SIGNAV Lab –
Signal Processing and
Navigation Research
Group

Analysis and Improvement of GNSS Navigation Message Demodulation Performance in Urban Environments

PhD Dissertation Defense
by Marion Roudier

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Introduction

GNSS: **G**lobal **N**avigation **S**atellite **S**ystem

is a satellite-based system that allows a user to determine its position and velocity anywhere at any time, and to synchronize its clock with the ultra precise GPS time.

To compute a position:

- At least 4 emitting satellites are needed
- For each emitting satellite:
  - Satellite-receiver pseudo-range estimation
  - Navigation message demodulation: Key information:
    - Satellite position (= Ephemeris)
    - Satellite Clock error corrections

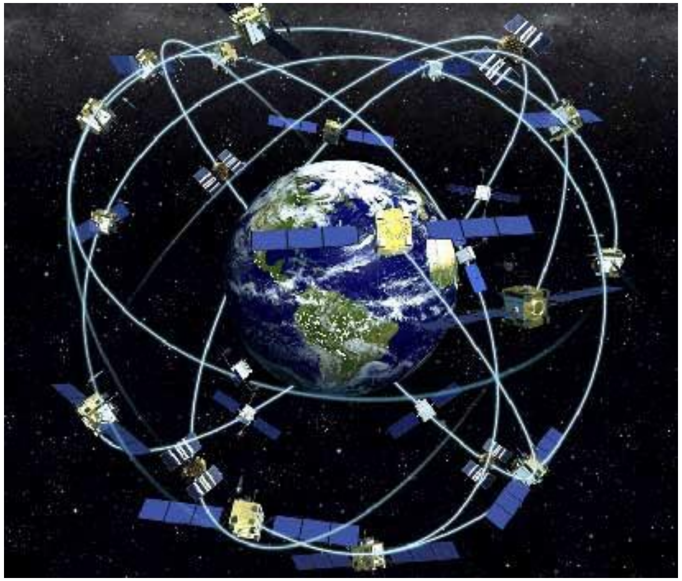

Figure 1: GNSS

= **CED** (**C**lock error corrections & **E**phemeris **D**ata)

Introduction - Problematic

- The majority of new GNSS applications takes place in urban environments
- In these obstructed environments, the transmitted signal is impacted by obstacles
- This impact induces fading and multipath on the resulting received signal
- As a consequence, it can be difficult for the receiver to be able to process the received signal
- Therefore, the performance in urban environments is degraded with respect to an AWGN channel
- It is thus necessary to assess, and if needed to improve, the GNSS signals performance in an urban channel

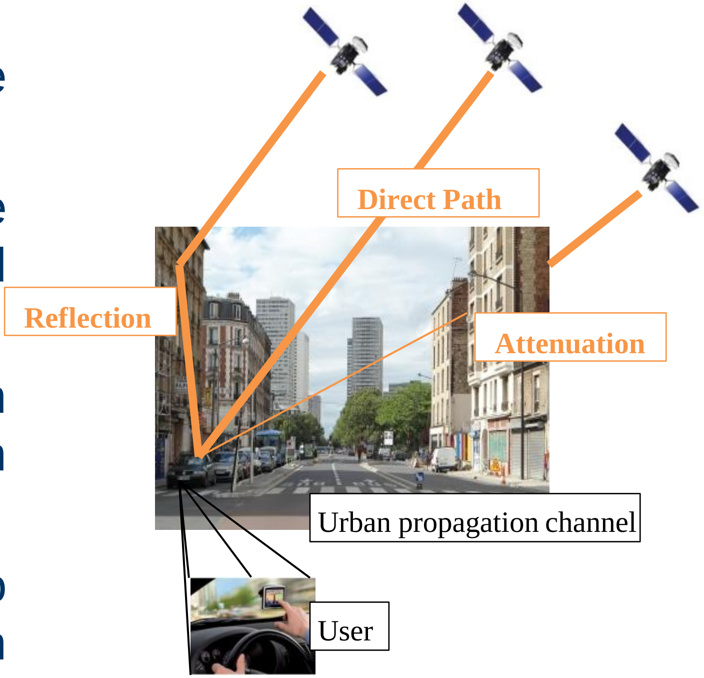

Figure 2: Urban Environment

Introduction - Objectives

- The GNSS signals performance in urban environments can be improved in investigating:
  - The satellite-receiver pseudo-range estimation process
  - The **navigation message demodulation** process

    = only this aspect has been investigated during the PhD thesis

- Final PhD thesis objective:

  To make the GNSS navigation message more robust to the distortions introduced by the urban environment, optimizing:

  - Channel coding
  - Navigation message and signal structures

Introduction - Logic

- Development of a software simulator in C language, modeling the GNSS signal emission/reception chain in urban environments

- Development of an innovative method specially adapted to provide the GNSS signals demodulation performance in urban environments

- Provision of the GPS L1C signal demodulation performance in an urban environment for narrowband and wideband propagation channel models

- Demodulation performance improvement at the receiver level:
  - Development of an advanced method to adapt the decoding process

- Demodulation performance improvement at the signal level:
  - Design of a new GNSS signal, with an optimized channel code

Outline

1) Simulator Presentation
2) Demodulation Performance Analysis in Urban Environments
3) Demodulation Performance Improvement by Decoding Optimization
4) Demodulation Performance Improvement by Designing a New Signal
5) Conclusion

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1) Simulator Presentation - Model

Objective: To simulate the GNSS communication chain, with simulations as less time-consuming as possible, in keeping a real behavior.

❖ Emitted GNSS signals:

$$s_e(t) = A_{data}\, C_{data}(t)\, D(t) + A_{pilot}\, C_{pilot}(t)$$

- A_{data} and A_{pilot} are respectively the data and pilot emitted amplitudes,
- $C_{data}(t)$ and $C_{pilot}(t)$ correspond to the spreading codes,
- $D(t)$ is the data stream, protected by a channel code = the navigation message

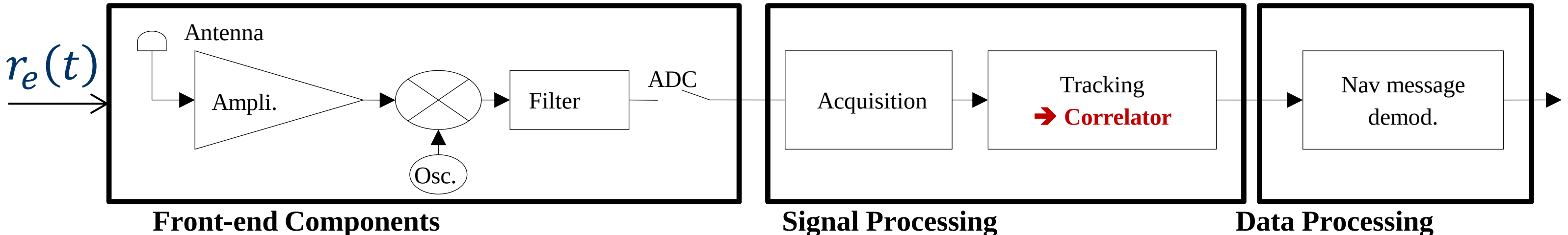
❖ Received signal:

$$r_e(t) = \int_{-\infty}^{+\infty} h_e(t;\tau) s_e(t-\tau) d\tau + n(t)$$

- $h_e(t;\tau)$ is the equivalent low-pass channel impulse response,
- $n(t)$ is the equivalent low-pass AWGN

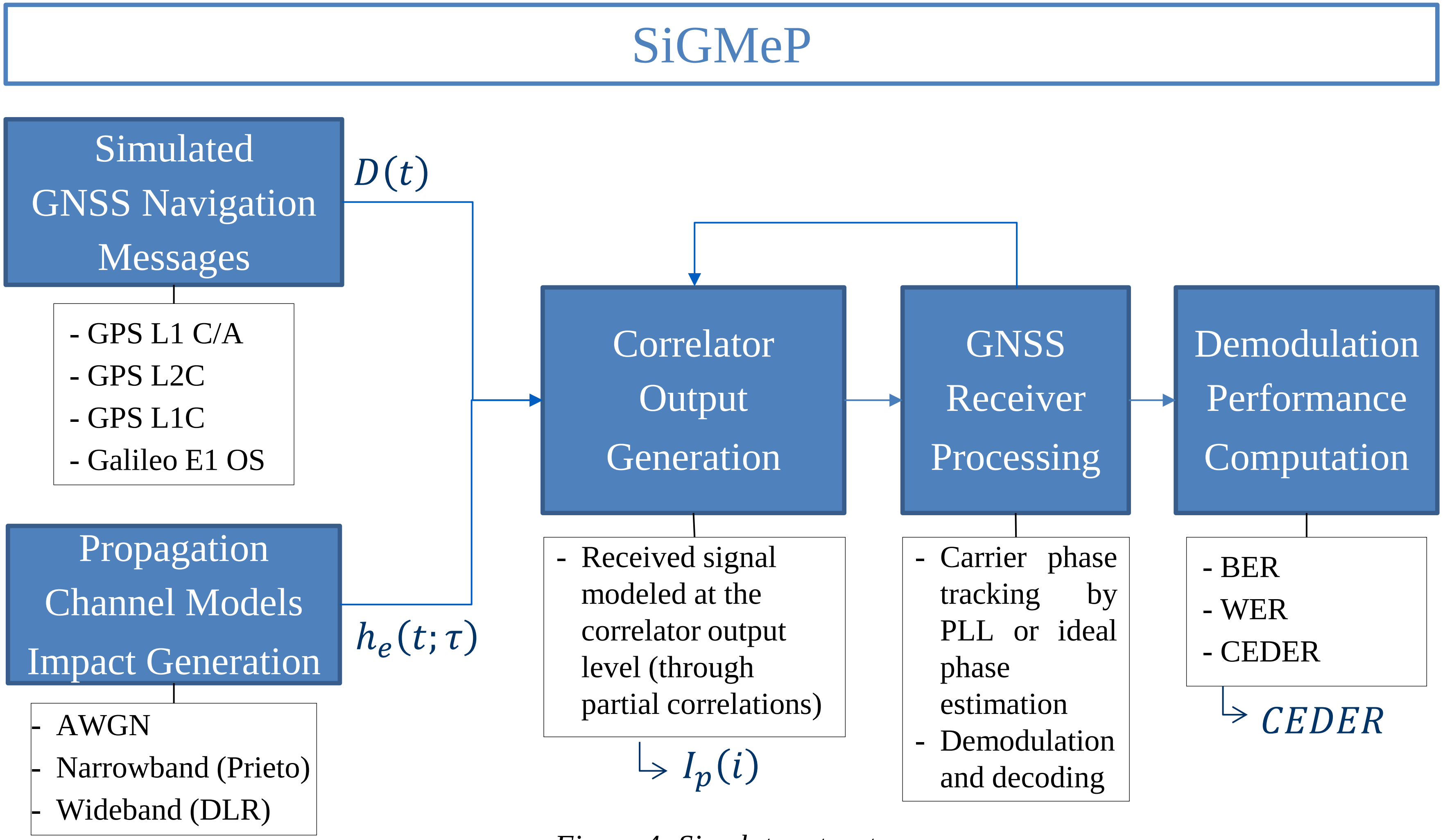
❖ GNSS receiver processing:

Figure 3: Real GNSS receiver block diagram



In the simulator, the signal is directly modeled at the correlator output level

1) Simulator Presentation - Simulator



SiGMeP

Simulated GNSS Navigation Messages

- GPS L1 C/A
- GPS L2C
- GPS L1C
- Galileo E1 OS

$D(t)$

Propagation Channel Models Impact Generation

- AWGN
- Narrowband (Prieto)
- Wideband (DLR)

$h_e(t;\tau)$

Correlator Output Generation

- Received signal modeled at the correlator output level (through partial correlations)

$I_p(i)$

GNSS Receiver Processing

- Carrier phase tracking by PLL or ideal phase estimation
- Demodulation and decoding

Demodulation Performance Computation

- BER
- WER
- CEDER

$CEDER$

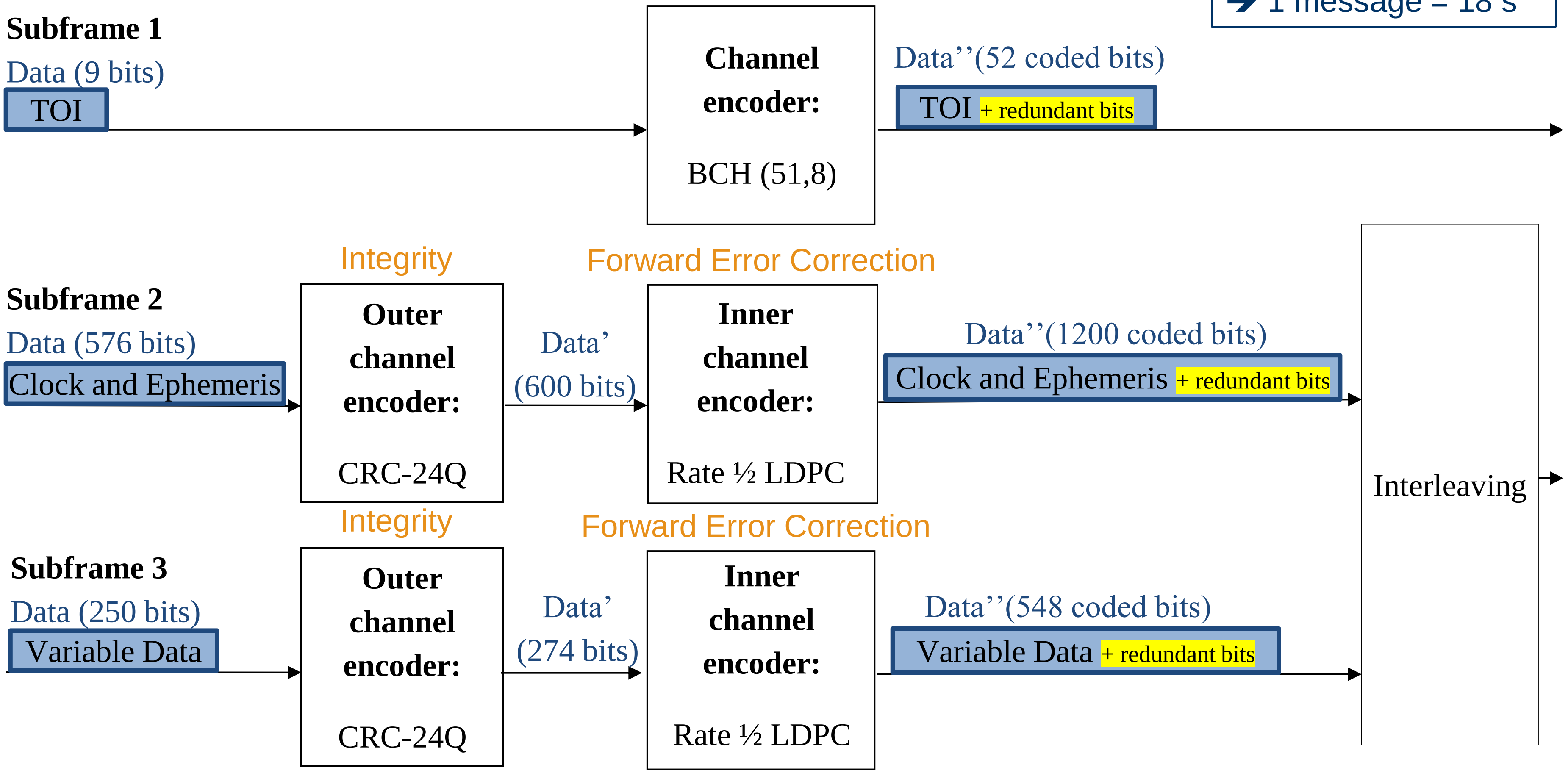
Figure 4: Simulator structure

1) Simulator Presentation - Navigation Message

GPS L1C Navigation message $D(t)$:

1 data symbol = 10 ms
Data rate = 100 sps
➔ 1 message = 18 s

Forward Error Correction



Subframe 1

Data (9 bits)

TOI

Channel encoder:

BCH (51,8)

Data''(52 coded bits)

TOI + redundant bits

Integrity

Forward Error Correction

Subframe 2

Data (576 bits)

Clock and Ephemeris

Outer channel encoder:

CRC-24Q

Data' (600 bits)

Inner channel encoder:

Rate ½ LDPC

Data''(1200 coded bits)

Clock and Ephemeris + redundant bits

Interleaving

Integrity

Forward Error Correction

Subframe 3

Data (250 bits)

Variable Data

Outer channel encoder:

CRC-24Q

Data' (274 bits)

Inner channel encoder:

Rate ½ LDPC

Data''(548 coded bits)

Variable Data + redundant bits

Figure 5: GPS L1C frame channel coding

1) Simulator Presentation - Propagation Channel

- The Land Mobile Satellite (LMS) channel model in urban environment for the demodulation point of view is targeted, there are 2 candidates:
  - A narrowband model: designed by **Perez-Fontan/Prieto**

    = The delay of the direct signal and the delays of the echoes are assumed to be equal
  - A wideband model: designed by **DLR**

    = The time delay of each multipath echo is individually modeled
- Both reference models:
  - The Perez-Fontan model was referenced in the COST (European Cooperation in the field Of Scientific and Technical Research) in 2002
  - The DLR model is the reference wideband model for the ITU (International Telecommunication Union) since 2009

1) Simulator Presentation - Propagation Channel

Perez-Fontan/Prieto Model

- Narrowband $h_e(t;\tau) = c(t)\delta\big(t - \tau_{direct}(t)\big)$

$$r_{e_{nb}}(t) = c(t)\big[A_{data}\, C_{data}\big(t - \tau_{direct}(t)\big)\, D\big(t - \tau_{direct}(t)\big) + A_{pilot}\, C_{pilot}\big(t - \tau_{direct}(t)\big)\big]$$

With: $\boldsymbol{c(t) = a_{channel}(t)e^{j\varphi_{channel}(t)}}$

- The amplitude of the received signal complex envelope is statistically determined: follows a Loo distribution with parameters (M_A, Σ_A, MP)

$$\text{Loo} \sim \boldsymbol{c(t)} = \underset{\underset{\text{Log-Normal}(M_A,\Sigma_A)}{\wr}}{\boldsymbol{a_{direct}}}\boldsymbol{(t)e^{j\varphi_{direct}(t)}} + \underset{\underset{\text{Rayleigh}(MP)}{\wr}}{\boldsymbol{a_{multipath}}}\boldsymbol{(t)e^{j\underset{\underset{\text{Uniform}(0,2\pi)}{\wr}}{\varphi_{multipath}}(t)}}$$

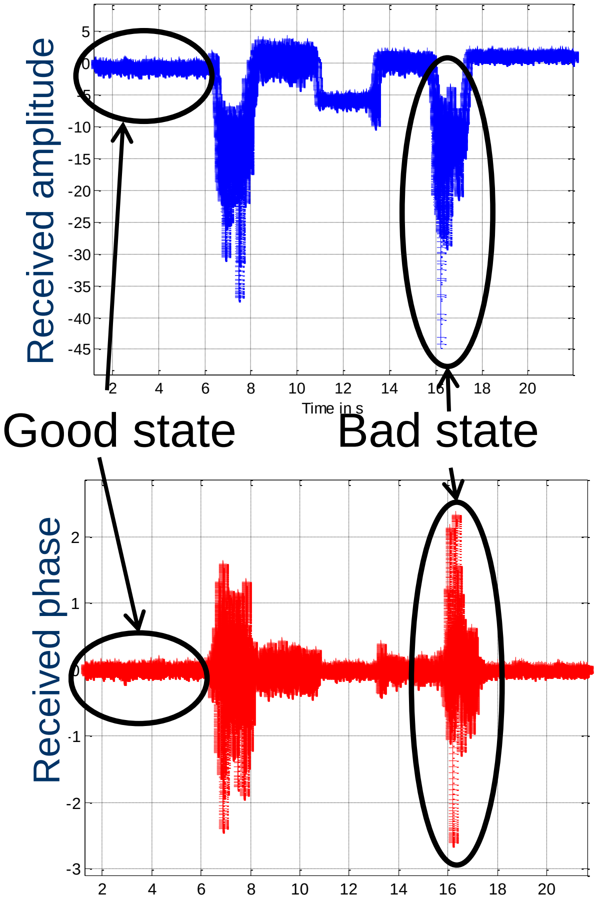
- The Loo parameters (M_A, Σ_A, MP) are not fixed, they follow a distribution law which parameters depend on the environmental conditions

1) Simulator Presentation - Propagation Channel

Perez-Fontan/Prieto Model

Channel states

- The received signal is classified into **2 states**, according to the shadowing/blocking level of the direct signal component:
  - "Good" for direct signal to moderate shadowing
  - "Bad" for moderate to deep shadowing
- The Loo parameters (M_A, Σ_A, MP) depend on the state
- Consecutive states: from bad to good, with a state duration variable which follows a log-normal distribution



User Speed	50 km/h
Band of the measurements	S-band
Satellite Elevation Angle	40°

Figure 6: Prieto received amplitude and phase

1) Simulator Presentation - Propagation Channel

DLR Model

- Wideband $h_e(t,\tau) = c_{direct}(t)\delta\left(\tau - \tau_{direct}(t)\right) + \sum_{l=1}^{L} c_l(t)\delta(\tau - \tau_l(t))$

$$r_{e_{wb}}(t) =$$

$$c_{direct}(t)\left[A_{data}\, C_{data}\left(t - \tau_{direct}(t)\right)D\left(t - \tau_{direct}(t)\right) + A_{pilot}\, C_{pilot}\left(t - \tau_{direct}(t)\right)\right] + \sum_{l=1}^{L} c_l(t)\left[A_{data}\, C_{data}\left(t - \tau_l(t)\right)\, D\left(t - \tau_l(t)\right) + A_{pilot}\, C_{pilot}\left(t - \tau_l(t)\right)\right]$$

  - $c_{direct}(\mathrm{t})$ is the channel impact on the direct signal component,
  - L is the number of echoes,
  - $\boldsymbol{c_l(t) = a_{channel,l}(t)e^{j\varphi_{channel,l}(t)}}$ is the channel impact on the *l*th echo,
  - $\tau_l(t)$ is the propagation time of the *l*th echo.

- The model is based on an artificial scene with potential obstacles: buildings, trees, lampposts, reflectors

- Obstacles are statistically generated, but the resulting impact on the received signal is mainly deterministic, based on ray tracing and geometric techniques

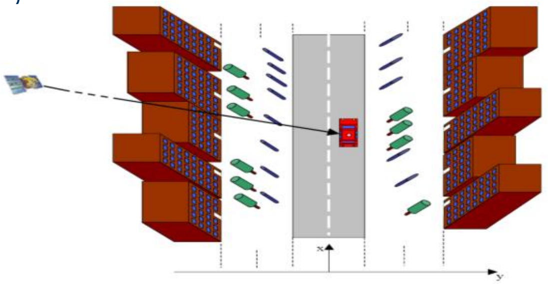


Figure 7: DLR model artificial scene

1) Simulator Presentation - Propagation Channel

Comparison between both models:

	Perez-Fontan/Prieto	DLR
Multipath modeling	Narrowband	Wideband
Model type	Statistical	Hybrid: statistical/deterministic
Measurement campaigns date	1990	2002
Calculation burden	Simple to implement	Heavy and time-consuming

Figure 8: Characteristics of two LMS channel models examples

The Perez-Fontan/Prieto model is less time-consuming, but the DLR model is supposed to be more representative of reality thanks to its wideband characteristic.

➔ Both models has thus been used, to investigate the narrowband/wideband modeling effect on demodulation performance

1) Simulator Presentation - Correlator Output Model

- **Classical correlator output model:**

$$I_{p_{nb}}(i) = \frac{A}{2}\, d_i\, R\left[\varepsilon_{\tau_i}\right] a_{channel}(i)\ cos\left(\varphi_{channel}(i) - \varphi_{rep}(i)\right) + n_I(i)$$

Integration Time T_I	Usually: $T_I =$ spreading code sequence duration multiple Examples: $T_I = 20\ ms$ (GPS L1C/A), $10\ ms$ (GPS L1C), $4\ ms$ (Galileo E1 OS)

Under these assumptions:

1) The phase error between the received signal and the local replica is constant over T_I,
2) The propagation channel amplitude $a_{channel}(t)$ is constant over T_I.

- **But in urban environments, these assumptions are not validated**

A T_I duration where the assumptions are validated is researched

- **A new correlator output model is proposed, based on partial correlations:**

The T_I duration is thus divided into *N* smaller intervals lasting $T_{I_{part}}$ seconds, where we assume that:

1) $R\left[\varepsilon_{\tau_i}\right]$ can be divided into *N* equal portions corresponding to partial correlations,
2) The phase error between the received signal and the local replica is constant over $T_{I_{part}}$,
3) The propagation channel amplitude $a_{channel}(t)$ is constant over $T_{I_{part}}$

1) Simulator Presentation - Correlator Output Model

Partial correlation duration analysis:

- To investigate the optimal choice of the partial correlation duration $T_{I_{part}}$

- Several values of $T_{I_{part}}$ have been tested with the simulator SiGMeP, following two principles:
  - The $T_{I_{part}}$ value has to be as long as possible in order to reduces the number of partial correlations to be generated,
  - The data error rate computed at the receiver output must be as faithful as possible to reality

- To determine the maximum acceptable $T_{I_{part}}$ duration, a "reference case" supposed to represent reality with $T_{I_{part}} = 0.01\,ms$ has been simulated with SiGMeP and compared with the "tested cases" with $T_{I_{part}} > 0.01\,ms$
  - BER degradation computation

Reference Partial Integration Time $T_{I_{part}}{}^{ref}$	$T_{I_{part}}{}^{ref} = 0.01\,ms$
Tested Partial Integration Time $T_{I_{part}}{}^{tested}$	$T_{I_{part}}{}^{tested} = 0.05\,ms, 0.1\,ms, 0.5\,ms, 1\,ms$

➔ **Simulations show that:** $T_{I_{part_{MAX}}} = 0.1\,ms$

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2) Demodulation Performance Analysis in Urban Environments
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5) Conclusion

2) Demodulation Performance Analysis in Urban Environments

- Historically, GNSS signals have been firstly designed for **open environments**:

  ➔ Demodulation performance studied in the **AWGN channel model**

- However, new GNSS applications are emerging in **urban environments**:

  ➔ Necessary to assess the GNSS signals demodulation performance in an **urban channel model**

- The urban channel is very different from the AWGN channel:

  ➔ Necessary to **adapt the methodology** of representing the GNSS signals demodulation performance in urban environments

2) Demodulation Performance Analysis in Urban Environments

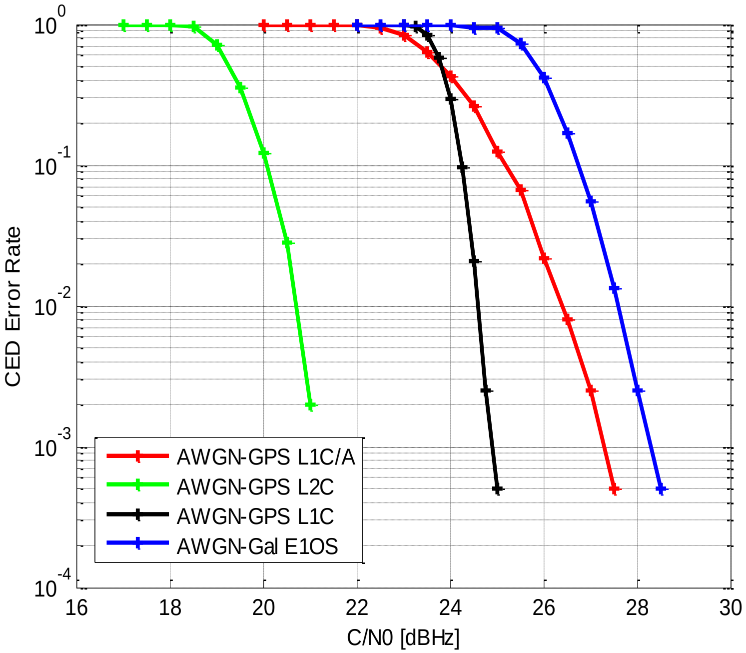


Figure 9: GNSS signals demodulation performance

Classical Method Limitation n°1:

The received C/N_0 is not constant in urban environments

Objective:

- Find a C/N_0 which is constant for a long time for any urban user
- Find a C/N_0 which is representative from an operational point of view

Proposition:

To use the theoretical $C_{pre\text{-}urban}/N_0$

with $C_{pre\text{-}urban}$ = received direct signal power without channel attenuation

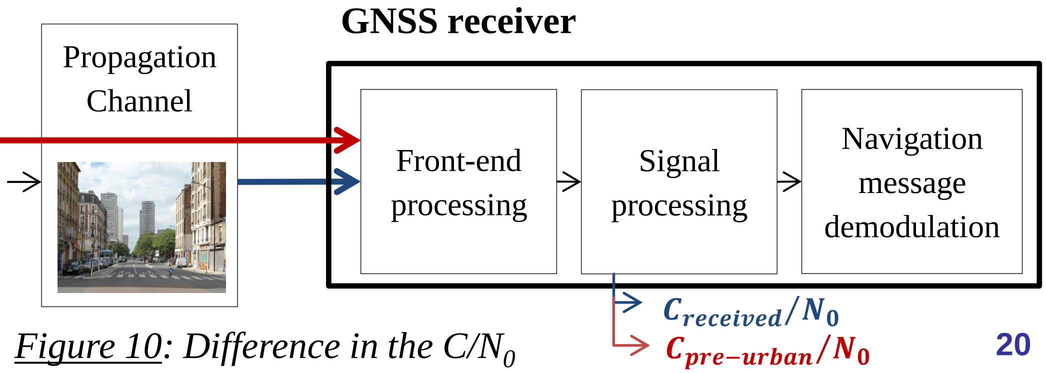


Figure 10: Difference in the C/N_0

2) Demodulation Performance Analysis in Urban Environments

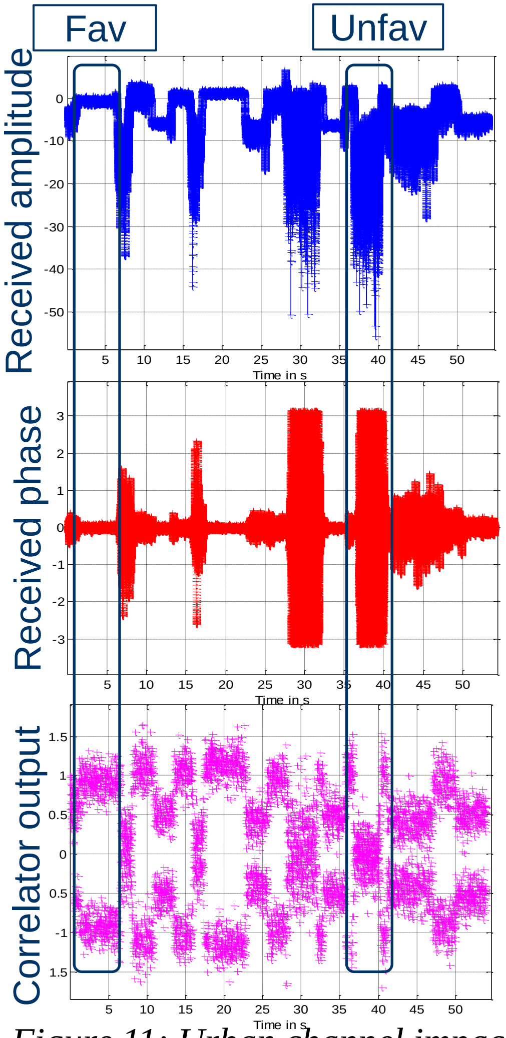


Figure 11: Urban channel impact on the received signal

Classical Method Limitation n°2:

Only punctual instead of continuous message demodulations are required because in GNSS the same information set is repeated for a given time interval (example: CED information set).

Objective:

Combine the next characteristics:

- GNSS requires punctual demodulation
- Urban environments have dynamic signal reception conditions

Proposition:

- To provide the **demodulation performance** for **favorable reception conditions** together with **statistical information about its occurrence**

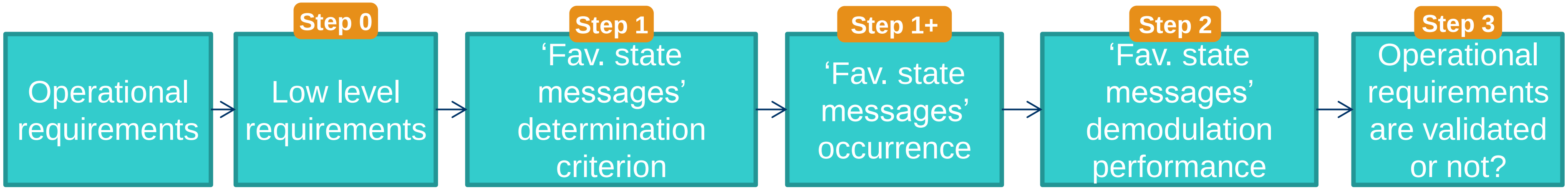
2) Demodulation Performance Analysis in Urban Environments

Which statistical occurrence values associated with demodulation performance are considered acceptable?

- Determined by the operational requirements
- Example: To determine if a GPS L1C receiver can calculate a continuous valid position during 4 consecutive hours, with a probability greater than 95%

How to link operational requirements with statistical occurrence and associated demodulation performance?

- In determining low level requirements = at least 1 demodulated information set by 1 satellite during a continuous duration



To define the best criterion determining 'favorable state messages'

Which meets the low level requirements

Figure 12: New method block diagram

2) Demodulation Performance Analysis in Urban Environments - Example

Strategy n°1 Operational Requirement Example
To determine if a GPS L1C receiver can calculate a continuous valid position during 4 consecutive hours, with a probability greater than 95%, and with a CED error rate equal to 10^{-2}.

Step 0 : Interpreting this ‘high level’ operational requirement through a ‘low level’.

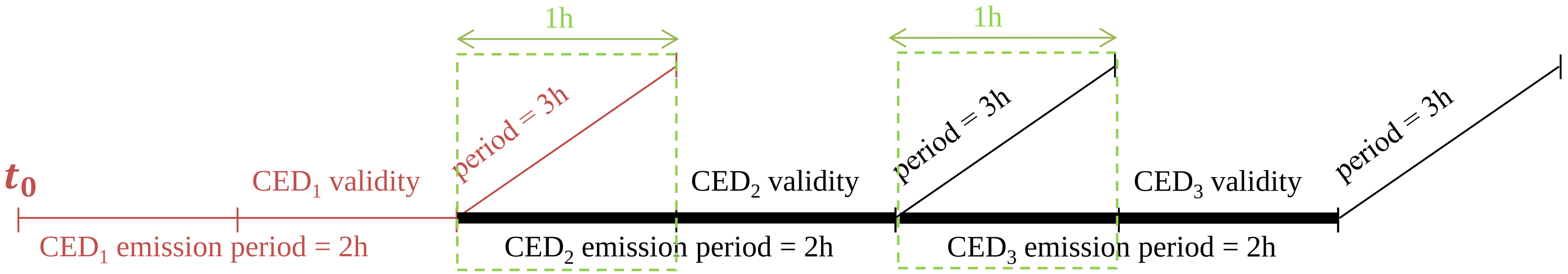


Figure 13: CED emission and validity periods diagram for GPS L1C

$$P_{final-4h} = 95\% = P_{1sat-4h}{}^{4} = \left(\boldsymbol{P_{1sat-1h}}{}^{2}\right)^{4} \Rightarrow \boldsymbol{P_{1sat-1h}} = \left(P_{final-4h}\right)^{1/8} = 0.9936$$

2) Demodulation Performance Analysis in Urban Environments - Example

Strategy n°1 Operational Requirement Example
To determine if a GPS L1C receiver can calculate a continuous valid position during 4 consecutive hours, with a probability greater than 95%, and with a CED error rate equal to 10^{-2}.

Step 0: Interpreting this ‘high level’ operational requirement through a ‘low level’.

Determining:

$P_{0fav-1h\,max}$ = the required probability that no ‘favorable state message’ has been received during the duration of interest $1h$, from 1 satellite,

According to the low level requirement $P_{1sat-1h}$ defined before.

$$P_{0fav-1h} \leq 1 - P_{1sat-1h} \Rightarrow P_{0fav-1h\,max} = 0.0064$$

2) Demodulation Performance Analysis in Urban Environments - Example

Strategy n°1 Operational Requirement Example
To determine if a GPS L1C receiver can calculate a continuous valid position during 4 consecutive hours, with a probability greater than 95%, and with a CED error rate equal to 10^{-2}.

Step 1 : Finding the criterion to separate the 'unfavorable state messages' from the 'favorable state messages' which provides the best demodulation performance.

Prieto model:

The received signal is classified into 2 states, 'Good' and 'Bad' according to the channel impact level

➔ 'Favorable state message' = message entirely received in 'Good' Prieto state

DLR model:

➔ 'Favorable state message' = message for which its estimated received C/N_0 is above a threshold

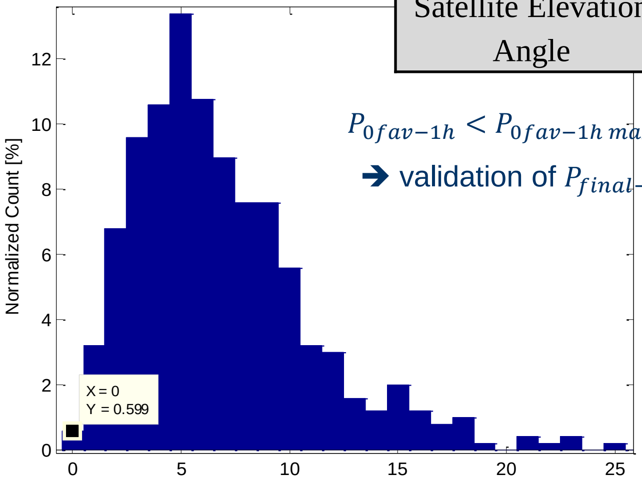
2) Demodulation Performance Analysis in Urban Environments - Example

Strategy n°1 Operational Requirement Example
To determine if a GPS L1C receiver can calculate a continuous valid position during 4 consecutive hours, with a probability greater than 95%, and with a CED error rate equal to 10^{-2}.

Step 1+

Prieto model:

Simulation Conditions	
Environment	Urban
Database Band	S
Satellite Elevation Angle	40°



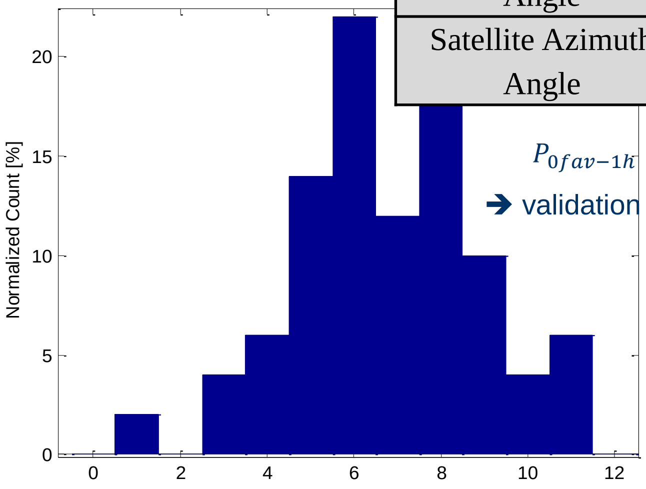
Number of fav. state messages in 1 hour

$P_{0fav-1h} < P_{0fav-1h\,max} = 0.0064$

➔ validation of $P_{final-4h} > 95\%$

DLR model:

Simulation Conditions	
Environment	Urban
Satellite Elevation Angle	40°
Satellite Azimuth Angle	30°



Number of fav. state messages in 1 hour

$P_{0fav-1h} < P_{0fav-1h\,max}$

➔ validation of $P_{final-4h} > 95\%$

Figure 14: 'Favorable state messages' histogram, for GPS L1C

2) Demodulation Performance Analysis in Urban Environments - Example

Step 2 Calculating the CED Error Rate during 'Favorable States'

Prieto

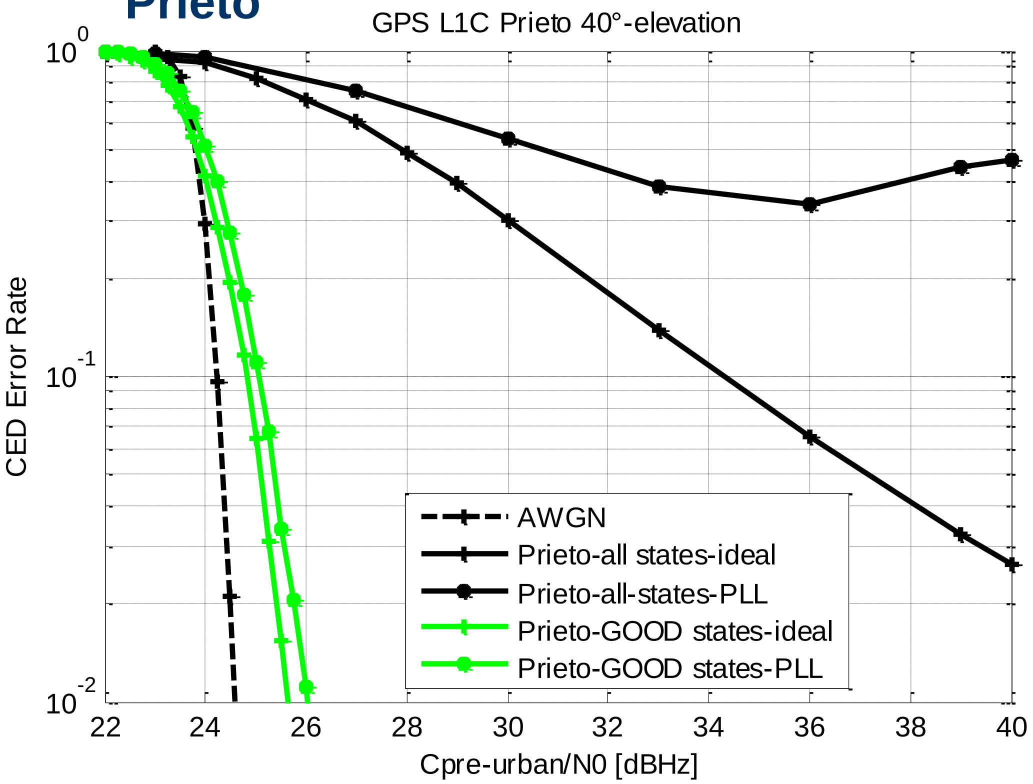


Figure 15: GPS L1C GOOD state CED demodulation performance and total CED demodulation performance

- ❖ For the PLL tracking case, the CEDER presents a **floor**, due to PLL losses of lock during unfavorable conditions
- ➔ It seems never possible to demodulate with $CEDER = 10^{-2}$ with the classical method
- ➔ The most relevant information is hidden: the possibility of punctually obtaining much better demodulation performance in favorable reception conditions = new method (green lines)

2) Demodulation Performance Analysis in Urban Environments - Example

Step 2 Calculating the CED Error Rate during 'Favorable States'

DLR

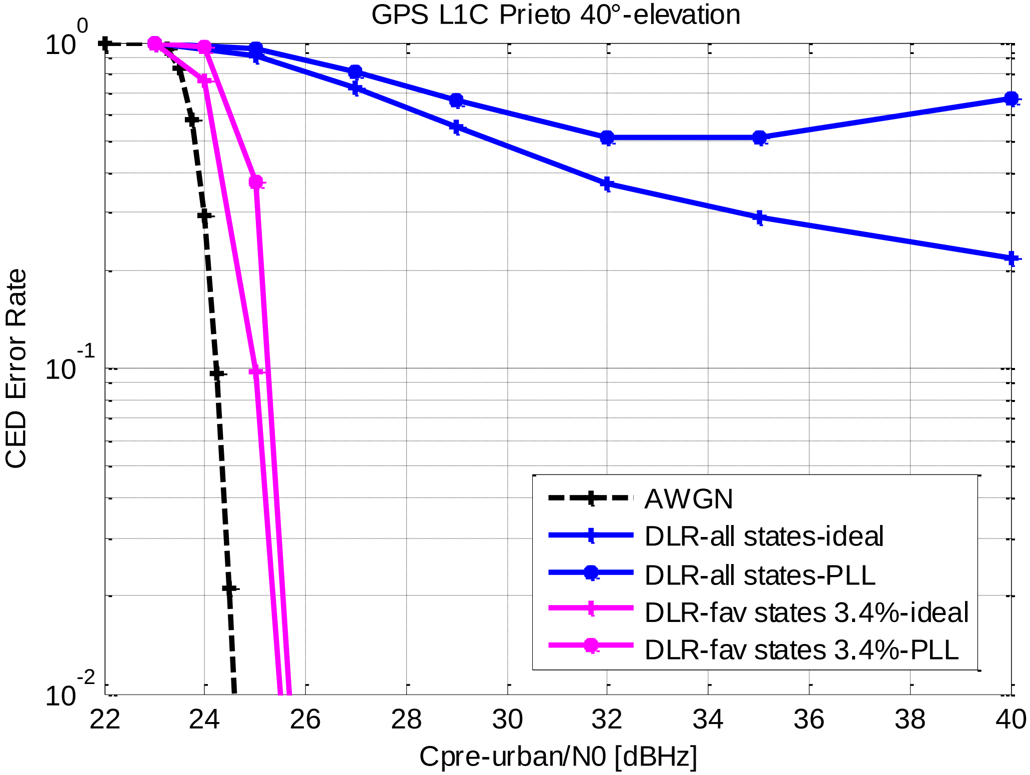


Figure 16: GPS L1C GOOD state CED demodulation performance and total CED demodulation performance

- ❖ For the PLL tracking case, the CEDER presents a **floor**, due to PLL losses of lock during unfavorable conditions
- ➔ It seems never possible to demodulate with $CEDER = 10^{-2}$ with the classical method
- ➔ The most relevant information is hidden: the possibility of punctually obtaining much better demodulation performance in favorable reception conditions = new method (green lines)

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2) Demodulation Performance Analysis in Urban Environments - Example

Strategy n°1 Operational Requirement Example
To determine if a GPS L1C receiver can calculate a continuous valid position during 4 consecutive hours, with a probability greater than 95%, and with a CED error rate equal to 10^{-2}.

Step 3: Operational requirements validation or non-validation

$$P_{final-4h} = {P_{1sat-1h,abs}}^{8} = \left(P_{1fav}.P_1 + P_{2fav}.P_2 + \cdots + P_{200fav}.P_{200}\right)^8$$

$$P_{final-4h} = \Big(P_{1fav}.\left(1 - CEDER_{C/N_0}\right) + P_{2fav}.\left(1 - {CEDER_{C/N_0}}^{2}\right) + \cdots + P_{200fav}.\left(1 - {CEDER_{C/N_0}}^{200}\right)\Big)^8$$

Prieto model:

For $C_{pre-urban}/N_0 > 26\ dBHz$

$P_{final-4h} \approx 95.3\ \%$

DLR model:

For $C_{pre-urban}/N_0 > 25.5\ dBHz$

$P_{final-4h} \approx 99.8\ \%$

➔ the required $P_{final-4h}$ equal to 95% being thus validated

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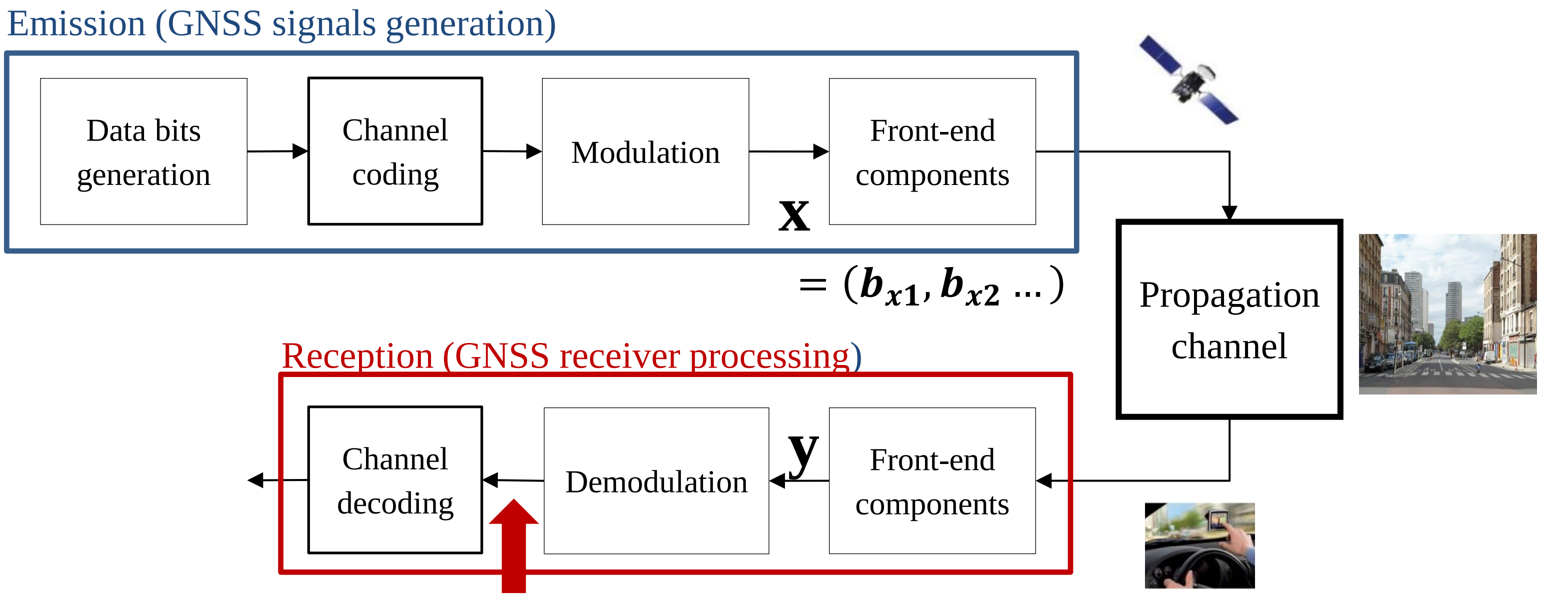
3) Demodulation Performance Improvement by Decoding Optimization

MAP decoding criterion: $If\ \frac{p(b_x=+1/y)}{p(b_x=-1/y)} > 1$ or $\text{LLR} = log\left(\frac{p(b_x=+1/y)}{p(b_x=-1/y)}\right) > 0 \rightarrow \hat{x} = +1$



Emission (GNSS signals generation)

Data bits generation → Channel coding → Modulation → Front-end components

$\mathbf{x} = (\boldsymbol{b_{x1}}, \boldsymbol{b_{x2}} \ldots)$

Propagation channel

Reception (GNSS receiver processing)

Front-end components → $\mathbf{y}$ → Demodulation → Channel decoding →

Log **L**ikelihood **R**atio → **LLR** $= log\left(\frac{p(b_x=+1/y)}{p(b_x=-1/y)}\right)$

Figure 17: GNSS emission/reception chain block diagram

Objective: Since in classical receivers the LLR is derived assuming an AWGN channel whereas urban environments are targeted here, we want to derive the LLR for any urban user.

3) Demodulation Performance Improvement by Decoding Optimization

Detection function ➔ LLR $= log\left(\frac{p(y/x=+1)}{p(y/x=-1)}\right)$

In GNSS, the received symbol y to be decoded is the data component correlator output I_P modeled through partial correlations for a narrowband channel by:

$$y(i) = I_P(i) = \sqrt{P}x(i)\left[\sum_{n=1}^{N} a_{channel}(n+(i-1)N)\ \cos(\varepsilon_\theta(n+(i-1)N))\right] + n_I(i)$$

Normalization by $\sqrt{P}$:

$$y(i) = x(i)\left[\sum_{n=1}^{N} a_{channel}(n+(i-1)N)\ \cos(\varepsilon_\theta(n+(i-1)N))\right] + n'_I(i)$$

3) Demodulation Performance Improvement by Decoding Optimization

Usually, the expression of the soft channel decoder input in GNSS receivers is obtained assuming an AWGN propagation channel

Assumptions:

- The propagation channel is considered as an **AWGN channel**
- The noise power ${\sigma^2}_{n_I'}$ is known

$$y(i) = I_P'(i) = x(i)\left[\sum_{n=1}^{N} \underbrace{a_{channel}(n+(i-1)N)}_{=1}\ \cos(\underbrace{\varepsilon_\theta(n+(i-1)N))}_{=0}\right] + {n_I}'(i)$$

The decoder input is thus: $LLR_{AWGN}(i) = log\ \left(\frac{p(x=+1/y)}{p(x=-1/y)}\right) = \frac{2y(i)}{{\sigma^2}_{n_I'}}$

Objective:

To derive the detection function LLR assuming an urban channel, considering 2 cases:

1) **Perfect** propagation channel impact knowlegde is assumed
2) **No** propagation channel impact knowlegde is assumed

3) Demodulation Performance Improvement by Decoding Optimization

Case 1: However, urban environments are targeted. Thus, the detection function must consider an urban channel. Firstly, perfect Channel State Information is assumed = ideal case ➔ best achievable performance

Assumptions:

- The propagation channel is considered as an **urban channel**
- The channel impact on $I'_P(i)$ is perfectly known
- The noise power ${\sigma^2}_{{n_I}'}$ is known

$$y(i) = I'_P(i) = x(i)\underbrace{\left[\sum_{n=1}^{N} a_{channel}(n+(i-1)N)\ \cos(\varepsilon_\theta(n+(i-1)N))\right]}_{\text{Perfectly known}} + {n_I}'(i)$$

The decoder input $LLR_{Perfect\ CSI}$ is thus:

Difference with the AWGN LLR expression

$$LLR_{Perfect\ CSI}(i) = \frac{2\left[\sum_{n=1}^{N} \boldsymbol{a_{channel}(n+(i-1)N)\ cos(\varepsilon_\theta(n+(i-1)N))}\right]y(i)}{{\sigma^2}_{{n_I}'}}$$

3) Demodulation Performance Improvement by Decoding Optimization

Case 1 Simulations Results

Simulation Conditions	
Signals	GPS L1C
Channel Model	Perez-Fontan/Prieto
Environment	Urban
Database Band	S
Satellite Elevation Angle	40°
Phase Estimation	Ideal/PLL

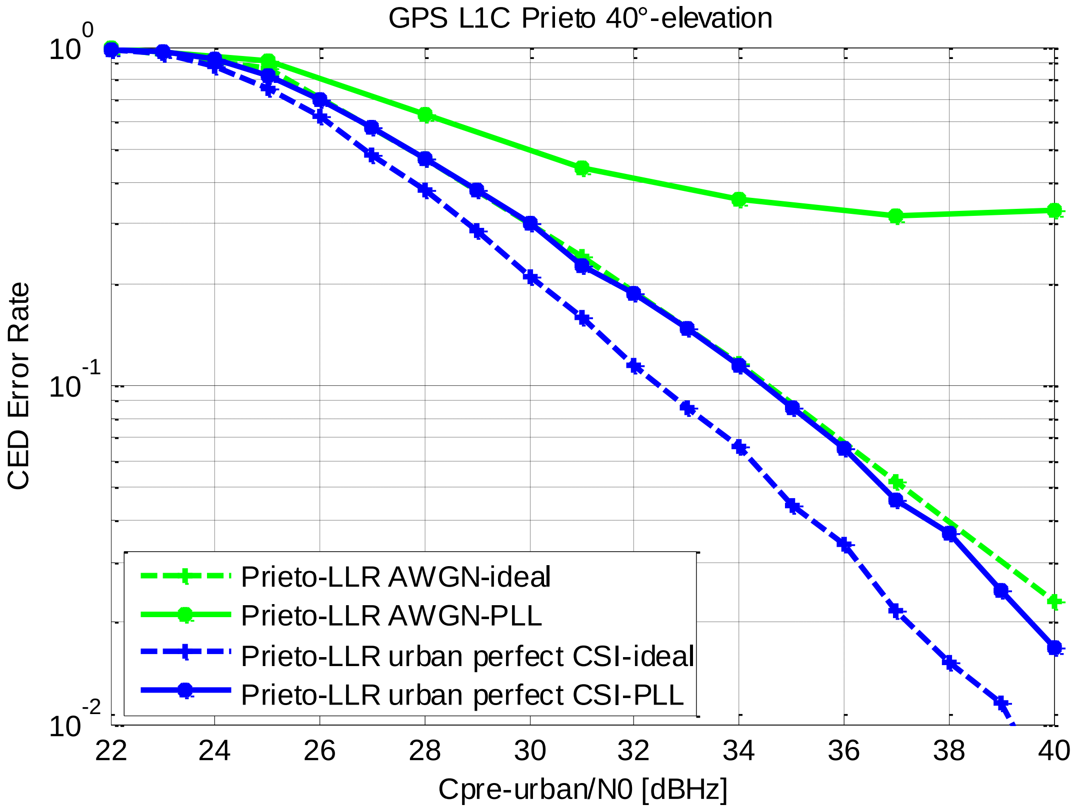


Figure 18: GPS L1C demodulation performance obtained with LLR_{AWGN} and $LLR_{Perfect\ CSI}$ in the Prieto channel model

- For the PLL tracking case, the CEDER **floor** obtained using LLR_{AWGN} due to PLL losses of lock **totally disappears** with the use of $LLR_{Perfect\ CSI}$
- In the ideal phase estimation case, **decoding gain of 3 dB**

➔ It is really promising since it is represents the best achievable demodulation performance

3) Demodulation Performance Improvement by Decoding Optimization

Case 2: However, urban environments are targeted. Thus, the detection function must consider an urban channel. Secondly, no Channel State Information is assumed = real cases

Assumptions:

- The propagation channel is considered as an **urban channel**
- The channel impact on $I'_P(i)$ is unknown

$$y(i) = I'_P(i) = x(i)\underbrace{\left[\sum_{n=1}^{N} a_{channel}(n+(i-1)N)\ \cos(\varepsilon_\theta(n+(i-1)N))\right]}_{\text{Unknown}} + n_I{}'(i)$$

Inspired by the $LLR_{Perfect\ CSI}$ expression, the detection function is modeled by a linear function of the observations y *[Yazdani, 2009]*:

$$LLR_{No\ CSI}(i) = \boldsymbol{\alpha} y(i)$$

3) Demodulation Performance Improvement by Decoding Optimization

Case 3:

$$LLR_{No\ CSI}(i) = \boldsymbol{\alpha} y(i)$$

α is determined maximizing the mutual information $I(LLR;X)$ *[Yazdani, 2009]*:

$$\alpha_{MCLA} = \arg\max_{\alpha} \, I(LLR;X)$$

With $I(LLR;X)$ estimated with no learning sequence (x unknown) and without any statistical knowledge (LLR's pdf unknown).

Over a sliding windows of several symbols y, $I(LLR;X)$ is estimated for each tested α

The α value which provides the maximum estimated $I(LLR;X)$ is chosen

For the corresponding symbol, the LLR is computed with this α value

3) Demodulation Performance Improvement by Decoding Optimization

Case 2 Simulations Results

Simulation Conditions	
Signals	GPS L1C
Channel Model	Perez-Fontan/Prieto
Environment	Urban
Database Band	S
Satellite Elevation Angle	40°
Phase Estimation	Ideal/PLL

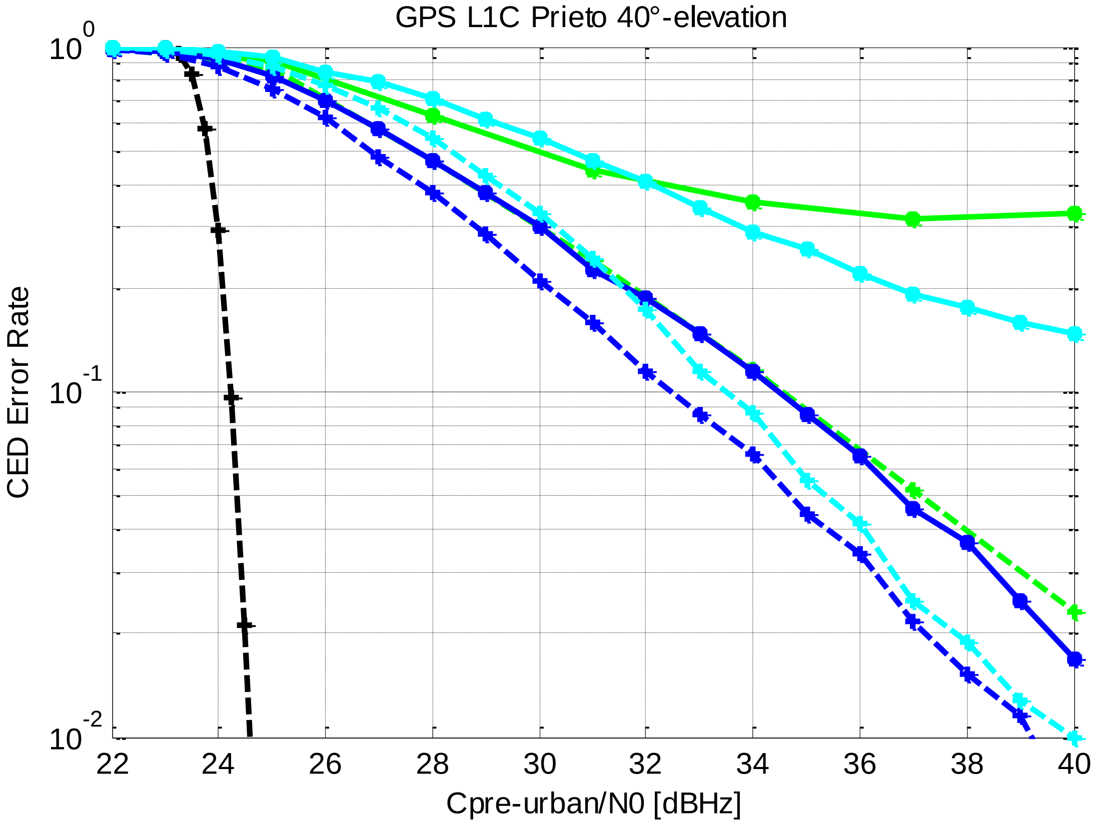


Figure 19: GPS L1C demodulation performance obtained with LLR_{AWGN} and $LLR_{Perfect\ CSI}$ in the Prieto channel model

- For ideal phase estimation, we approach the **ideal case** using $LLR_{no\ CSI}$
- For the PLL tracking case, the CEDER **floor** obtained using LLR_{AWGN} **still remains** with the use of $LLR_{no\ CSI}$ but at a lower level

- The optimization method could be more investigated, especially for an important PLL estimated phase error (by channel estimation or taking into account a phase error model or the PLL losses of lock detector output)

Outline

1) Simulator Presentation
2) Demodulation Performance Analysis in Urban Environments
3) Demodulation Performance Improvement by Decoding Optimization
4) Demodulation Performance Improvement by Designing a New Signal
5) Conclusion

4) Demodulation Performance Improvement by Designing a New Signal

Objective

New GNSS signal design with improved demodulation performance in urban environments

Research axis

- LDPC channel code
  - ➔ Modern channel code able to approach the channel capacity
- CSK modulation
  - ➔ Possibility to non-coherently demodulate the navigation message

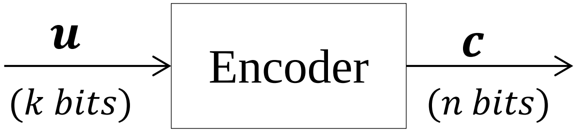
Proposition

LDPC code optimization for a GNSS CSK-based signal.

4) Demodulation Performance Improvement by Designing a New Signal - LDPC Channel Coding

LDPC = Low-Density Parity-Check

- Able to provide performance which approaches the best possible performance: the channel capacity
- Linear block codes:



$\boldsymbol{u}$ $(k\ bits)$ → Encoder → $\boldsymbol{c}$ $(n\ bits)$

$$c = uG$$

or $cH^T = 0$

with *H* obtained by $GH^T = 0$

Channel code rate: $R = \frac{k}{n}$

Generator matrix: G

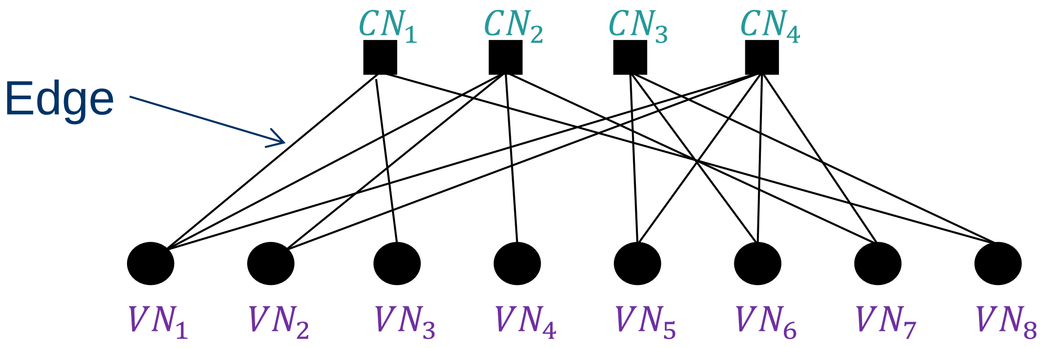
Parity check matrix: H

- Defined by the null space of the parity-check matrix H $C = \{c \in GF(2)^{\times n} / cH^T = 0\}$ that has a low density of 1s

4) Demodulation Performance Improvement by Designing a New Signal - Tanner Graph

A Tanner graph, based on the parity-check matrix *H*:

- Completely represents a LDPC encoder
- Is made by nodes, separated into two types:
  - The Variables Nodes (VN), representing the **coded bits**
  - The Check Nodes (CN), representing the **parity check equations**
- Is drawn as follows: the Check Nodes CN_i are connected to the Variable Nodes VN_j whenever element h_{ij} in the parity check matrix *H* is equal to 1:



$$H = \begin{array}{cl} \begin{array}{cccccccc} VN_1 & VN_2 & VN_3 & VN_4 & VN_5 & VN_6 & VN_7 & VN_8 \end{array} & \\ \begin{pmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 1 & 0 & 0 & 1 & 1 & 1 & 0 \end{pmatrix} & \begin{array}{l} CN_1 \\ CN_2 \\ CN_3 \\ CN_4 \end{array} \end{array}$$

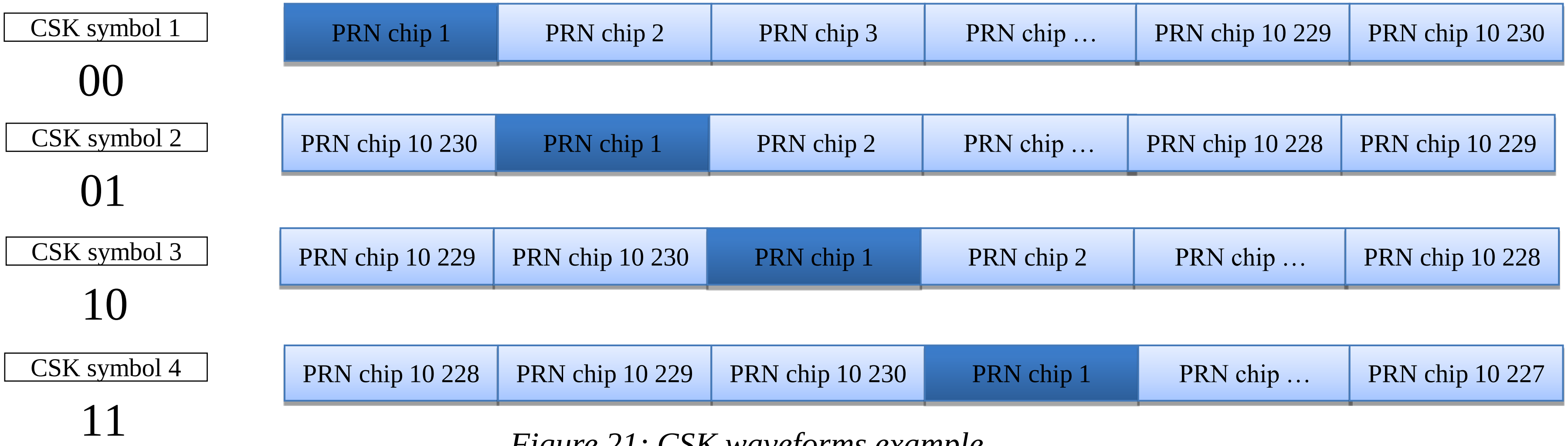
Figure 20: Tanner graph example

- Node degree = number of edges connected to a node, $d_{v\,max}$ and $d_{c\,max}$ = maximum degrees

4) Demodulation Performance Improvement by Designing a New Signal - CSK Modulation

CSK = Code Shift Keying

- ❖ M-ary orthogonal modulation
- ❖ Each waveform corresponds to the same spreading sequence, but circularly shifted:



CSK symbol 1	00	PRN chip 1	PRN chip 2	PRN chip 3	PRN chip …	PRN chip 10 229	PRN chip 10 230
CSK symbol 2	01	PRN chip 10 230	PRN chip 1	PRN chip 2	PRN chip …	PRN chip 10 228	PRN chip 10 229
CSK symbol 3	10	PRN chip 10 229	PRN chip 10 230	PRN chip 1	PRN chip 2	PRN chip …	PRN chip 10 228
CSK symbol 4	11	PRN chip 10 228	PRN chip 10 229	PRN chip 10 230	PRN chip 1	PRN chip …	PRN chip 10 227

Figure 21: CSK waveforms example

- ❖ Possibility to non-coherently demodulate the navigation message
- ❖ Data rate increase

4) Demodulation Performance Improvement by Designing a New Signal - LLR$_{CSK}$

LLR derivation for a GNSS CSK-modulated signal in an AWGN channel:

$$LLR_{q-CSK} = log\left(\frac{p\left(b_{x_q} = 1/y\right)}{p\left(b_{x_q} = 0/y\right)}\right)$$

$$LLR_{q-CSK} = \underbrace{log\left(\frac{\sum_{\substack{All\ CSK\ symbols \\ which\ b_{x_q}=1}}\left[e^{\frac{1}{\sigma_b^2}\sum_{i=1}^{N}\left(y_{chip_i}x_{chip_i}\right)}\prod_{j\neq q}p\left(b_{x_j}\right)\right]}{\sum_{\substack{All\ CSK\ symbols \\ which\ b_{x_q}=0}}\left[e^{\frac{1}{\sigma_b^2}\sum_{i=1}^{N}\left(y_{chip_i}x_{chip_i}\right)}\prod_{j\neq q}p\left(b_{x_j}\right)\right]}\right)}_{LLR_{\boldsymbol{E}_q}} + \underbrace{log\left(\frac{p\left(b_{x_q} = 1\right)}{p\left(b_{x_q} = 0\right)}\right)}_{LLR_{\boldsymbol{A}_q}}$$

Extrinsic:
Information exclusively brought by the other bits

A priori:
Input information

4) Demodulation Performance Improvement by Designing a New Signal - Iterative Decoding

The decoding process can be made through two different methods:

Classical Decoding

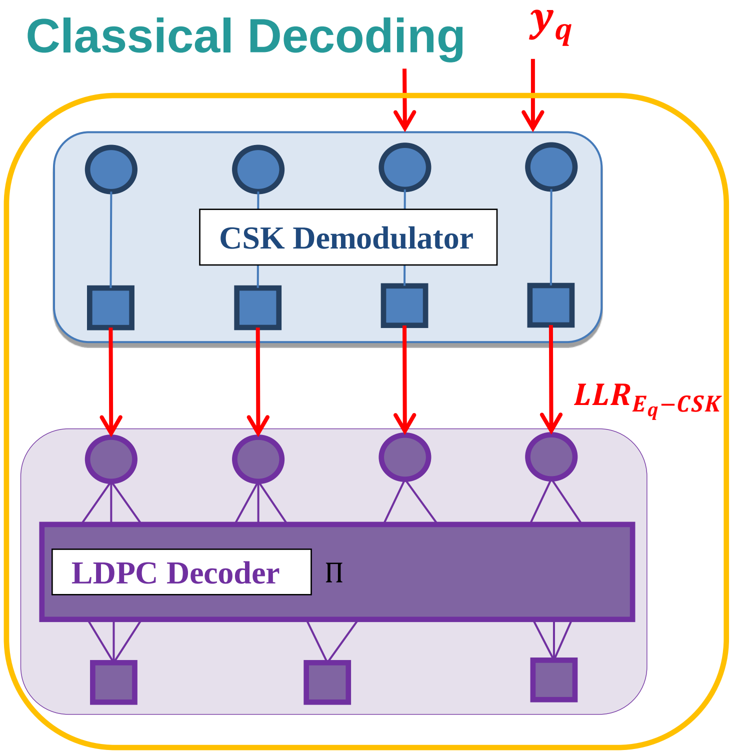


Figure 22: CSK demodulator and LDPC decoder combination, for the classical decoding method

Iterative Decoding

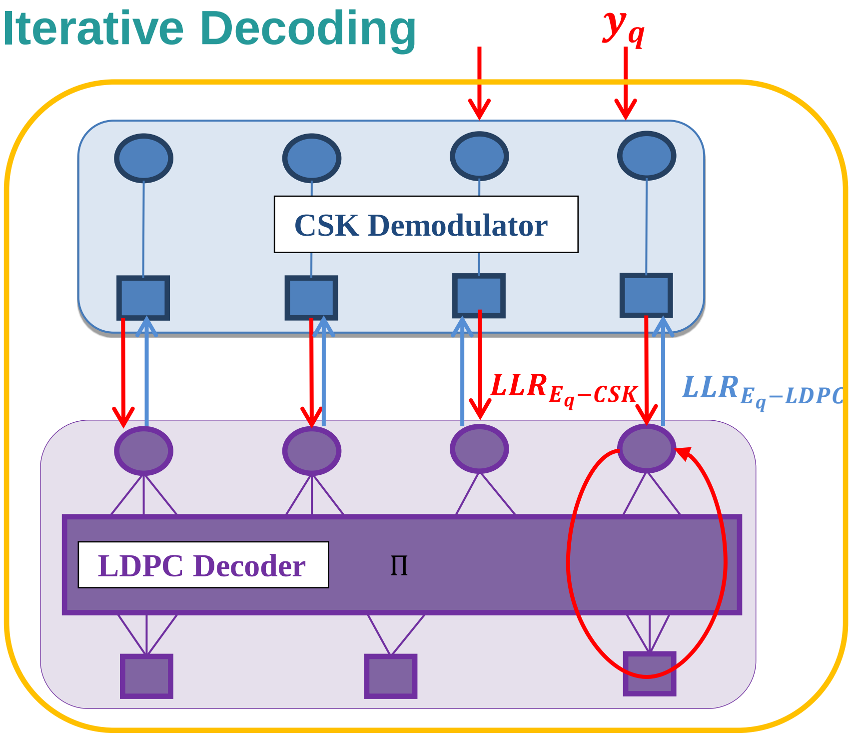


Figure 23: CSK demodulator and LDPC decoder combination, for the iterative decoding method

4) Demodulation Performance Improvement by Designing a New Signal - EXIT Chart

To determine if iterative decoding provides better performance than non-iterative decoding in the case of a CSK-modulated GNSS signal:

➔ the **EXtrinsic-Information-Transfer (EXIT) chart** is used

- Developed in the late 1990s
- Consists in plotting the output metric of interest, the extrinsic mutual information I_E, as a function of the input metric of interest, the a priori mutual information I_A
- $\boldsymbol{I_E} = I(LLR_E; b_x)$ is the mutual information between the emitted coded bit b_x and the **extrinsic** LLRs and $\boldsymbol{I_A} = I(LLR_A; b_x)$ is the mutual information between the emitted coded bit b_x and the **a priori** LLRs
- If I_E increases with I_A (= if bringing more a priori information to the demodulator involves a higher extrinsic information quantity at its output), it means that iterative decoding will improve the performance

4) Demodulation Performance Improvement by Designing a New Signal - EXIT Chart Plots

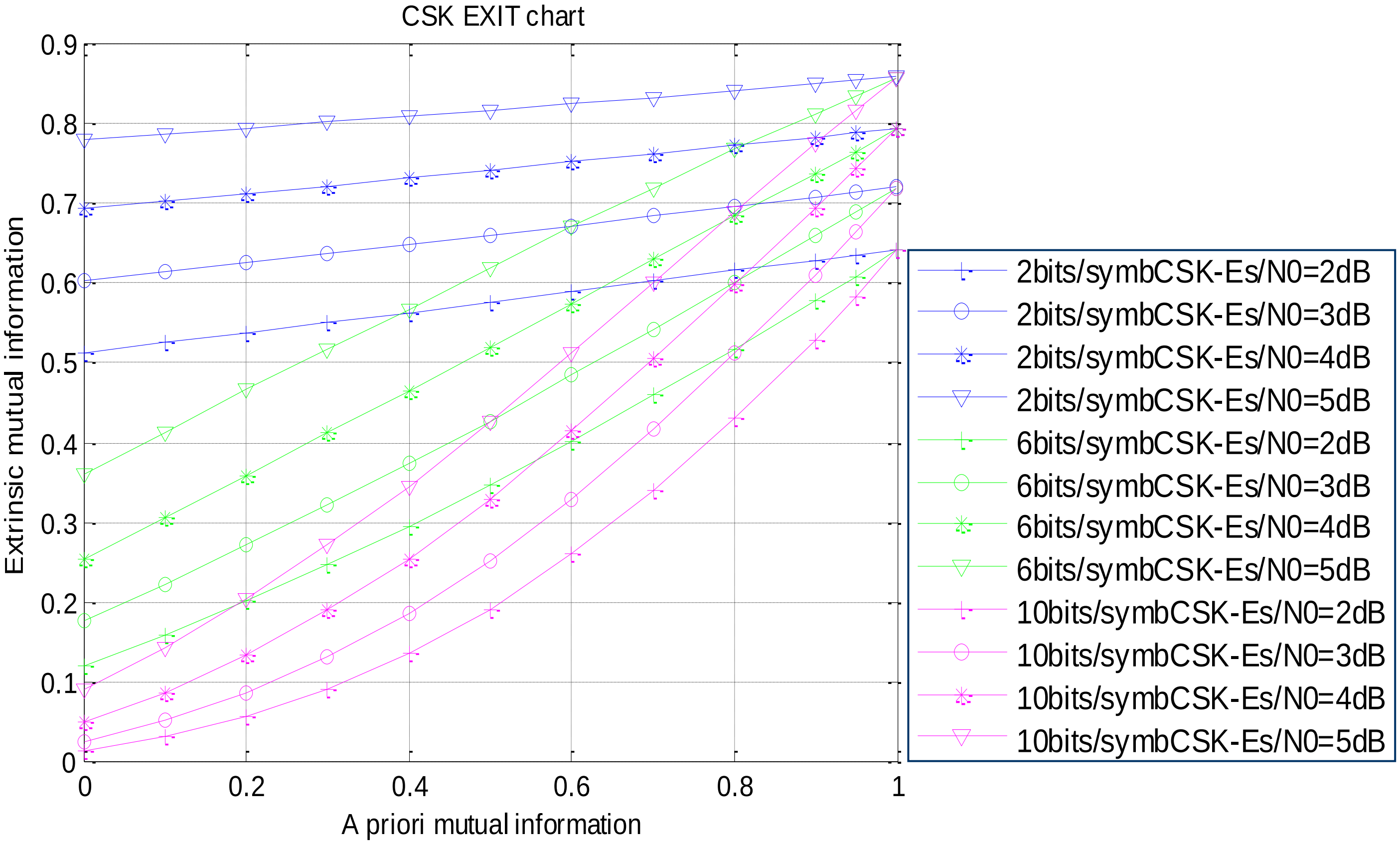


Figure 24: CSK EXIT charts for different numbers of bits per CSK symbols

- bringing more a priori information to the demodulator involves a higher extrinsic information quantity at its output, meaning that **iterative decoding will improve the performance**

➔ Optimization of the LDPC code for a CSK-modulated signal in an AWGN channel, considering iterative decoding.

4) Demodulation Performance Improvement by Designing a New Signal - EXIT Chart Areas

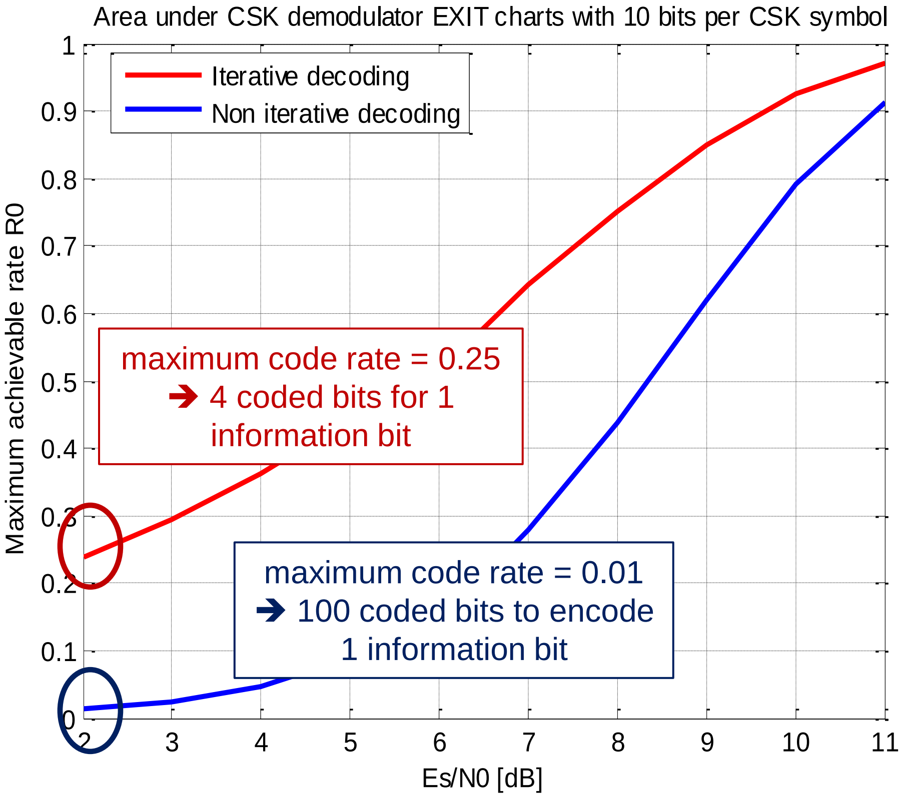
The area under the CSK demodulator EXIT curve can be linked to the capacity:

$$A_{CSK} = \int_0^1 T_{CSK}(i)di \approx R_0$$

Where:

- A_{CSK} is the area under the EXIT chart of the CSK demodulator,
- T_{CSK} is the EXIT chart function associated with the CSK demodulator,
- **R_0 is the maximum achievable channel code rate:**

  = the maximum channel code rate at which reliable communication (arbitrarily small error probability) is possible



maximum code rate = 0.25
➔ 4 coded bits for 1 information bit

maximum code rate = 0.01
➔ 100 coded bits to encode 1 information bit

Figure 25: Comparison between the maximum achievable code rate R_0 with iterative and non-iterative decoding

4) Demodulation Performance Improvement by Designing a New Signal - LDPC Optimization

Derivation of the **asymptotic analysis** for the LDPC code optimization under iterative decoding *[Ten Brink, 2004] [Poulliat, 2010]*:

- Method based on the demodulator EXIT chart function and on the updating equations of the exchanged LLR messages between the demodulator and the decoder
- Consists in solving a linear programming optimization problem, the cost function being to maximize the channel code rate
- Leading to the optimized degree distributions for the LDPC channel code parameters (the edges profile)

4) Demodulation Performance Improvement by Designing a New Signal - LDPC Codes Generation

According to the asymptotic analysis, **generation of finite length H matrices**:

- 2 bits and 6 bits per CSK symbol
- 600 information bits with channel code rate ½

  since the GPS L1C signal is used as a benchmark to test the demodulation performance improvement
- Different maximum VN degrees: $d_{v\,max}$= 10, 15
- Number of degree 2 VNs: limited or no limited

➔ Finite length H matrices generation with the PEG algorithm

PEG algorithm: well-known to construct LDPC codes at finite block lengths with very good performance

<u>Comparison between</u>:

Signal 0 (600 info bits, code ½): GPS L1C LDPC code + BOC modulation + non-iterative decoding

Signal 1 (600 info bits, code ½): GPS L1C LDPC code + CSK modulation + non-iterative decoding

Signal 2 (600 info bits, code ½): GPS L1C LDPC code + CSK modulation + iterative decoding

Signal 3 (600 info bits, code ½): Optimized LDPC code 1 + CSK modulation + iterative decoding

Signal 4 (600 info bits, code ½): Optimized LDPC code 2 + CSK modulation + iterative decoding

4) Demodulation Performance Improvement by Designing a New Signal - Optimized LDPC Results

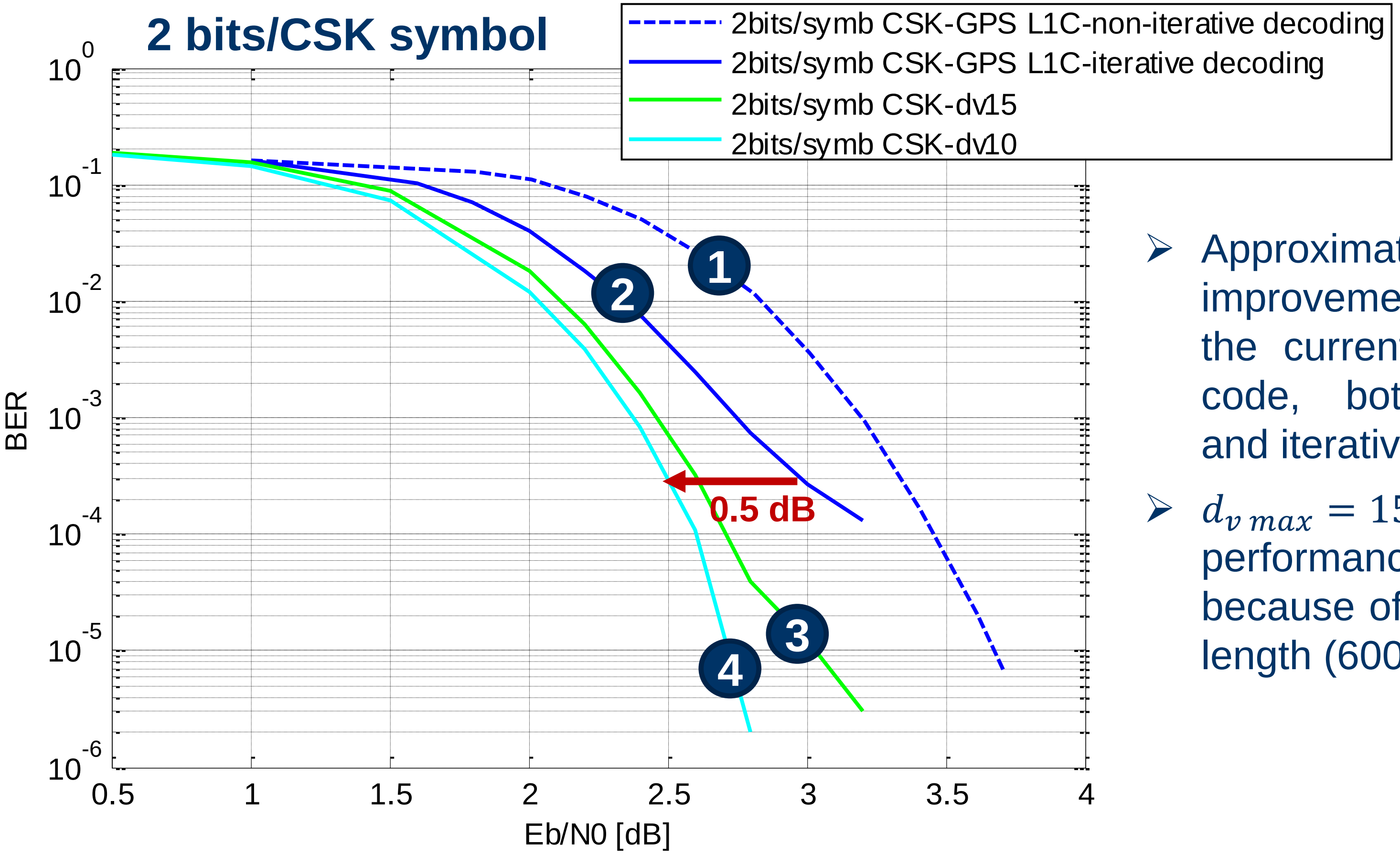


Figure 26: Finite length results: BER according to Eb/N0 for 2 bits per CSK symbol

- Approximately 0.5 dB of improvement compared with the current GPS L1C LDPC code, both CSK-modulated and iteratively decoded
- $d_{v\,max} = 15$ provides worse performance than $d_{v\,max} = 10$, because of the short message length (600 bits)

4) Demodulation Performance Improvement by Designing a New Signal - Optimized LDPC Results

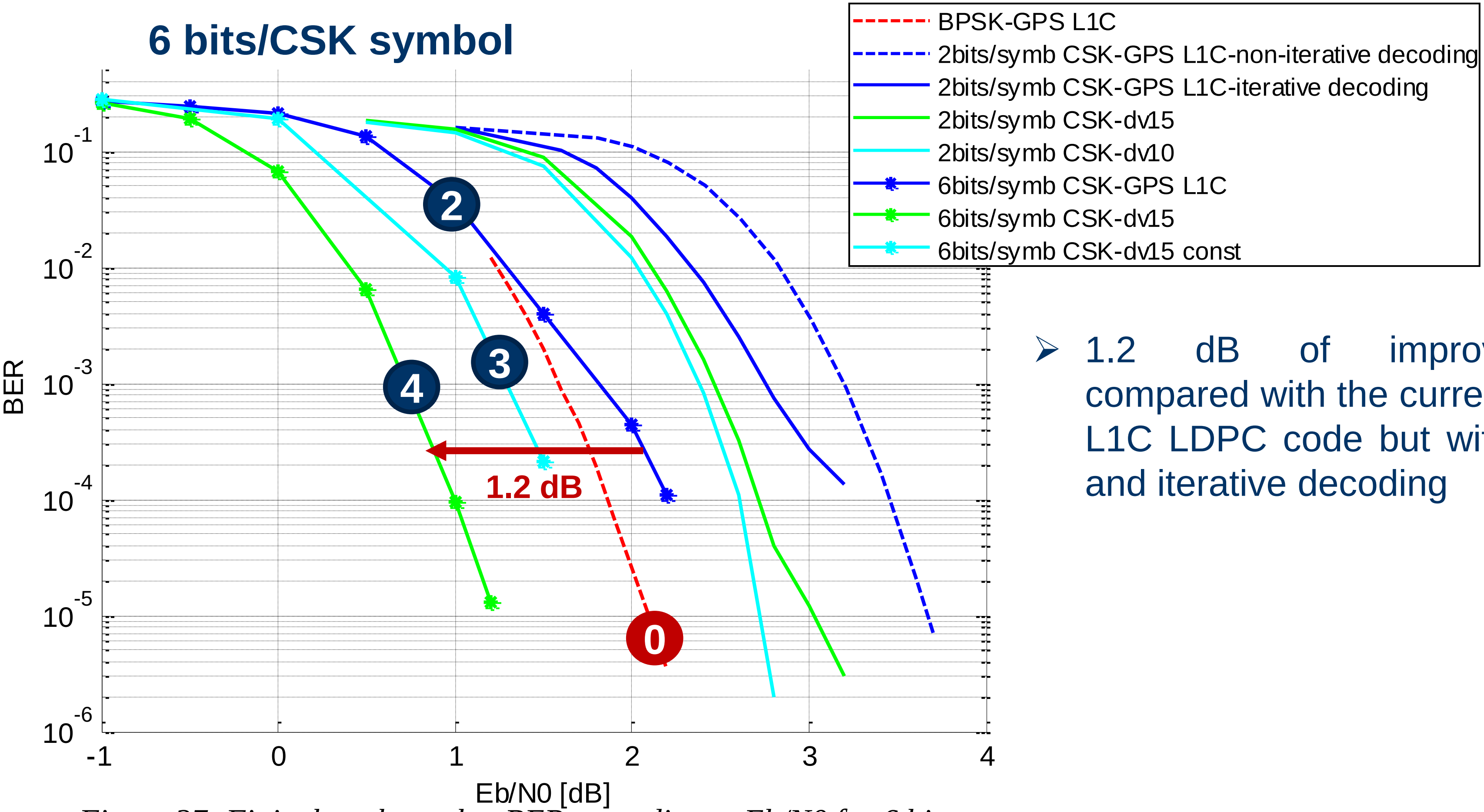

6 bits/CSK symbol

Figure 27: Finite length results: BER according to Eb/N0 for 6 bits per CSK symbol

- 1.2 dB of improvement compared with the current GPS L1C LDPC code but with CSK and iterative decoding

Outline

1) Simulator Presentation
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Conclusion

- Development of a software simulator, able to model the entire GNSS signal emission/reception chain in urban environments
- Development of an innovative method specially adapted to provide the GNSS signals demodulation performance in urban environments, able to evaluate the fulfillment of operational needs
- Detection function computation adaptation to any kind of user reception environment, without any CSI knowledge, improving the demodulation performance compared with the classical detection function use, only in modifying a part of the receiver process
  - The demodulation performance is improved by 3 dB in the ideal phase estimation
  - If a PLL phase tracking is considered, the floor due to PLL losses of locks drops
- Optimization of a LDPC code profile for a CSK-modulated signal and iterative decoding in an AWGN propagation channel model, thanks to the EXIT charts analysis and asymptotic optimization method
  - The best performing designed code outperforms significantly the GPS L1C LDPC code under iterative decoding by about 1.2 dB at BER= 10^{-4} for 6 bits per CSK symbol

Future Work

- It would be interesting to exhibit all the current GNSS signals demodulation performance in urban environments with the new method and to vary the user speed, the emitting satellites elevation angle and the azimuth angle
- Demodulation performance has been investigated through the CED error rate, but Time To First Fix (TTFF) is a figure of merit which remains to be studied
- Future work on the detection function optimization would consists in improving the innovative method for PLL tracking
- The new designed LDPC-coded and CSK-modulated signal dedicated to iterative decoding needs to be compared with the current GPS L1C signal, and tested in urban environments
- Future investigations will consider the extension to the non-binary case, since our work leads us to cycles codes.

Questions

Publications:

- M. Roudier, T. Grelier, L. Ries, A. Garcia-Pena, O. Julien, C. Poulliat, M.-L. Boucheret, and D. Kubrak, "GNSS Signal Demodulation Performance in Urban Environments," in *Proceedings of the 6th European Workshop on GNSS Signals and Signal Processing*, Munich, Germany, 2013.
- M. Roudier, A. Garcia-Pena, O. Julien, T. Grelier, L. Ries, C. Poulliat, M.-L. Boucheret, and D. Kubrak, "New GNSS Signals Demodulation Performance in Urban Environments," in *Proceedings of the 2014 International Technical Meeting of The Institute of Navigation*, San Diego, California, 2014.
- M. Roudier, C. Poulliat, M.-L. Boucheret, A. Garcia-Pena, O. Julien, T. Grelier, L. Ries, and D. Kubrak, "Optimizing GNSS Navigation Data Message Decoding in Urban Environment," in *Proceedings of the 2014 IEEE/ION Position Location and Navigation Symposium of The Institute of Navigation*, Monterey, California, 2014.
- M. Roudier, A. Garcia-Pena, O. Julien, T. Grelier, L. Ries, C. Poulliat, M.-L. Boucheret, and D. Kubrak, "Demodulation Performance Assessment of New GNSS Signals in Urban Environments," in *Proceedings of the 2014 ION GNSS+ of The Institute of Navigation*, Tampa, Florida, 2014.