accurate covariance matrix are erased by an inaccurate estimate of the C/N_0



Characterization impact RMSE along the horizontal plane



C/N_0 estimator impact – RMSE along the horizontal plane

6. Navigation modules and results

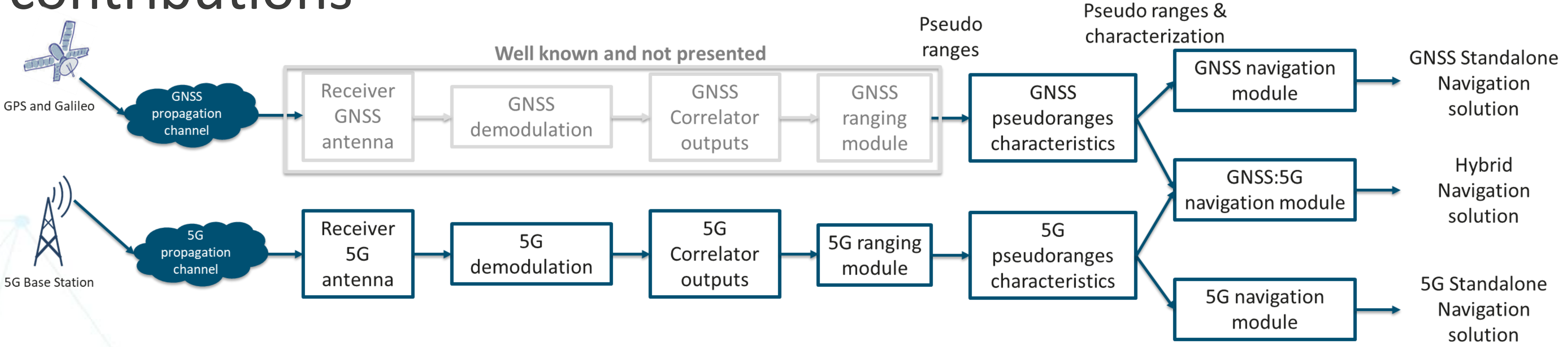
6.4. Conclusions

- Identification of the optimal EKF and UKF tuning
  - 99.9% overbounding characterization with a 1 Hz DLL loop bandwidth and a FLL
- Impact analysis
  - Impact of the navigation filter
    - The use of the hybrid navigation solution is recommended
    - The use of the UKF is recommended compared to the EKF.
  - Impact of the measurement error characterization
    - An accurate approximation of the pseudo range measurement errors improves the performances of the navigation filters
  - Impact of the C/N_0 estimator
    - The UKF hybrid navigation solution are degraded by approximately 40 cm with the use of the NWPR C/N_0 phase corrected estimator along the horizontal plane.

Outline

7. Conclusions (1/4)

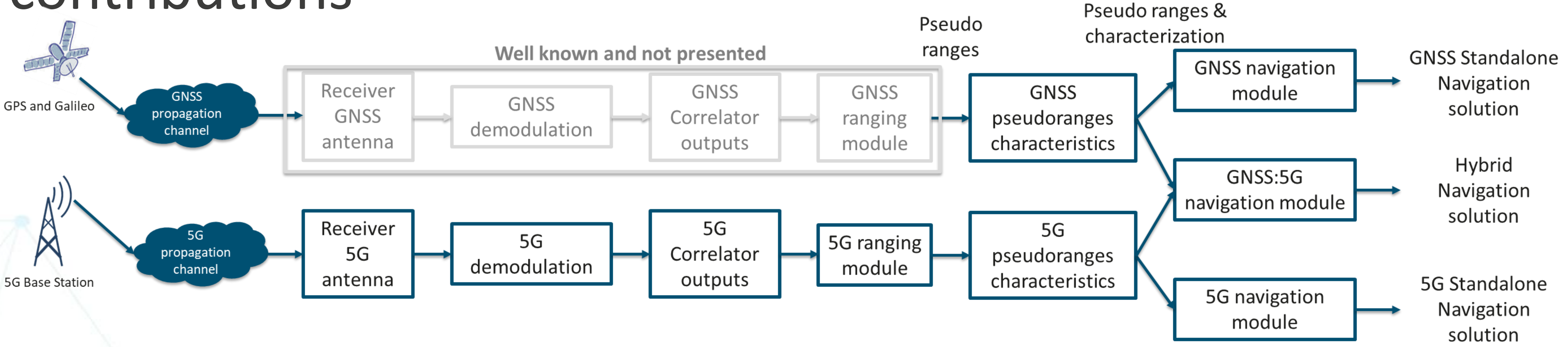
- Main contributions



  - A **description of the 5G physical layer**, and notably the Synchronization Signal: SS PBCH
  - The selection and mathematical model definition of a **5G compliant propagation channel**. Methods have been designed to study the evolving parameters of the propagation channel and to select the required propagation channel sampling rate generation.
  - The development of **mathematical models of 5G correlator outputs**, taking into account the effects of non-constant propagation channel parameters, noise.

7. Conclusions (2/4)

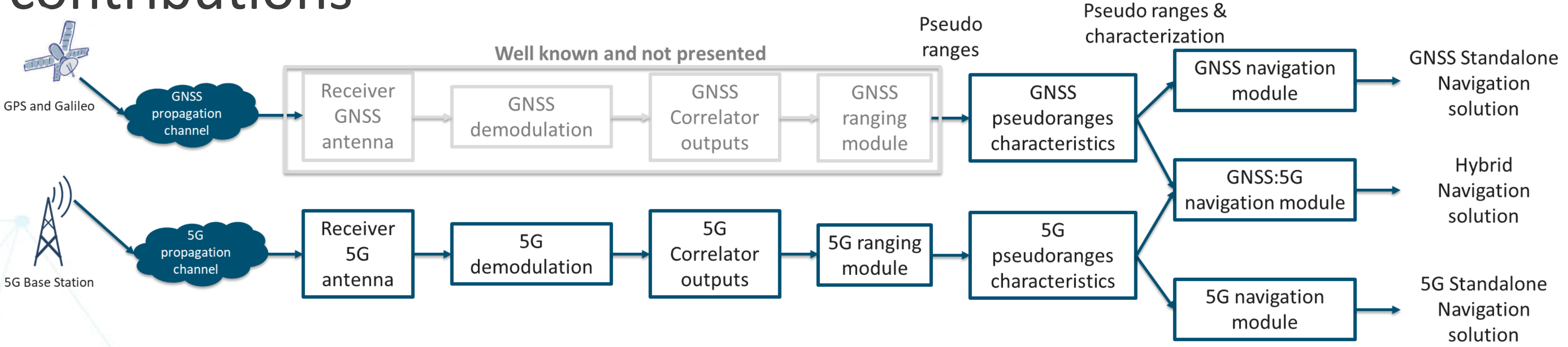
- Main contributions



  - The proposition of a **simplified model of 5G correlator outputs**, which is valid in a LOS scenario for sub-6 GHz carrier frequency
  - The proposition of a **statistical model for the interference term**, which can be generate as a Gaussian variable with a mean and a variance derived in the study
  - A synchronization module based on a **DLL** and on a potential **FLL** has been derived. The synchronization module also implements a C/N_0 **estimator**.

7. Conclusions (3/4)

- Main contributions



  - The development of a **simulator, coded in C**, providing ranging measurements from GNSS and 5G tracking loops, taking into account simulated multipath propagation channels
  - The development of methods to **characterize GNSS and 5G ranging measurement errors** in urban environment.
  - The proposition of **Gaussian modeling of ranging measurements as a function of C/N_0**
  - The study of simulated positioning performances using different **navigation filters** (EKF, UKF) and various parameters.

7. Conclusions (4/4)

- Future work
  - Real data collect
  - Correlator output mathematical model
    - The interference term of the correlator output mathematical model for NLOS scenario must be completed; therefore, the pseudo range measurements quality will be degraded and consequently, the positioning solution obtained will be less accurate.
  - Pseudo range error characterization
    - To derive the characterization for the NLOS scenario
    - To derive the characterization for mmW
  - Navigation solution
    - The development of Particle Filters could be implemented. The main advantage of PF is that they do not rely on a Gaussian PDF approximation contrary to Kalman Filters; an a-priori information on the distributions must be provided, and such information has been derived in this study.
    - The GNSS and 5G pseudo range measurements models used in the navigation filter could be refined by adding the time shifts between the transmitters and the reference time (GNSS or 5G) which are considered as perfectly corrected in this PhD

Thank you!
Any questions?

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