TELECOM LAB - SIGNAL PROCESSING AND NAVIGATION RESEARCH GROUP

Processed 5G Signals Mathematical Models for Positioning Considering a Non-Constant Propagation Channel

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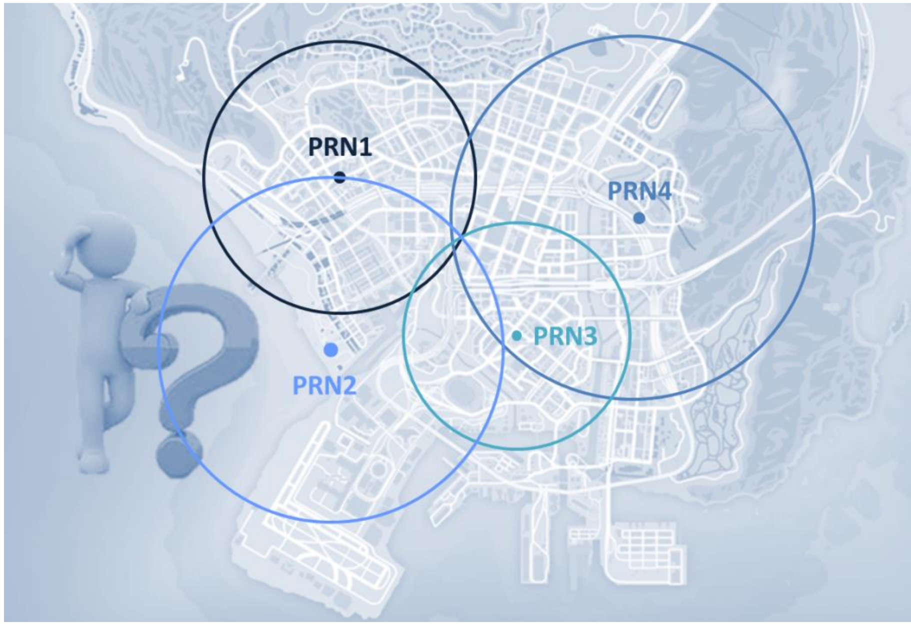
Introduction – Context

- The need for positioning in constraint environment (urban, indoor) is in constant growth.
- The widely spread way to get a position consists in using Global Navigation Satellite System (GNSS) of which the best known constellation is GPS (USA system)
- The working principle of GNSS system is based on multilateration
- Using the distances measured between the receiver and at least 4 satellites, the receiver position can be computed
- 4 measures are required to solve the timing biases



Source: [1]

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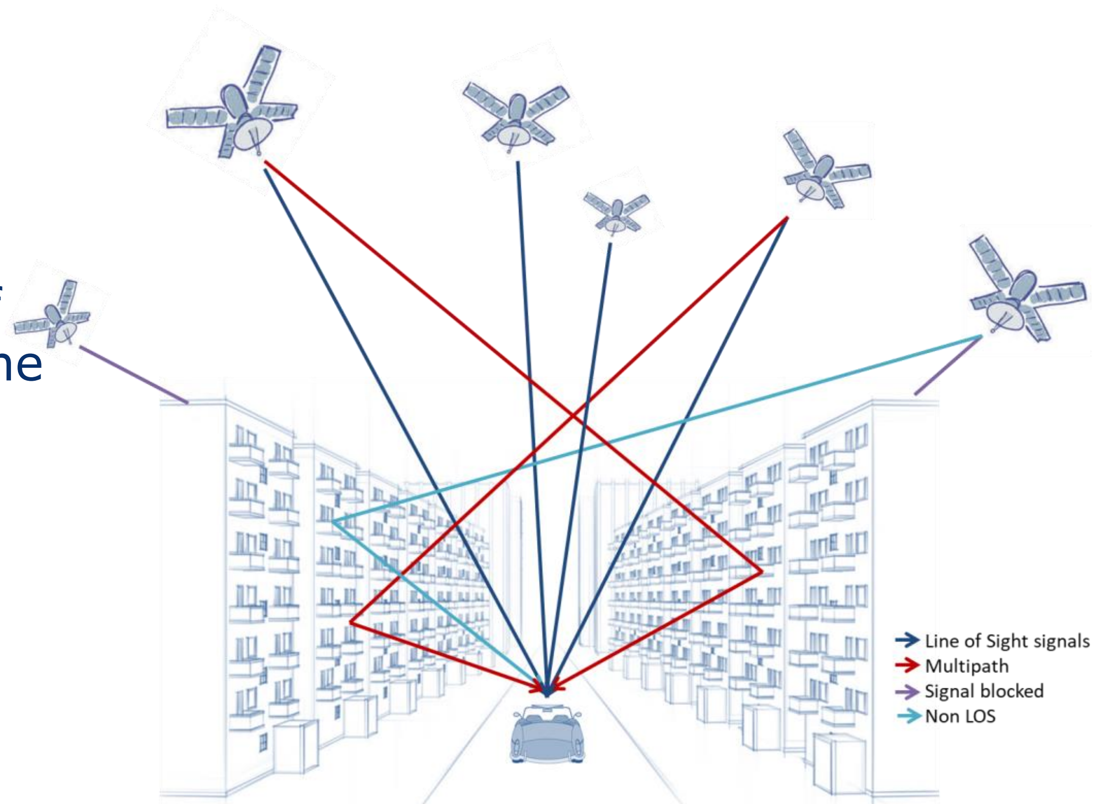
Introduction – Context

- In constraint environment, GNSS is facing several issues degrading its performances and making its positioning solution mostly
  - Multipath
  - Lack of satellite visibility
  - Signal blockage

- Alternatives are already developed such as the use of additional captors (IMU) or the use of Signals of Opportunity (SoO)

- SoO are signals used for navigation but not normally intended for navigation (TV signal, cellular network signal,…)



Sources: [2], [3], [4], [6], [11], [12]

Introduction – Context

- The upcoming fifth generation (5G) radio networks are expected to provide remarkable improvements in the user experience.
- Its capabilities as SoO have to be studied.
- 5G interests:
  - Dense network (lots of available signal)
  - Usage of new antennas (beam-forming,…)
  - Usage of new frequencies: millimeter waves (particular propagation conditions, wider bandwidth,…)

Source: [13]

Introduction – objectives

- The objective of the study is to develop a **positioning hybridized scheme**, using both GNSS and 5G measurements.
- For GNSS, models are already known and mastered. 5G is being developed, models have to be derived and studied.
- 5G systems use 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 **the CIR cannot be considered as constant** over the duration of an OFDM symbol.

Introduction – objectives

- **PhD objectives**:
  - To study a 5G signals ranging module for time-evolving CIR propagation channels.
  - To develop an evolved mathematical model for 5G signals correlator outputs which takes into account the CIR evolution, since correlator outputs are the basis of the ranging module.
- **Presentation objectives:**
  - To present 5G signals
  - To present the signal processing architecture for positioning
  - To present the correlation operation
  - To present the correlator output mathematical models
  - To apply these models to a delay tracking

Outline

1 – The OFDM modulation

2 – Signal processing architecture for positioning

3 – Correlation mathematical model

4 – Correlation simplified model

5 – Model application to delay tracking

6 – Conclusion and Future Work

Outline

1 – The OFDM modulation

2 – Signal processing architecture for positioning

3 – Correlation mathematical model

4 – Correlation simplified model

5 – Model application to delay tracking

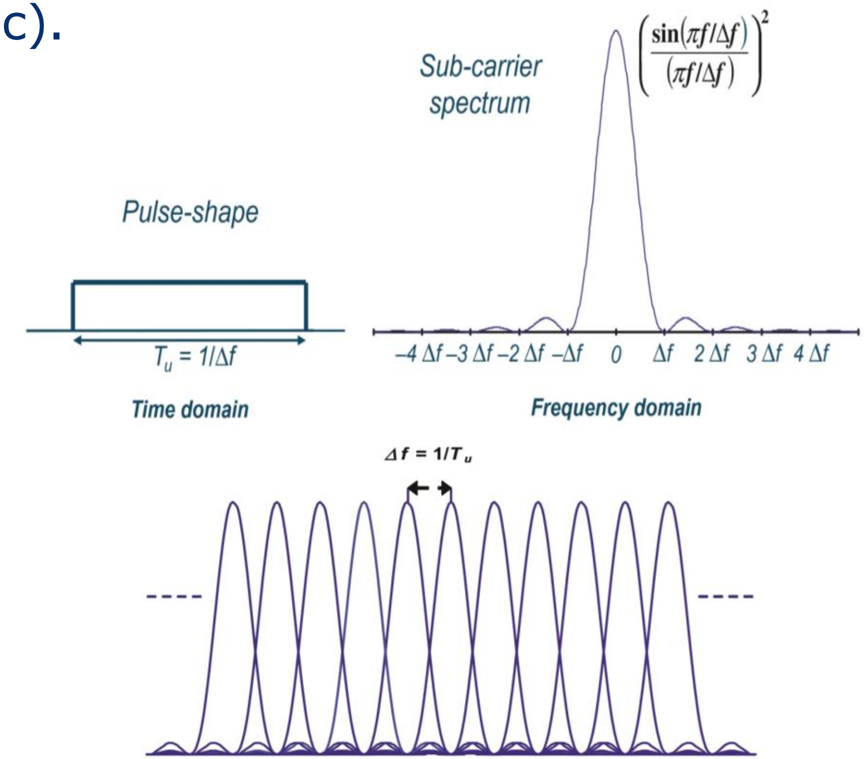
6 – Conclusion and Future Work

1 – The OFDM modulation (1/9)

- 5G signals will use Orthogonal Frequency Division Multiplexing (OFDM) modulation.

- It consists in transmitting in parallel N complex data symbols over N orthogonal narrowband subcarriers (sc).

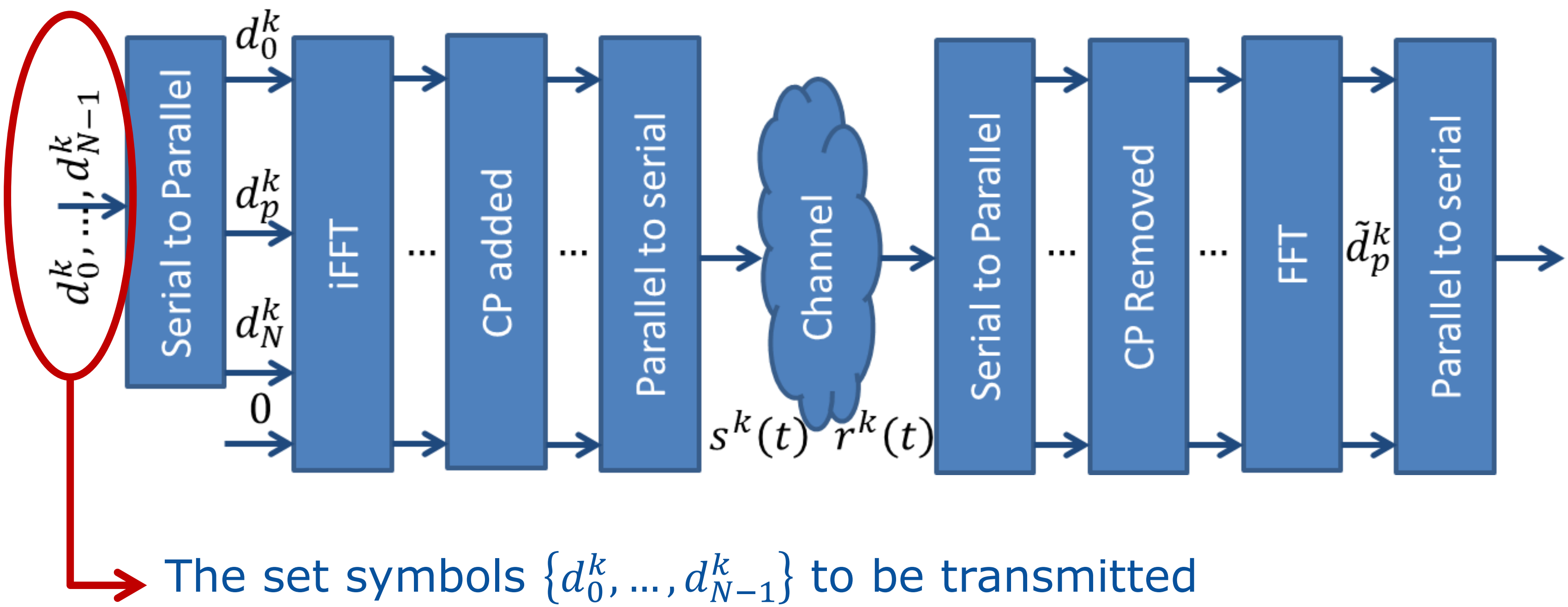
- Principle:
  - Each sc transmits a low rate data signal modulation where its pulse shaped is a rectangular pulse.
  - Each sc is frequency spaced so that the 0 of one sc spectrum correspond to the peaks of the neighbouring sc. This permits to avoid sc interferences and this is why the term orthogonal is used



Sources: [6], [7], [13]

1 – The OFDM modulation (2/9)

- Objective:
  - To present the process to generate an OFDM signal

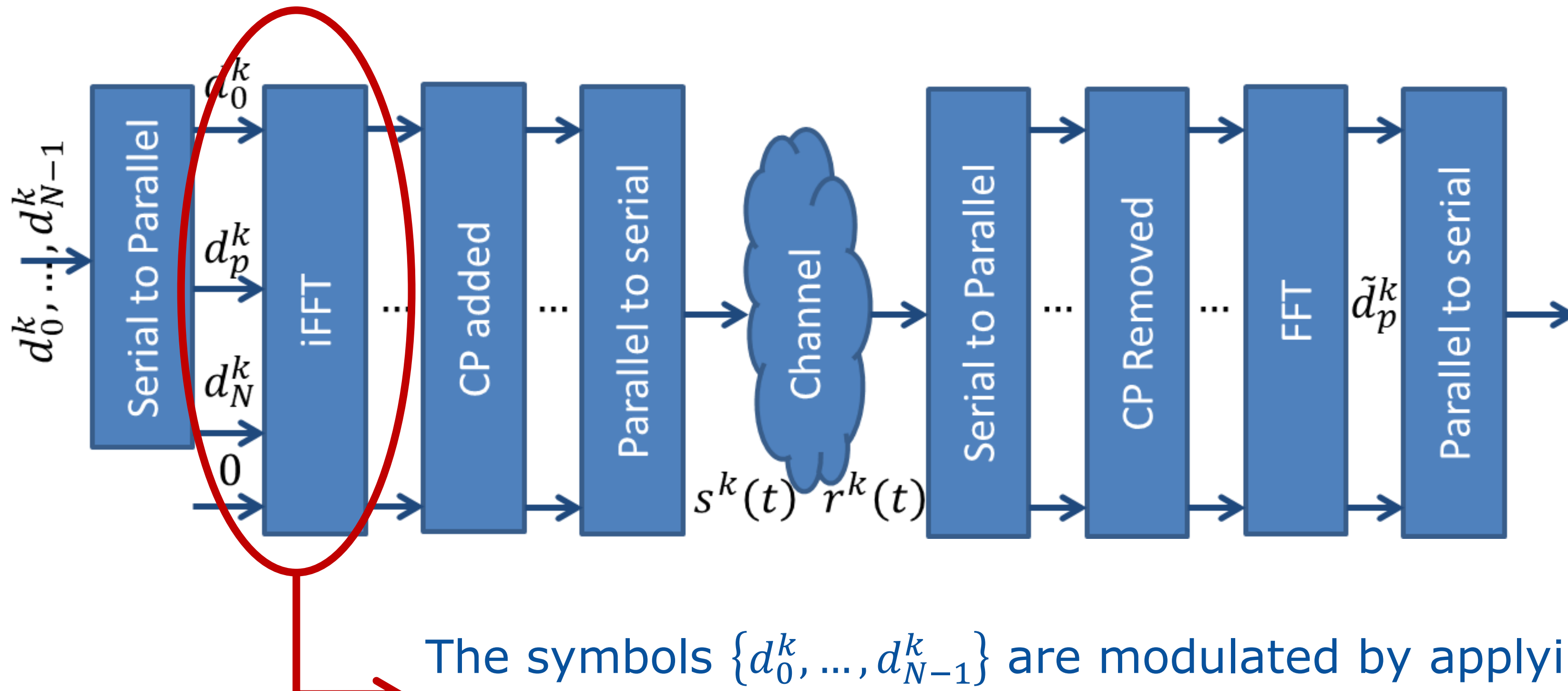


The set symbols $\{d_0^k, \dots, d_{N-1}^k\}$ to be transmitted

Sources: [6], [7], [13]

1 – The OFDM modulation (3/9)

- Process to generate an OFDM signal

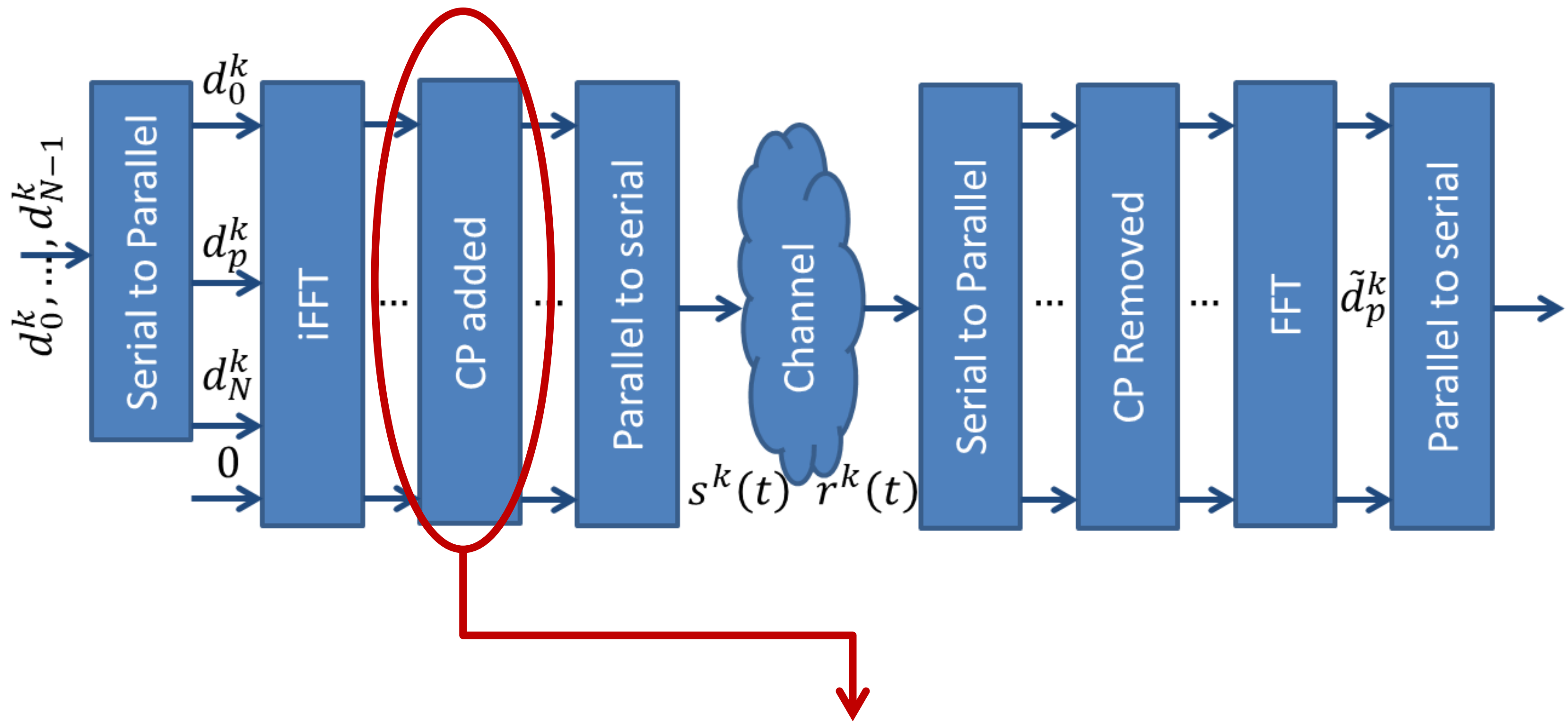


The symbols $\{d_0^k, \dots, d_{N-1}^k\}$ are modulated by applying an inverse Fast Fourier Transform (IFFT).

Sources: [6], [7], [13]

1 – The OFDM modulation (4/9)

- Process to generate an OFDM signal

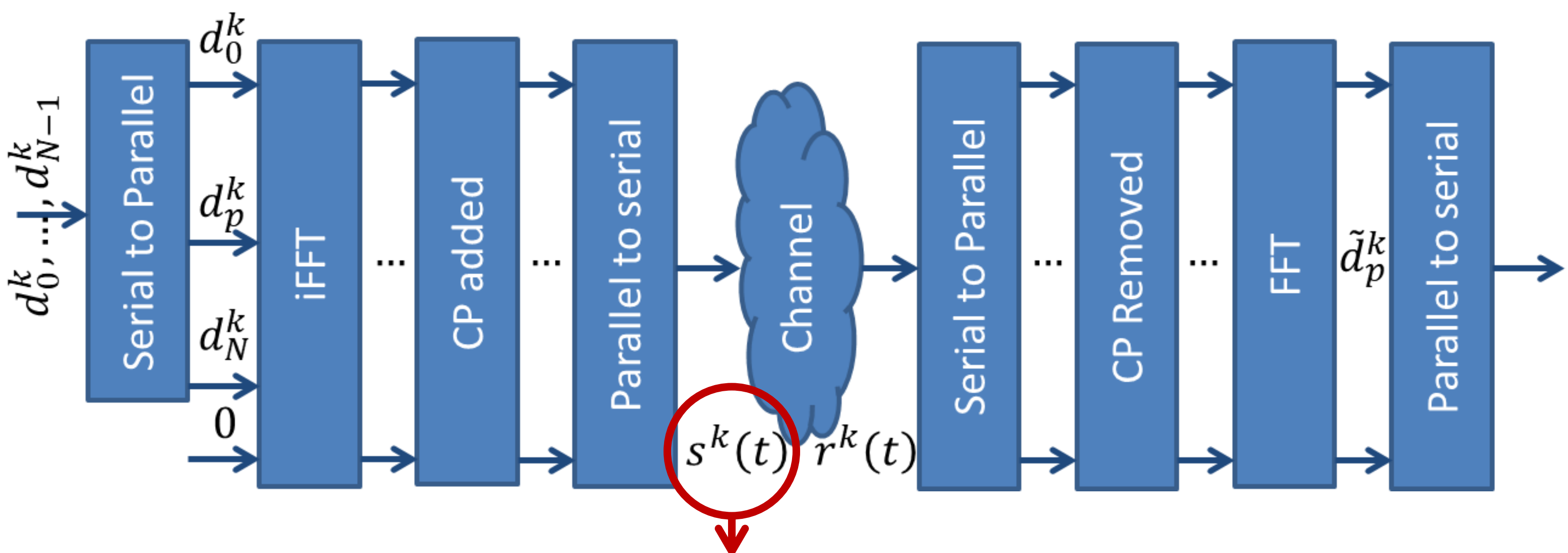


The Cycle Prefix (CP) is added creating an OFDM time symbol

Sources: [6], [7], [13]

1 – The OFDM modulation (5/9)

- Process to generate an OFDM signal



$$s^k[n] = \sum_{p=0}^{N_{FFT}-1} d_p^k e^{\frac{i2\pi pn}{N_{FFT}}}$$

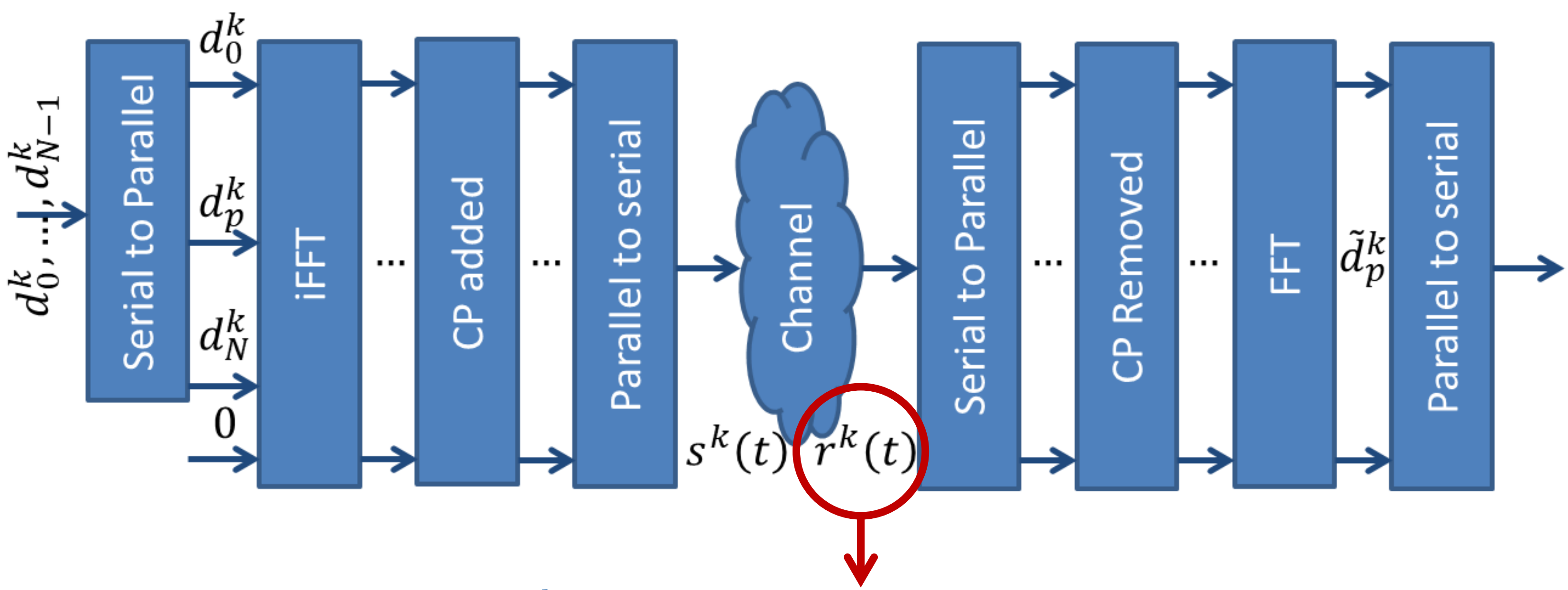
$$-N_{CP} \leq n \leq N_{FFT} - 1$$

- N_{CP}: number of Cycle Prefix samples
- N_{FFT}:size of the FFT window
- p: the subcarrier
- n: n^{th} discrete time epoch
- k: k^{th} OFDM symbol
- d_p^k: k^{th} modulated symbol carried by the p^{th} subcarrier

Sources: [6], [7], [13]

1 – The OFDM modulation (6/9)

- Process to generate an OFDM signal



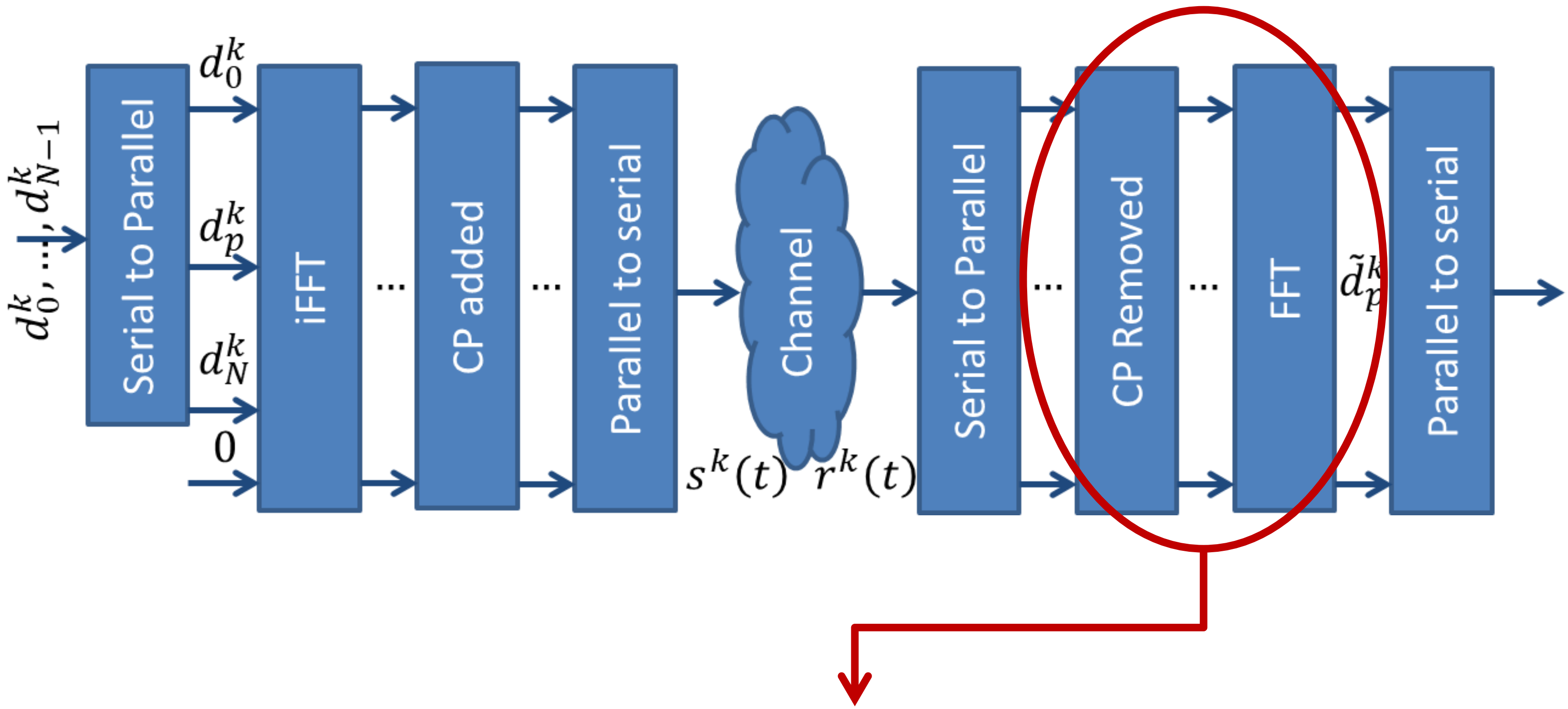
$$r^k(t) = s^k(t) * \alpha^k(t)$$

- $r^k(t)$ expresses the noiseless received signal before the ADC/AGC.
- The propagation channel CIR mathematical model is usually expressed as $\alpha^k(t)$

Sources: [6], [7], [13]

1 – The OFDM modulation (7/9)

- Process to generate an OFDM signal



The Cycle Prefix (CP) is removed and the signal is demodulated by applying a Fast Fourier Transform (FFT).

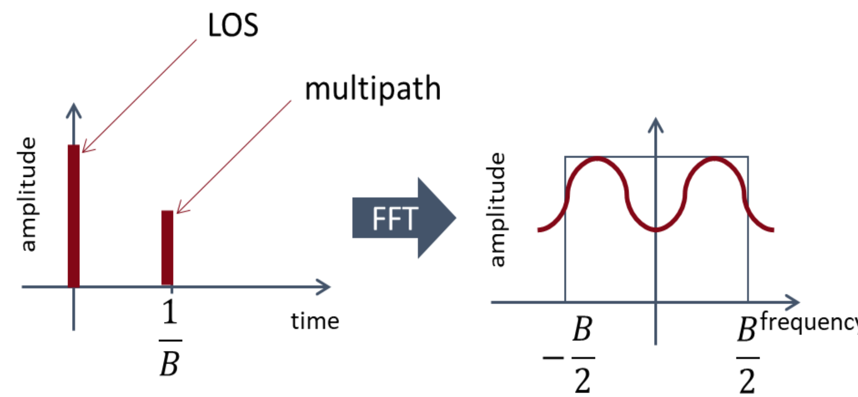
Sources: [6], [7], [13]

1 – The OFDM modulation (8/9)

- One additional advantage of the OFDM modulation is its behaviour in multipath environment

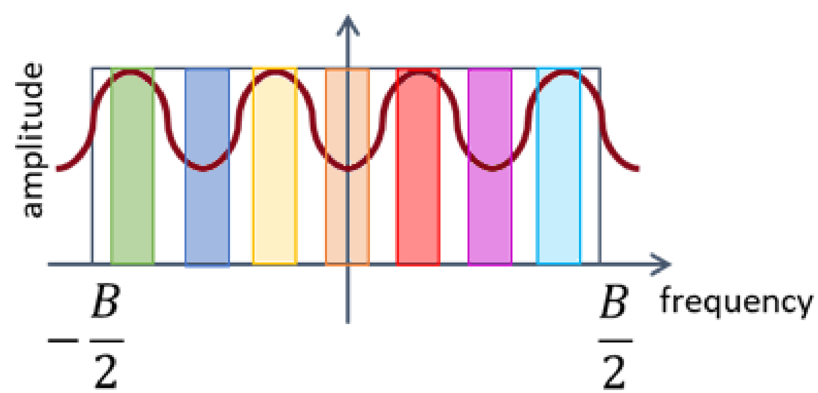
- OFDM combats frequency selectivity, a phenomenon appearing when the multipath component reaches the receiver with a large delay

  → **signal highly distorted**



Frequency selective fading

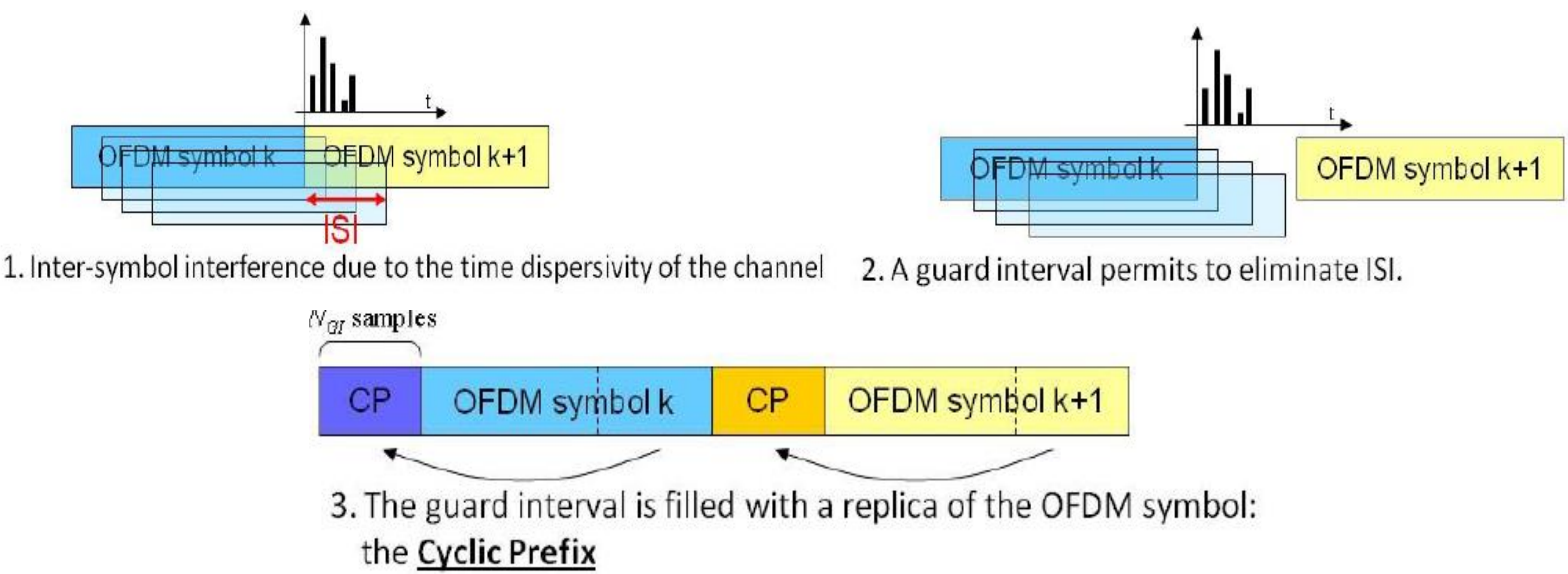
- By using narrow bandwidths for each sc, the fading can be considered as “flat” on each subcarrier. The signal is barely not distorted



Sources: [6], [7], [13]

1 – The OFDM modulation (9/9)

- One additional advantage of the OFDM modulation is its behaviour in multipath environment
- OFDM combats time dispersity, a phenomenon due to the spreading of the symbols' power over time, thanks to the CP



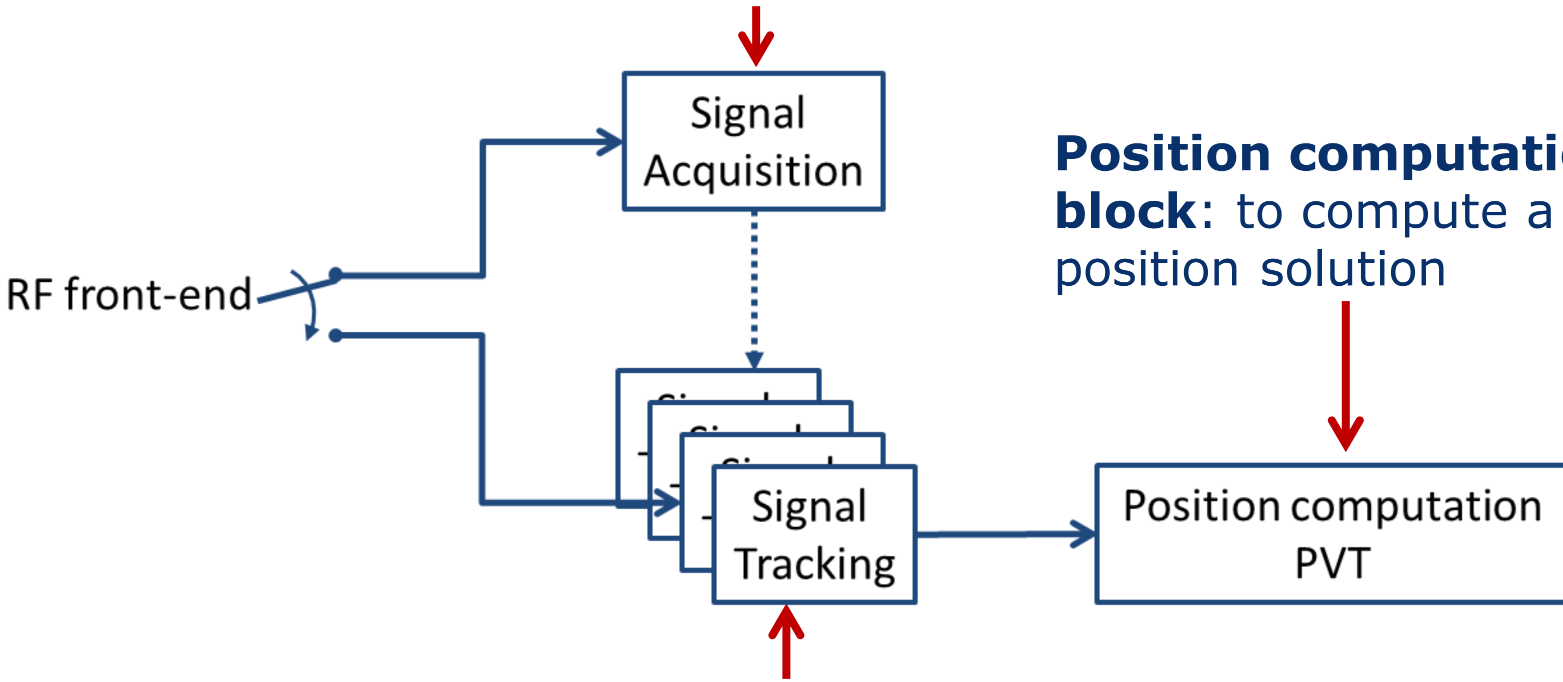
Sources: [6], [7], [13]

Outline

2.1 – High level architecture (1/2)

Acquisition block: to achieve a rough time and frequency synchronization with the incoming signal

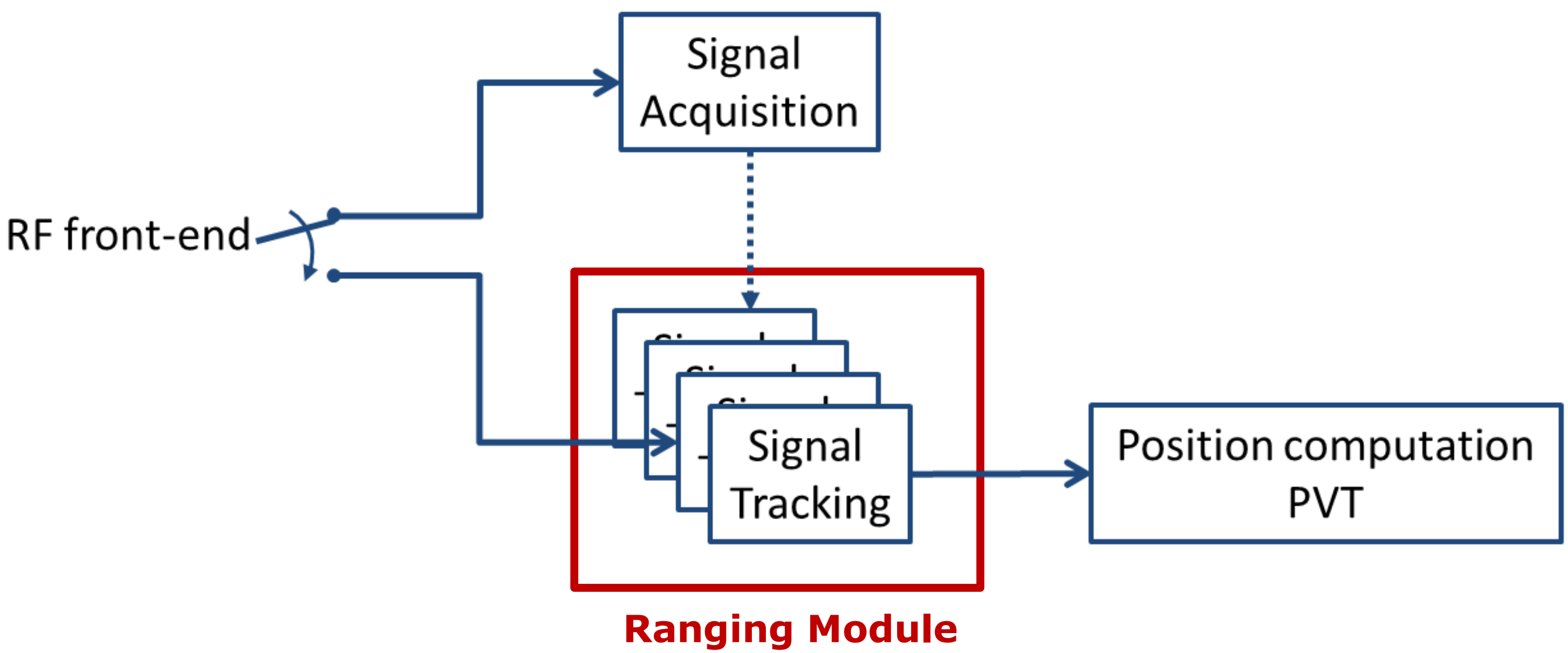
Position computation block: to compute a position solution



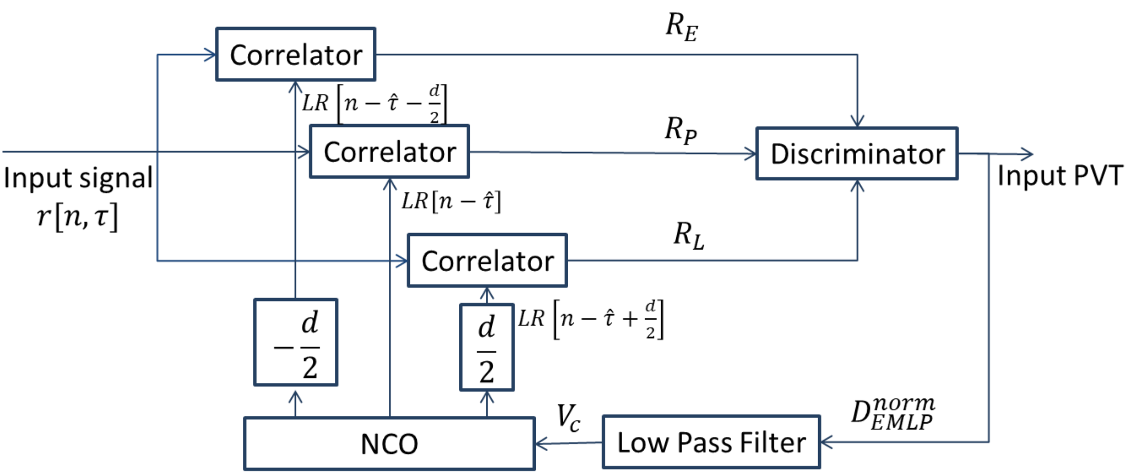
Signal tracking block: to achieve a fine synchronization with the incoming signal

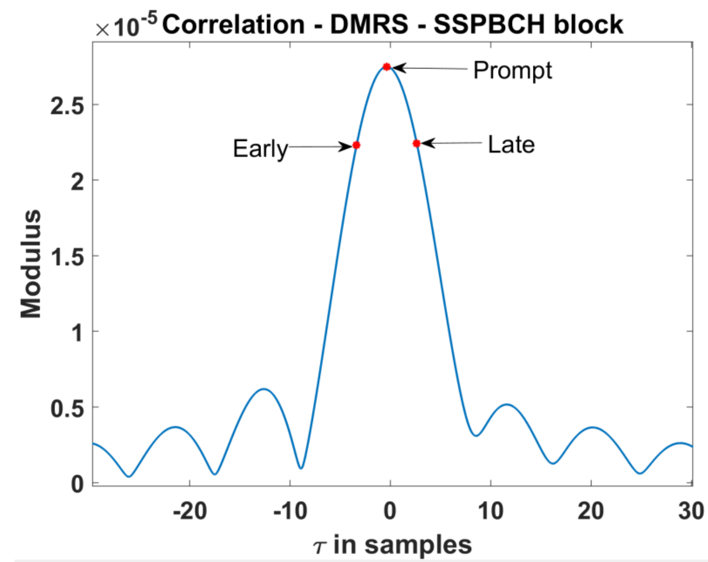
2.1 – High level architecture (2/2)

- Objective: To develop a 5G signals ranging module (Delay Lock Loop – DLL)



2.2 – Presentation of the ranging module





- The DLL makes use of **correlation** between the incoming signal, $r[n,\tau]$, and a local replica, $LR[n-\hat{\tau}]$, in order to estimate the propagation time.
- The objective is to track the main peak of the correlation using **correlator outputs** (Early, Prompt, Late,…)
- In order to optimally study the DLL performances, these correlator outputs must be perfectly modeled

Outline

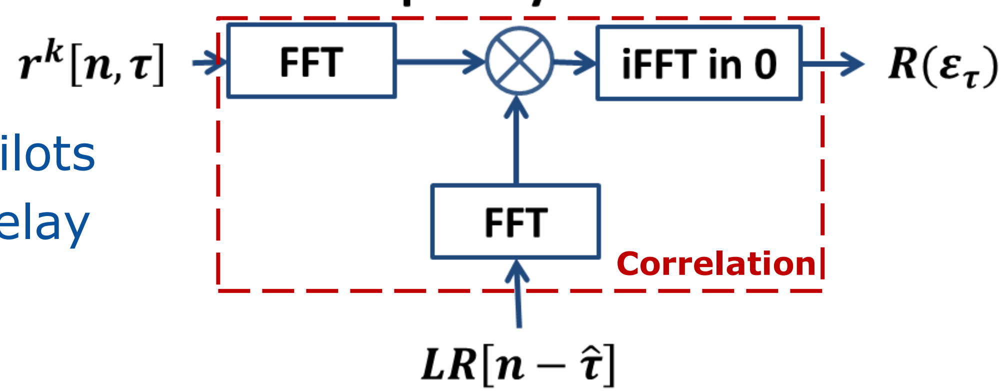
3.1 – Correlation operation definition (1/2)

- The aim of the correlation is to **compare the incoming signal with a local replica** in a given observation interval

- The correlation operation can be defined from its **frequency-domain expression**.

- Notation:
  - k is for the k^{th} OFDM symbol
  - LR is the local replica of the pilots
  - $\varepsilon_{\tau} = \tau - \hat{\tau}$ is the propagation delay estimation error

Correlation operation in the frequency domain



Source: [14]

3.1 – Correlation operation definition (2/2)

- The received signal model is:

$$\boldsymbol{r^k[n,\tau]} = \boldsymbol{\alpha^k(n,u)} * \boldsymbol{s^k(u)}\Big|_{\boldsymbol{u=n}}$$

- α^k is the Channel Impulse Response
- s^k is the OFDM received signal
- k is the OFDM symbol considered and the integration time

Constant propagation channel

$$\alpha^k(n,u) = \sum_{l=0}^{L-1} \boldsymbol{\alpha_l^k} \delta(u - \tau_l)$$

Time-evolving propagation channel

$$\alpha^k(n,u) = \sum_{l=0}^{L-1} \boldsymbol{\alpha_l^k(n)} \delta(u - \tau_l)$$

Source: [14]

3.2 – Correlator output mathematical models

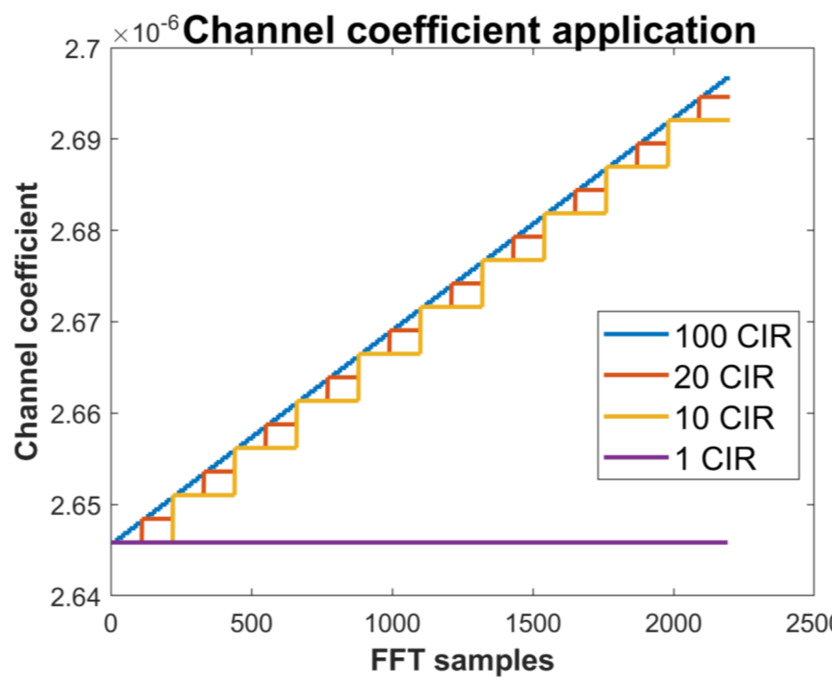
	Propagation channel model	Correlator output mathematical models for one OFDM symbol
Constant 1 path	$\alpha^k(n,u) = \alpha^k(u) = \alpha_l^k \delta(u-\tau_l)$	$\alpha_l^k R_{const_l}^k(\varepsilon_{\tau_l}) = \alpha_l^k \cdot \begin{cases} \frac{1}{N_P} e^{\frac{i\pi(2\beta+\gamma(N_P-1))\varepsilon_{\tau_l}}{N_{FFT}}} \frac{\sin\left(\frac{\pi\gamma\varepsilon_{\tau_l} N_P}{N_{FFT}}\right)}{\sin\left(\frac{\pi\gamma\varepsilon_{\tau_l}}{N_{FFT}}\right)} & \varepsilon_{\tau_l} \neq 0 \\ 1 & \varepsilon_{\tau_l} = 0 \end{cases}$
Constant L paths	$\alpha^k(n,u) = \alpha^k(u) = \sum_{l=0}^{L-1} \alpha_l^k \delta(u-\tau_l)$	$R(\varepsilon_\tau) = \sum_{l=0}^{L-1} \alpha_l^k R_{const_l}^k(\varepsilon_{\tau_l})$
Evolving L paths	$\alpha^k(n,u) = \sum_{l=0}^{L-1} \alpha_l^k(n) \cdot \delta(u-\tau_l)$	$R(\varepsilon_\tau) = \sum_{l=0}^{L-1} \frac{A_l^k}{N_{FFT}} R_{const_l}^k(\varepsilon_{\tau_l}) + ICI$ Where $A_l^k = \sum_{n=0}^{N_{FFT}-1} \alpha_l^k(n)$

- Time-evolving model changes:
  - A_l^k the channel contribution term
  - ICI the Inter-Carrier Interference term

Source: [14]

3.3 – Example of application for 5G signals (1/4)

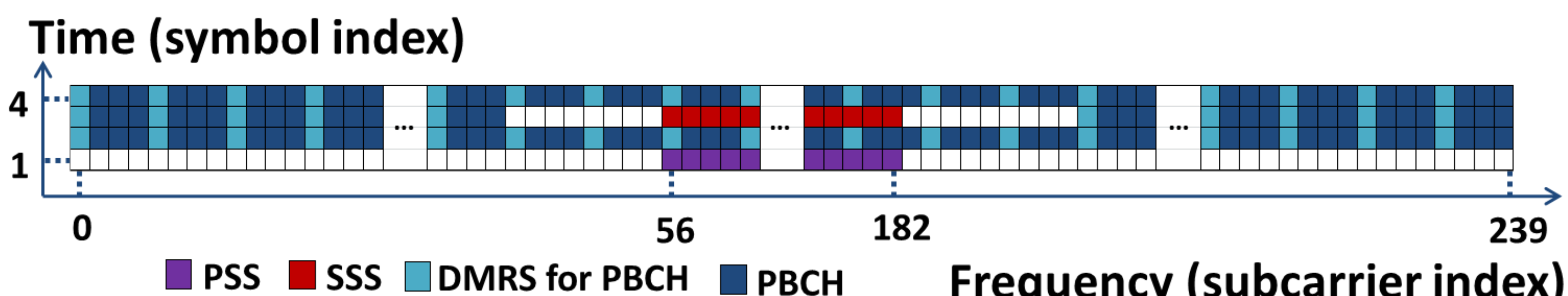
- Presentation of QuaDRiGa
  - QuaDRiGa is presented as a reference implementation of the 3GPP standard.
  - The evolution of the propagation channel over 1 OFDM symbol cannot be neglected; a CIR sampling rate must be selected.
  - The propagation channel is assumed to be constant piecewise:
    - 100 CIR per OFDM symbol can be assimilated to a time-continuous propagation channel (reference)
  - 1 CIR per OFDM symbol is equivalent to a constant propagation channel



Source: [8]

3.3 – Example of application for 5G signals (2/4)

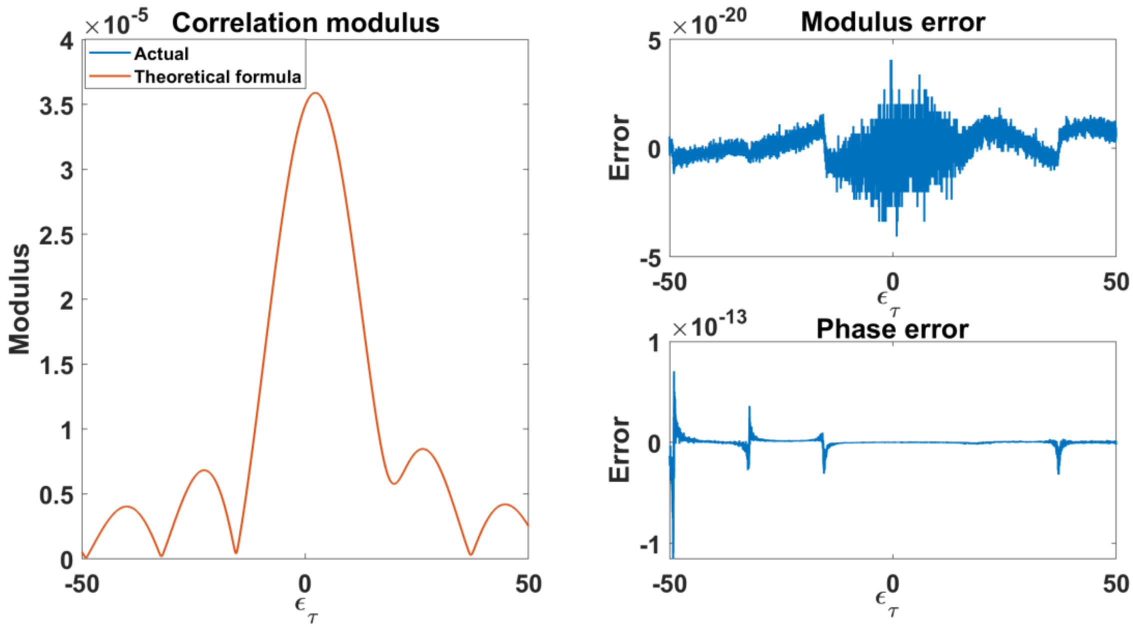
- Pilots selected for the study
  - The correlation is performed over the **pilots only**
  - $P = \gamma q + \beta, q \in [0 \ldots N_P]$
    - N_p: number of pilot symbols
    - β is the subcarrier index of the first pilot in the symbol
    - γ period of repetition of the pilots in the OFDM symbol
  - The set of pilots selected for the study is the **DMRS symbols contained into the SSPBCH Synchronization block** defined in the 3GPP standard



Source: [9]

3.3 – Example of application for 5G signals (3/4)

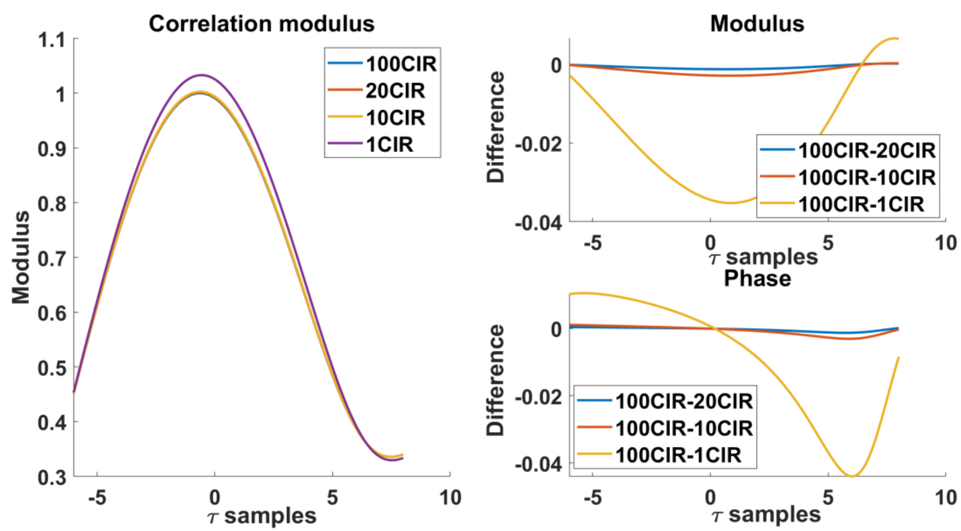
- Objective: Time-evolving formula validation
  - Method: The reference correlation function (ie using 100 CIR per OFDM symbol) is compared to the model developed before



  - Observations:
    - The comparison to a true correlator outputs validates the model.
    - ICI term has been proved to be negligible for QuaDRiGa channel

3.3 – Example of application for 5G signals (4/4)

- Objective: CIR sampling rate impact
  - Method: The impact of the CIR sampling rate is illustrated in terms of correlation output for 4 sampling rates (1, 10, 20 and 100 CIR per OFDM symbol)



  - Observations:
    - CIR impact is non negligible on the correlation function
    - Using 10 CIR per OFDM symbol is a good compromise between realism and computation burden

Outline

4.1 – Reminders and problematic (re)formulation

- CIR consideration:
  - The propagation channel cannot be considered as constant; to get a time continuous channel 100 CIR per OFDM symbol are required.
  - Drawback: The generation time in QuaDRiGa is huge
  - Solution: Using 10 CIR permits to get a representative channel while keeping the CIR generation rate low

Is it possible to reduce even more the number of samples?

- Correlator output model consideration:
  - The mathematical model for a time-evolving channel is developed and validated
  - Drawback: The developed model is computationally heavy
  - Solutions:
    - A first simplification permits to neglect the ICI term
    - The model contains a channel contribution term: $A_l^k = \sum_{n=0}^{N_{FFT}-1} \alpha_l^k(n)$

Is it possible to simplify this term?

4.2 – Simplified mathematical model

- The objective is to simplify the channel contribution term:

$$A_l^k = \sum_{n=0}^{N_{FFT}-1} \alpha_l^k(n) = \sum_{n=0}^{N_{FFT}-1} |\alpha_l^k(n)| e^{2i\pi\theta_l^k(n)}$$

- The simplified proposal is:

$$A_l^k \approx \frac{|\alpha_l^k(0)| + |\alpha_l^{k+1}(0)|}{2} e^{i(\theta_0 + \pi\delta_f \cdot (N_{FFT}-1))} \frac{sin(\pi\delta_f N_{FFT})}{sin(\pi\delta_f)}$$

Where: θ_0^k is the phase of the first propagation channel sample of symbol k

$\delta_f = (\theta_0^k - \theta_0^{k+1})/(2\pi N_{FFT})$ is the normalized Doppler frequency.

Model	CIR samples generation	CIR samples Correlation
Correlation operation	100	100
Correlation operation	10	10
Simplified model	1	2

4.3 – Validation of the simplified model

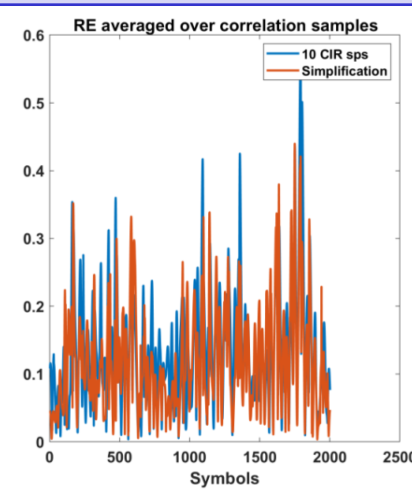
- Simulation set up

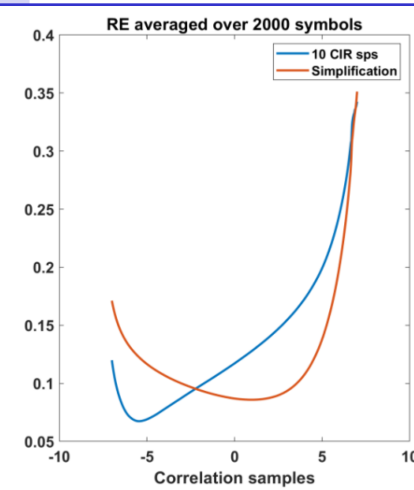
Channel	Values	Cases	CIR rate	Figure of merit
Carrier frequency	6GHz	Correlation operation	100 CIR	Reference
Subcarrier spacing	15kHz	Correlation operation	10 CIR	Mean and Variance of the relative evolution (wrt reference)
High level scenario	LOS scenario	Simplified model	1 CIR	

- Results

The simplificated model is validated.

Model	μ	σ
10CIR	0.1346%	0.0862%
Simplification	0.1201%	0.0776%





- A NLOS scenario has also been tested and validated

Outline

5 – Model application to delay tracking (1/2)

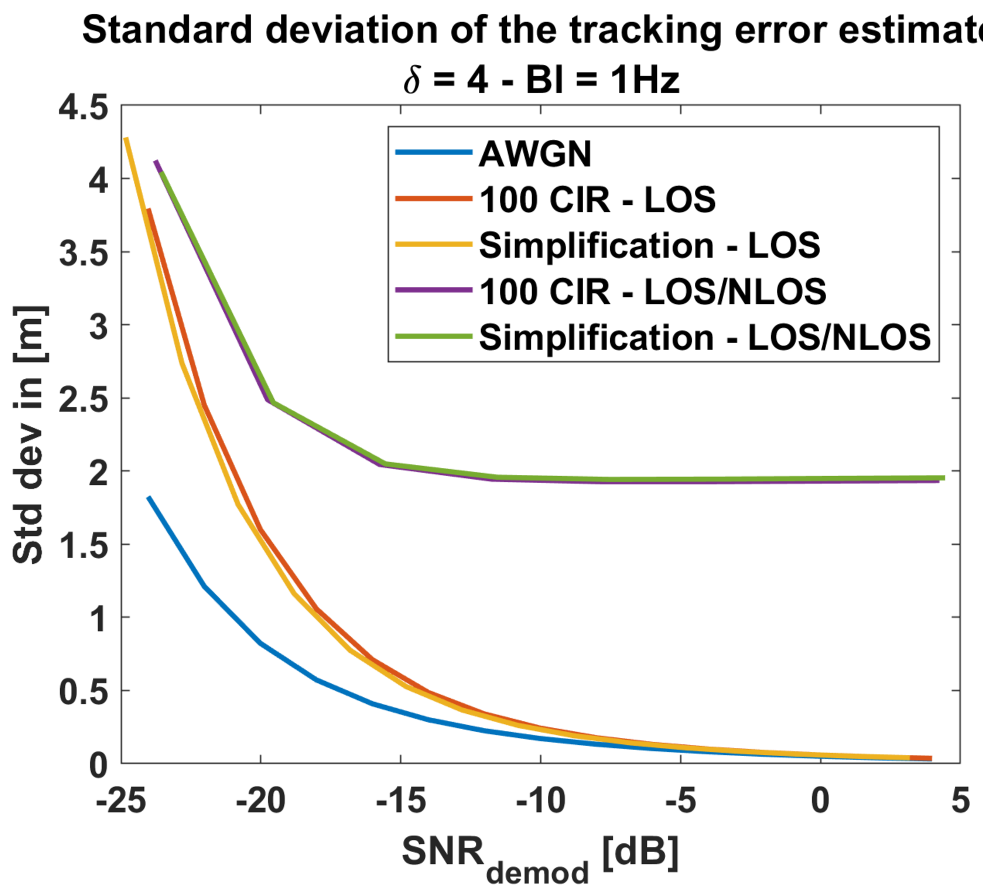
- Objectives:
  - To apply the developed correlator output mathematical to the delay tracking of a 5G signal-type.
  - To verify that the standard deviation of the tracking error estimate obtained with the simplified model is equal to the reference
- Simulation set up:

Channel	Values	Cases	CIR rate	Figure of merit
Carrier frequency	6GHz	Correlation operation	100 CIR	Standard deviation of the tracking error estimate
High level scenario	LOS scenario	Simplified model	1 CIR	

DLL characteristics	Loop order	2
	Correlator spacing δ	4 samples
	Loop bandwidht B_l	1 Hz

5 – Model application to delay tracking (2/2)

- Results:
  - In red and yellow, the standard deviation is provided for a channel composed of one LOS path; using the reference correlation (with 100 CIR sampling rate) and the simplified model respectively.
  - Time computation gain is around 12 for the LOS/NLOS channel for the DLL computation
  - There is already a gain in the CIR generation with QuaDRiGa (>100)



Outline

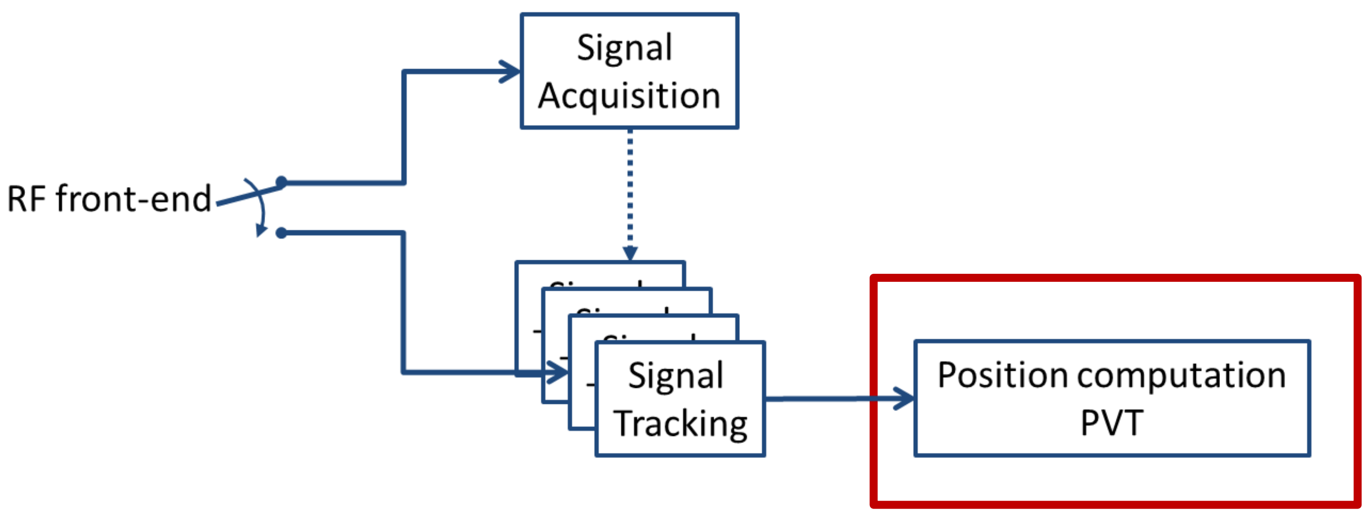
6 – Conclusion and Future work

6.1 – Conclusion

- For a 5G compliant propagation channel, the **time-evolution** has to be taken into account and **cannot be ignored**
- A **correlator output mathematical** model considering a time evolving propagation channel has been **derived**
- The studies performed proves the **negligibility of the OFDM orthogonality loss** (ICI term) for a QuaDRiGa propagation channel
- A **simplificated correlator output mathematical model has been proposed**; it offers significant computation gain in terms of
  - Coefficient generation in QuaDRiGa (1 CIR per OFDM symbol compared to 100 CIR)
  - DLL simulation time
- **Preliminary studies on a 5G ranging module performances** have been performed

6.2 – Future Work

- To use the simplified correlator output model **to evaluate the 5G positioning performance**
- To determine the **statistics of the correlator outputs**
- To develop innovative techniques to optimize the processing of such signal for positioning.



- To apply the correlator output model on 5G mm-wave signals
- **To develop a GNSS/5G hybridized arnging module**

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Thank you!
Any questions?

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