Association of Non-Binary code and CCSK modulation

Quasi Cyclic Short Packets Project

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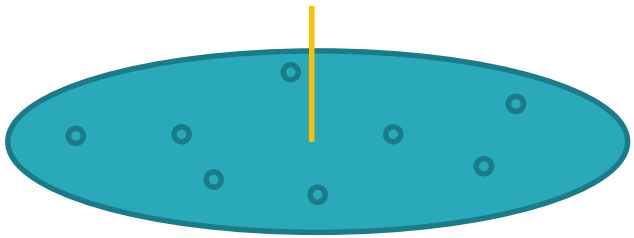
Massive IoT: first paradigm shift

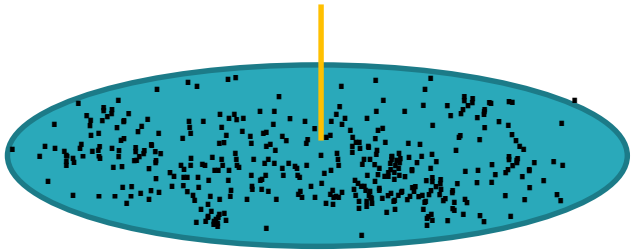
Broadband cellular



100 User Terminals at 1 Mbit/s

⇒ 0.1% for coordination
⇒ 99.9% for data

Wide area IoT network



1M de sensors, 100 bit/s

⇒ 99.9% for coordination
⇒ 0.1% for data

Classical cellular methods are simply not adapted for massive IoT.

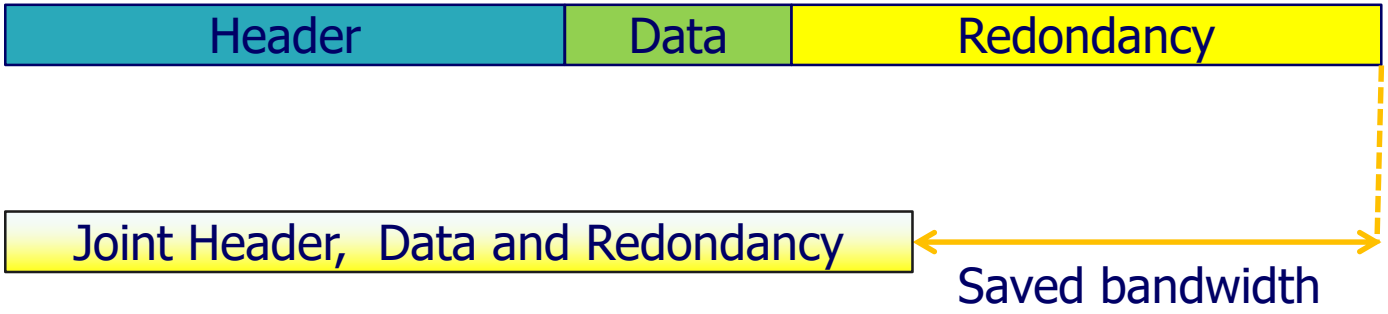
Solution: just suppress coordination… and accept collision [1].

[1] G. Durisi, T. Koch, and P. Popovski, “Toward Massive, Ultrareliable, and Low-Latency Wireless Communication With Short Packets,” Proceedings of the IEEE, vol. 104, no. 9, pp. 1711–1726, Sep. 2016.

Massive IoT: second paradigm shift

Second problem: Classical model of frame is inefficient for small payload,

=> Header, Data and Redundancy should be merged.



Big bet: new waveform for IoT for low cost sensors, unsupervised network

From space to earth

- **Cyclic-Code Shift Keying (CCSK)** used in Quasi-Zenith Satellite system (Japanese GPS enhancement system). 2003 **[1]**

- **Non-binary error correcting codes (NB-ECC)** used in BeiDou (Chinese GPS-like system) 2017 **[2]**.

QCSP Approach: CCSK modulation and NB-code association

[1]: G. M. Dillard et al. "Cyclic code shift keying: a low probability of intercept communication technique". In: *IEEE Transactions on Aerospace and Electronic Systems* 39.3 (**2003**), pp. 786–798.
[2]: China Satellite Navigation Office, *BeiDou Navigation Satellite System, Signal In Space, Interface Control Document, Open Service Signals, Dec.* **2017**
http://en.beidou.gov.cn/SYSTEMS/Officialdocument/201806/P020180608525871869457.pdf

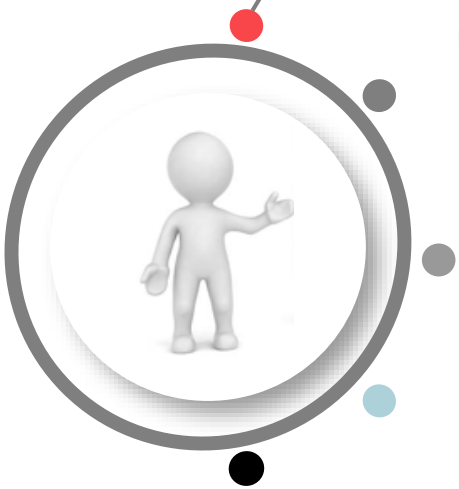
About QCSP project

- Project funded by ANR (French Research Funding Agency).
- 4 years project started in October 2019.

Objective : Evolution of IoT frames

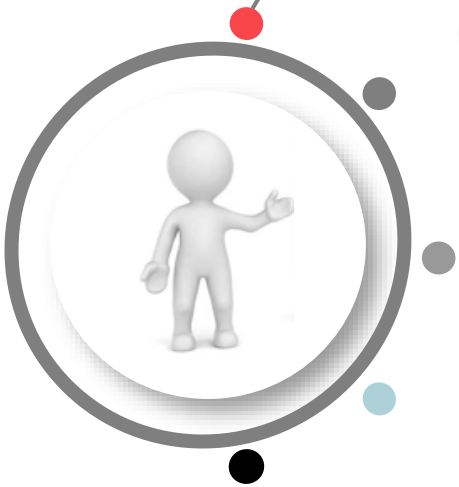
ANR-19-CE25-0013-01

Outline



- QCSP system model
- Receiver processing
- GNU Radio implementation
- Rate adaptative QCSP
- Conclusion and perspectives

Outline



- **QCSP system model**
- Receiver processing
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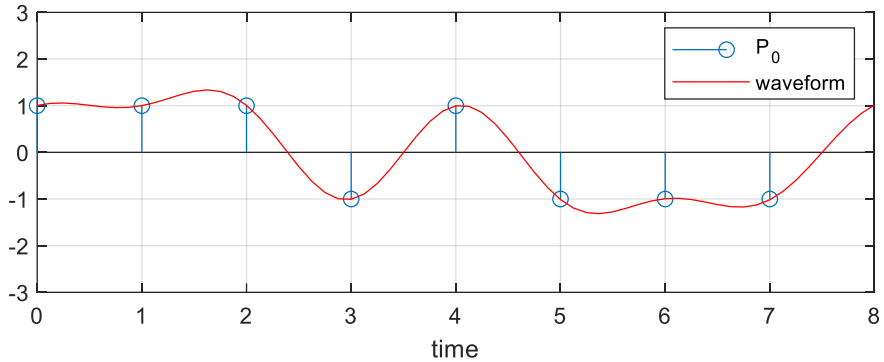
Cyclic Code Shift Keying modulation

P_0 = 11101000 + BPSK modulation, roll-off factor 0.35, q = 8



- CCSK modulation:
  - P_0 = 11101000
  - P_1 = 01110100
  - P_2 = 00111010
  - P_3 = 00011101
  - P_4 = 10001110
  - P_5 = 01000111
  - P_6 = 10100011
  - P_7 = 11010001

Binary message : 011001100

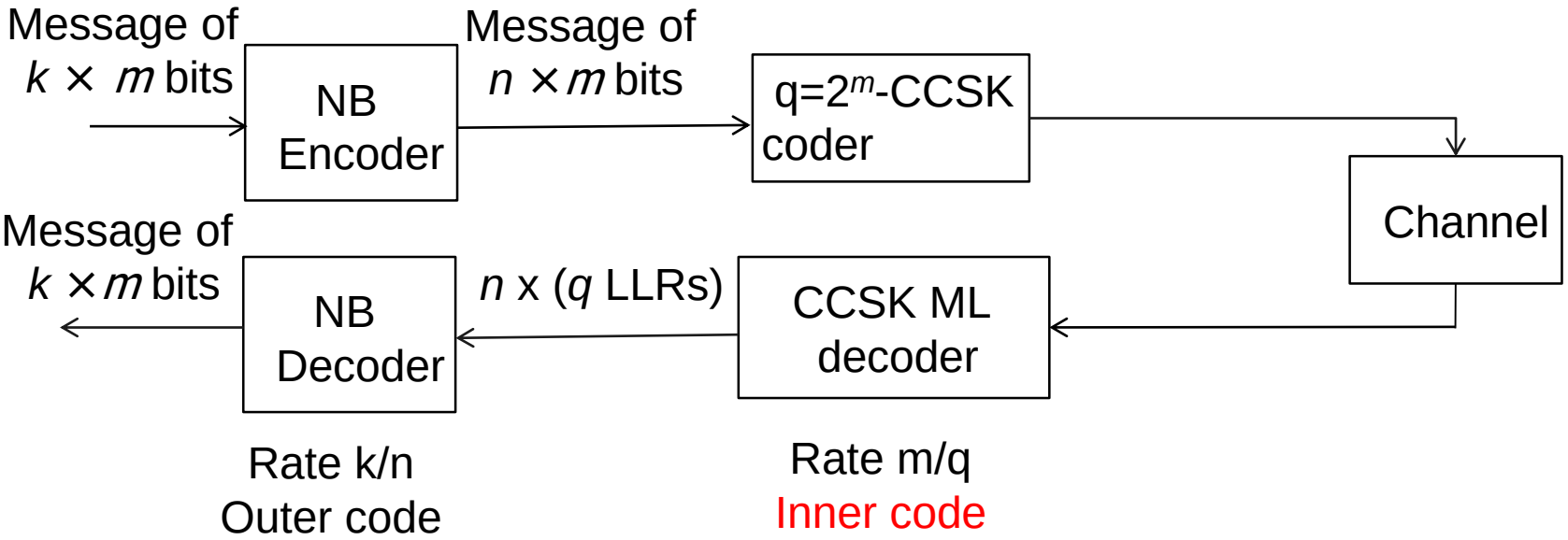
Make 3-uplet symbols: $(011)_2(001)_2(100)_2$

Take decimal value: 3 1 4

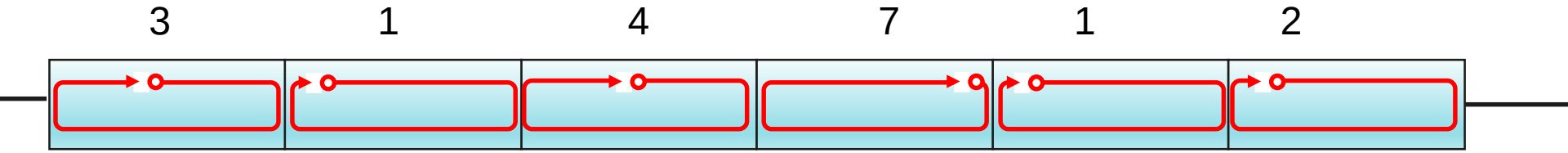
Associate CCSK symbol P_3 P_1 P_4

Send => 000111010111010010001110

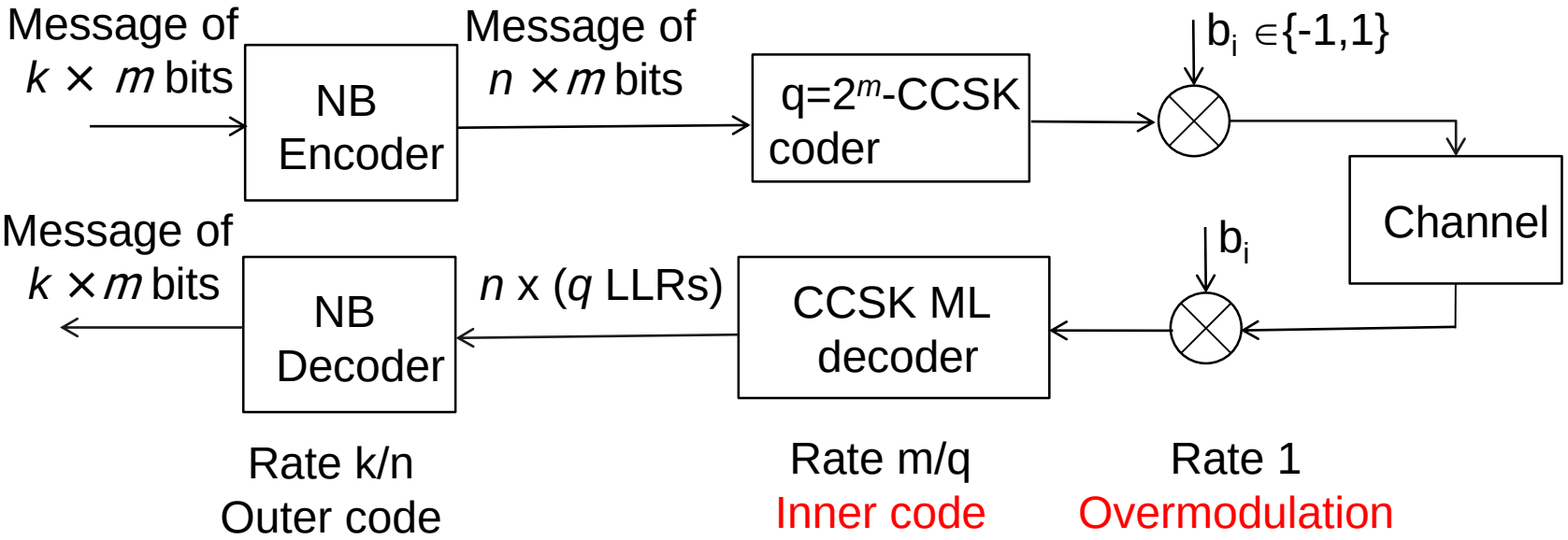
QCSP frame structure ($q = 2^m$)



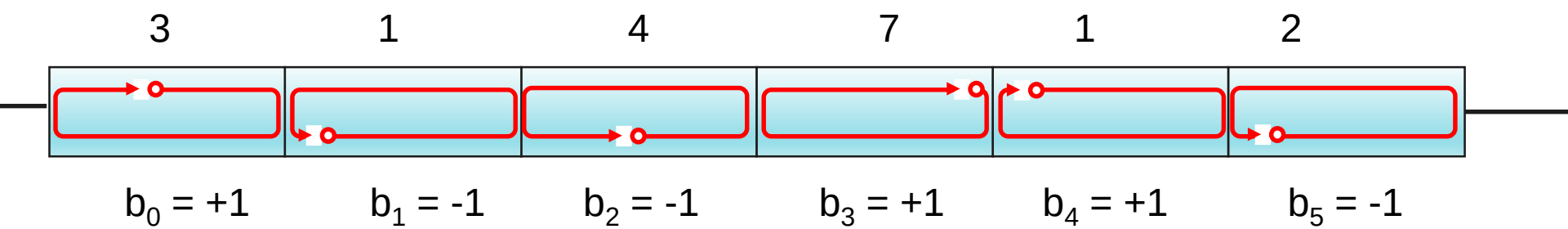
- The frame is composed of N segments of CCSK sequence (or symbol)



QCSP frame structure ($q = 2^m$)

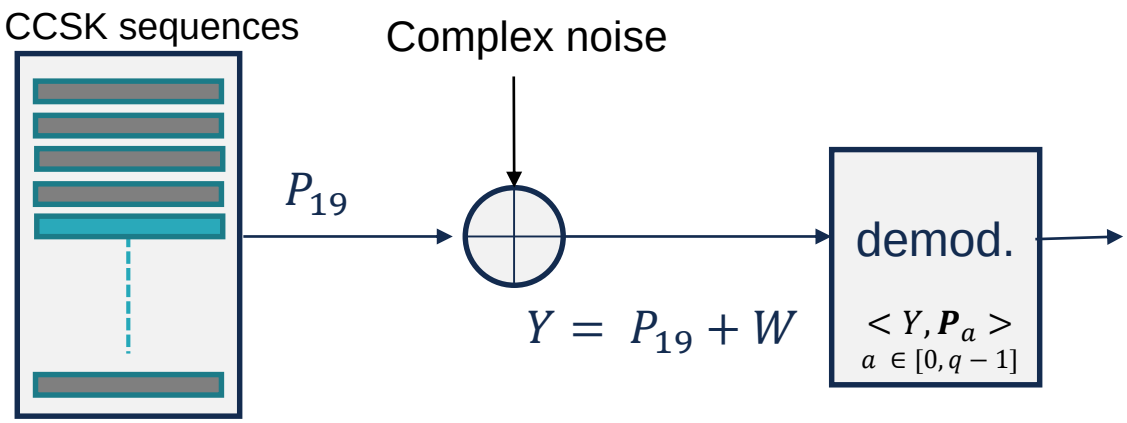


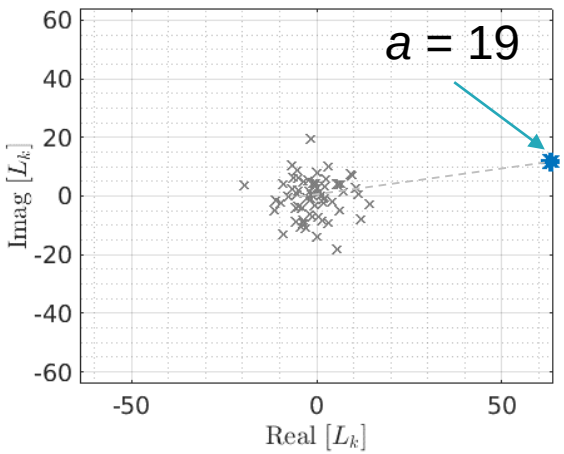
- The frame is composed of *N* segments of CCSK sequence (or symbol)



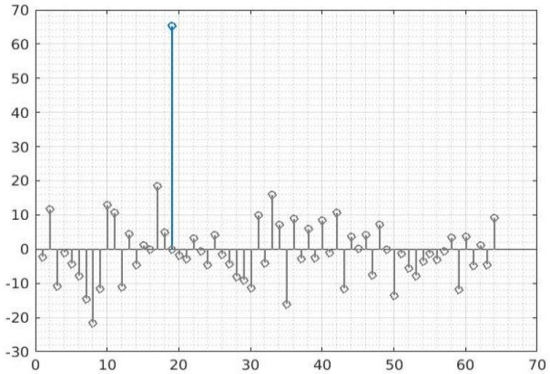
Demodulation of CCSK frame in complex noise

Correlation between each of the received symbols Y and the q CCSK sequences.





$$\log\left(\mathrm{Prob}(Y|P_a)\right) \sim \boxed{\mathrm{Real}\left(\sum_{k=0}^{q-1} Y(k)P_a(k)\right)}$$

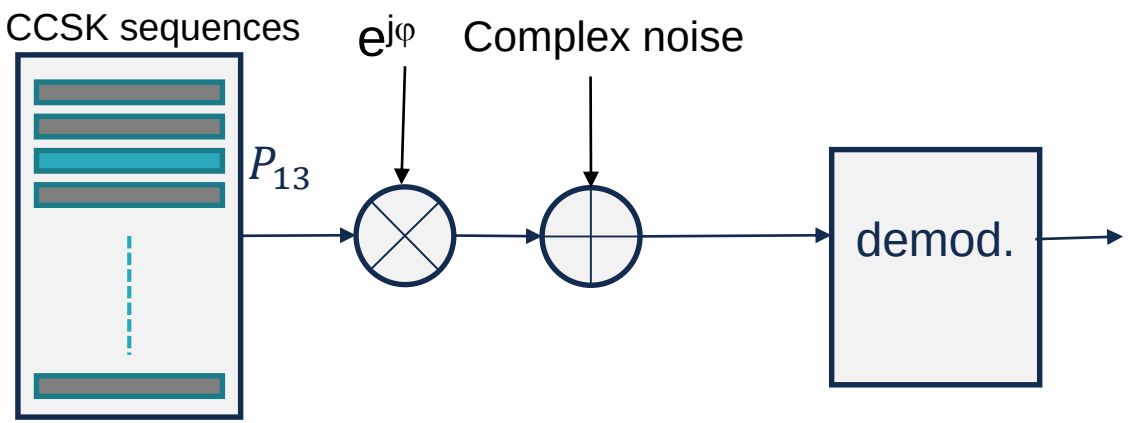


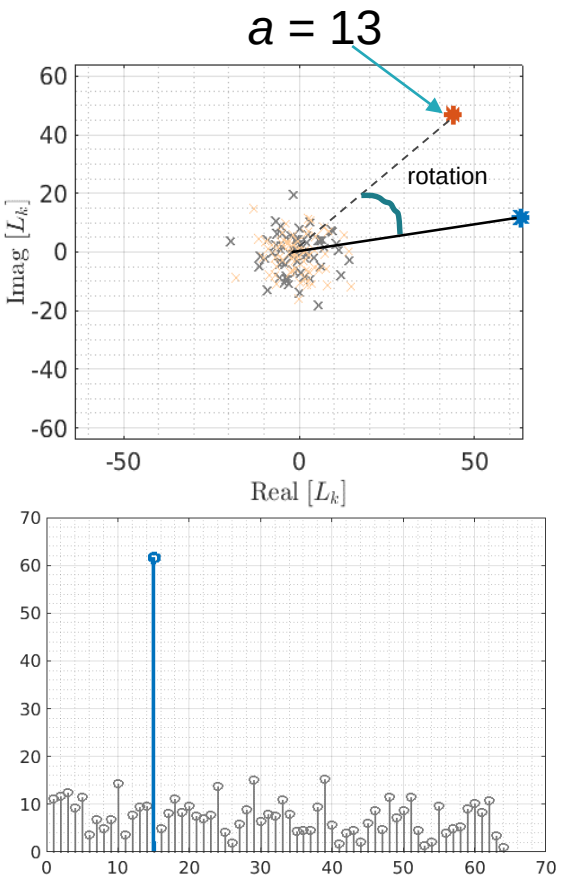
$$\log\left(\mathrm{Prob}(Y|P_{19})\right) \sim \mathrm{Real}\left(\sum_{k=0}^{q-1} (P_{19}(k) + W(k))P_{19}(k)\right)$$

$$\sim q + Noise$$

Demodulation with phase offset

Effect of Doppler of local oscillators mismatch

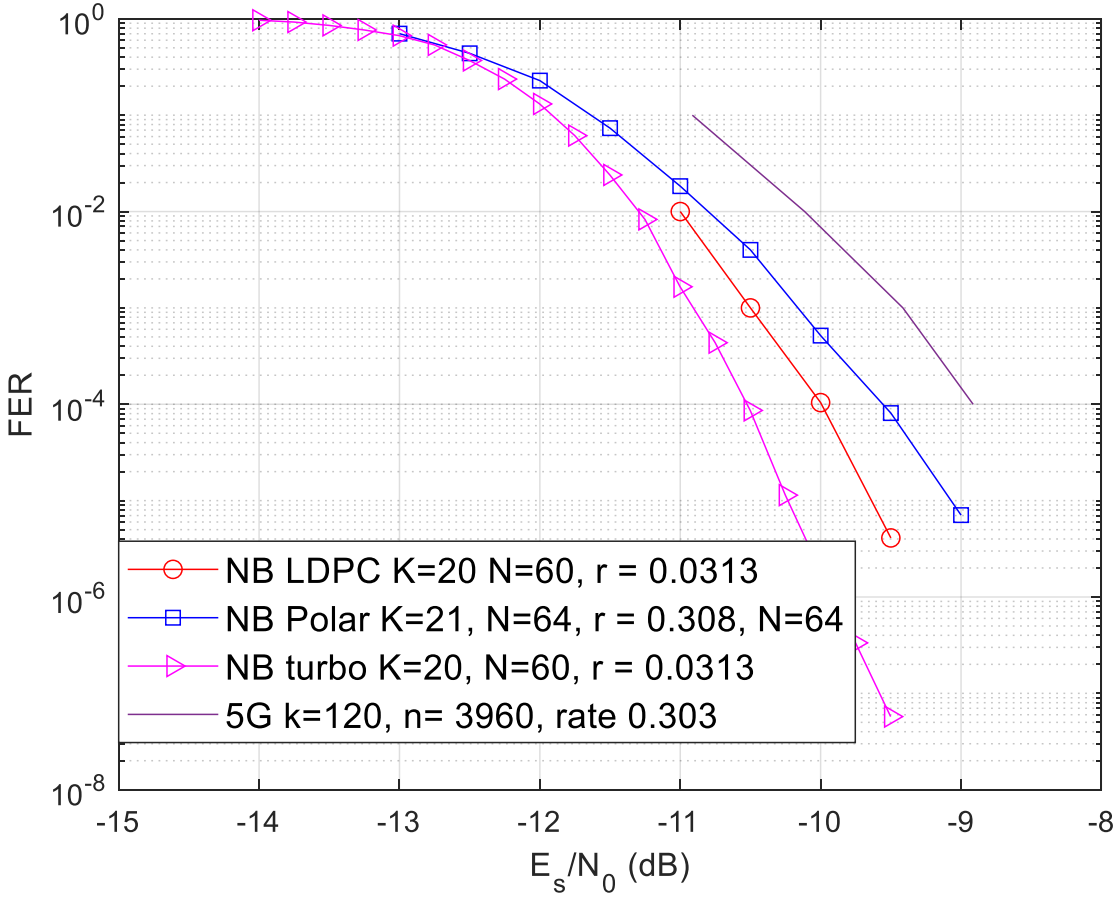




$$\log\left(\mathrm{Prob}(Y|P_a)\right) \sim \left|\mathrm{Real}\left(\sum_{k=0}^{q-1} Y(k)P_a(k)\right)\right|$$

Phase and/or frequency offset require non-coherent demodulation.

Example of performance



Perfect synchronization.

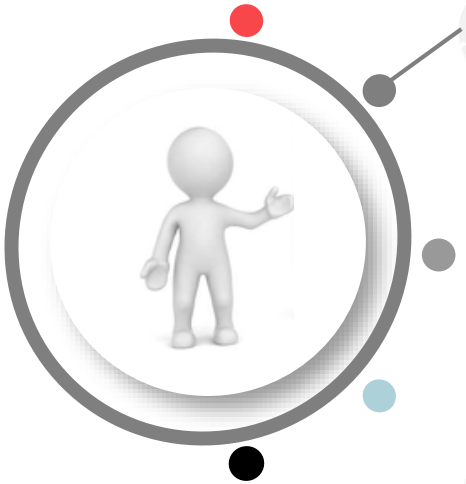
QCSP:
NB code rate r ≈1/3
CCSK: m =n6 bits, q = 64
=> rate 6/64.
Global rate ≈
6/64x1/3=0.0313

5G:
rate 1/3 binary LDPC code + 11 repetitions.

Global rate: 1/33 = 0.0303

Outline

QCSP system model



Receiver algorithms

GNU Radio implementation

Work in progress on QCSP

Conclusion and perspectives

Receiver principle…

Signal Processing factory

NB decoder engine

Messages
& Noise
& Time?
& Freq?

Coherently
demodulated
messages

Inner
Code

Over
Mod.

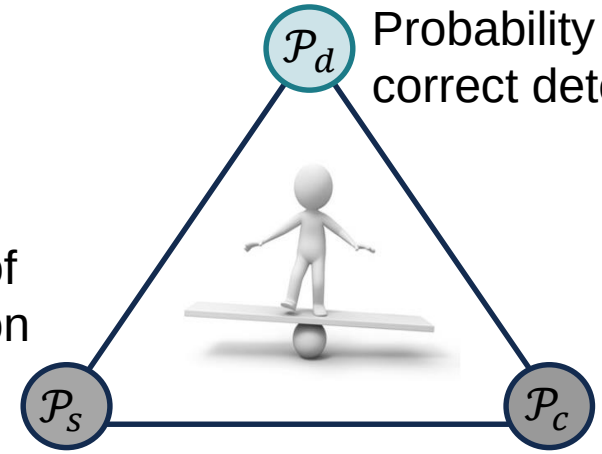
Outer
Code

Used redundancy

Decoded
messages

Objective

Developing blind detection and self-synchronization algorithms for achieving correct preamble-less short packet reception at very low SNRs.



Probability of correct detection

Probability of correct synchronization

Probability of correct decoding

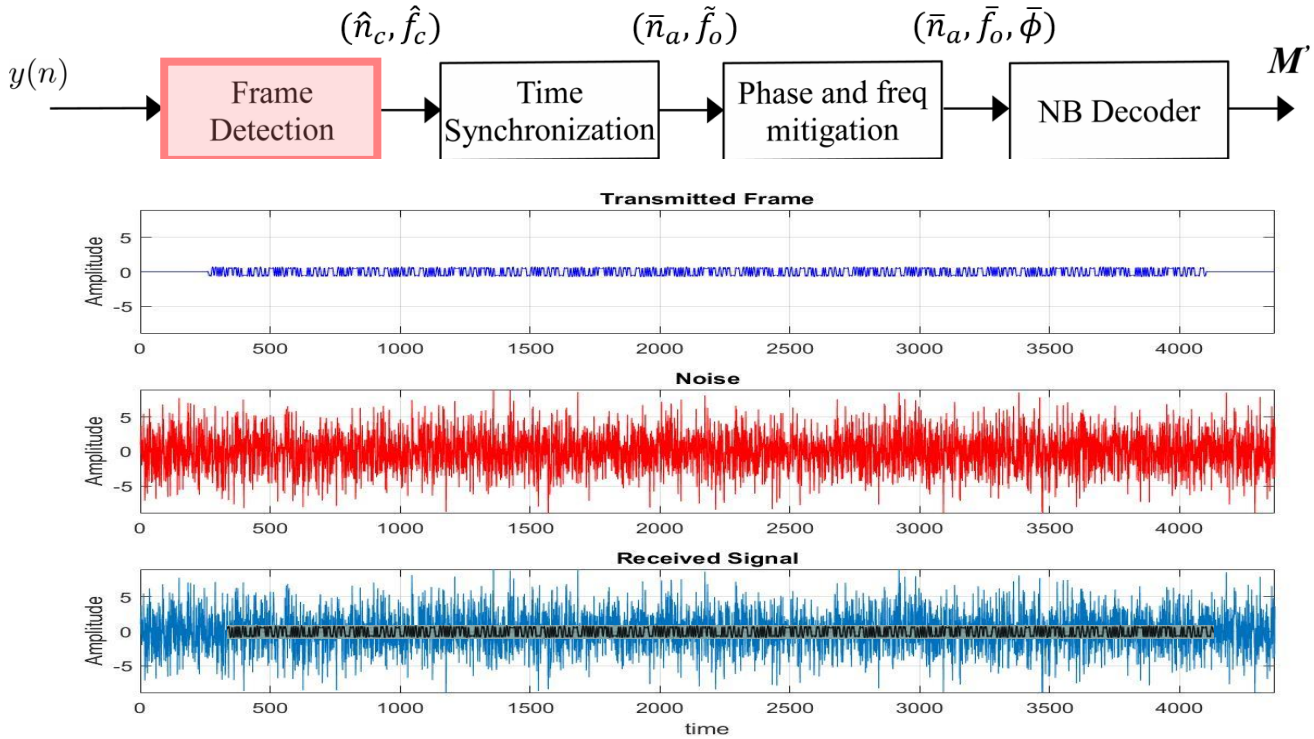
Joint overall probability:

$\mathcal{P} \approx \mathcal{P}_d \times \mathcal{P}_s \times \mathcal{P}_c$

➔ Aiming to maximize the overall probability is achieved by maximizing the weakest probability:

Max(min($\mathcal{P}_d, \mathcal{P}_s$, $\mathcal{P}_c$)).

Detection problem



- Test in real time different time/frequency hypothesis on frame arrival.
- Accumulate maximum absolute correlation between received symbols and codebook over the frame size.
- Declare detection if score above a threshold.

Toy example

$\boldsymbol{P}_0$ = ABAABB

Message = {0,0,0} (N = 3)

{ABAABB, ABAABB, ABAABB}

P_0 P_0 P_0

Message = {3,0,5} (N = 3)

{ABBABA, ABAABB, BABAAB}

P_3 P_0 P_5

ABBABAABAABBBABAAB → Channel delay → XXXXABBABAABAABBBABAABXXX

Toy example

Y_0

XXXXABBABAABAABBBABAABXXX

$L_0 = \{<Y_0, P_a>\}_{a = 0, 1,\ldots,5}$

```
ABAABB------------------------------- 1
BAABBA------------------------------- 0
AABBAB------------------------------- 2
ABBABA------------------------------- 0
BBABAA------------------------------- 1
BABAAB------------------------------- 2
```

$\mathrm{Max}(L_0)=2$

2

Toy example

Y_1

```
XXXXABBABAABAABBBABAABXXX

-ABAABB------------------------------- 3
-BAABBA------------------------------- 1
-AABBAB------------------------------- 1
-ABBABA------------------------------- 2
-BBABAA------------------------------- 0
-BABAAB------------------------------- 2

23
```

$\text{Max}(L_1)=3$

Toy example

Y_2

```
XXXXABBABAABAABBBABAABXXX

--ABAABB------------------------------ 2
--BAABBA------------------------------ 4
--AABBAB------------------------------ 1
--ABBABA------------------------------ 2
--BBABAA------------------------------ 3
--BABAAB------------------------------ 0

234
```

$\mathrm{Max}(L_2)=4$

Toy example

Y_3

```
XXXXABBABAABAABBBABAABXXX

---ABAABB------------------------------ 1
---BAABBA------------------------------ 2
---AABBAB------------------------------ 5
---ABBABA------------------------------ 1
---BBABAA------------------------------ 3
---BABAAB------------------------------ 3

2345
```

$\mathrm{Max}(L_3)=5$

Toy example

Y_4

```
XXXXABBABAABAABBBABAABXXX

----ABAABB---------------------------- 3
----BAABBA---------------------------- 2
----AABBAB---------------------------- 2
----ABBABA---------------------------- 6
----BBABAA---------------------------- 1
----BABAAB---------------------------- 1

23456
```

$\text{Max}(L_4) = 6$

Toy example

Y_5

```
XXXXABBABAABAABBBABAABXXX

-----ABAABB---------------------------- 2
-----BAABBA---------------------------- 4
-----AABBAB---------------------------- 1
-----ABBABA---------------------------- 2
-----BBABAA---------------------------- 6
-----BABAAB---------------------------- 1

234566
```

$\text{Max}(L_5)=6$

Toy example

Y_6

```
XXXXABBABAABAABBBABAABXXX

------ABAABB------------------------- 2
------BAABBA------------------------- 2
------AABBAB------------------------- 4
------ABBABA------------------------- 2
------BBABAA------------------------- 2
------BABAAB------------------------- 6

2345666
```

$\mathrm{Max}(L_6)=6$

Toy example

Y_7

```
XXXXABBABAABAABBBABAABXXX

--------ABAABB------------------------- 5
--------BAABBA------------------------- 2
--------AABBAB------------------------- 1
--------ABBABA------------------------- 4
--------BBABAA------------------------- 2
--------BABAAB------------------------- 1

23456665
```

$\mathrm{Max}(L_7)=5$

Toy example

Y_{13}

```
XXXXABBABAABAABBBABAABXXX

--------------ABAABB------------------- 3
--------------BAABBA------------------- 1
--------------AABBAB------------------- 5
--------------ABBABA------------------- 3
--------------BBABAA------------------- 3
--------------BABAAB------------------- 3

23456665556545565432100 00
```

$\text{Max}(L_{13})=5$

Toy example

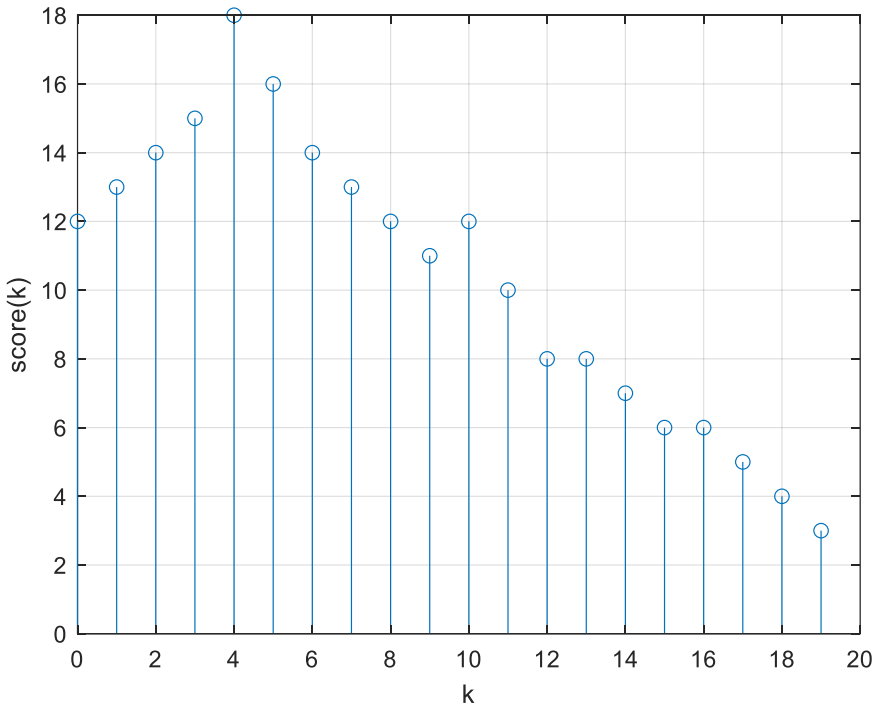
$$\text{Score}(k) = \max(L_k) + \max(L_{k+6}) + \max(L_{k+12})$$

```
XXXXABBABAABAABBBABAABXXX

-----------ABAABB----------
-------------------------
-------------------------
-----ABBABA-------------
-------------------------
-----------------BABAAB---

23456665556545556543210000
```

Score(4)



$$\text{Score}(4) = \max(L_4) + \max(L_{10}) + \max(L_{16}) = 18$$

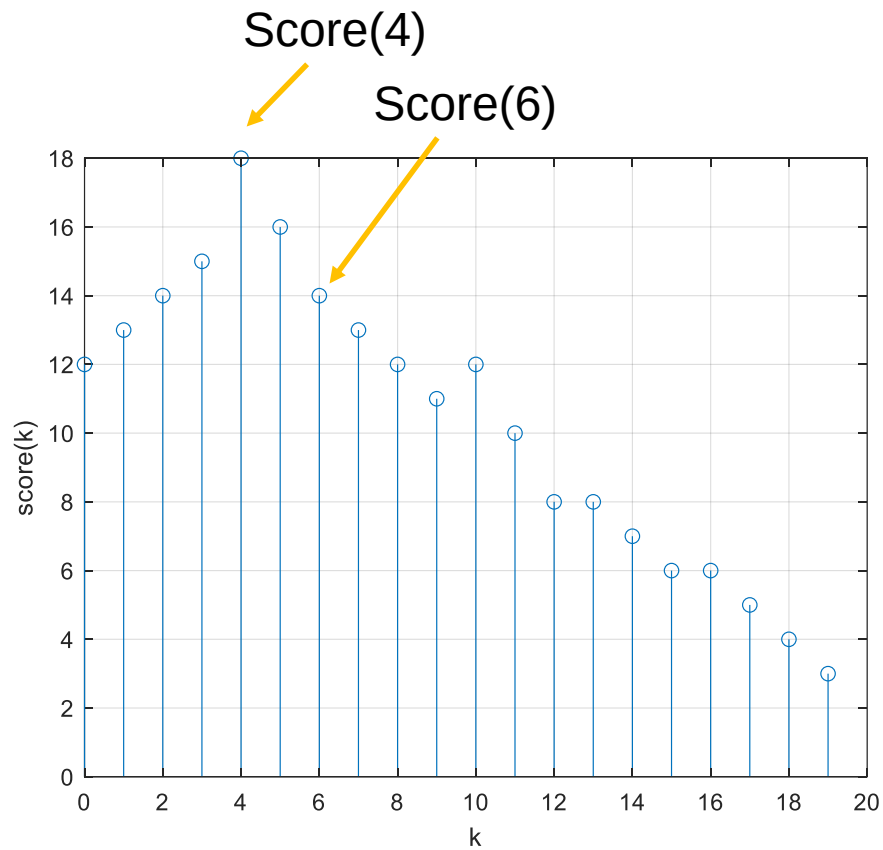
Toy example

$$\text{Score}(k) = \max(L_k) + \max(L_{k+6}) + \max(L_{k+12})$$

```
XXXXABBABAABAABBBABAABXXX

-----------ABAABB----------
-------------------------
-------------------------
-----ABBABA-----------------
-------------------------
-----------------BABAAB---

23456665556545556543210000
```



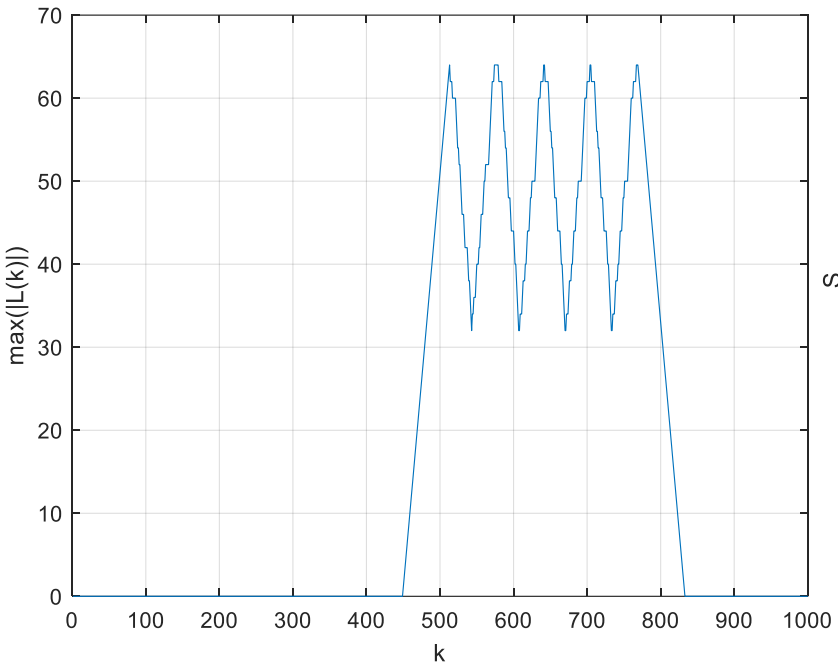
$$\text{Score}(6) = \max(L_6) + \max(L_{12}) + \max(L_{18}) = 14$$

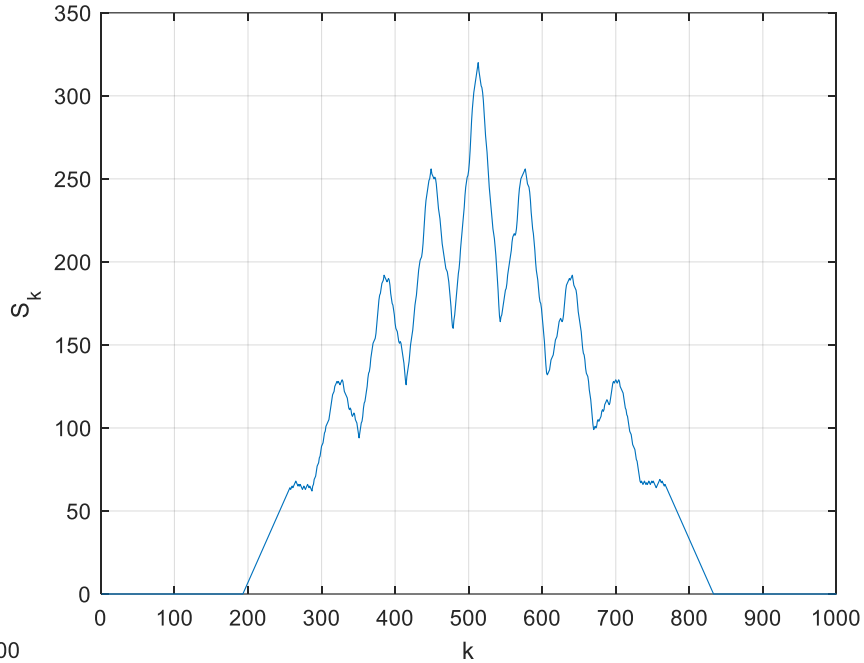
Detection problem: general case

N = 5, q = 64, no noise

$$S_{\mathrm{k}}(\mathrm{Y}) = \sum_{n=0}^{4} \max(|\boldsymbol{L_{k+64n}}|)$$

$$\max(|\boldsymbol{L_k}|)$$

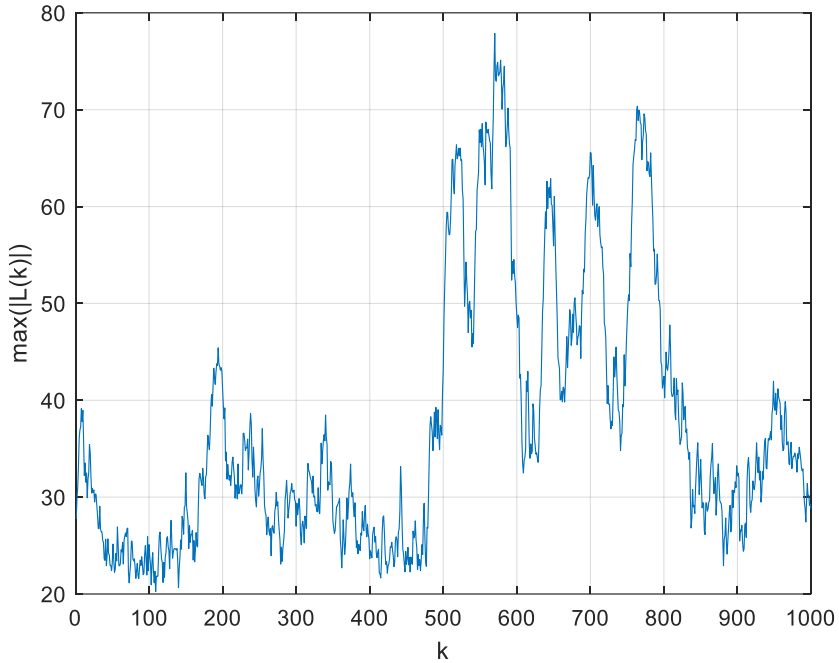




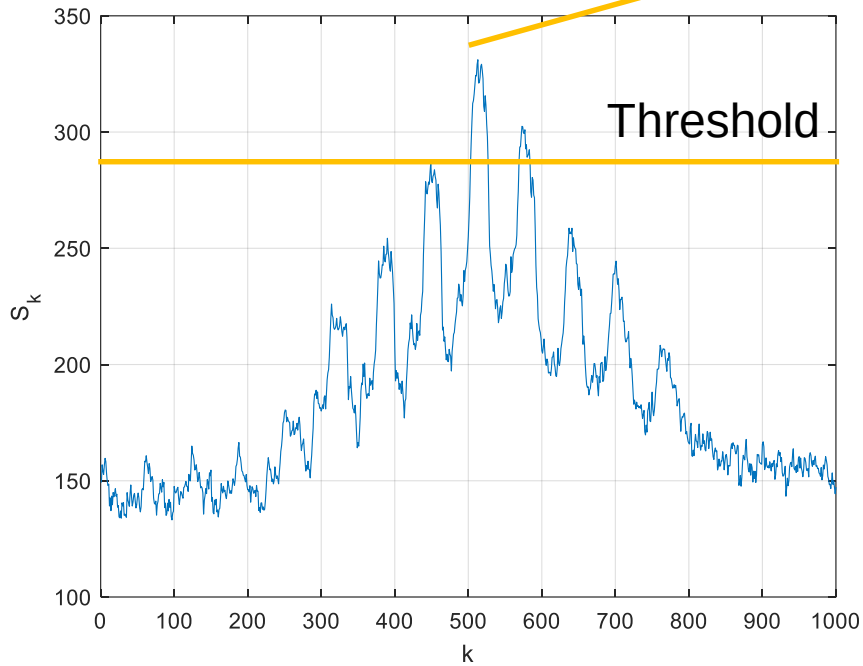
Detection problem: general case

N = 5, q = 64, with noise (-4 dB)

$$\max(|\boldsymbol{L_k}|)$$

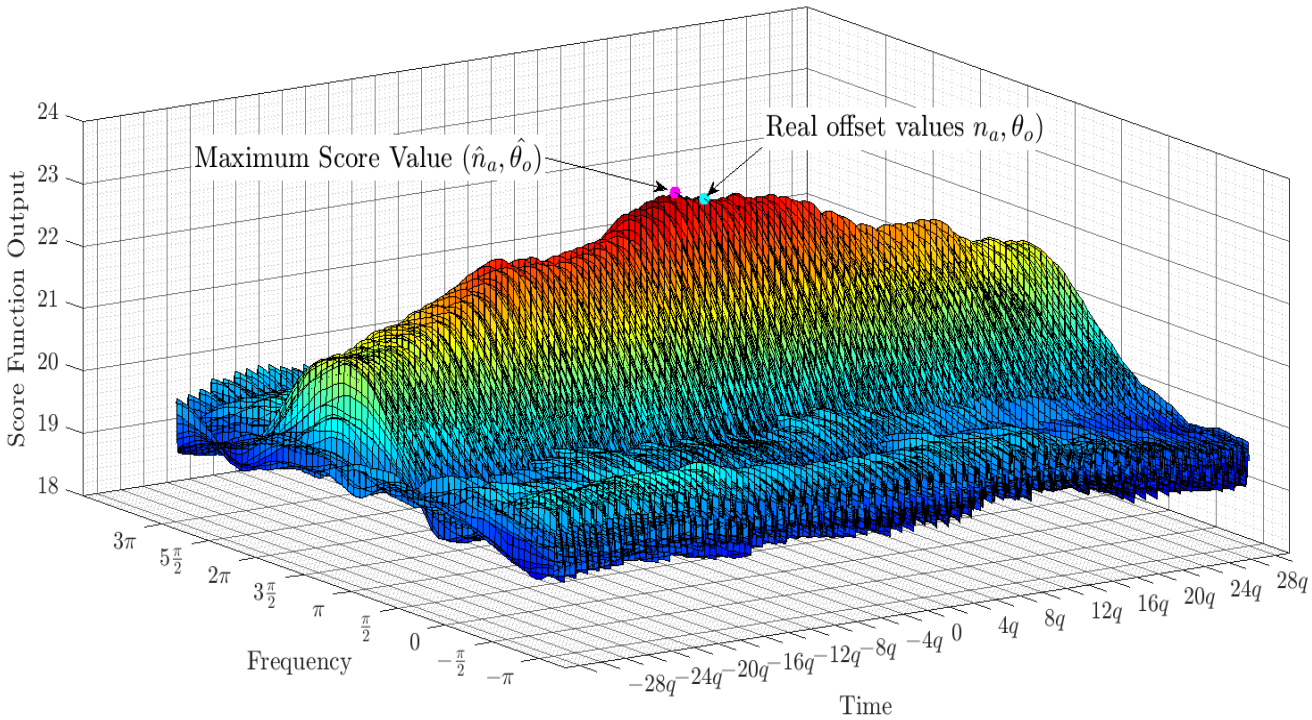


$$S_{\mathrm{k}}(\mathrm{Y}) = \sum_{n=0}^{4} \max(|\boldsymbol{L_{k+64n}}|)$$



Impact of the frequency offset

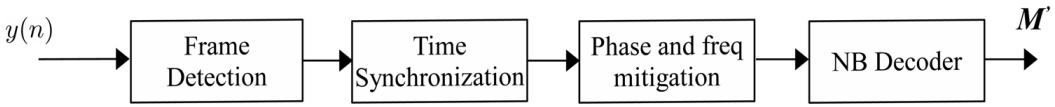
Score values in 3D grid where $\mathrm{N} = 60,\ q = 64$ and a frequency offset.



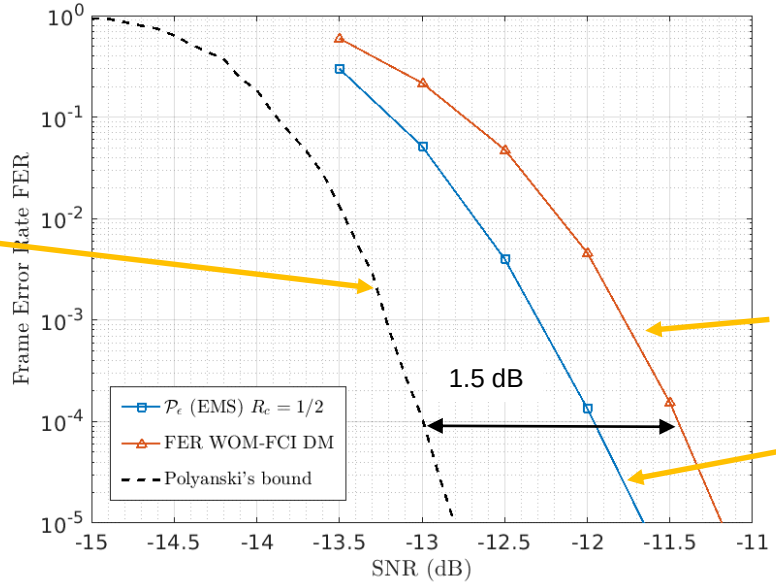
Requires a 2D dimensionnal search

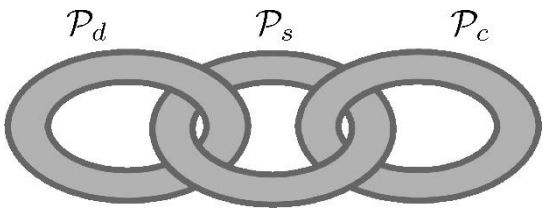
Overall performance

The QCSP parameters we choose to work on: $N = 120$ symbols, $q = 64$, $R_c = 1/2$
Asynchronous AWGN channel



Theoretical Lower bound [1,2]





FER async.

FER sync. channel

[1] Polyanskiy, Y., Poor, H. V. & Verdu, S., Channel Coding Rate in the Finite Blocklength Regime, *IEEE Transactions on Information Theory* **56,** 2307–2359, issn: 1557-9654 (May 2010).
[2] Savin, V., *Non-Binary Polar Codes for Spread-Spectrum Modulations in 2021 11th International Symposium on Topics in Coding (ISTC)* (2021), 1–5.

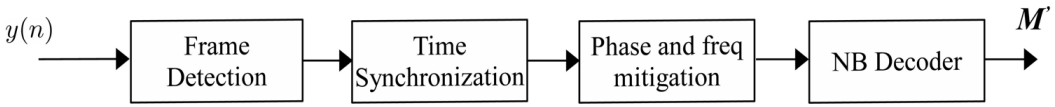
Time, Frequency & Phase synchronization

- Use information given by overmodulation to mitigate time ambiguity at CCSK symbol level [1]
- Use redundancy of outer code to mitigate time ambiguity at the chip level [1]
- Use soft information given by inner code decoding + redundancy of the outer code to estimate residual Frequency&Phase ambiguity [2].
- Perform coherent demodulation before NB-Decoder

[1] K. Saied, A. Ghouwayel, E. Boutillon, «Time-Synchronization of CCSK Short Frames», WiMob'2021.
[2] K. Saied, A. Al Ghouwayel, E. Boutillon, «Phase Synchronization for Non-Binary Coded CCSK Short Frames », VTC'2022

Overall performance

The QCSP parameters we choose to work on: $N = 120$ symbols, $q = 64$, $R_c = 1/2$
Asynchronous AWGN channel



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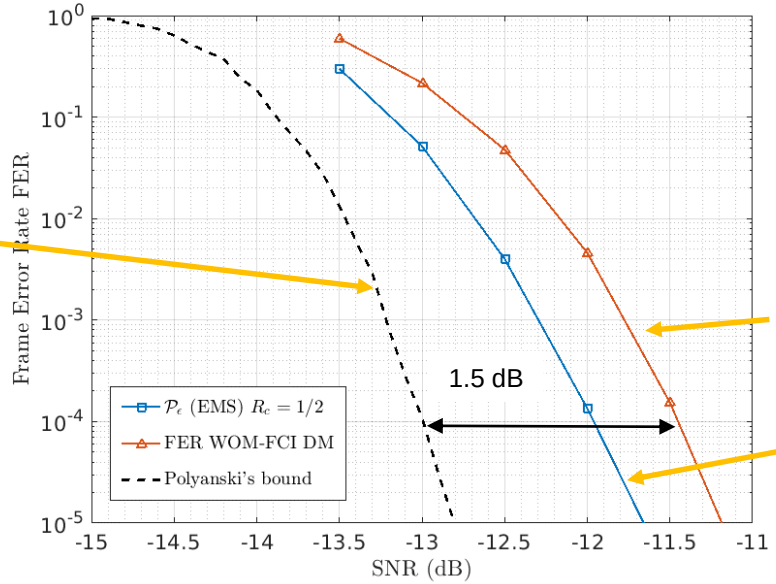

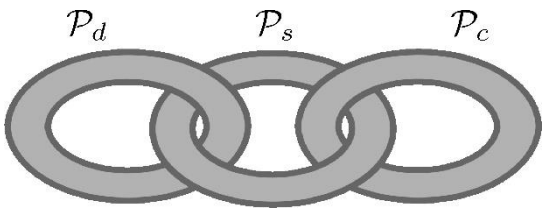

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Outline

QCSP system model

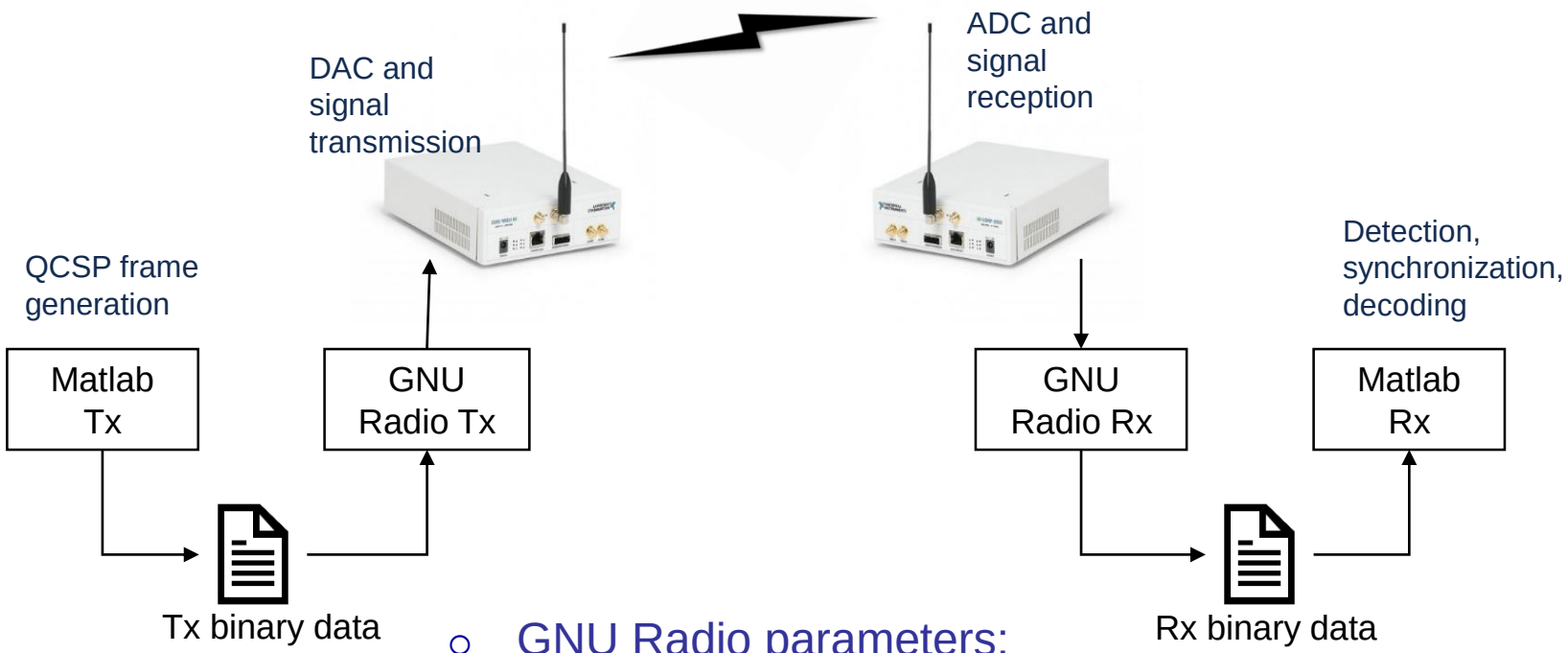
Receiver processing

GNU Radio implementation

Work in progress

Conclusion and perspectives

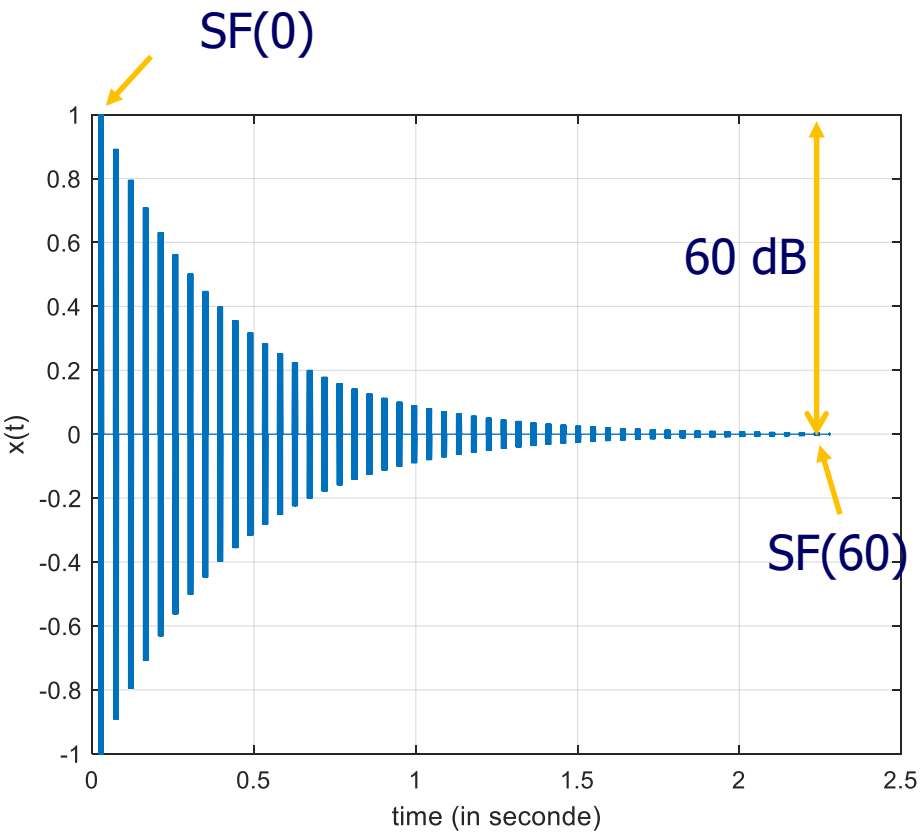
Offline experimental set-up



- GNU Radio parameters:
  - F = 433.950 MHz
  - Chip rate = 500 kHz
  - Bit information rate 0.5×6/64×1/3 = 15.6 Kbit/s

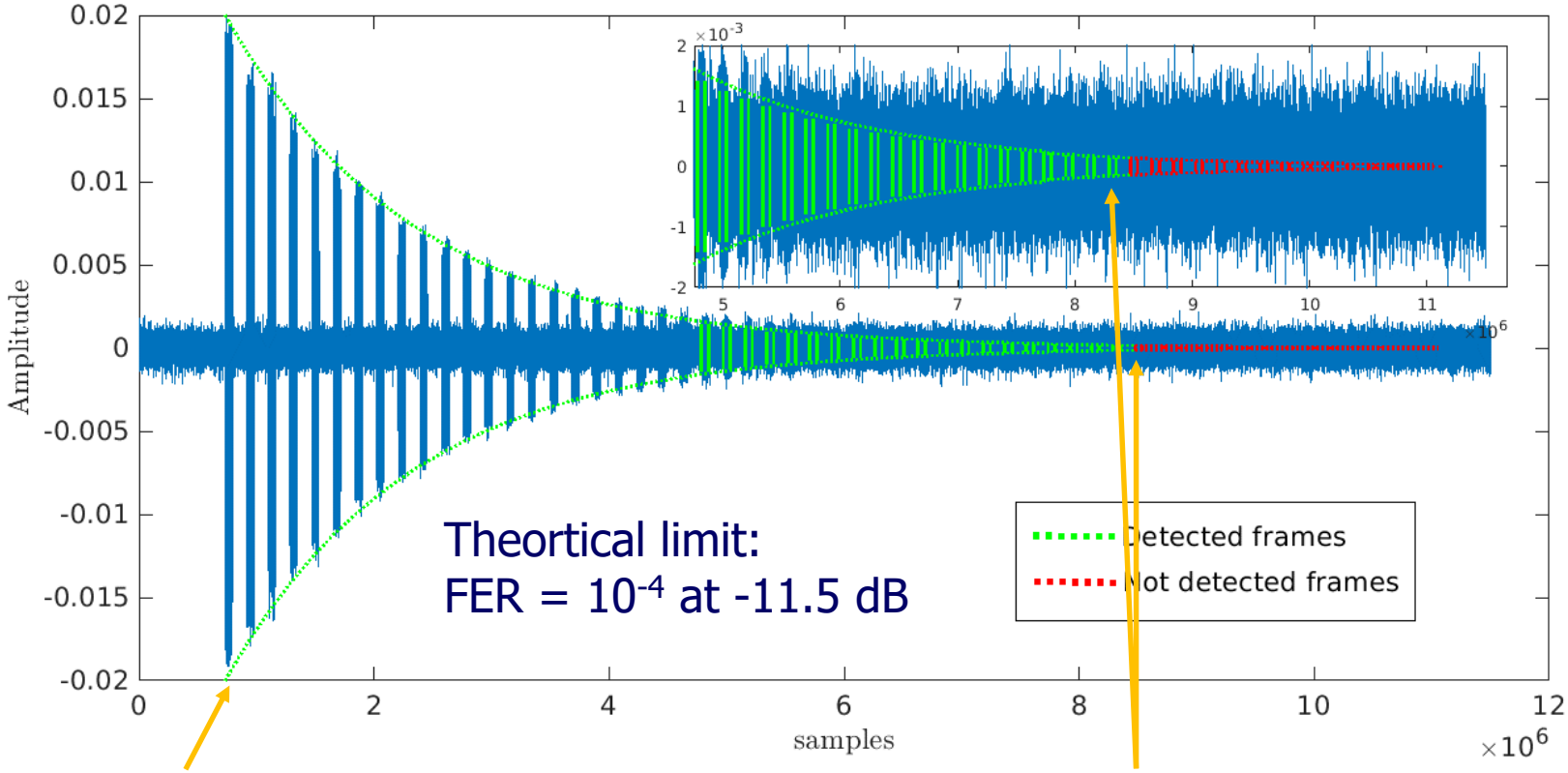
Note: Indoor test from 2 different rooms

Super-Frame structure



- Super Frame (SF) composed of 61 QCSP frames
- -1 dB of energy between two consecutive frames.
- QCSP frame: k = 120 bits.

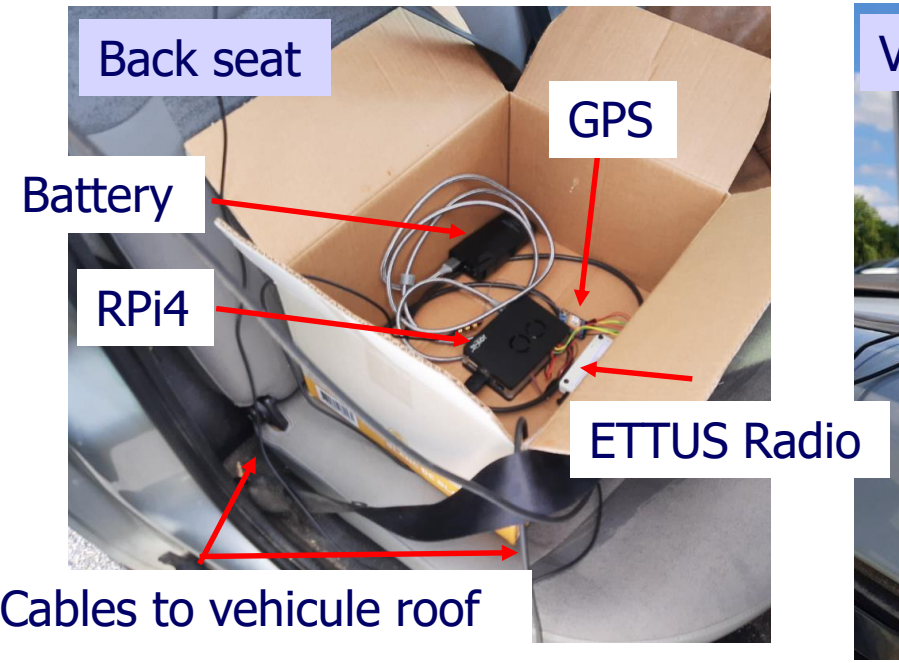
Received signal

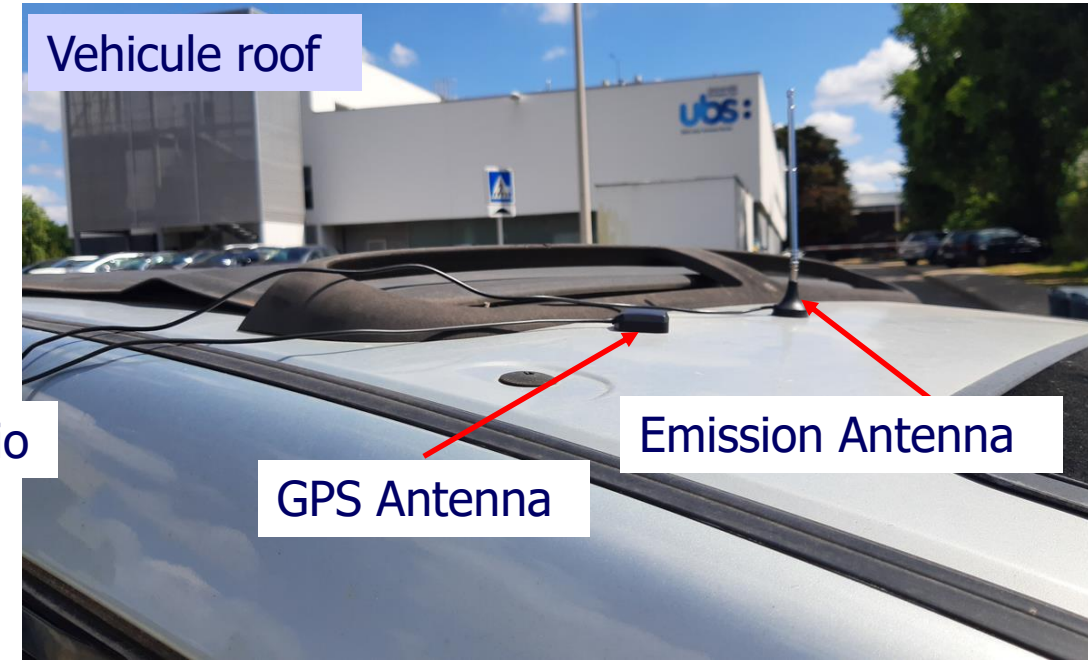


Es/N_0 = 29.5 dB
ΔF = 4006 Hz
No error before NB-decoder

$Es/N_0 \approx$ -12.5 dB
ΔF = 4012 Hz
35% of uncorrectly detected symbols before NB-decoder.

Real-time experimental set-up: Emission

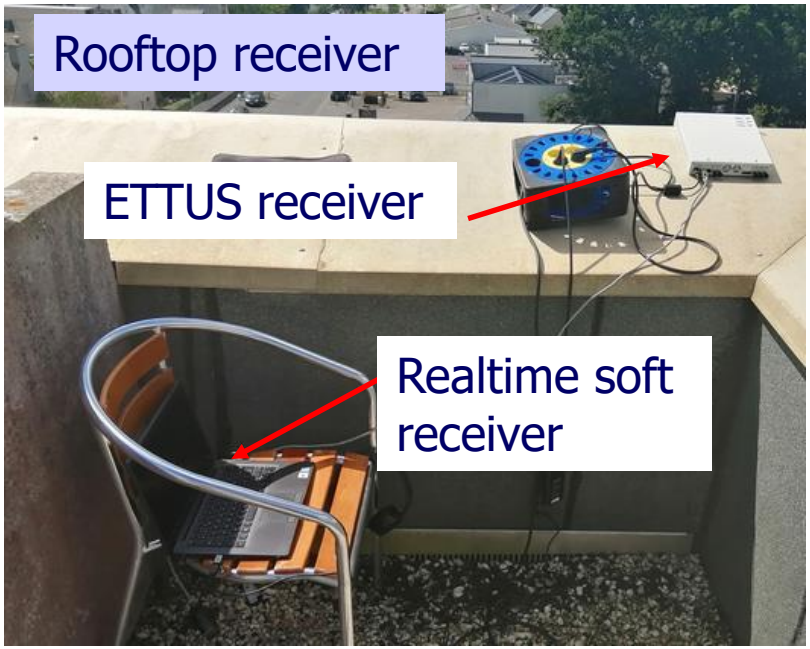




- Payload: k = 120 bits that contains
  - Localization given by GPS module
  - + Time, RPi4 Temperature and a frame number.

- New message every 4 secondes

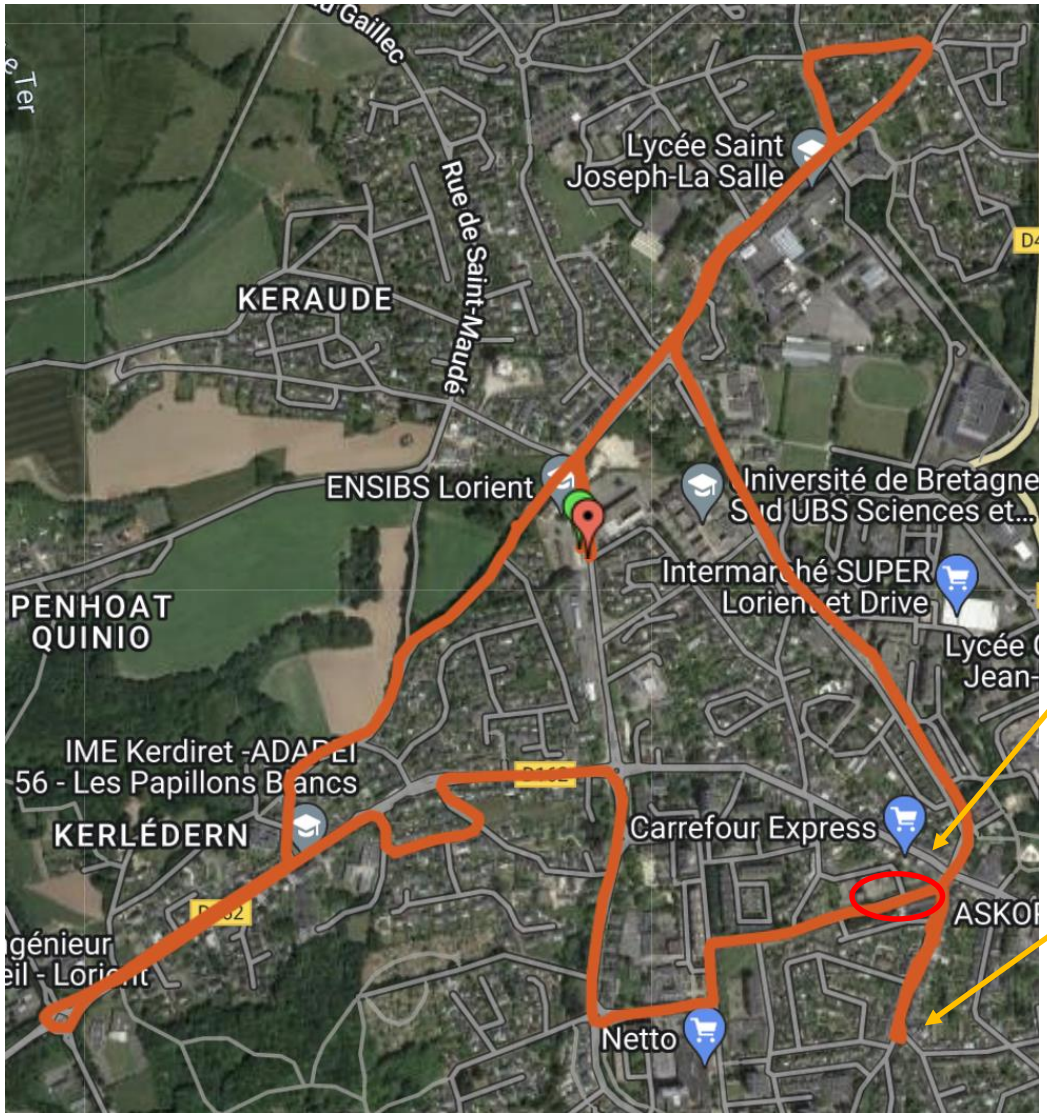
Real-time experimental set-up: Receiver



- Radio Settings in Transmission
  - Measured RF emission Power: 4.5 dBm
  - Carrier Frequency: F_c = 433.950 MHz

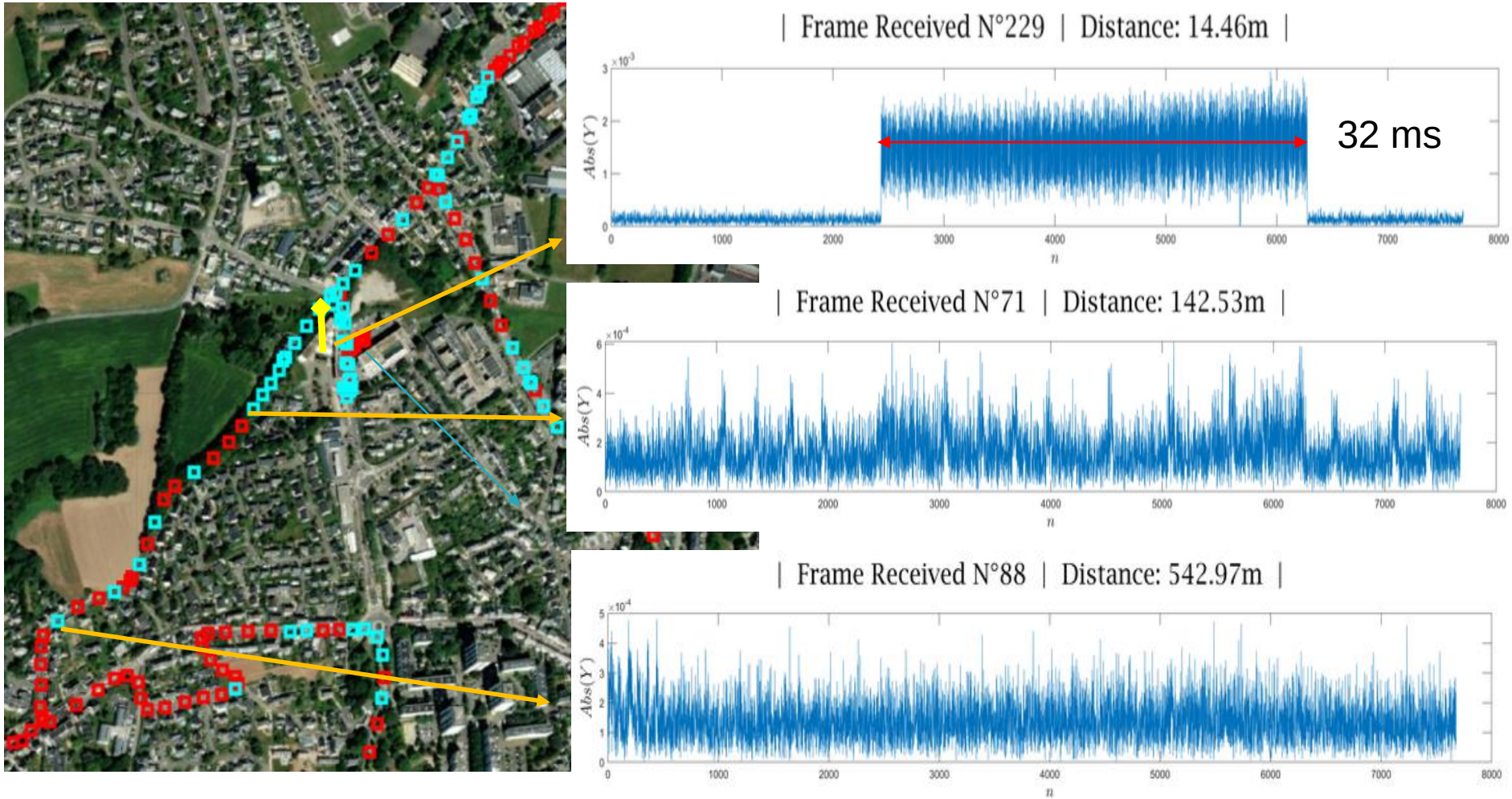
- Bit information rate : 3.9 Kbit/s
- Message duration: 32 ms.

Path in Lorient



Except for residents

Result of the experimentation



Interactive map: https://qcsp.univ-ubs.fr/events/

Result of maritime experimentation (12/2022)

THALOS
ADVANCED MARITIME SOLUTIONS

Dec. 2022: Proof of communication at 433 Mhz from a buoy to a boat with significant distance.
March 2023: Next round of experimentation.

Outline

QCSP system model

Receiver algorithms

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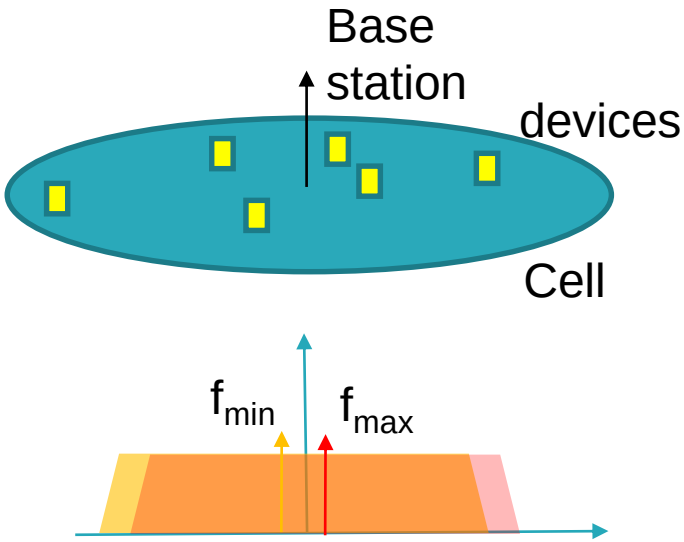
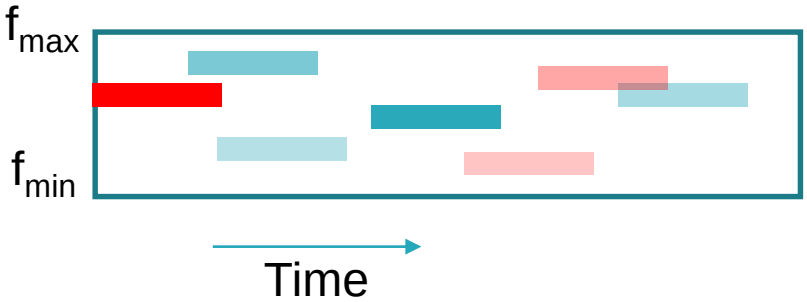
Work in progress

Conclusion and perspectives

Multi-users detection: first results

- 2 orthogonal CCSK sequences PN1, PN2.
- Random time of emission, random frequency of emission within [Fmin, Fmax], random position of emission.



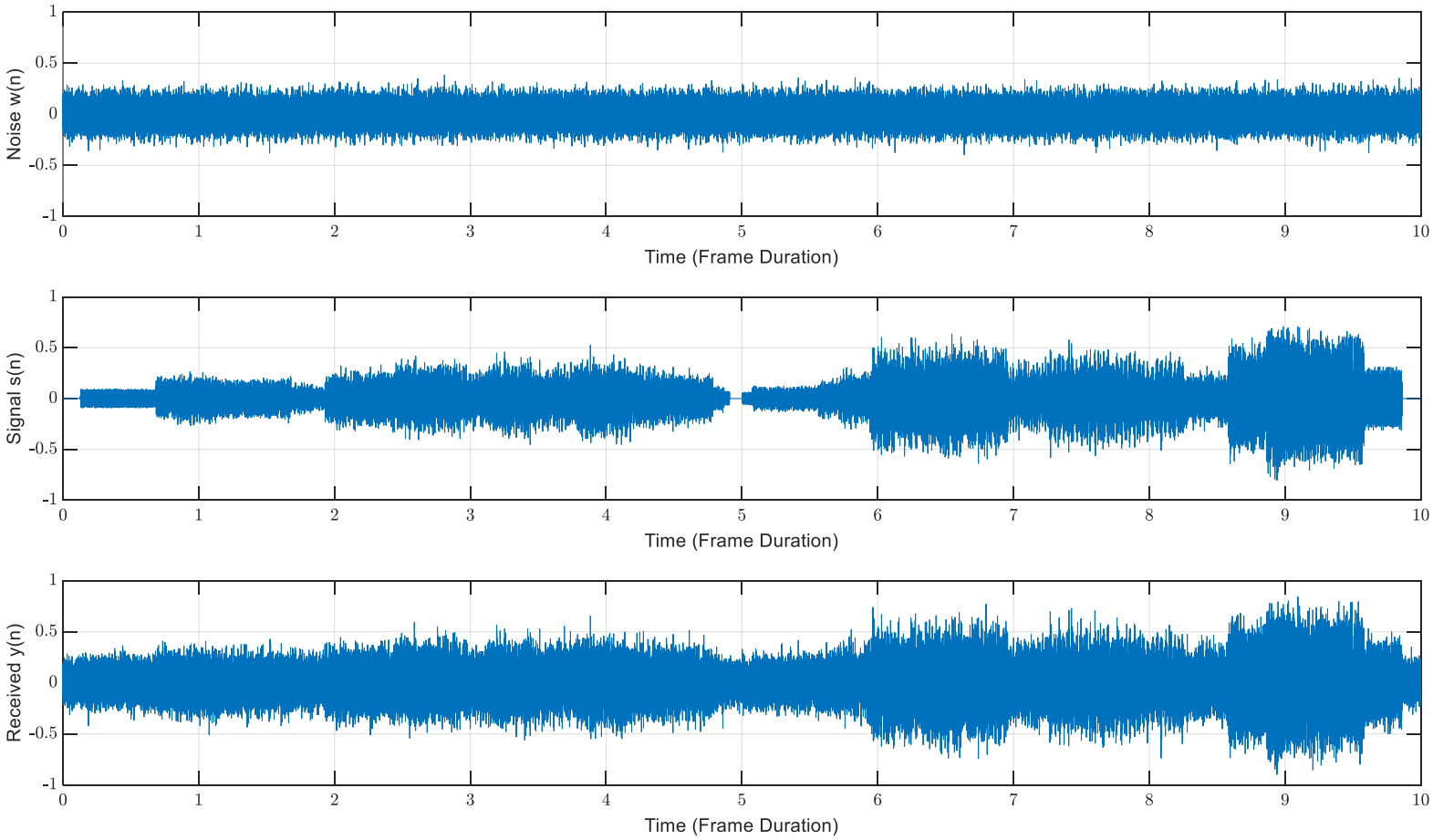


$F = F_0 \pm 12{,}5\%$ of signal bandwidgh

Successive Interference Cancellation

- Layer by layer, you get the very center of the onion.
- SIC decoder is (almost) the same principle

Input signal in time



Noise w(n)

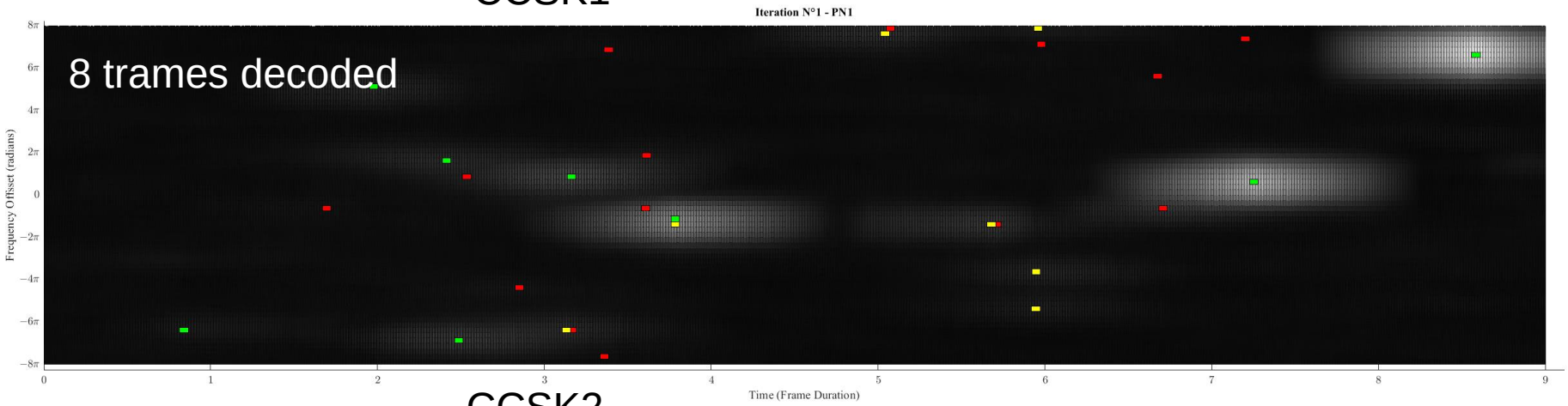
Signal s(n)

y(n) = s(n) + w(n)

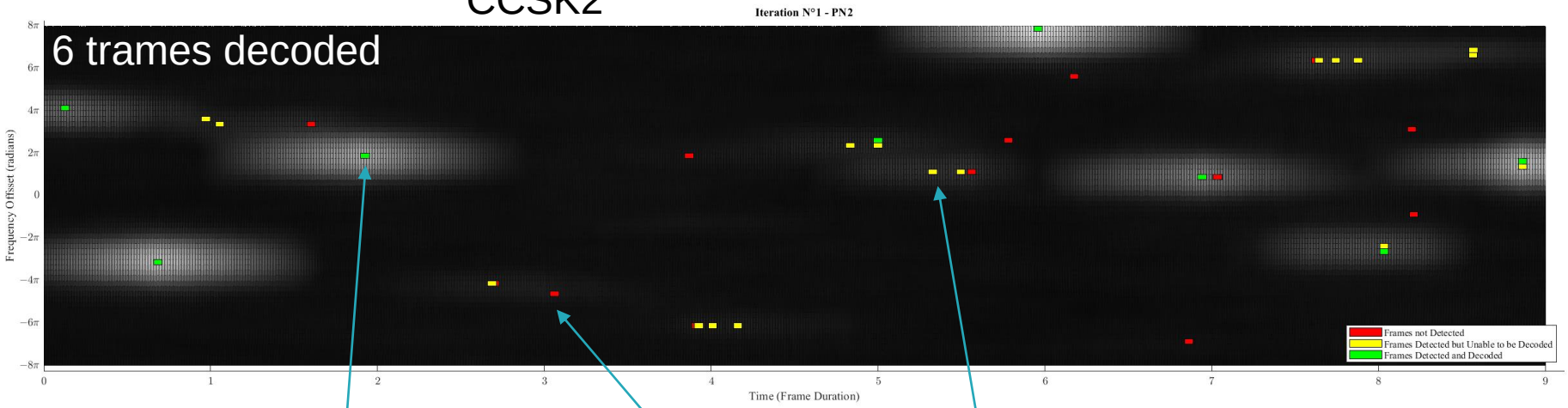
45 frames received

Output of detection match filter

CCSK1



CCSK2

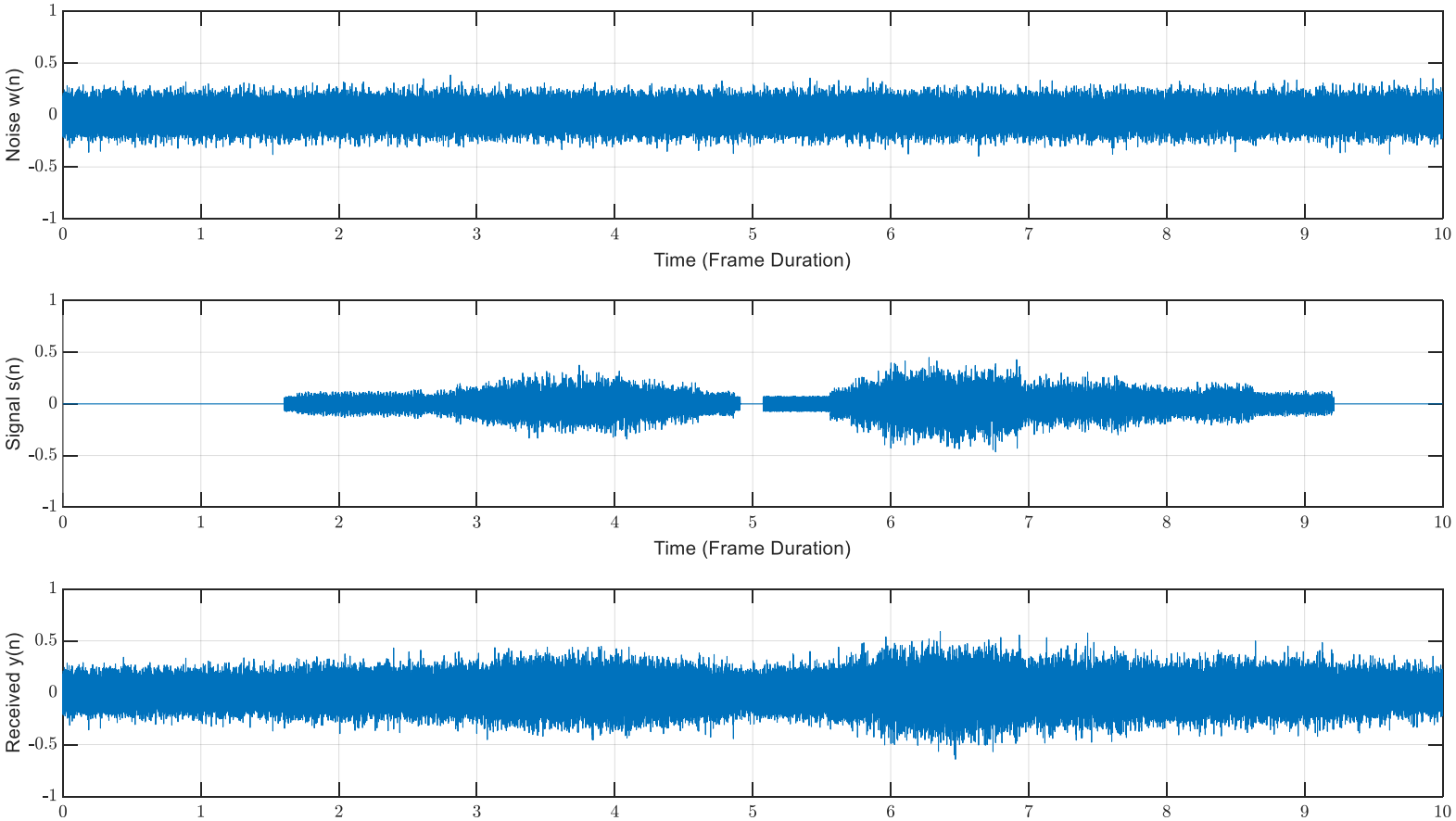


Detected/corrected

Not detected

Detected but not decoded

SIC receiver: second iteration



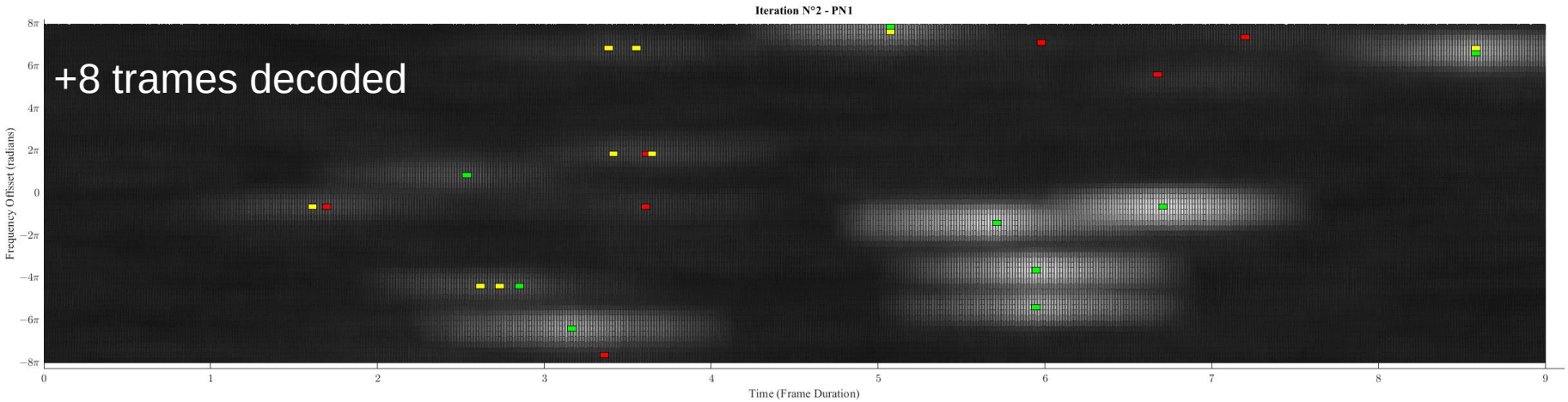
Noise w(n)

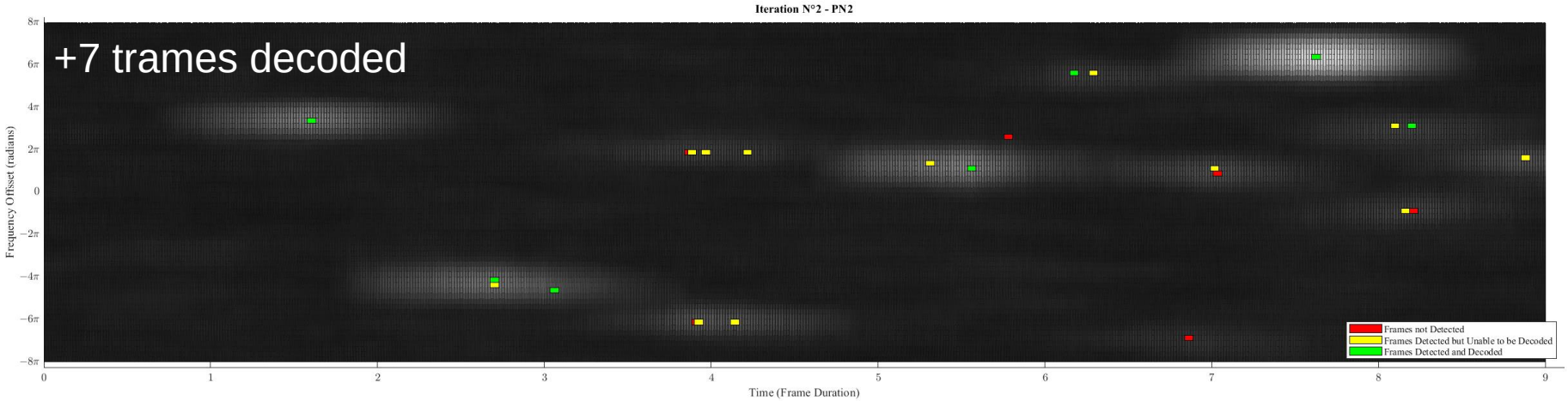
Signal s(n)

y(n) = s(n) + w(n)

- Detected trames are subtracted to the incoming signal
  => Then detection done again.

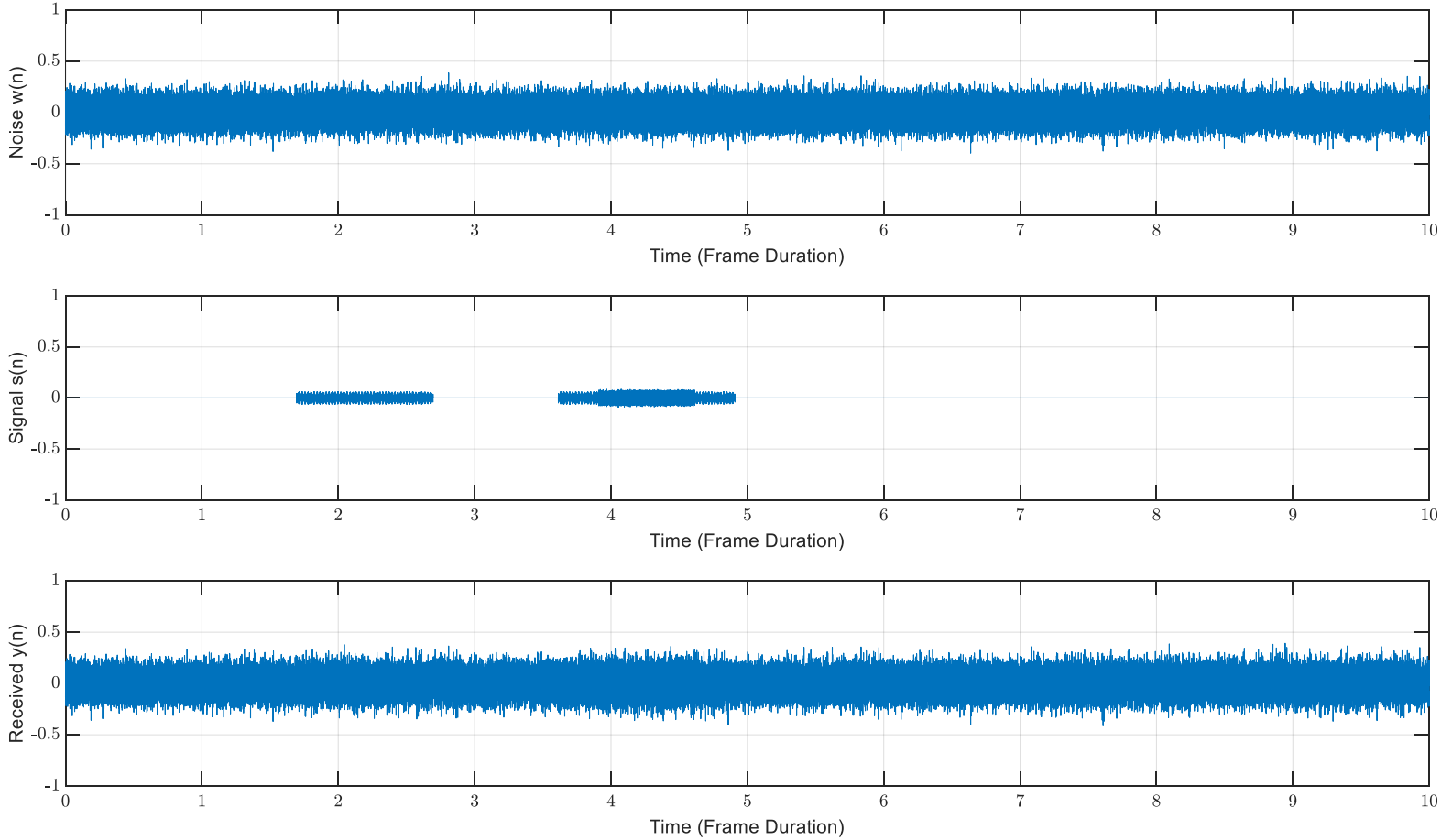
SIC receiver: second iteration





Total: 14 (first iteration) + 15 (second iteration) = 29 decoded frames among 45

State at the end of fourth iteration



Only 3 remaing frames undecoded among 45
=> 93 % of decoding sucess !

QCSP for rate-adaptive code

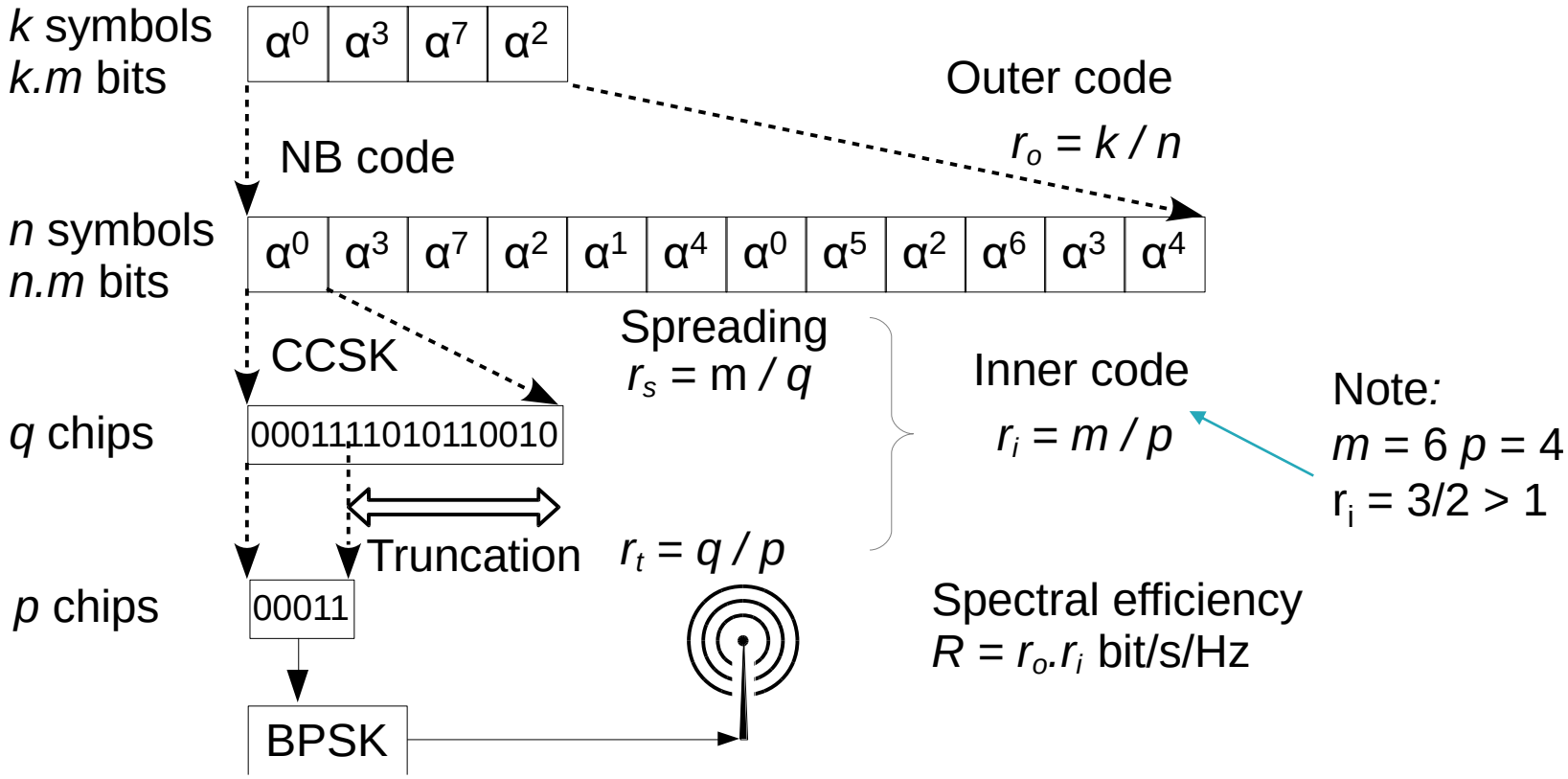
- Variation on channel conditions
  - Optimized Modulation/code for each channel.
  - Complexity => Cost.

- State of the art solution
  - Probabilistic shaping

- Other Solution
  - One NB decoder optimized for a single code rate
  - One Inner code responsible of rate matching

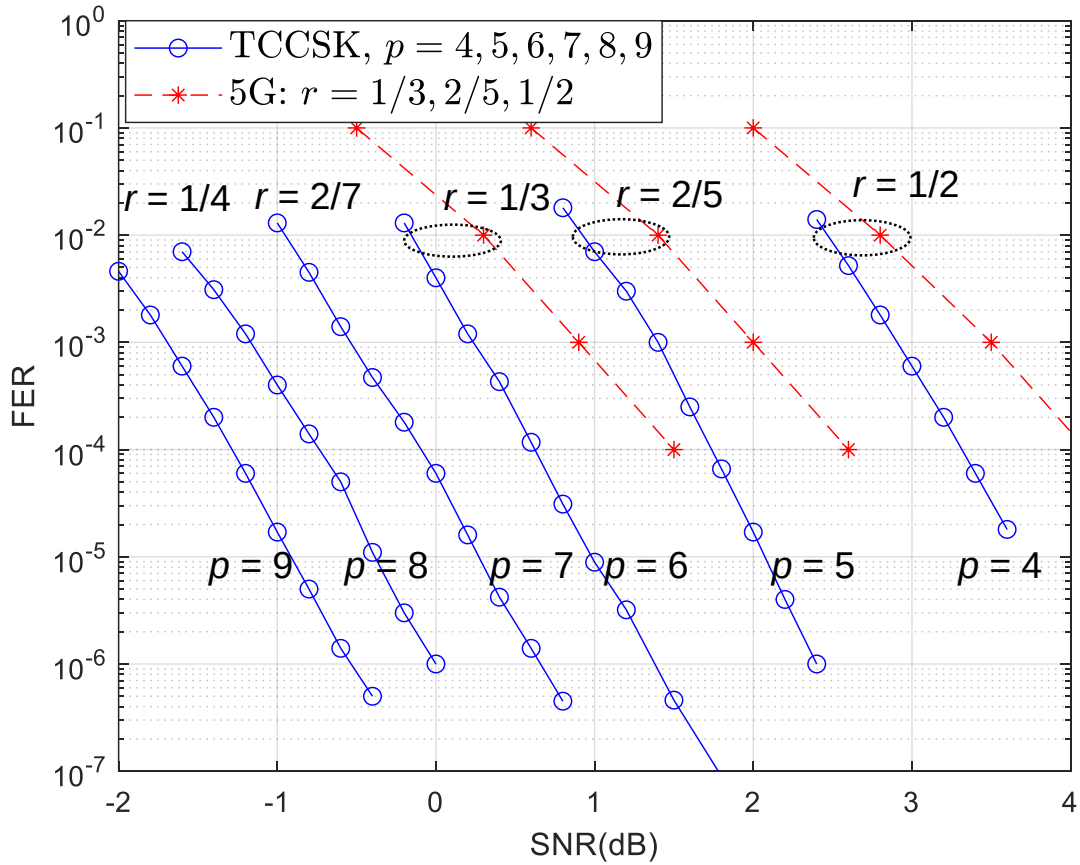
→ The Truncated CCSK (presented in ISTC'2021)
→ The Truncated Non Binary-CCSK (new results)

Inner Truncated CCSK code: principle



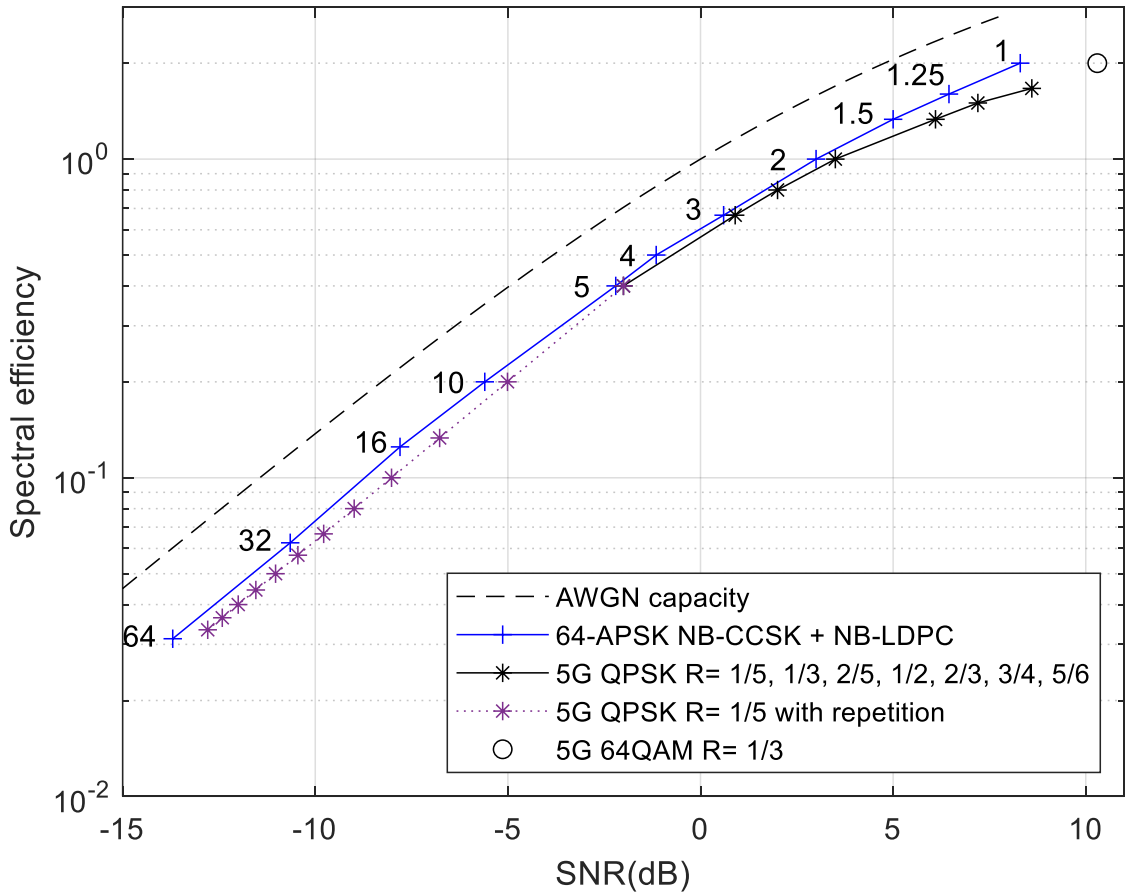
C. Marchand, E. Boutillon, "Rate-adaptive Inner Code for Non-Binary Decoders" ISTC'2021.

Inner TCCSK code: performance, k = 120 bits, GF(64)



C. Marchand, E. Boutillon, "Rate-adaptive Inner Code for Non-Binary Decoders" ISTC'2021.

Performance with 64-APSK-CCSK sequence, *q* = 64, k = 120 bits.



FER 10^{-3}

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Conclusion

- This work has required…

Signal processing theory

Each output O_m of parity check can be calculated as:

$$O_m^z = \frac{I_r^1(x) \times h_{c_m,v_x} + I_r^1(y) \times h_{c_m,v_y}}{h_{c_m,v_z}}$$

where $m \in [0, N-K-1]$

$$H_2(U|Y) \triangleq \mathbb{E}_Y \left[- \sum_{s \in \mathbb{Z}_q} L(s) (\log_q(L(s))^2 \right], \qquad (37)$$

- No parity checks fulfilled and $I_k \neq O_x \neq O_y$.

$$L_{kq}^{-}(c_{k-1} + \Delta) = e^{j\psi_k} \sum_{n=0}^{\Delta-1} e^{j2\pi f_o n} = e^{j\psi_k^{-}} \left(\frac{\sin(\pi f_o \Delta)}{\sin(\pi f_o)} \right), \qquad (21)$$

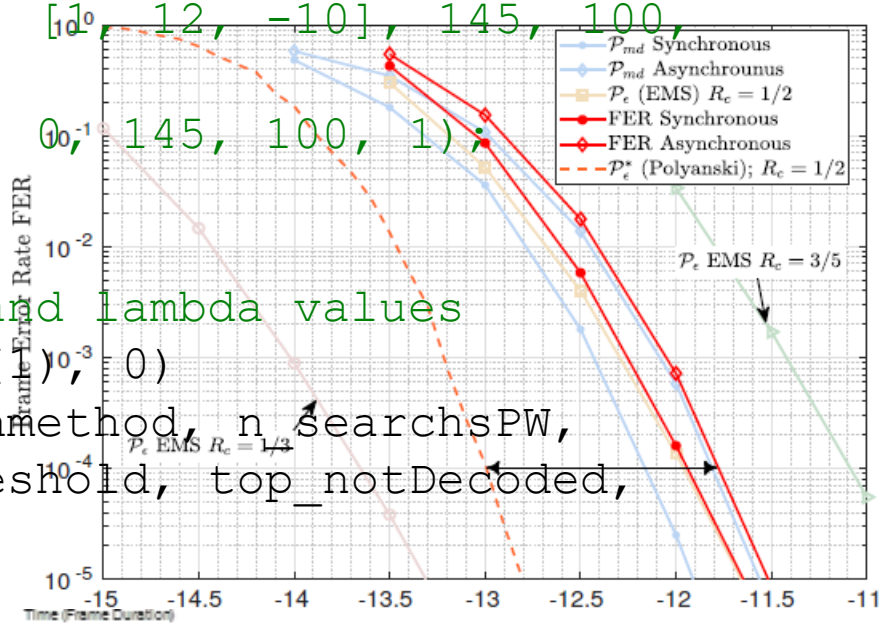
$(\Psi_k)_{k=0,1,\ldots,N-1} \ni \Psi_k = \Theta_k + w_k$, with $\Theta_k =$ and w_k is RV of PDF,

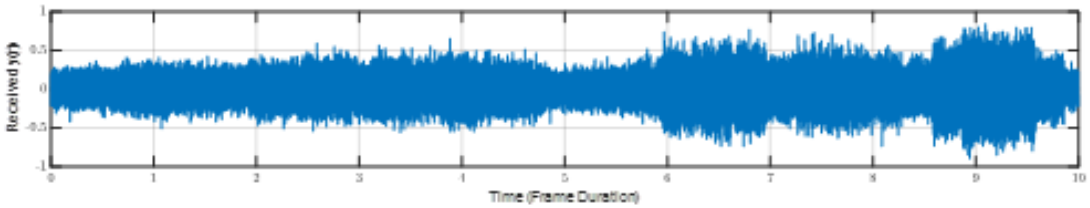
$$f_{\mathcal{P}_{0/R}}(x) = (1 - \mathcal{P}_{0/R}) f_N(x) + \mathcal{P}_{0/R} f_U(x) = \frac{1 - \mathcal{P}_{0/R}}{\rho_R \sqrt{2\pi}} \exp\left(-\frac{x^2}{2\rho_R^2}\right) + \frac{\mathcal{P}_{0/R}}{2\pi}.$$

$$f_{M_k}(x) = \frac{2x}{\sigma^2} e^{\left(-\frac{x^2}{q\sigma^2}\right)} \left[1 - e^{\left(-\frac{x^2}{q\sigma^2}\right)} \right]^{q-1}. \qquad (33)$$

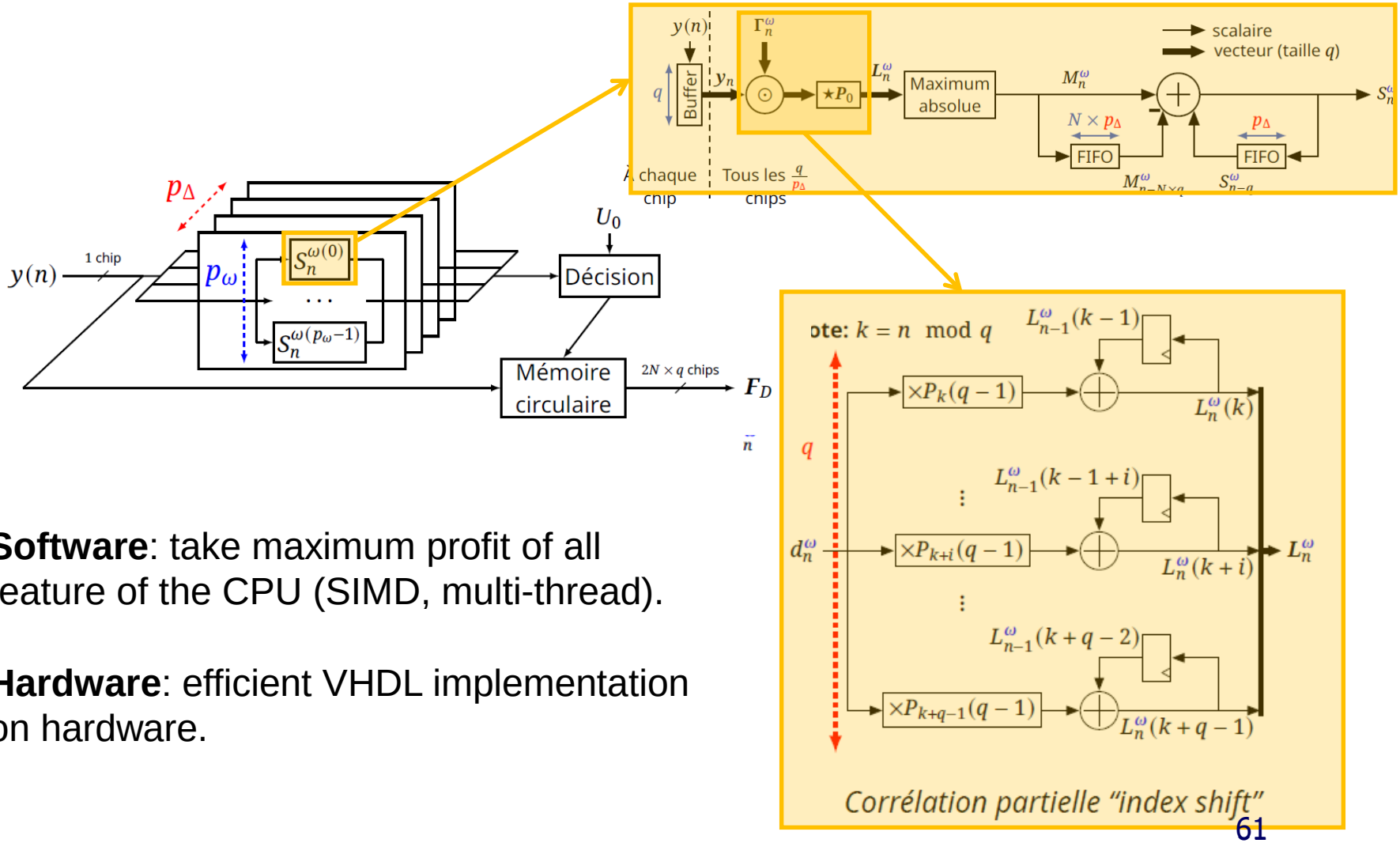
Algorithm/simulation work

```
function ToRun2(searchmethod, n_searchsPW, PNs_group,
alllambdaetsnrs, threshold, top_notDecoded, n_simulations)

% Fixed lambda : ToRun2(1, 1, 1, [1, 12, -10], 145, 100,
1);
% All lambdas  : ToRun2(1, 1, 1, 0, 145, 100, 1);
    global LAMBDA

    % Case for fixed SNR range and lambda values
    if ~isequal(alllambdaetsnrs(1), 0)
        OneLambda2iterate(searchmethod, n_searchsPW,
PNs_group, alllambdaetsnrs, threshold, top_notDecoded,
n_simulations);
        return;
    end
```





Software/Hardware design



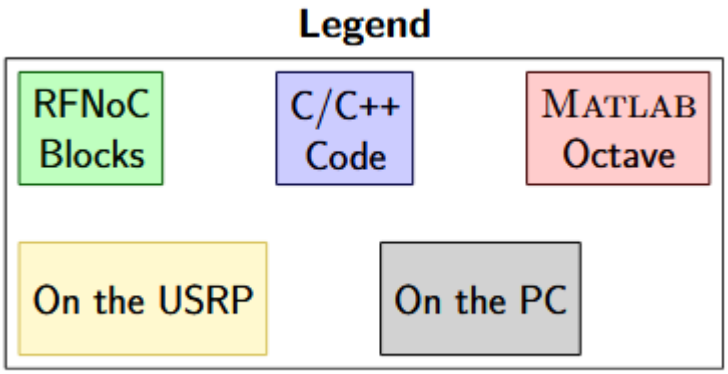
Software: take maximum profit of all feature of the CPU (SIMD, multi-thread).

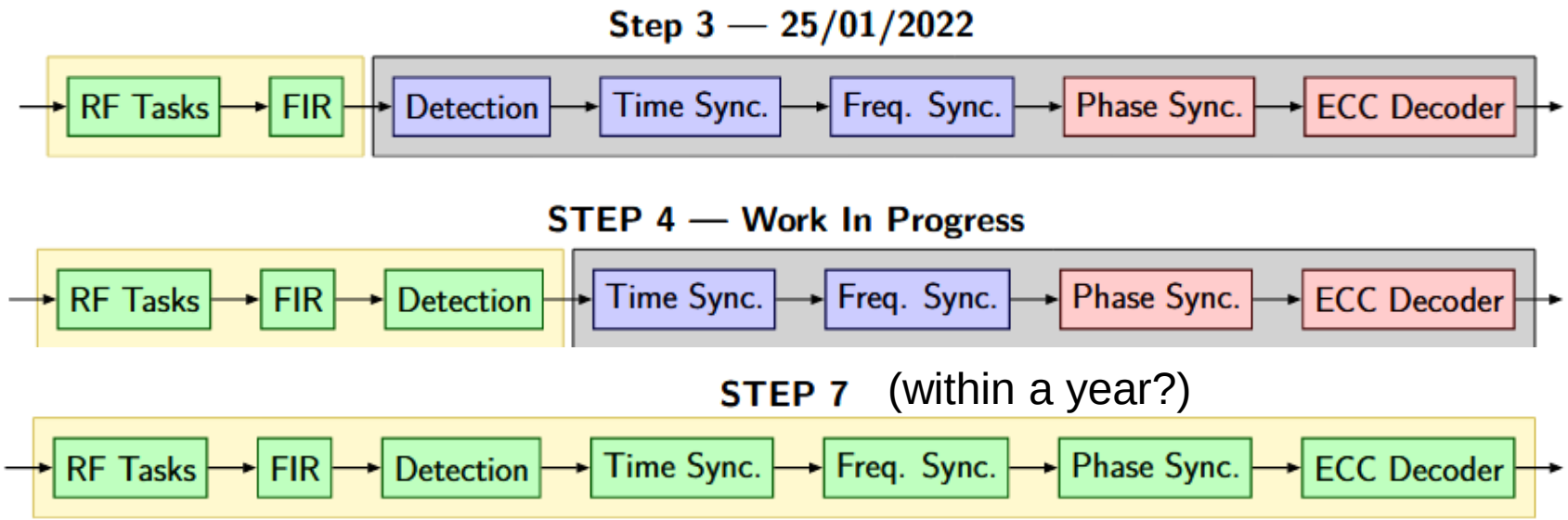
Hardware: efficient VHDL implementation on hardware.

Heterogeneous system integration

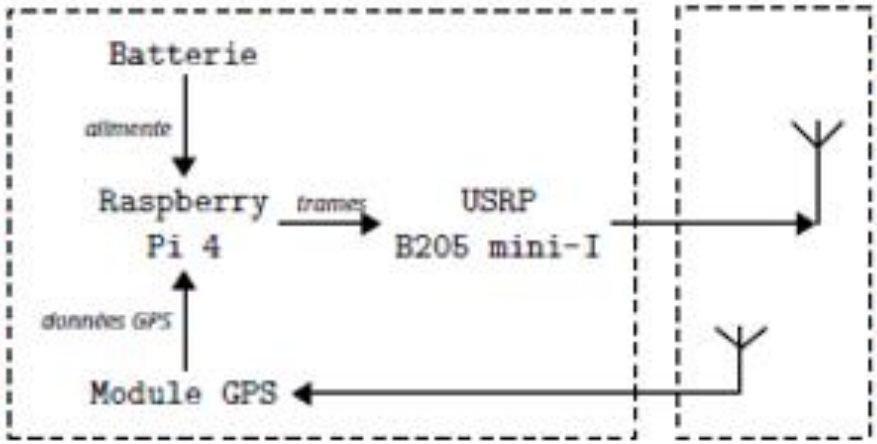
Hybrid real time receiver with hardware&software ressources.

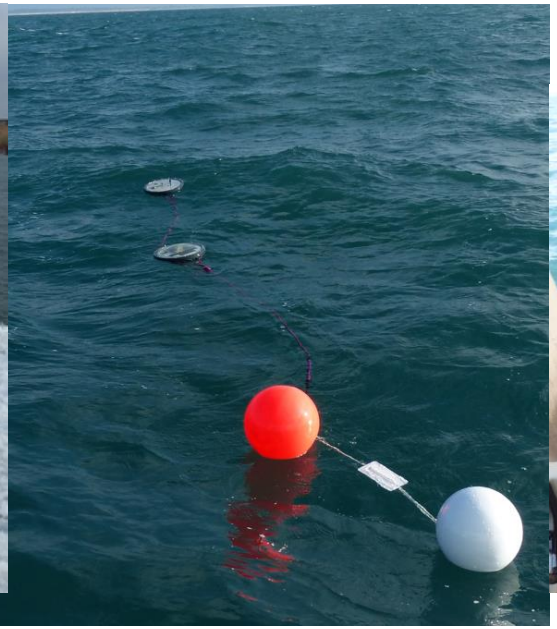
(LINUX)





Experimentations





Conclusion

- Take away on QCSP frames:
  - Very low complexity at emitter side
  - Close to theoretical limit in Gaussian channel
  - Proved efficient in several channels

Perspectives

- Improved hardware/software implementation of the receiver

- Multi-users detection with SIC
  - ⇒ Ongoing work for an average of 8 users in parallel.
  - ⇒ Extension to 64 users in parallel.

- Application for adaptive coding rate.

- From academics work to applications…

Potential applications

- Space (IoT – Low Earth Orbiter Satellite)
- Sea (Buoy-Boat)
- Gas/water Meters network
- Many others…

qcsp.univ-ubs.fr/

Thank you !