ANR-19-CE25-0013-01

Association of Non-Binary code and CCSK modulation

Quasi Cyclic Short Packets Project

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Massive IoT: two problems to be solved

First problem:

$10^9 = 100 \times 10^7 = 10^7 \times 100$

users payload (bits)

Equal In theory…

…not in practice

=> **unsupervised network.**

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

Header	Data	Redondancy

=> Header, Data and Redundancy should be merged.

Joint Header, Data and Redondancy

Saved bandwidth

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.
- 5 academics partners and CEA, Orange Labs and Sequans.

Objective : Evolution of IoT frames.

Outline

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

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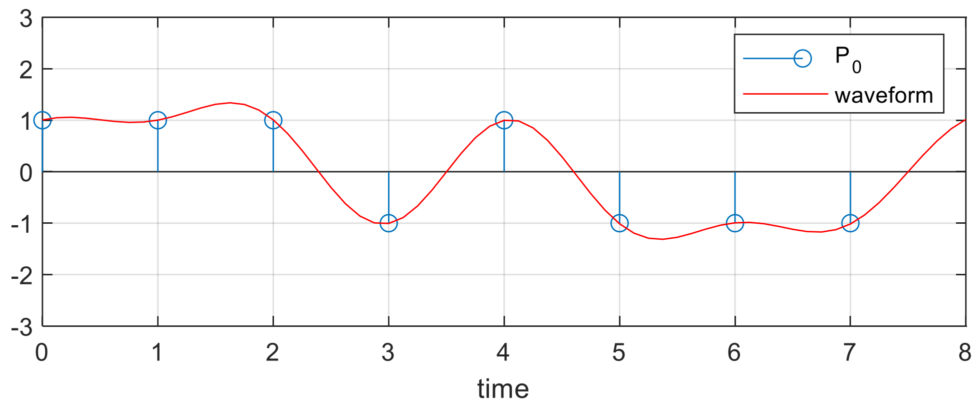
Cyclic Code Shift Keying modulation

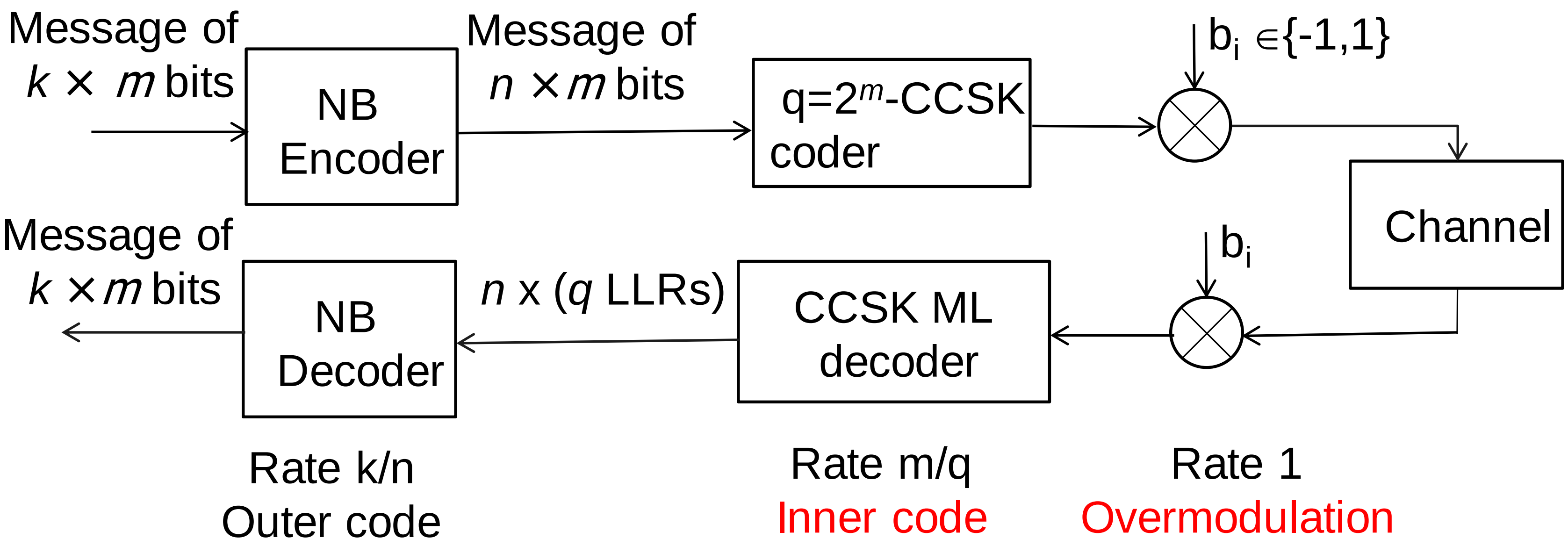
P_0 = 11101000 + BPSK modulation, roll-off factor 0.35, q=8

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

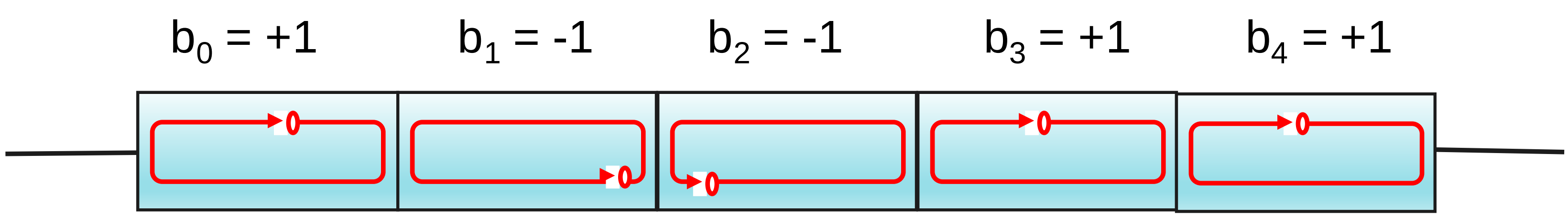


$P_a(k) = P_0(k-a)$, k = 0, 1, …, 7

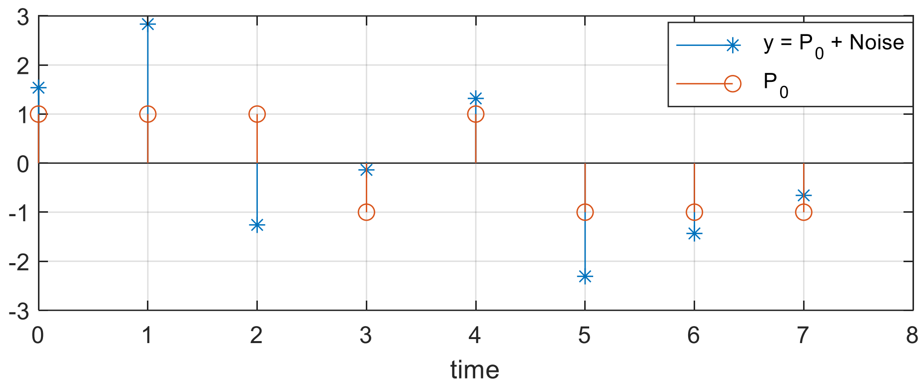
QCSP frame structure ($q = 2^m$)



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



Demodulation of a CCSK frame in AWGN Chanel



$$\log(P(Y|P_a)) \approx -d(P_a, Y)^2$$

$$d(P_a, Y)^2 = Y^2 + {P_0}^2 - 2R(< Pa, Y >)$$

$$LLR(a) = R(< P_a, Y >) = R\left(\sum_{k=0}^{q-1} P_0(k-a)Y(k)'\right)$$

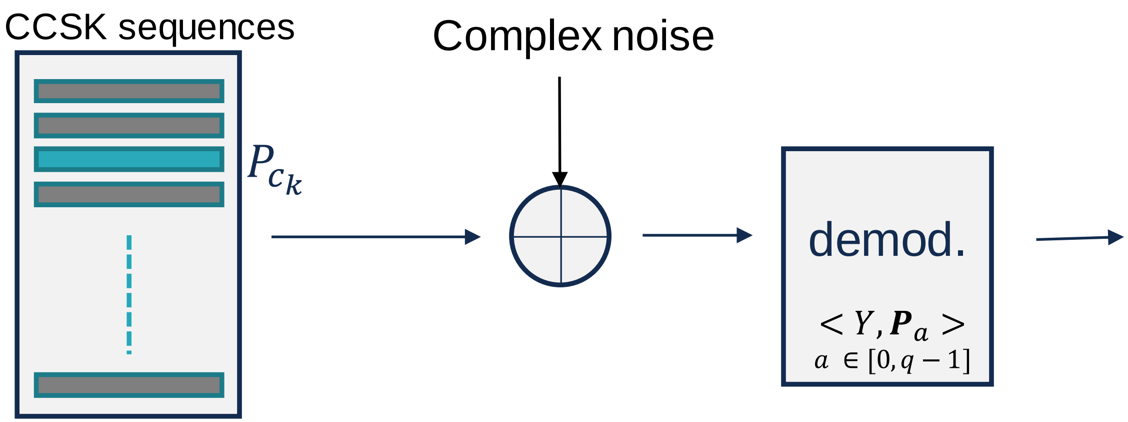
Circular convolution => product in frequency domain

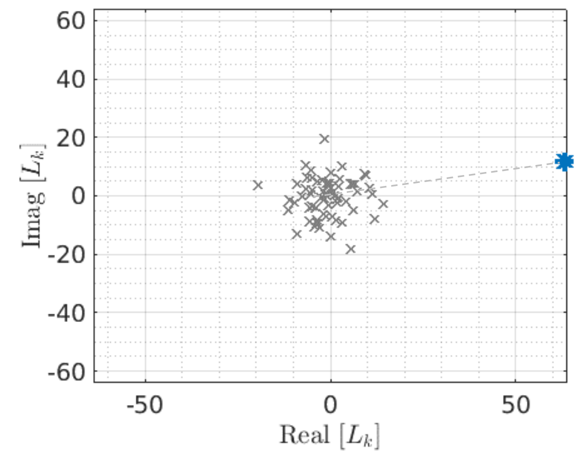
Optimal decoding of inner code: LLR = IFFT(FFT(Y)× FFT(P_0))

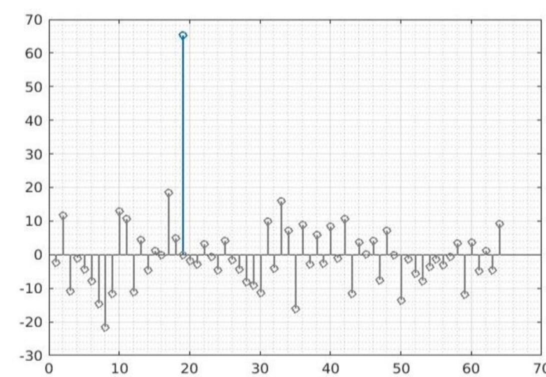
(not only ML => LLR of all codewords is known)

Demodulation of CCSK frame in complex noise

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







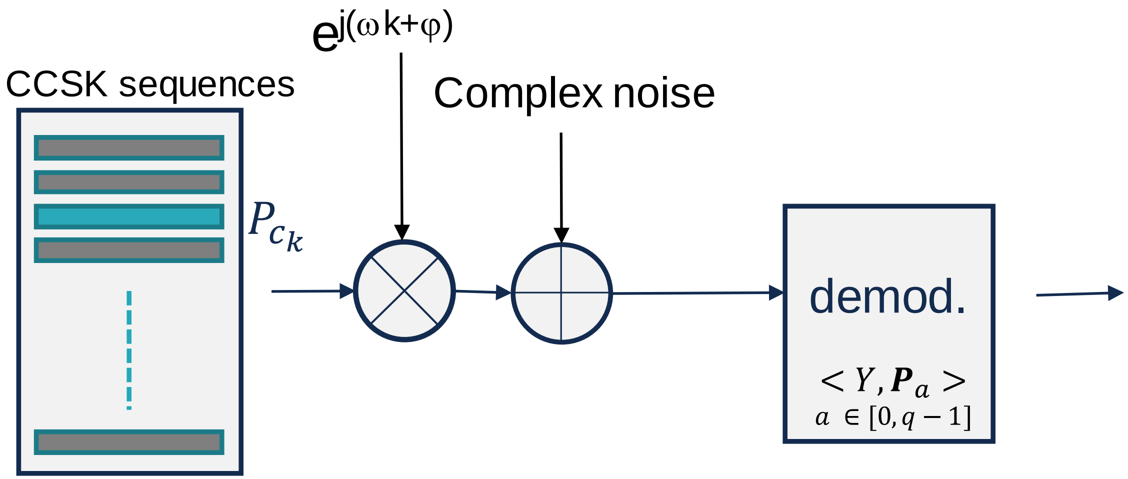
Y : noisy received sequence

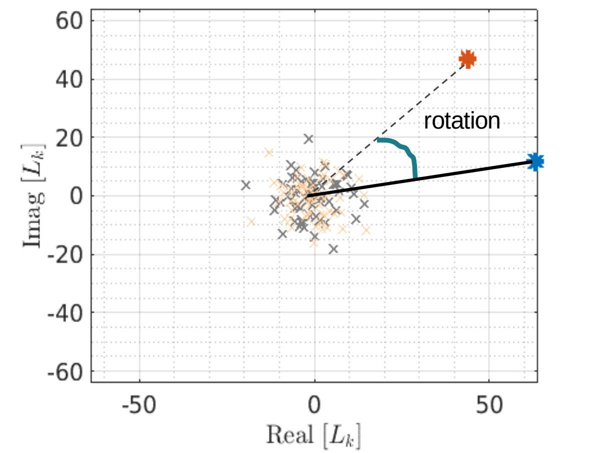
$\boldsymbol{L}$ = Log Likelihood Ratio

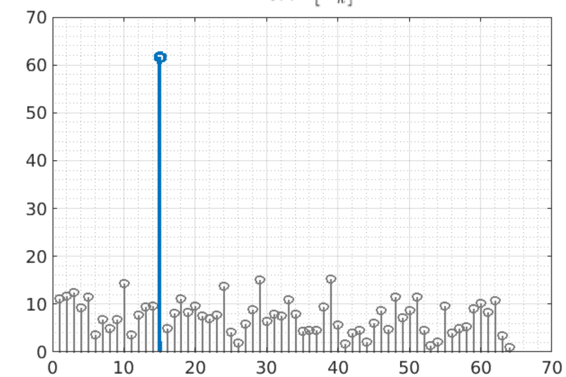
$$L(a) = Real(\log(\mathbb{P}(\boldsymbol{P}_a / Y)) \sim Real(< \boldsymbol{Y}, \boldsymbol{P}_a >) \; a = 0 \ldots q-1$$

Demodulation with phase offset

Effect of Doppler of local oscillator mismatch







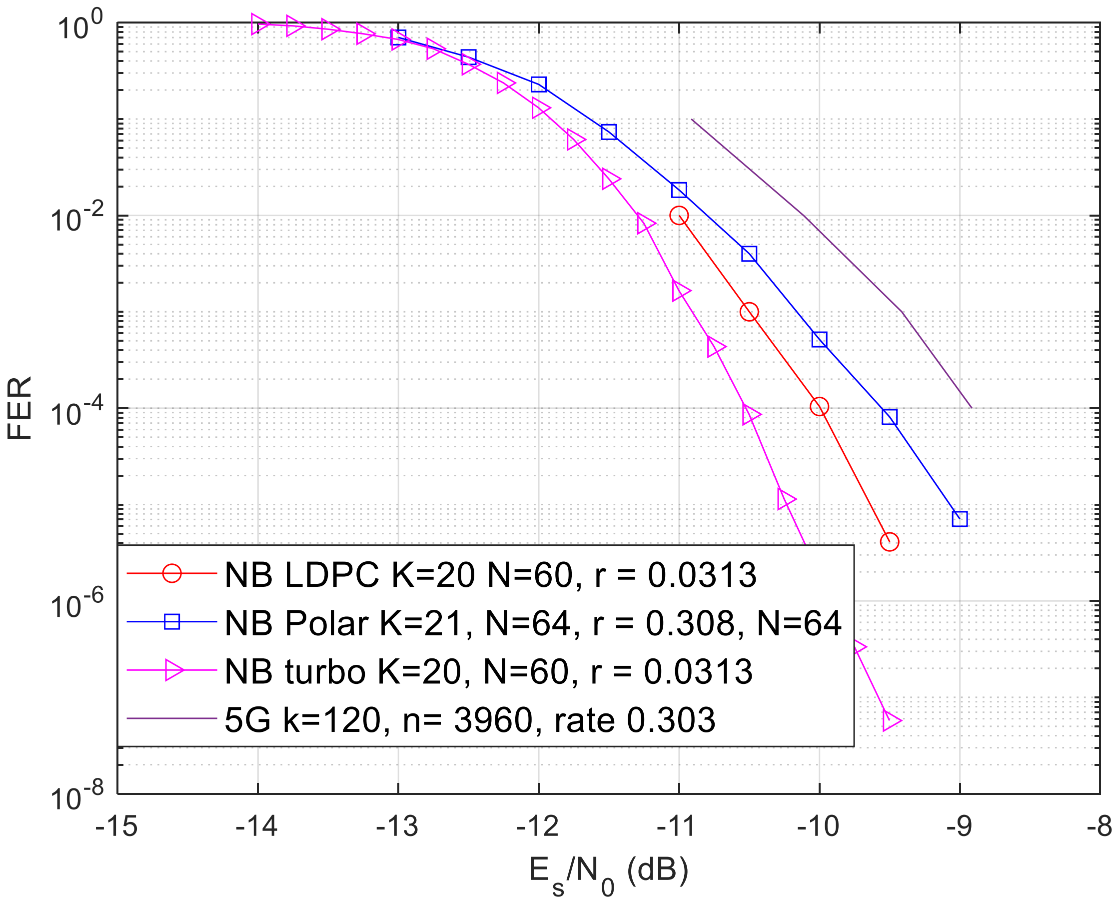
$\boldsymbol{Y}$: noisy received sequence

$\boldsymbol{L}$ = Log Likelihood Ratio

$$L(a) = |\log(\mathbb{P}(\boldsymbol{P}_a/Y))| \sim |< Y, \boldsymbol{P}_a >|, a = 0 \ldots q-1$$

With phase offset, non-coherent demodulation is required

Example of performance



Perfect synchronisation.

QCSP:
NB code rate r ≈1/3
CCSK: m=6 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

QCSP system model

Receiver algorithms

GNU Radio implementation

Rate adaptative QCSP

Conclusion and perspectives

Signal Processing factory

NB decoder engine

Messages
& Noise
& Time?
& Freq?

Coherently
demodulated
messages

Decoded
messages

Inner
Code

Over
Mod.

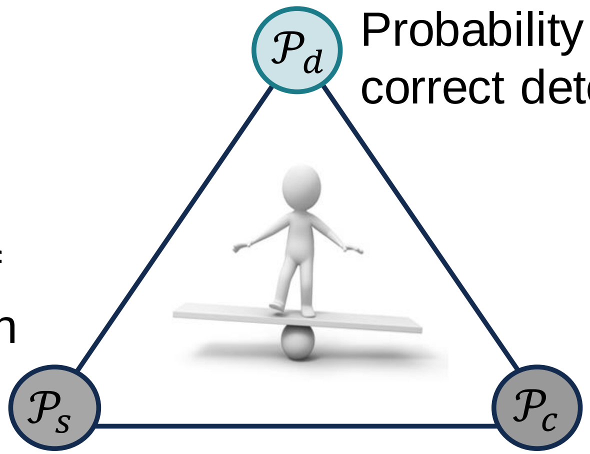
Outer
Code

Used redundancy

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

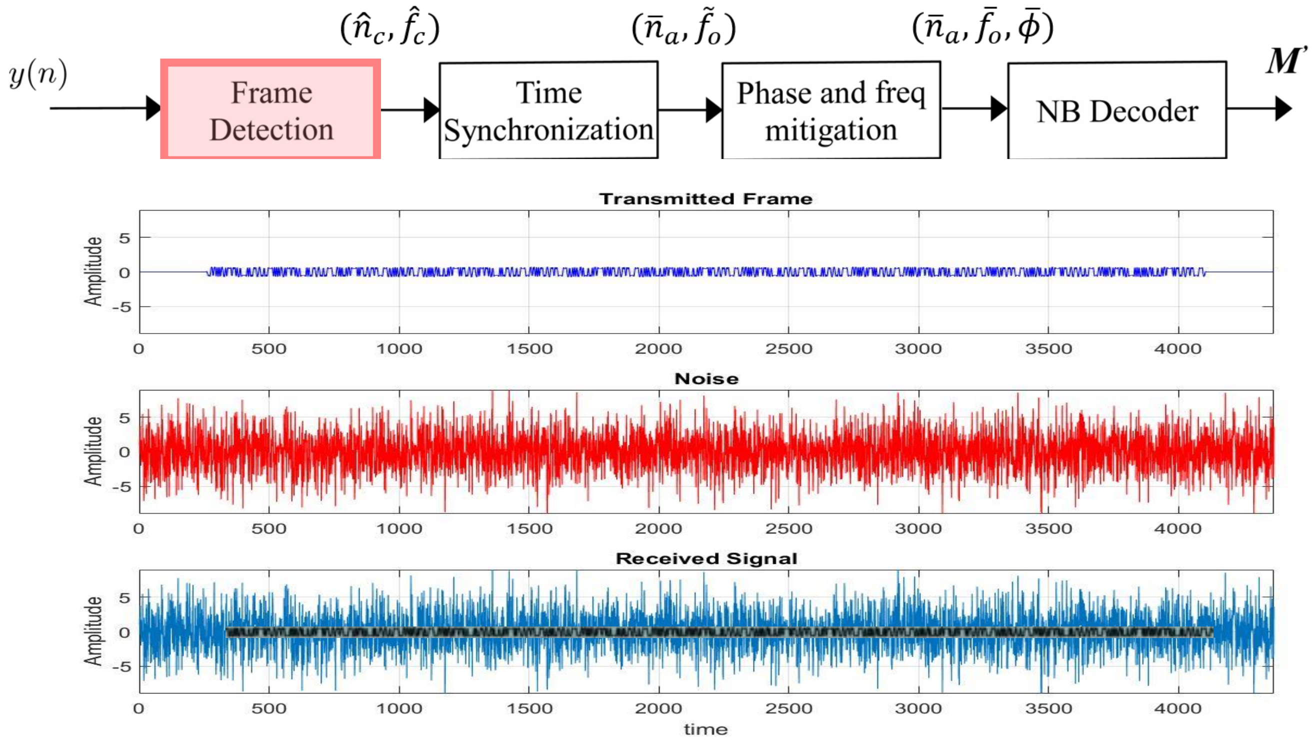
Joint overall probability:

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

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

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

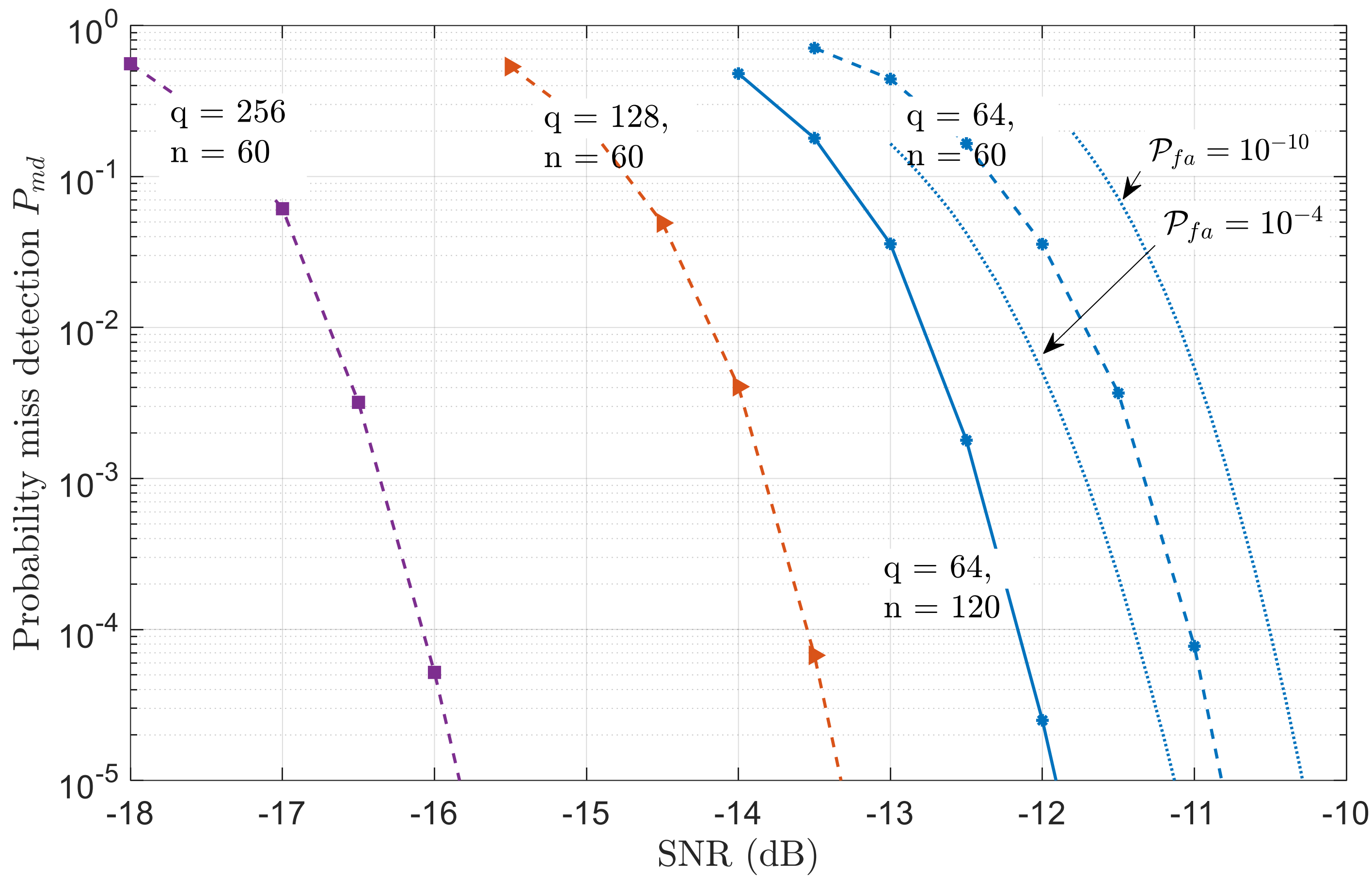
Detection problem



- 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.

Example of detection performance

Theoretical performance [1]: $P_{md} = (P_{fa}, q, n)$, confirmed by Monte-Carlo simulation.



$P_{fa} = 10^{-6}$

[1] K. Saied, A. Al Ghouwayel, E. Boutillon, «Short Frame Transmission at Very Low SNR by Associating CCSK Modulation with NB-Code », IEEE Transactions on Wireless Communications, 2022.

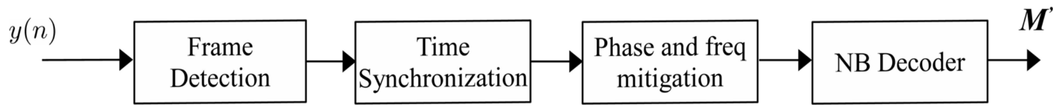
Time, Frequency & Phase synchronization

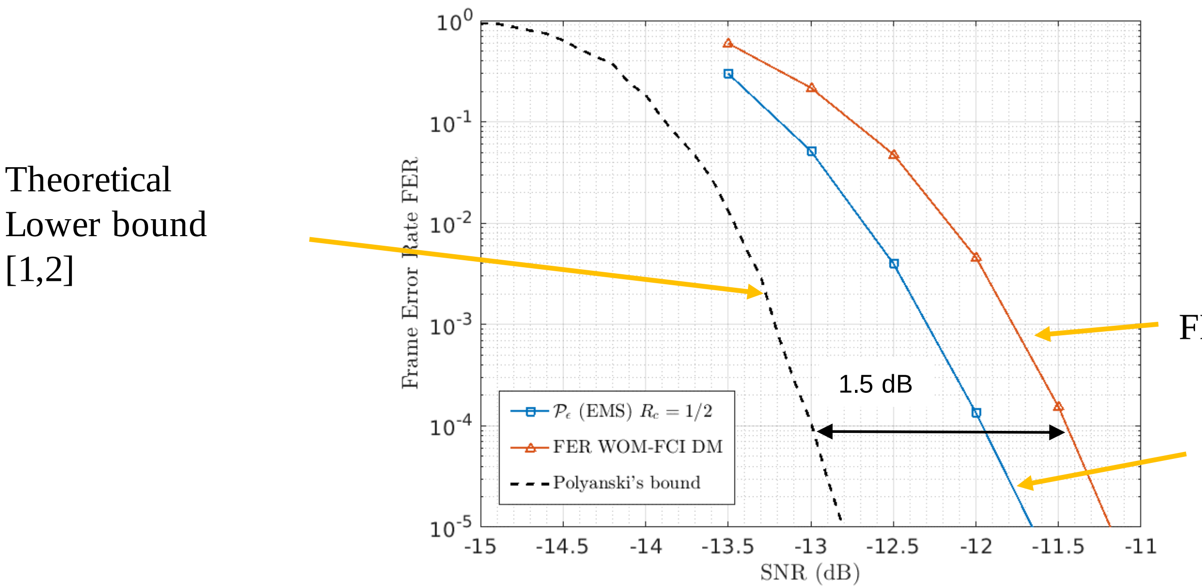
- Use information given by overmodulation to mitigate time ambiguity at CCSK symbol level [1]
- Use redundancy of outer code to mitigate time ambiguity at the chip level [1]
- Use soft information given by inner code decodign + redundancy of the outer code to estimate residual Frequency&Phase ambiguity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

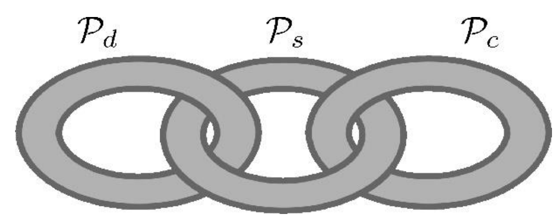
[1] K. Saied, A. Ghouwayel, E. Boutillon, «Time-Synchronization of CCSK Short Frames», WiMob'2021.
[2] K. Saied, A. Al Ghouwayel, E. Boutillon, «Phase Synchronization for Non-Binary Coded CCSK Short Frames », VTC'2022

Overall performance

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







[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.

Outline

QCSP system model

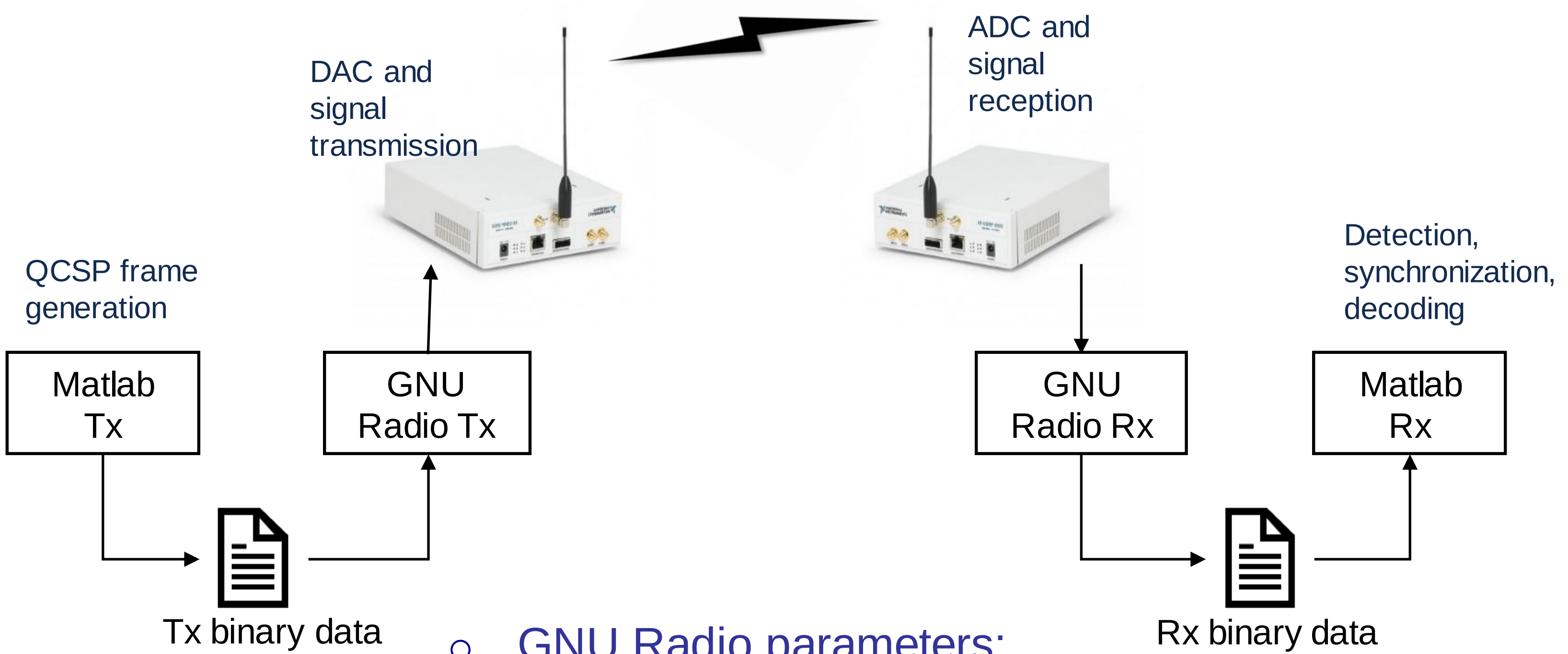
Receiver processing

GNU Radio implementation

Rate adaptative QCSP

Conclusion and perspectives

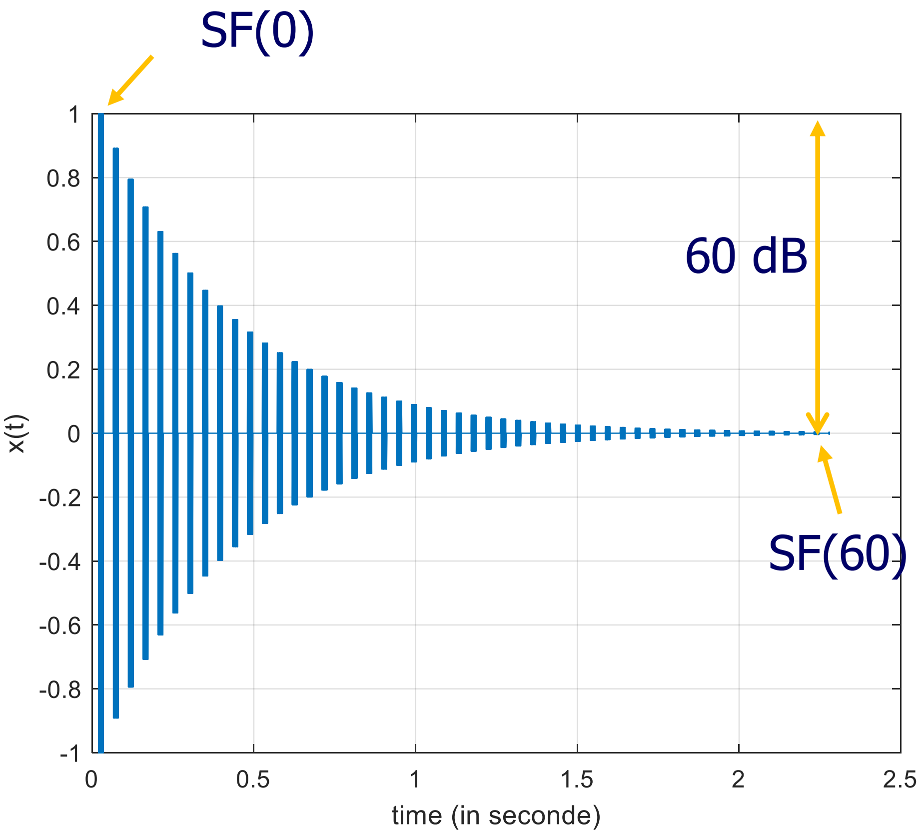
Offline experimental set-up



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

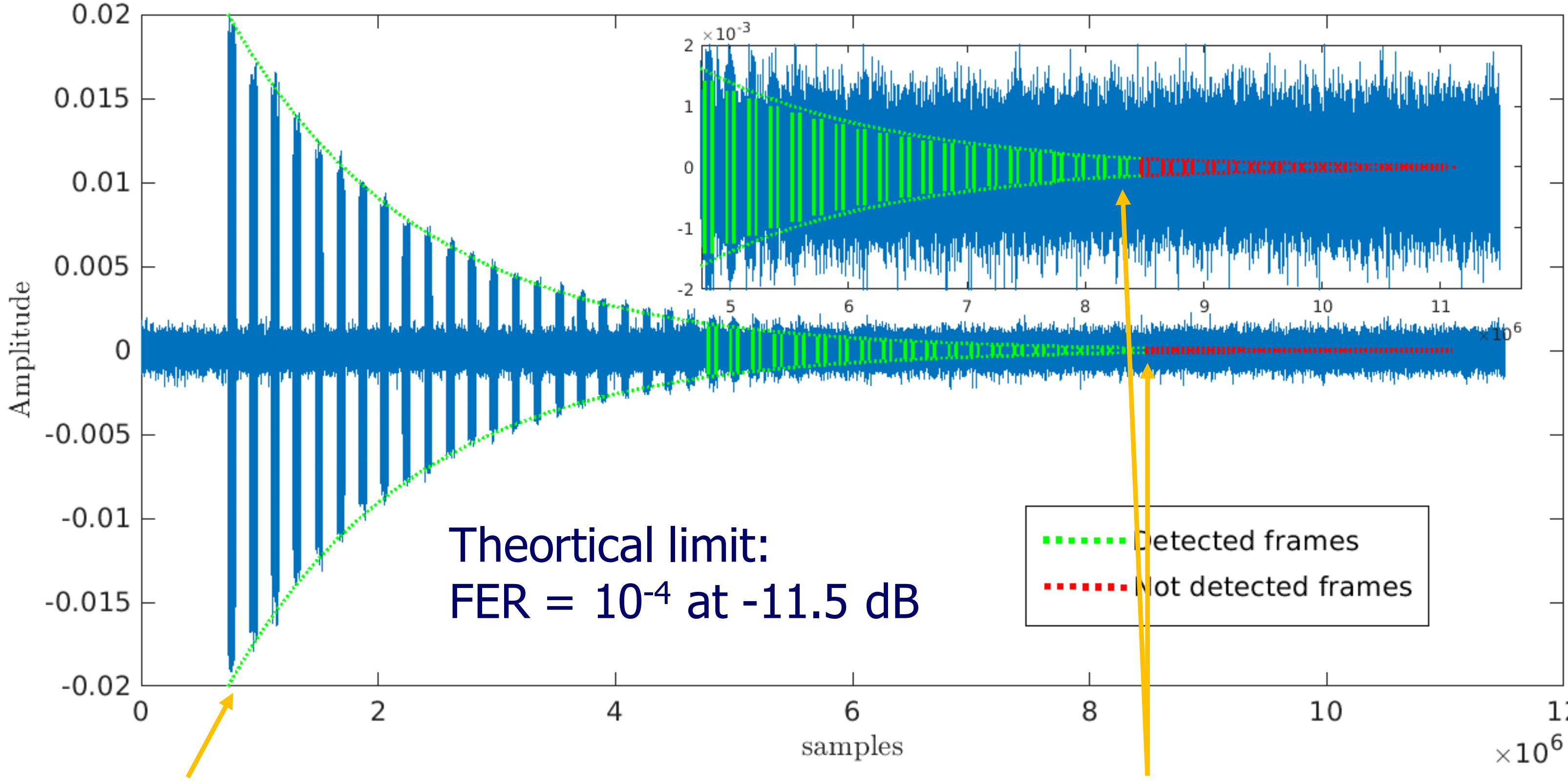
Note: Indoor test from 2 different rooms

Super-Frame structure



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

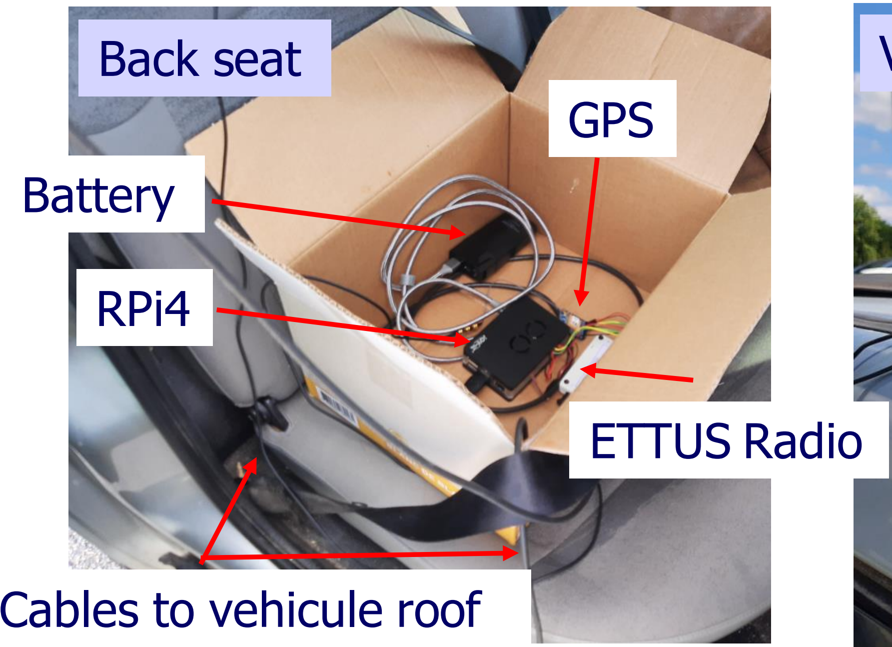
Received signal

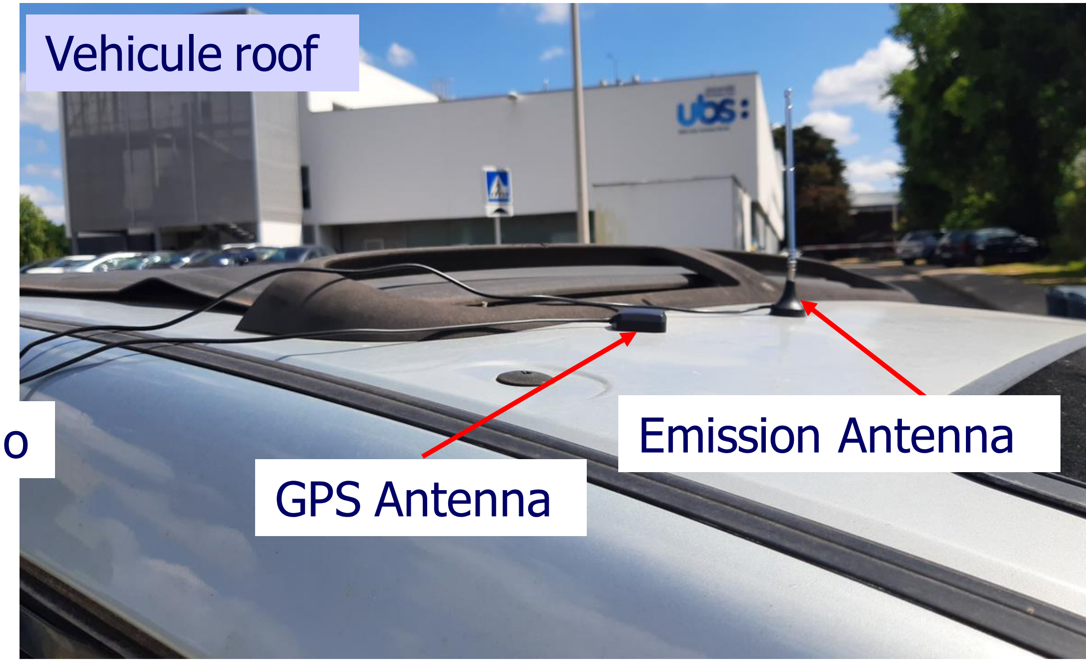


Es/N$_0$ = 29.5 dB
ΔF = 4006 Hz
No error before NB-decoder

Es/N$_0$ ≈ -12.5 dB
ΔF = 4012 Hz
35% of uncorrectly detected symbols before NB-decoder.

Real-time experimental set-up: Emission

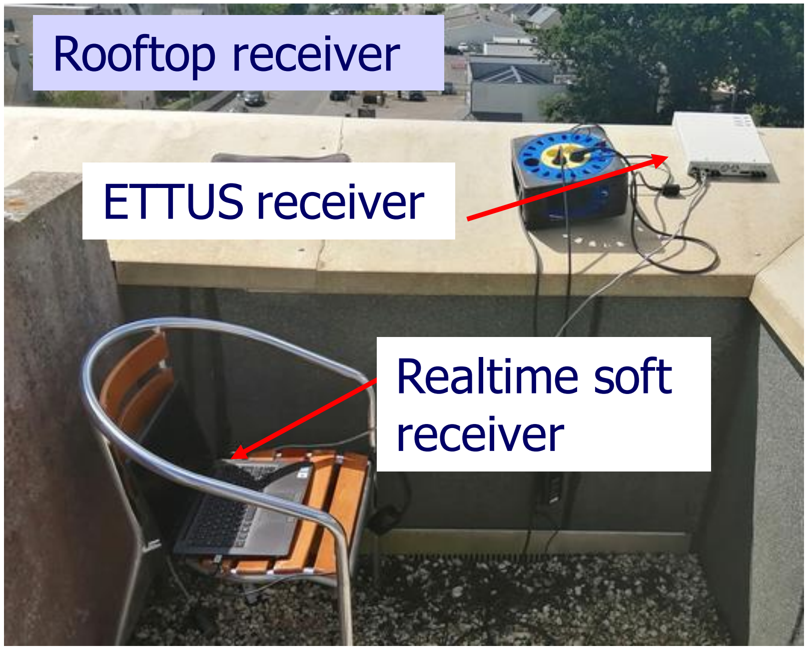


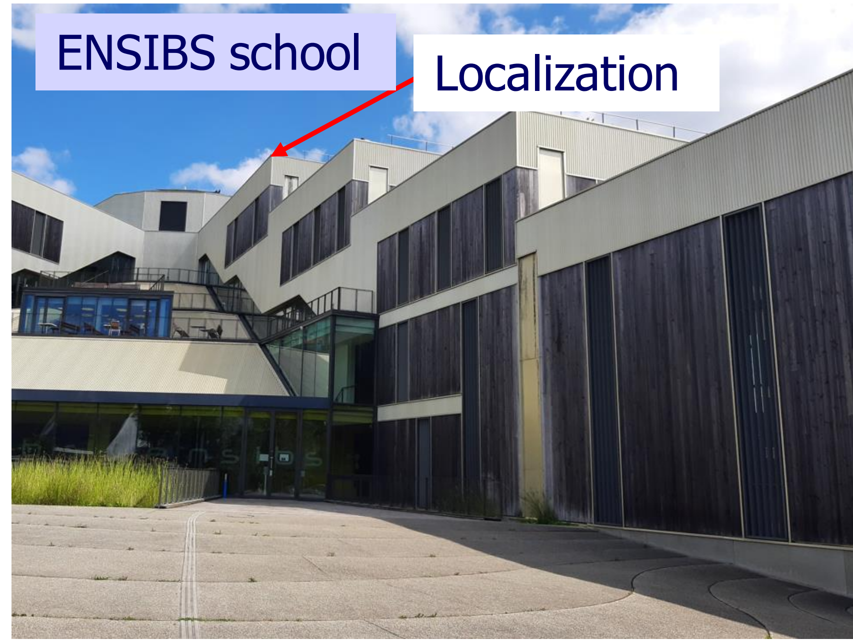


- Payload: k = 120 bits that contains
  - Localization given by GPS module
  - + Time, RPi4 Temperature and a frame number.

- New message every 4 secondes

Real-time experimental set-up: Receiver

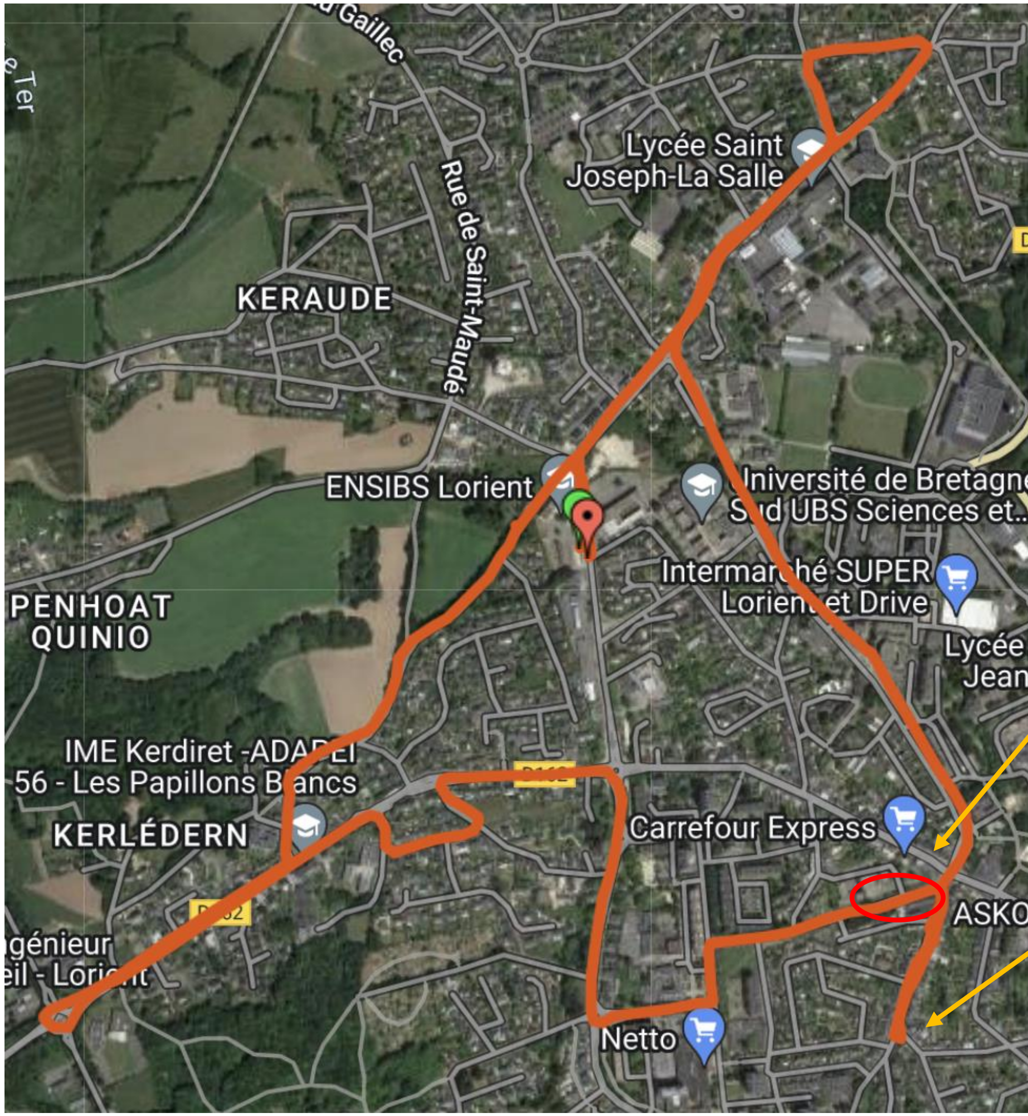




- Radio Settings in Transmission
  - Measured RF emission Power: 4.5 dBm
  - Carrier Frequency: F_c = 433.950 MHz

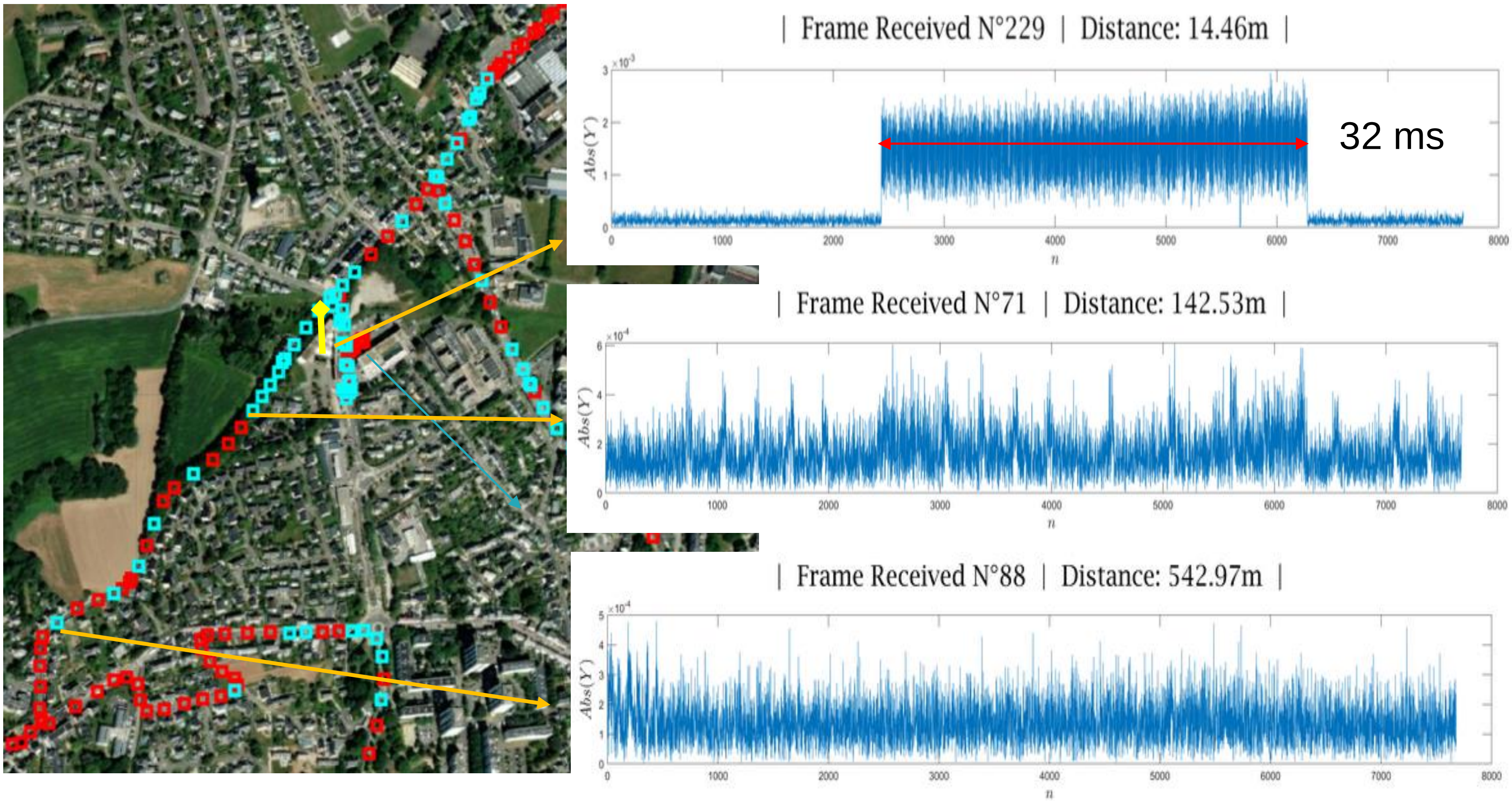
- ◇ Bit information rate : 3.9 Kbit/s
- ◇ Message duration: 32 ms.

Path in Lorient



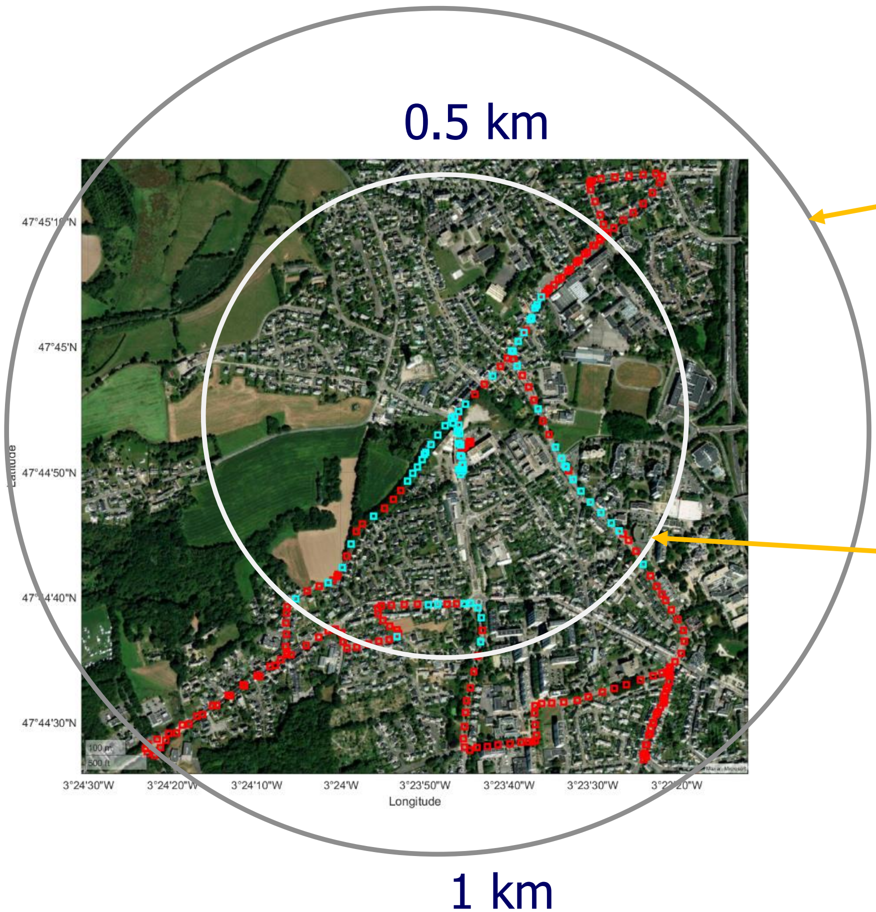
Except for residents

Result of the experimentation



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

Result of the experimentation



32 ms frame vs 56 ms for LORA (spreading Z = 7)

4.5 dBm vs 14 dBm for LORA

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Conclusion and perspectives

QCSP for rate-adaptive code

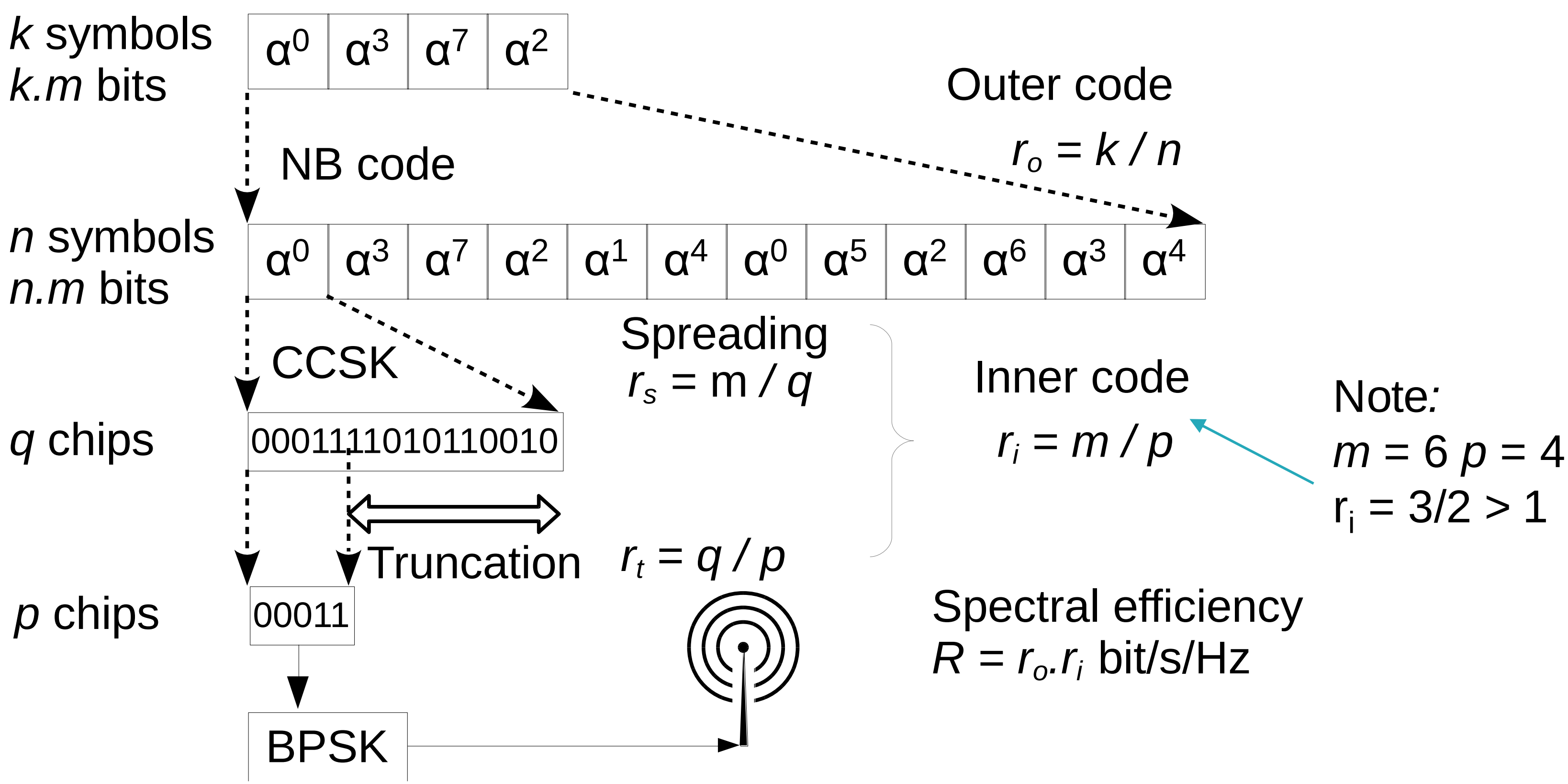
- Variation on channel conditions
  - Optimized Modulation/code for each channel.
  - Complexity => Cost.

- 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)

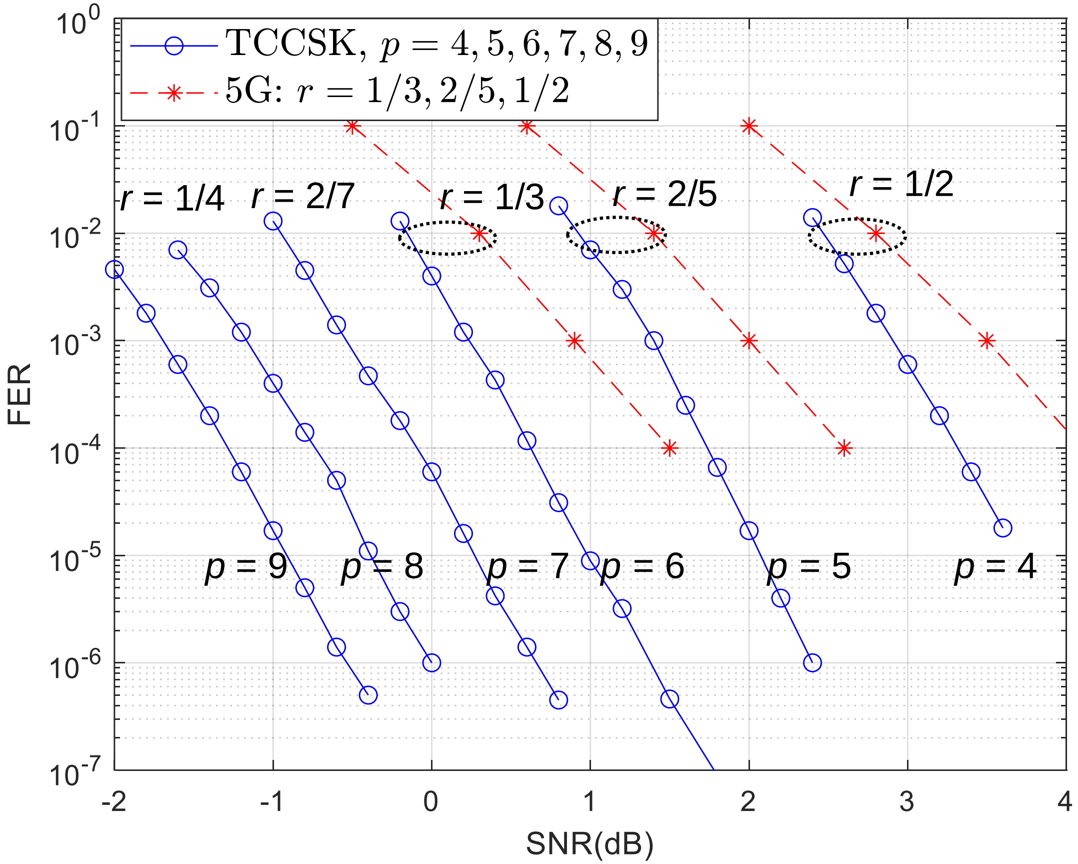
→ The Truncated Non Binary-CCSK (new results)

Inner Truncated CCSK code: principle



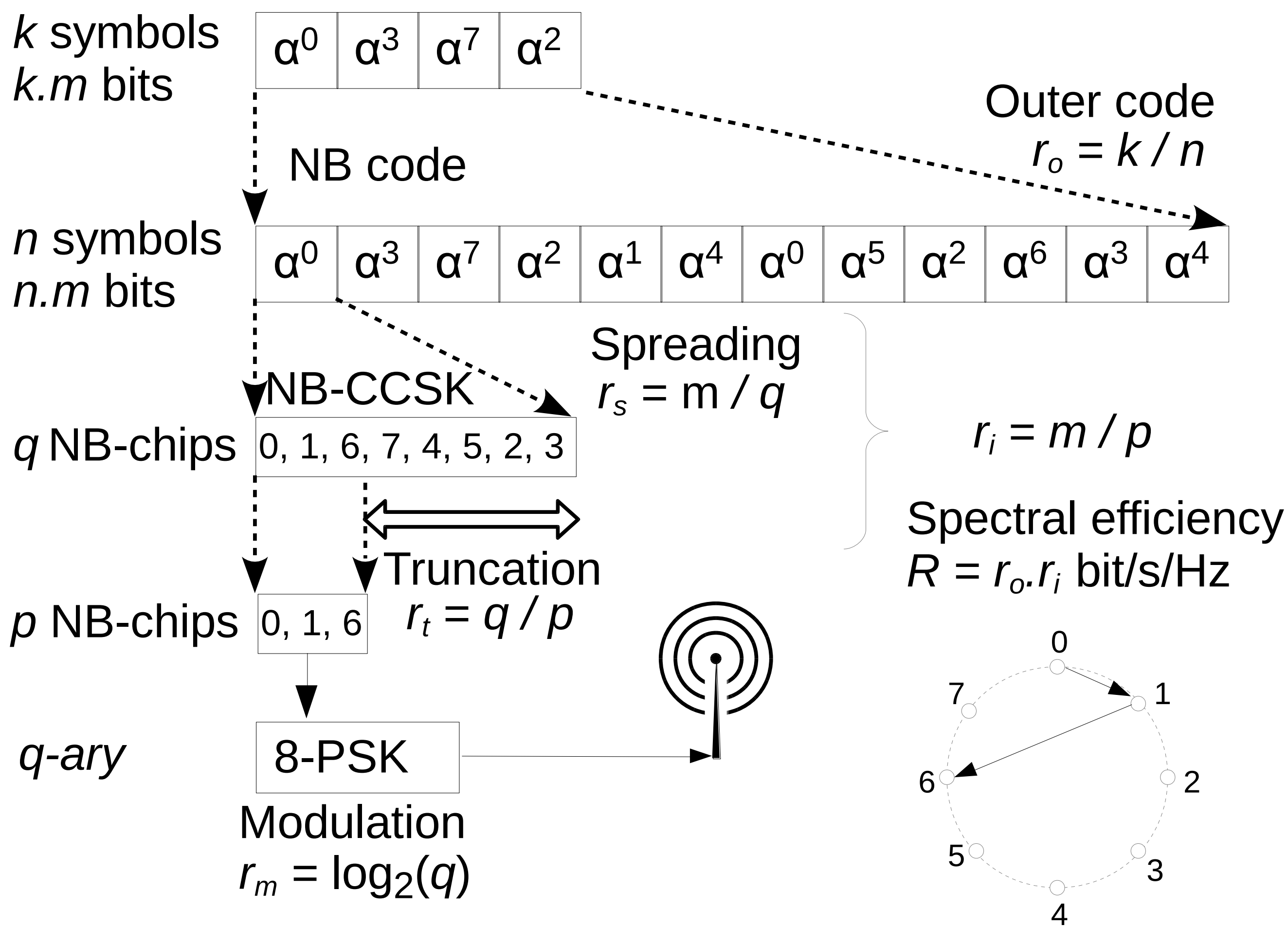
C. Marchand, E. Boutillon, "Rate-adaptive Inner Code for Non-Binary Decoders" ISTC'2021.

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



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

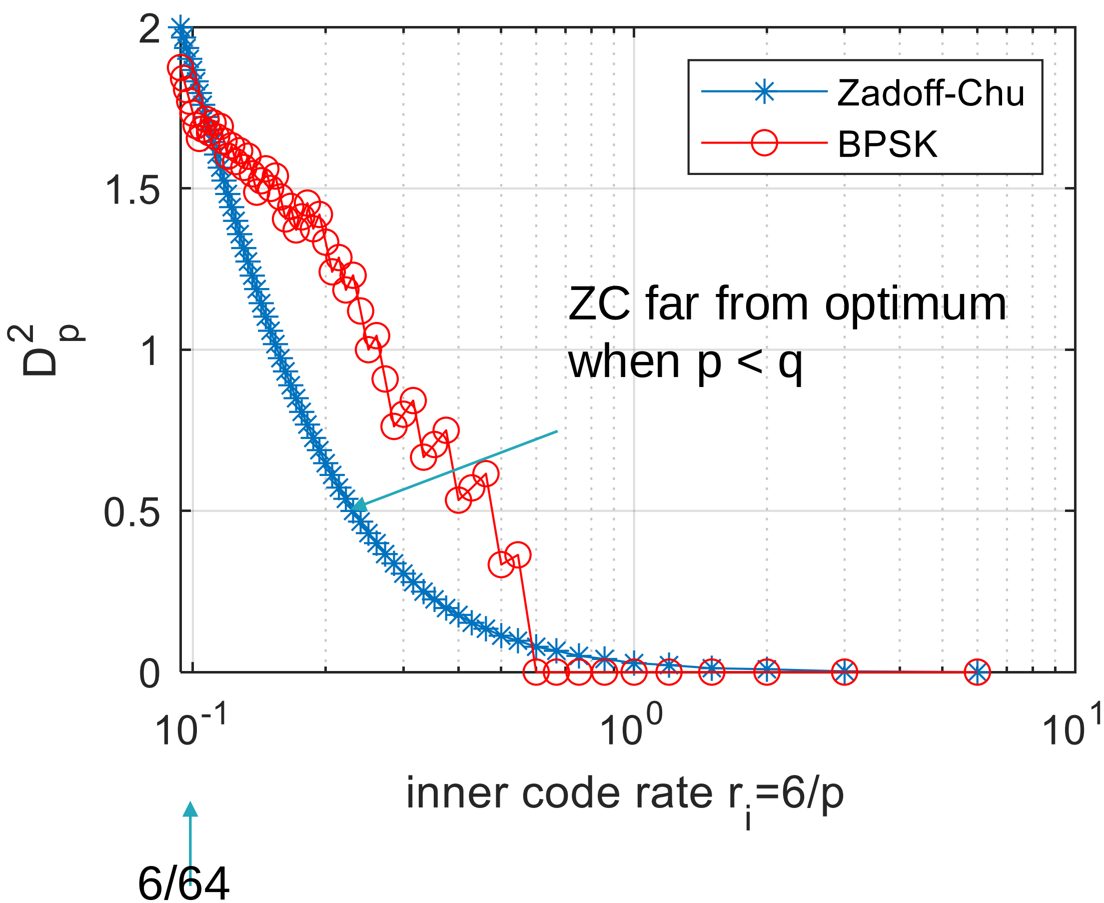
Non binary Truncated CCSK



- Use Zadoff-Chu sequence $P_0(n) = e^{\frac{2\pi j n^2}{64}}$, $n = 0,1,\ldots, q-1$

Minimum distance D_p for q = 64

- Let us defined $D_p^2 = \frac{1}{p}\min\{\|P_a(p) - P_b(p)\|^2, a \neq b\}$ be the minimum normalized distance of the inner code for a p-chips length truncation



ZC sequence:

$$a \neq b \Rightarrow \langle P_a(q), P_b(q)\rangle = 0$$

Thus

$$\|P_a(q) - P_b(q)\|^2$$

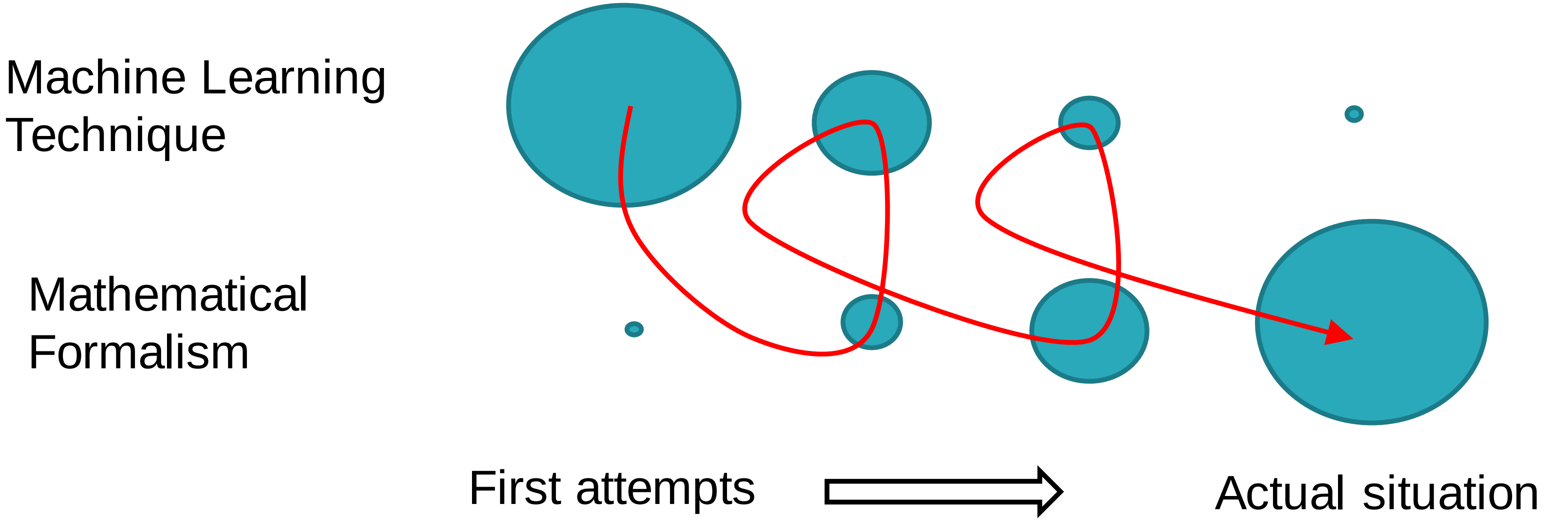
$$= \|P_a\|^2 + \|P_b\|^2 - 2Real\langle P_a, P_b\rangle$$

$$= \left(q + q\ - 2Real(0)\right) = 2q$$

$$D_{p=q}^2 = \ 2$$

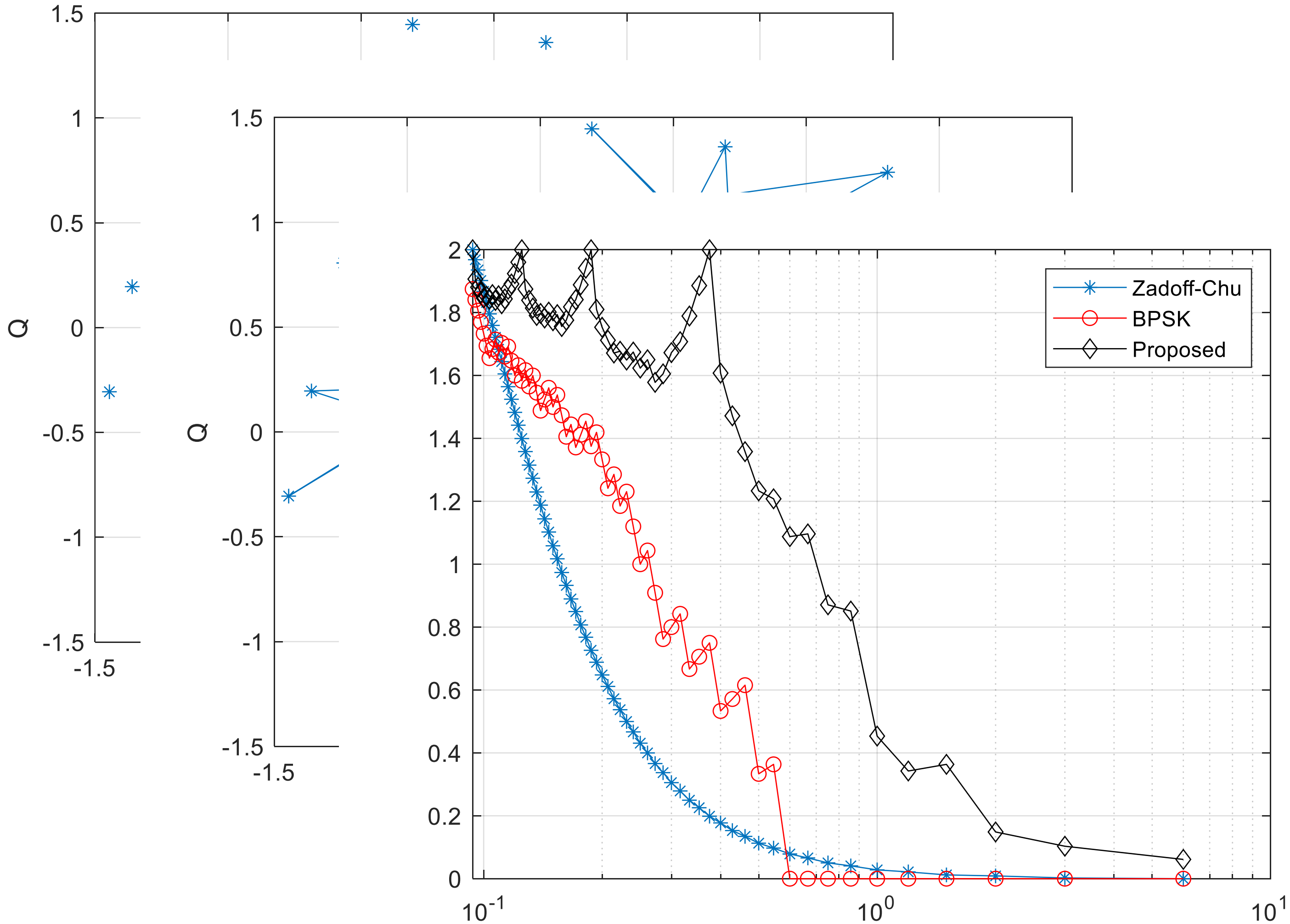
Optimization of NB-CCSK sequence

- Multi-objective optimization problem: maximize D_p^2 for p = 1, …, q-1.

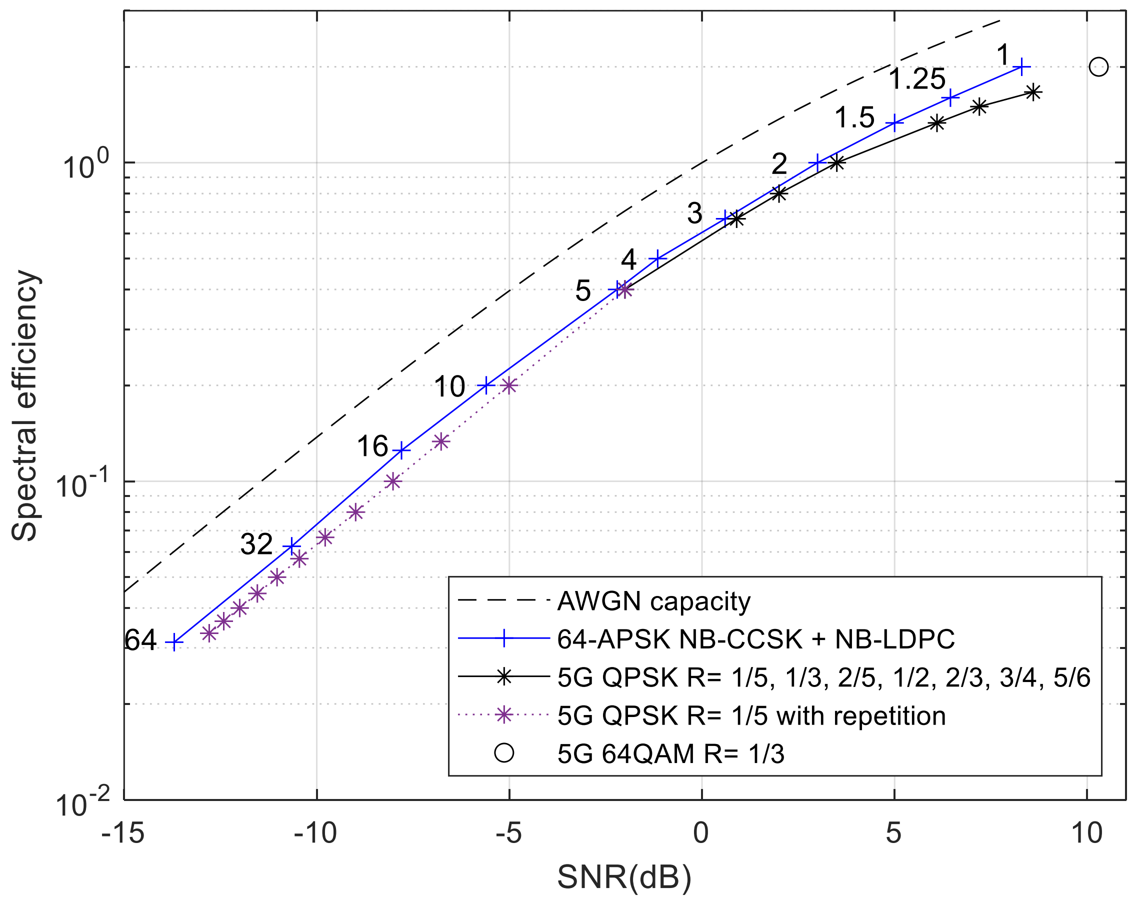


- Set of optimal solutions obtained.

Proposed modulation for q = 64



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



FER 10^{-3}

Outline

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Toward the multi-user context

Conclusion and perspectives

Conclusion

- Take away on QCSP frames:
  - Very low complexity at emitter side
  - Close to theoretical limit in Gaussian channel
  - Proved efficient in mobile channel (speed < 50 km/h).

- NB-TCSSK:
  - Efficient versatile communication scheme
  - Perfect for H-ARQ scheme
  - …papers in preparation.

Perspectives

- FGPA implementation of the receiver (almost finished for detection).

- Multi-users detection with SIC

  => Ongoing work: proof of concept with 10 users in parallel by simulation.

  => Future extension for hundred of users in parallel.

- Transmission “sensors –> satellite” with QCSP frames.

  => Great potential…

Questions?

From http://getdrawings.com/mc-escher-drawing

https://qcsp.univ-ubs.fr/