Quasi-Cyclic Short Packet (QCSP) transmission for Internet of Things

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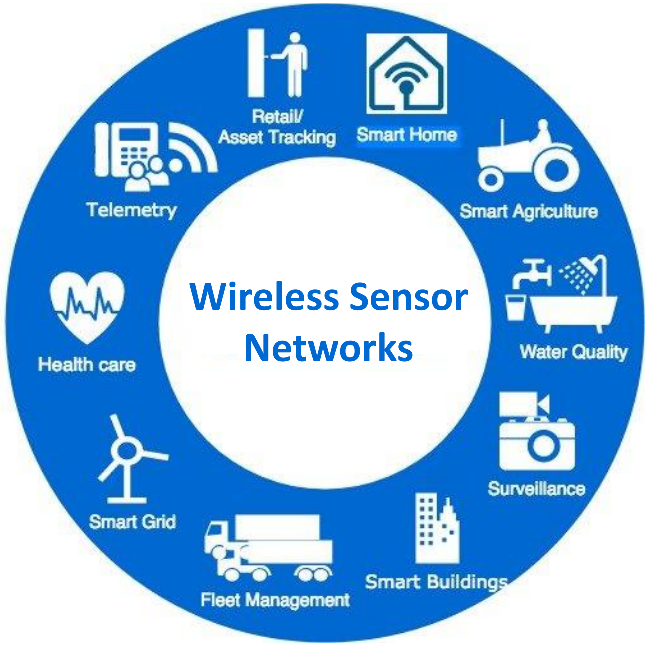
Wireless Sensor Networks (WSN)

- IoT becoming an increasingly growing topic of conversation
- WSN is a key enabler for the IoT technologies
- Transmitters are often idle
- Low Power Wide Area (LPWA) networks
- Low latency, high reliability, low SNRs
- Short data packets


Detection and Synchronization

Metadata | Payload data

Metadata | Data



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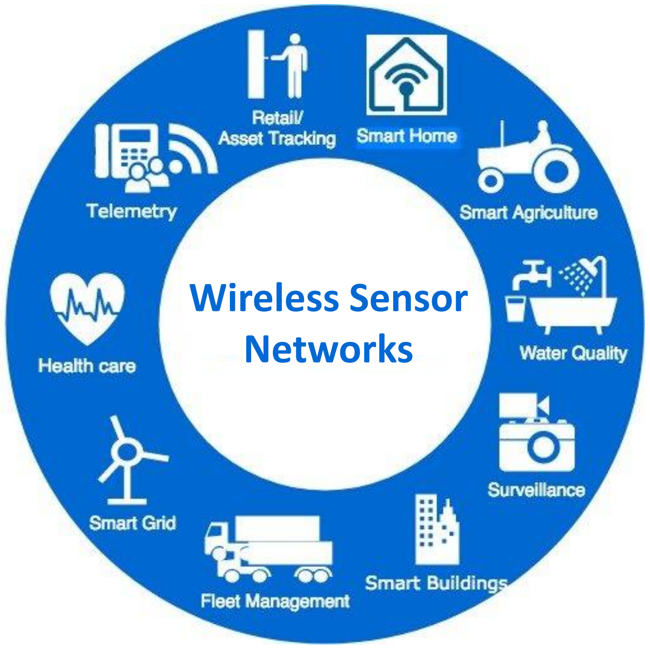

> “In a network, asynchronism (even with short packets) shouldn’t affect capacity [Ref1].”

Y. Polyanskiy (MIT)

[Ref1]: Polyanskiy, Y., Asynchronous Communication: Exact Synchronization, Universality, and Dispersion, *IEEE Transactions on Information Theory 59, 1256–1270 (Mar. 2013).*

From space to earth

- **Cyclic-Code Shift Keying (CCSK)** used in Quasi-Zenith Satellite system (Japanese GPS enhancement system) -2020- [Ref2].
- **Non-binary error correcting codes (NB-ECC)** used in BeiDou (Chinese GPS-like system) -2017- [Ref3].

➔ Space to earth comm. techniques are efficient at very low data rate and low SNRs ➔ adapt to IoT?!

[Ref 2]: "Quasi-Zenith Satellite System Interface Specification - Centimeter Level Augmented Service (IS-QZSS-L6-003)" Cabinet Office, August, 2020.

[Ref 3]: BeiDou Navigation Satellite System, Signal In Space, Interface Control Document, Open Service Signals B1C (Version 1.0) ” China Satellite Navigation Office , December, 2017.

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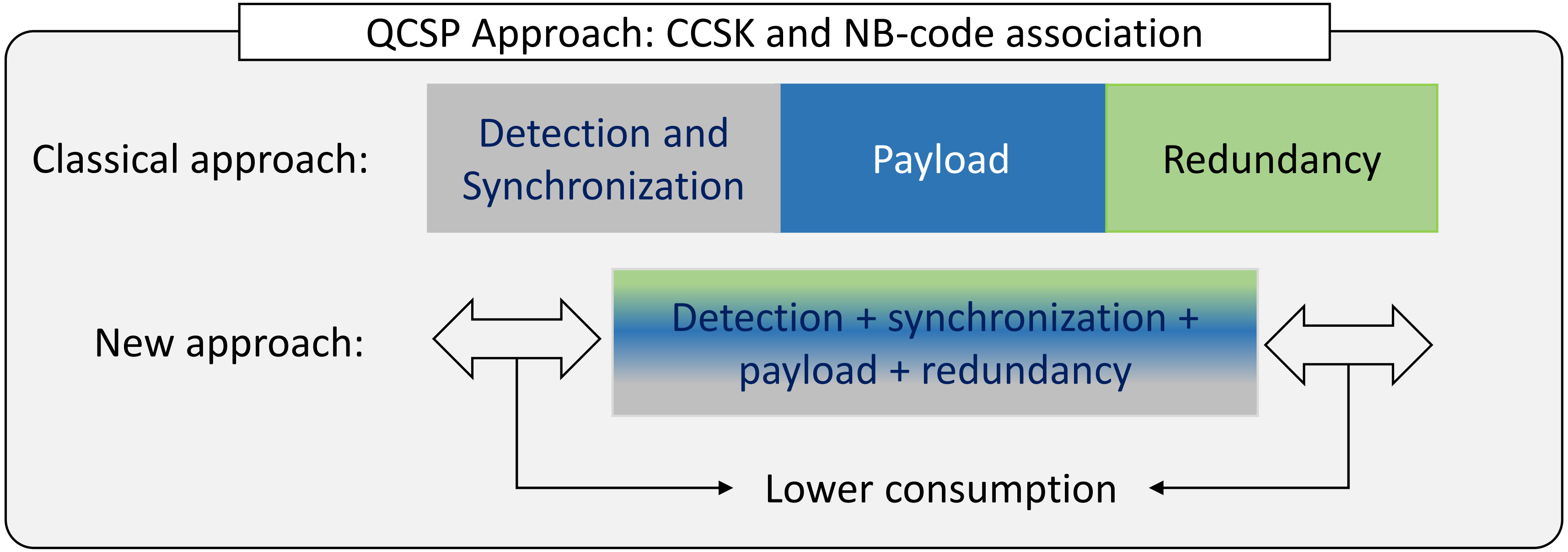

QCSP Approach: CCSK and NB-code association

Classical approach:	Detection and Synchronization	Payload	Redundancy

New approach: ⇔ Detection + synchronization + payload + redundancy ⇔

→ Lower consumption ←

➔ No Preamble – Low data rate – very Low SNRs

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Previous work

In finite block regime:

- Good theoretical understanding that describes the rate vs. error probability trade-off in the short-packets transmission.
- Most of the coding schemes are developed under the assumption of genius-aided detection and synchronization.
- But in real life, genius belongs to a fairy tale …

➔ **Problem of packet detection and synchronization should be tackled**

Objective

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- ➢ Contributing to the evolution of IoT networks.
- ➢ Developing blind detection and self-synchronization algorithms for achieving correct preamble-less short packet reception at very low SNRs.

Detection + synchronization + payload + redundancy

Objective

General context
○○○○●○

System model

Detection

Synchronization

QCSP performance

GNU Radio

Conclusion and Perspectives

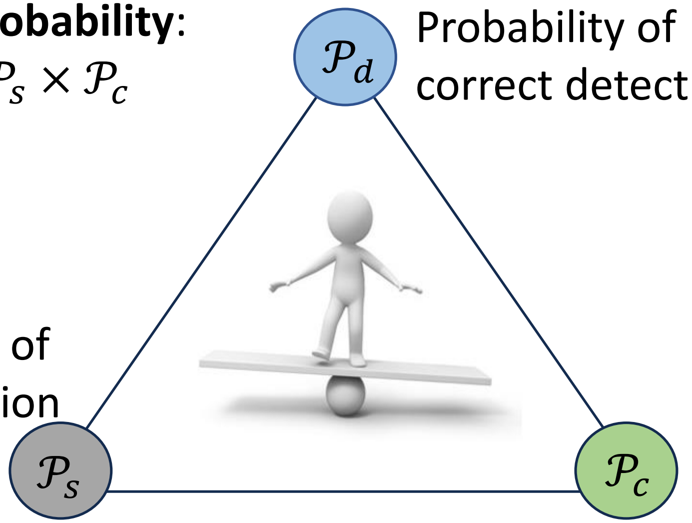
Objective

- ➢ Contributing to the evolution of IoT networks.
- ➢ Developing blind detection and self-synchronization algorithms for achieving correct preamble-less short packet reception at very low SNRs.

Detection + synchronization + payload + redundancy

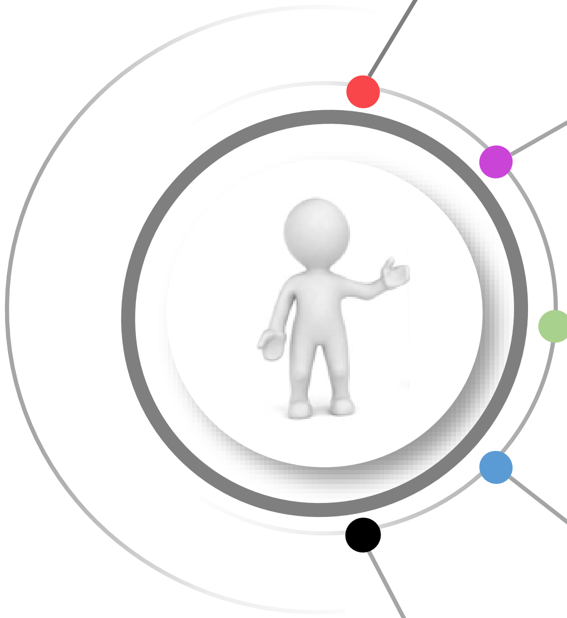
Joint overall probability:

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



➔ Aim: Maximizing the overall probability by maximizing the weakest one: Max(min($\mathcal{P}_d, \mathcal{P}_s, \mathcal{P}_c$)).

Outline



- QCSP system model
- Blind detection algorithm for QCSP
- Self synchronization algorithm for QCSP
- QCSP system performance
- Conclusion and perspectives

Outline

QCSP system model

Blind detection algorithm for QCSP

Self synchronization algorithm for QCSP

QCSP system performance

Conclusion and perspectives

Non Binary codes: Galois Field

- Galois Filed of order q (GF(q)) is a finite field that contains q elements, where q is a power of prime number, i.e, $q = 2^p$.
- It is defined using a primitive polynomial $\mathbb{P}_x$ of degree p, where all the operations in modulo $\mathbb{P}_x$.

Example: $p = 3$, GF$(q = 8)$, and $\mathbb{P} = 1 + x + x^3$

GF element	Binary represent.	Integer represent.
0	000	0
α^0	001	1
α^1	010	2
α^2	100	4
α^3	011	3
α^4	110	6
α^5	111	7
α^6	101	5

Addition example:

$X = (x_0x_1x_2)$, $Y = (y_0y_1y_2) \in \mathrm{GF}(8) \Rightarrow X \oplus Y = X\ \underline{\mathrm{XOR}}\ Y$

Eg.: $\alpha^4 \oplus \alpha^1 = 110\ \underline{\mathrm{XOR}}\ 010 = 100 = \alpha^2$

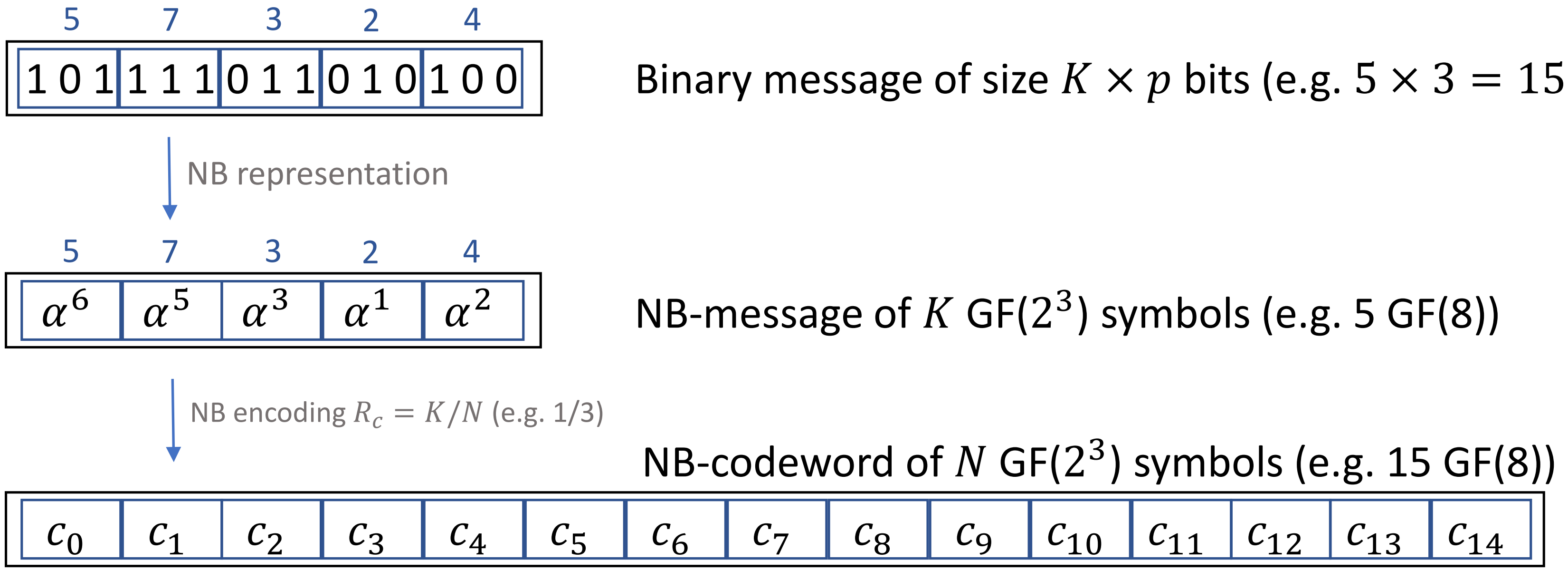
Multiplication example:

$0.\alpha^i = 0$ and $\alpha^i.\alpha^j = \alpha^{(i+j)\mathrm{mod(q\text{-}1)}}$

Eg.: $\alpha^4.\alpha^3 = \alpha^{7\ \mathrm{mod}\ (7)} = \alpha^0$

NB codes (NB-LDPC): Definition

NB Code, GF(2^3)



Binary message of size $K \times p$ bits (e.g. $5 \times 3 = 15$)

NB-message of K GF(2^3) symbols (e.g. 5 GF(8))

NB-codeword of N GF(2^3) symbols (e.g. 15 GF(8))

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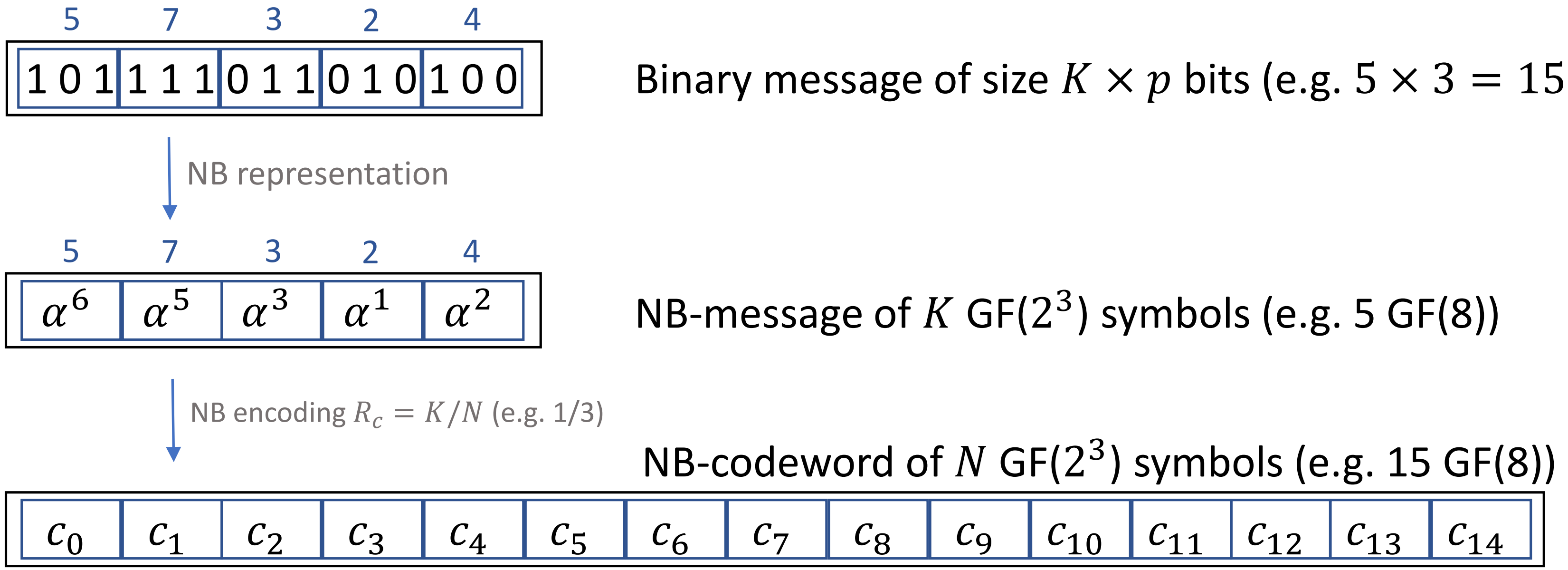

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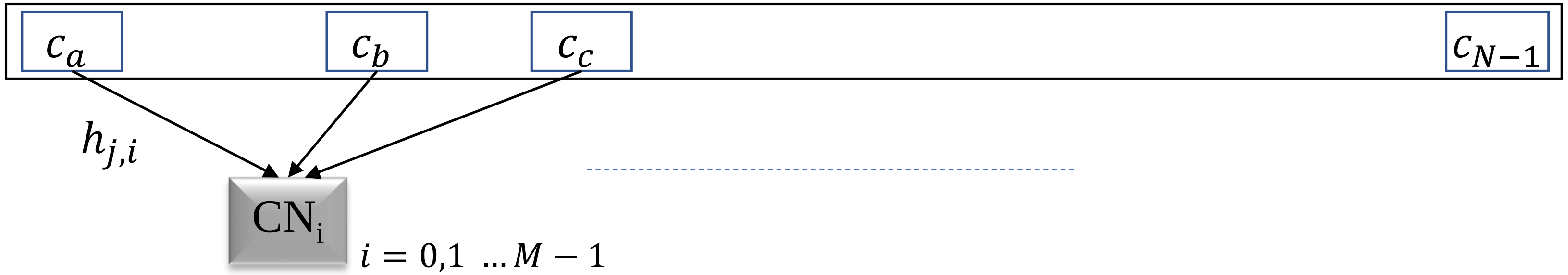
In a **NB-LDPC code**: a received message is a codeword if the set of GF parity checks are fulfilled:



$c_a.h_{a,i} \oplus c_b.h_{b,i} \oplus c_c.h_{c,i} = 0$ (in GF domain)

Cyclic-Code Shift Keying (CCSK)

- CCSK mapping is the construction of different sequences $\boldsymbol{P}_{c_k}$ from a basic sequence $\boldsymbol{P}_0$ of length $q = 2^p$; ➔ $R_m = p/q$
- A symbol c_k ∈ GF(8) is mapped to a circular rotation of a Pseudo-Noise sequence $\boldsymbol{P}_0$.

c_k ∈ GF(8)		Sequence $\boldsymbol{P}_s$
binary	integer	Chips
000	0	11101000
001	1	01110100
010	2	00111010
011	3	00011101
100	4	10001110
101	5	01000111
110	6	10100011
111	7	11010001

$$\boxed{P_s(k) = P_0(k - s \mod q) \text{ for } k = 0, 1, \dots, 7}$$

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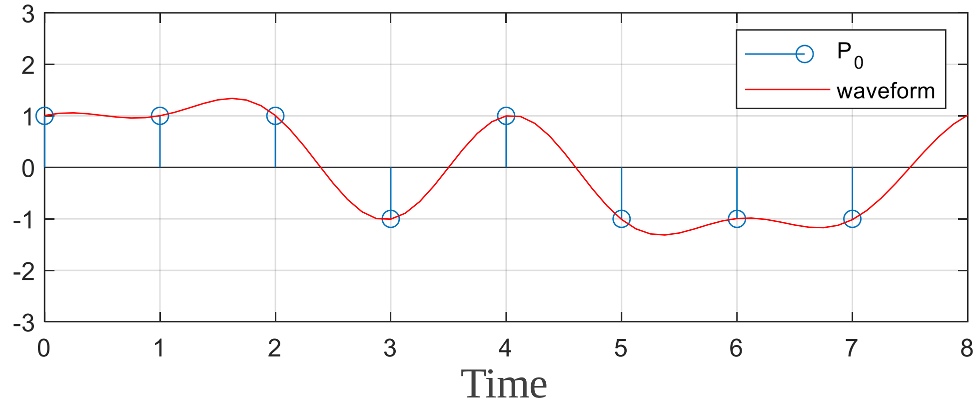
110	6	10100011
111	7	11010001

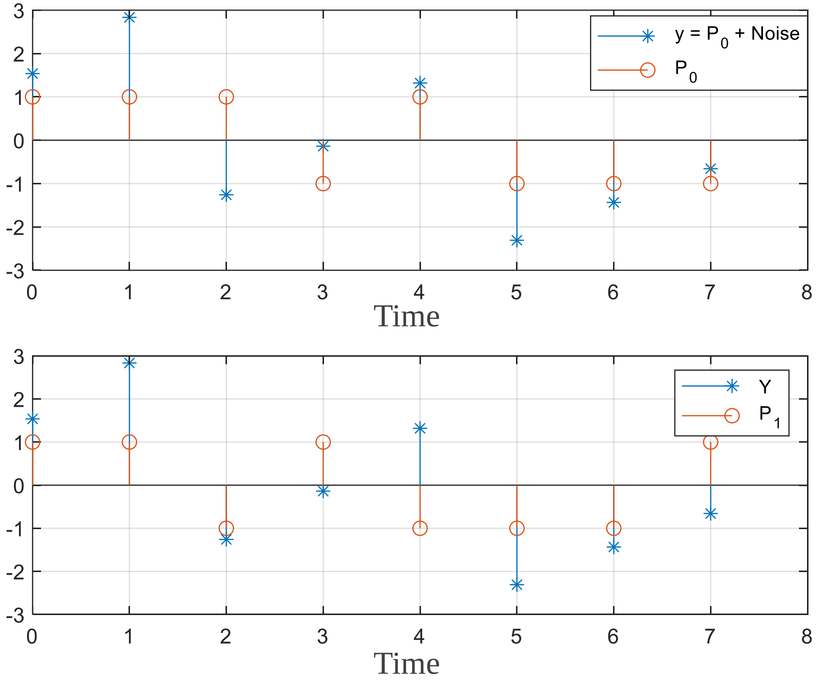
$$\boxed{P_s(k) = P_0(k - s \bmod q) \text{ for } k = 0, 1, \dots, 7}$$

- Transmission of $c_k = 0$; $\boldsymbol{P}_0$ + BPSK modulation, Root Raised Cosine (RRC) filter with roll-off factor of 0.35 :



Cyclic-Code Shift Keying (CCSK)

- Demodulation of a CCSK frame (P_0 is transmitted):



Relation between distance and correlation

$$\log(\mathbb{P}(\boldsymbol{y}|s)) \approx -\frac{d(\boldsymbol{P}_s,\boldsymbol{y})^2}{2\sigma^2}$$

$$d(\boldsymbol{P}_0,\boldsymbol{y})^2 = \boldsymbol{y}^2 + P_0{}^2 - 2\boxed{< P_0,\boldsymbol{y} >}$$

$$d(P_0,\boldsymbol{y})^2 = 21.5 + 8 - 2 \times \boxed{10.0} = 9.5$$

$$d(P_1,\boldsymbol{y})^2 = 21.5 + 8 - 2 \times \boxed{6.2} = 17.1$$

Correlation ↗ ⟺ Distance ↘

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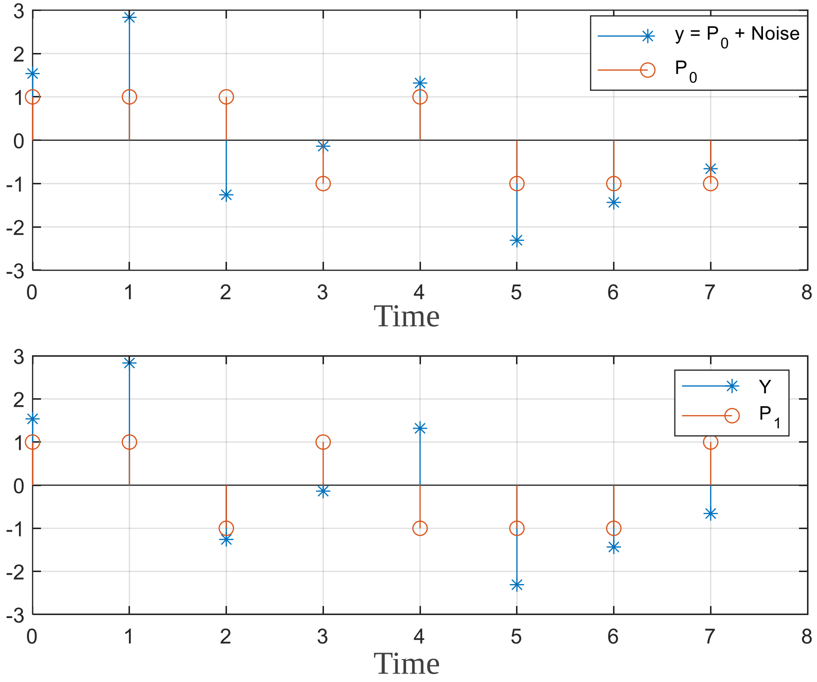

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Correlation ↗ ⟺ Distance ↘

Correlation in time and frequency domain

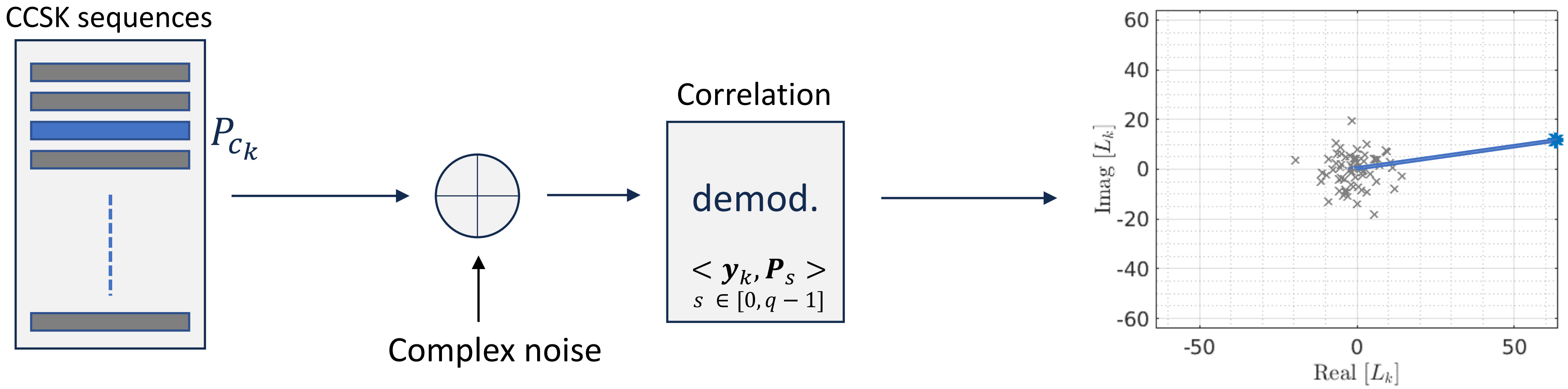
$$L(s) = < \boldsymbol{P}_s,\boldsymbol{y} > = \sum_{k=0}^{q-1} P_0(k-s)y(k)$$

$\boldsymbol{L}$ = IFFT(FFT($\boldsymbol{y}$) ⊙ FFT($\boldsymbol{P}_0$))

Circular convolution
➔ product in frequency domain

CCSK with complex noise

- Correlation output between each of the received symbols $\boldsymbol{y}_k$ and the q CCSK sequences $\boldsymbol{P}_s$



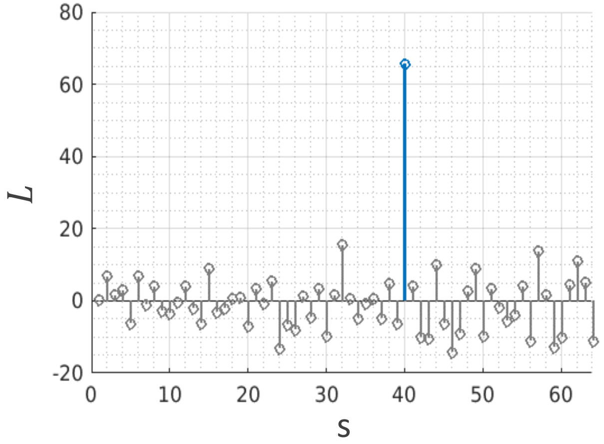
LLR Generation

$\boldsymbol{y}$: noisy received sequence

$\boldsymbol{L}$ = Log Likelihood Ratio

$$L(s) = Real(\log(\mathcal{P}(\boldsymbol{P}_s/\boldsymbol{y})) \sim Real(< \boldsymbol{y}, \boldsymbol{P}_s >) \; s = 0 \ldots q-1$$

$\boldsymbol{L}$ = *Real*(IFFT(FFT($\boldsymbol{y}_k$) ⊙ FFT($\boldsymbol{P}_0$))



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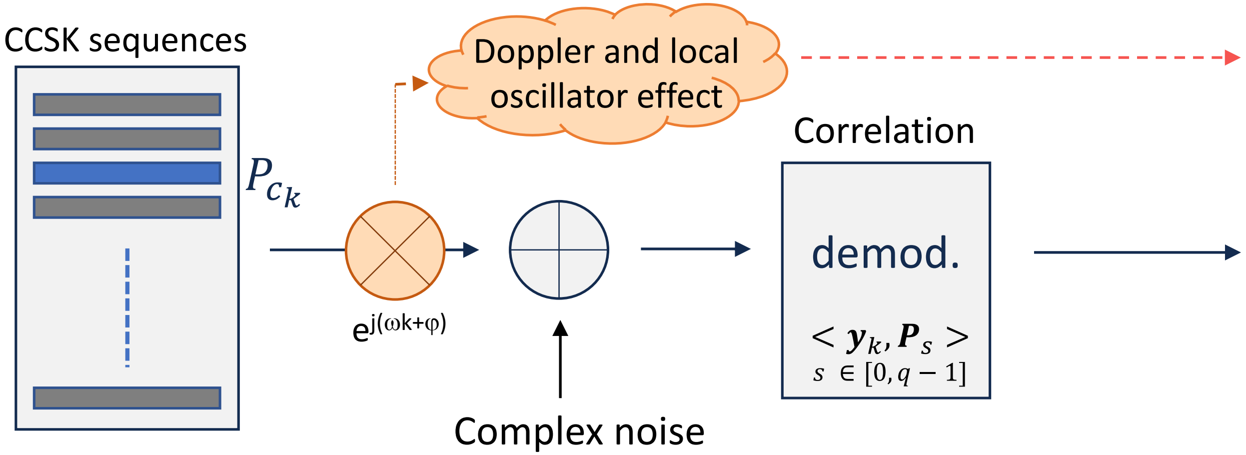

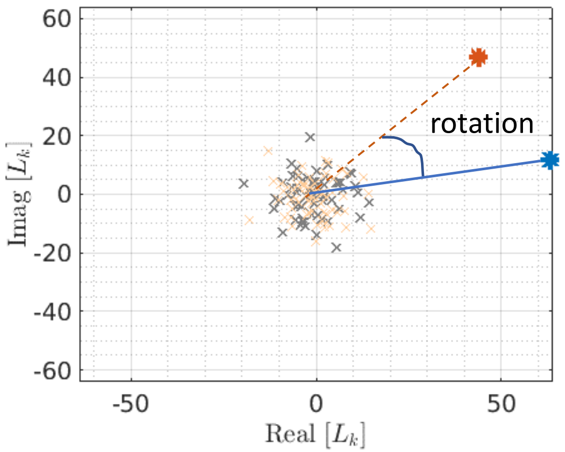

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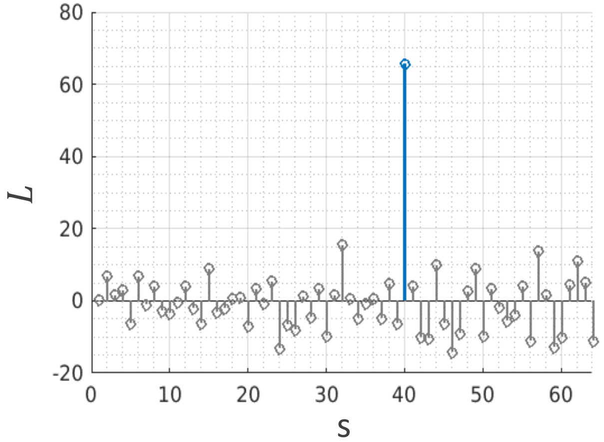

$\boldsymbol{L} = Real(\text{IFFT}(\text{FFT}(\boldsymbol{y}_k) \odot \text{FFT}(\boldsymbol{P}_0)))$

CCSK with complex noise

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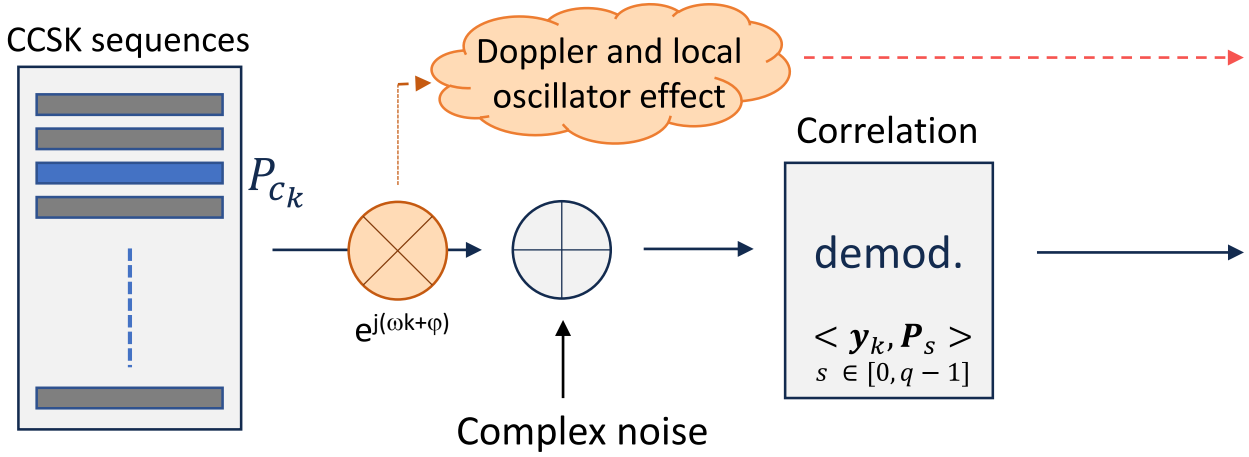


CCSK sequences

P_{c_k}

Doppler and local oscillator effect

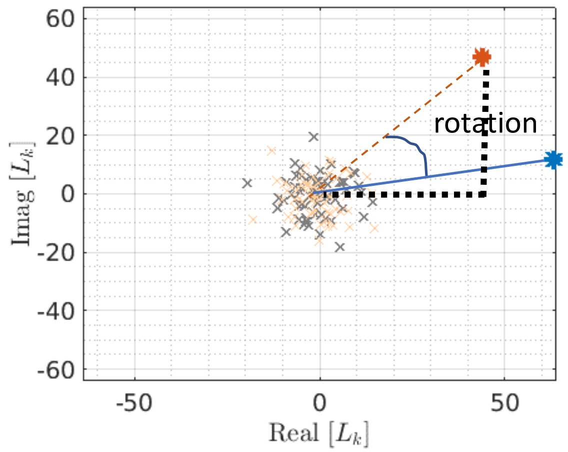
$e^{j(\omega k+\varphi)}$

Complex noise

Correlation

demod.

$< \boldsymbol{y}_k, \boldsymbol{P}_s >$
$s \in [0, q-1]$



LLR Generation

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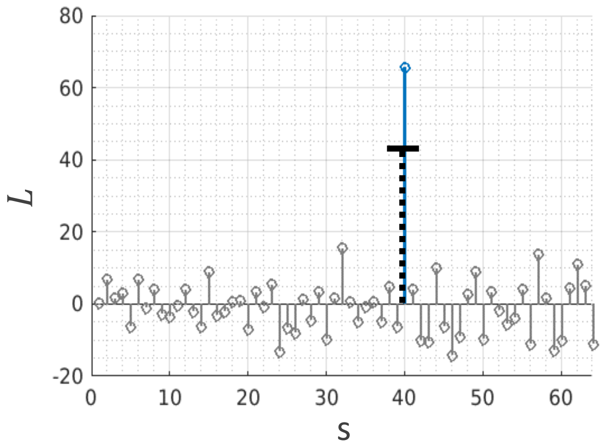
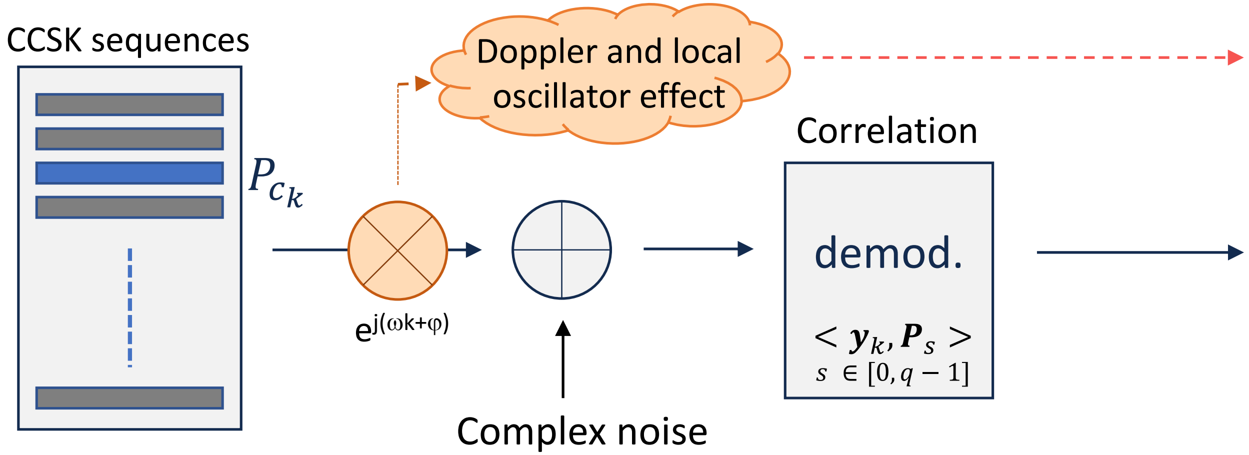
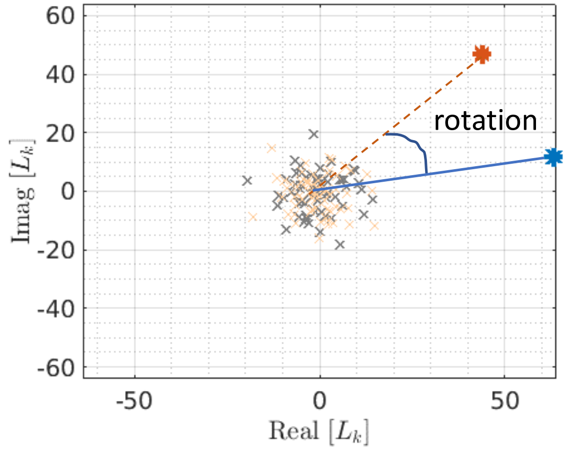


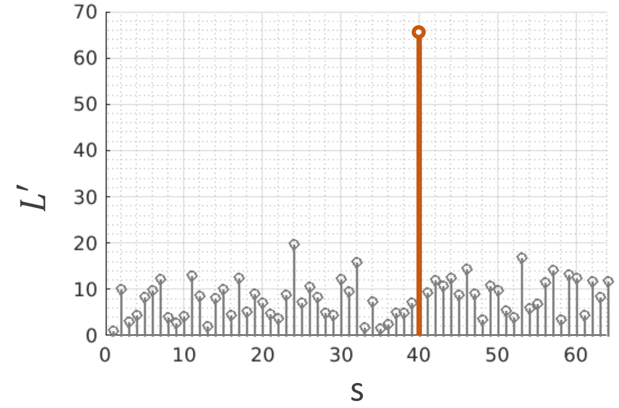
$\boldsymbol{L}$ = $Real$(IFFT(FFT($\boldsymbol{y}_k$) $\odot$ FFT($\boldsymbol{P}_0$))

CCSK with phase shift

- Correlation output between each of the received symbols $\boldsymbol{y}_k$ and the q CCSK sequences $\boldsymbol{P}_s$







Non-coherent demodulation

$\boldsymbol{y}$: noisy received sequence

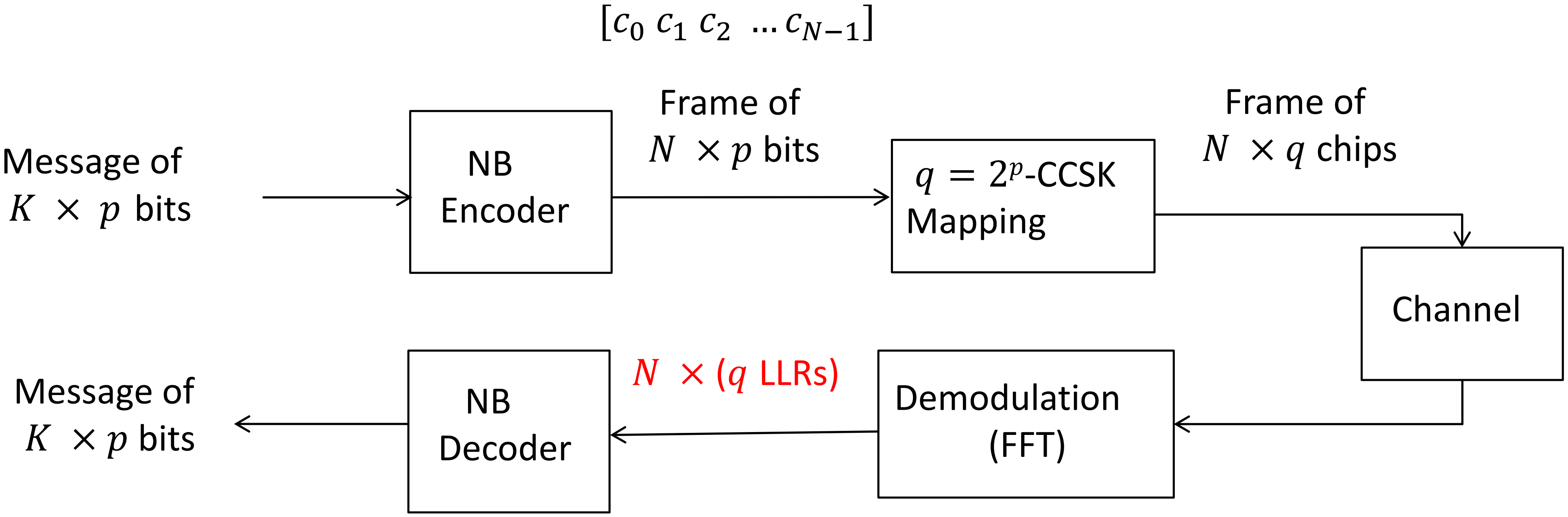
$\boldsymbol{L}$ = Log Likelihood Ratio

$$L'(s) = |\log(\mathcal{P}(\boldsymbol{P}_s/\boldsymbol{y})| \\ \sim | < \boldsymbol{y}, \boldsymbol{P}_s > | \quad s = 0 \ldots q-1$$

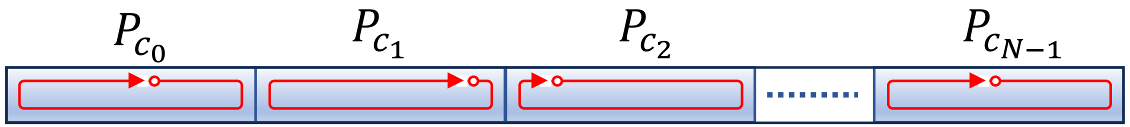
With phase offset, non-coherent demodulation is required

$\boldsymbol{L}' = abs(\text{IFFT}(\ \text{FFT}(\boldsymbol{y}_k) \odot \text{FFT}(\boldsymbol{P}_0)))$

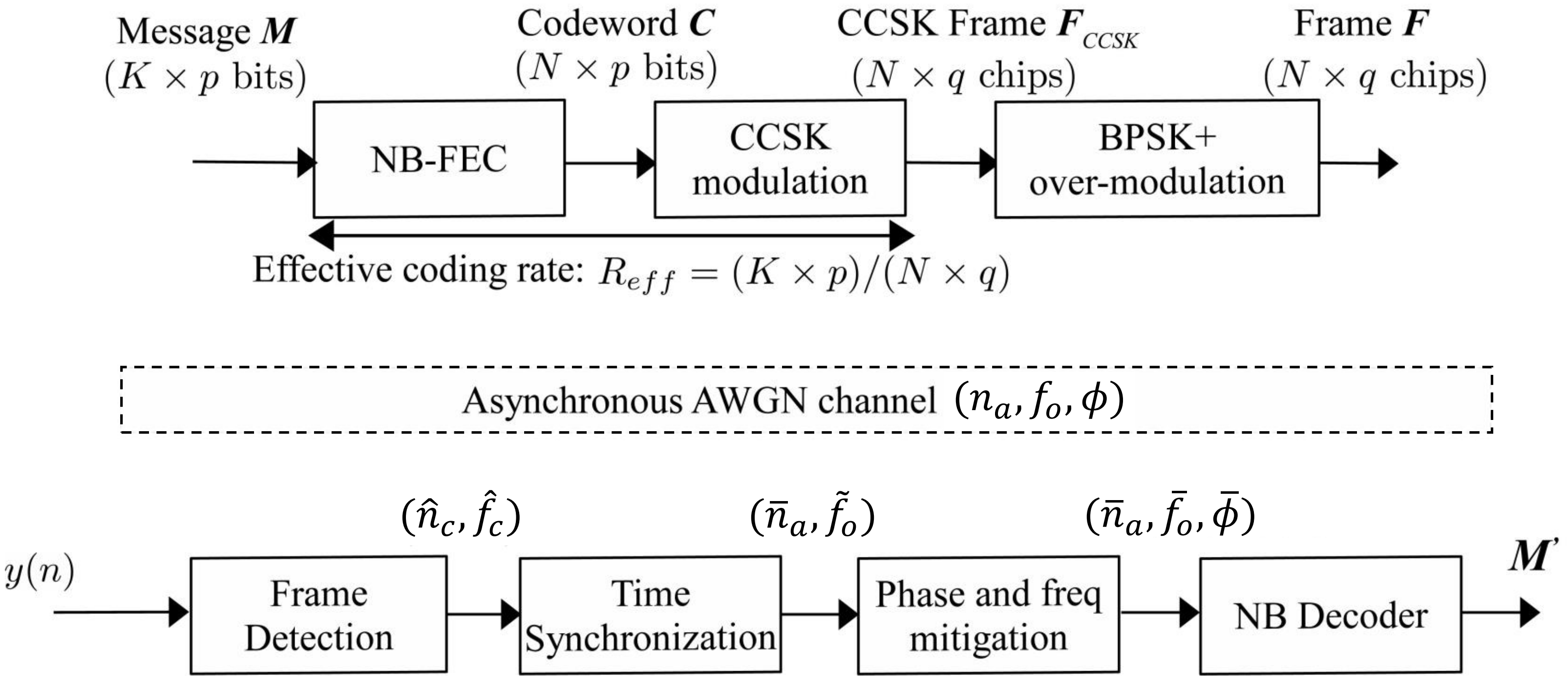
QCSP frame structure



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



Overall communication chain



Message $\boldsymbol{M}$ $(K \times p \text{ bits})$

Codeword $\boldsymbol{C}$ $(N \times p \text{ bits})$

CCSK Frame $\boldsymbol{F}_{CCSK}$ $(N \times q \text{ chips})$

Frame $\boldsymbol{F}$ $(N \times q \text{ chips})$

NB-FEC → CCSK modulation → BPSK+ over-modulation

Effective coding rate: $R_{eff} = (K \times p)/(N \times q)$

Asynchronous AWGN channel (n_a, f_o, ϕ)

$y(n)$ → Frame Detection $(\hat{n}_c, \hat{f}_c)$ → Time Synchronization $(\bar{n}_a, \tilde{f}_o)$ → Phase and freq mitigation $(\bar{n}_a, \bar{f}_o, \bar{\phi})$ → NB Decoder → $\boldsymbol{M}'$

- K: message length (symbols)
- N: codeword length (symbols)
- p: symbol size (bits)
- q: CCSK sized (chips)

- n_a: time of arrival in chips, $n_a = n_c + \Delta$
- f_o: frequency offset; $f_o \in [-\mathrm{F}_m, F_m]$
- ϕ: phase offset; $\phi \in [-\pi, \pi]$
- Complex AWGN; $N(o, \sigma^2)$ with $\sigma = \sqrt{\frac{10^{-SNR}}{2}}$

n_c: coarse time offset
f_c: coarse frequency offset

Outline

General context

System model

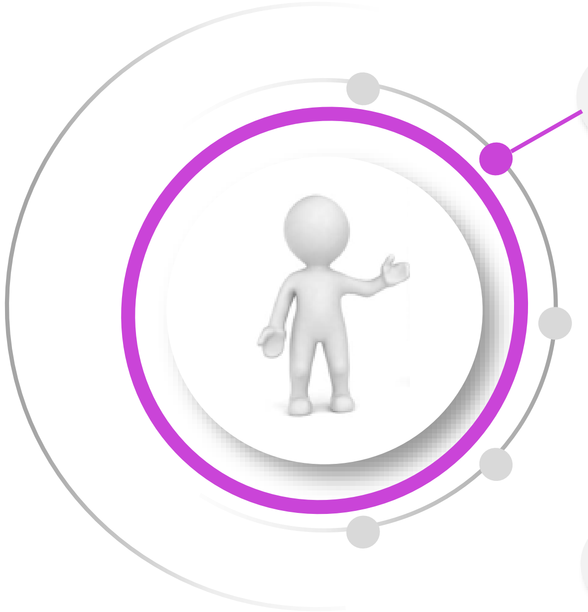
Detection
○○○○○○○

Synchronization

QCSP performance

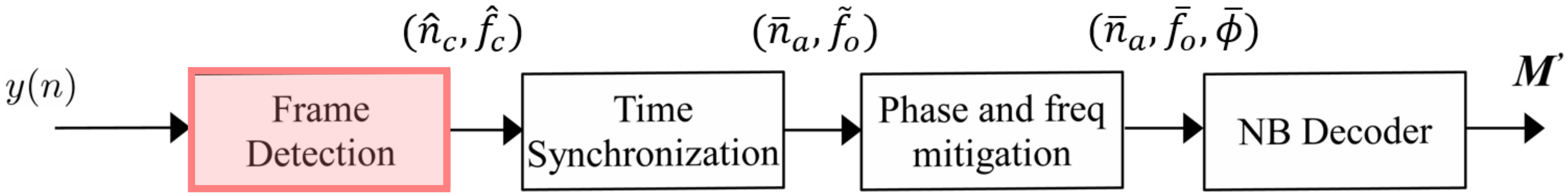
GNU Radio

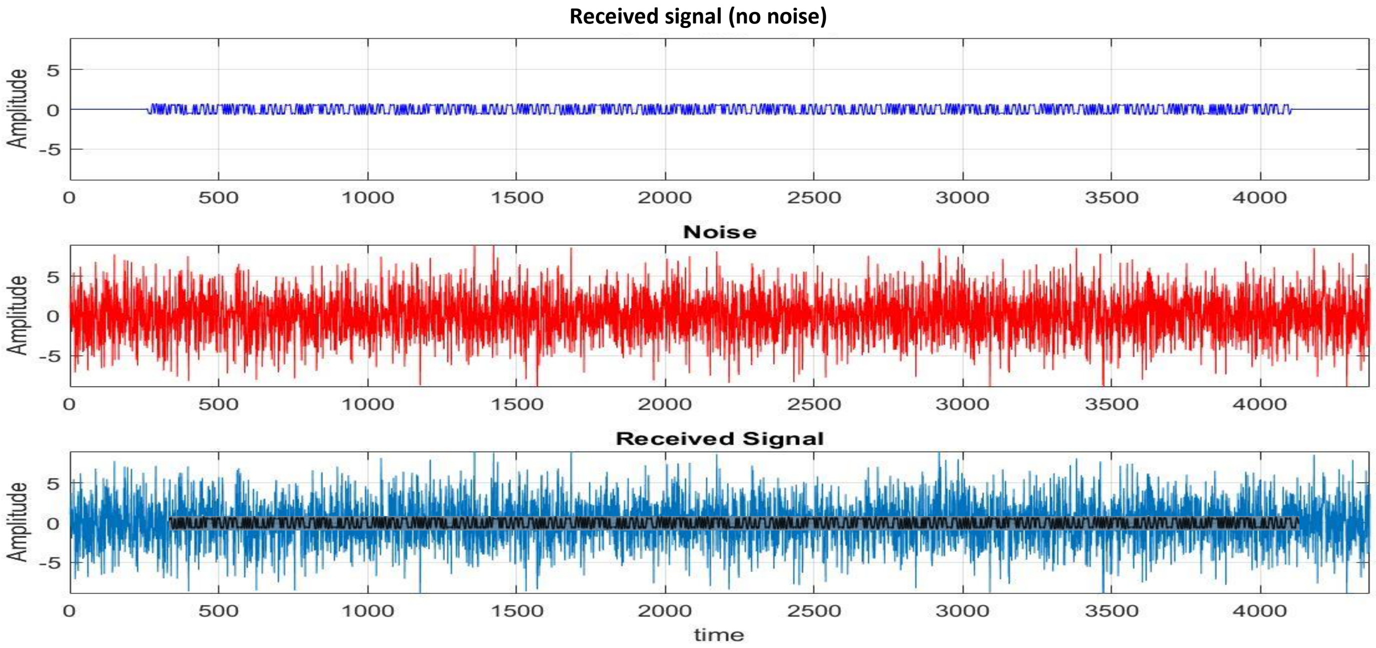
Conclusion and Perspectives



- QCSP system model
- **Blind detection algorithm for QCSP**
- Self synchronization algorithm for QCSP
- QCSP system performance
- Conclusion and perspectives

Detection problem





- ➢ Find a reliable way to asses the presence of a CCSK frame or not.
- ➢ Coarse time and frequency offsets estimation $(\hat{n}_c, \hat{f}_c)$.

CCSK based detection: Toy example

$\boldsymbol{P}_0$ = **A**BAABB

Message = {3,0,5}

CCSK Frame = {ABB**A**BA, **A**BAABB, BAABB**A**}

3 0 5

CCSK based detection: Toy example

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Emitter side = ABBABAABAABBBAABBA

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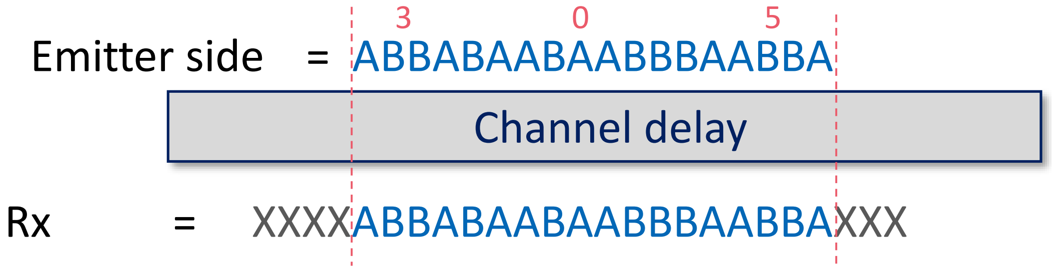


Emitter side = ABBABAABAABBBAABBA

Channel delay

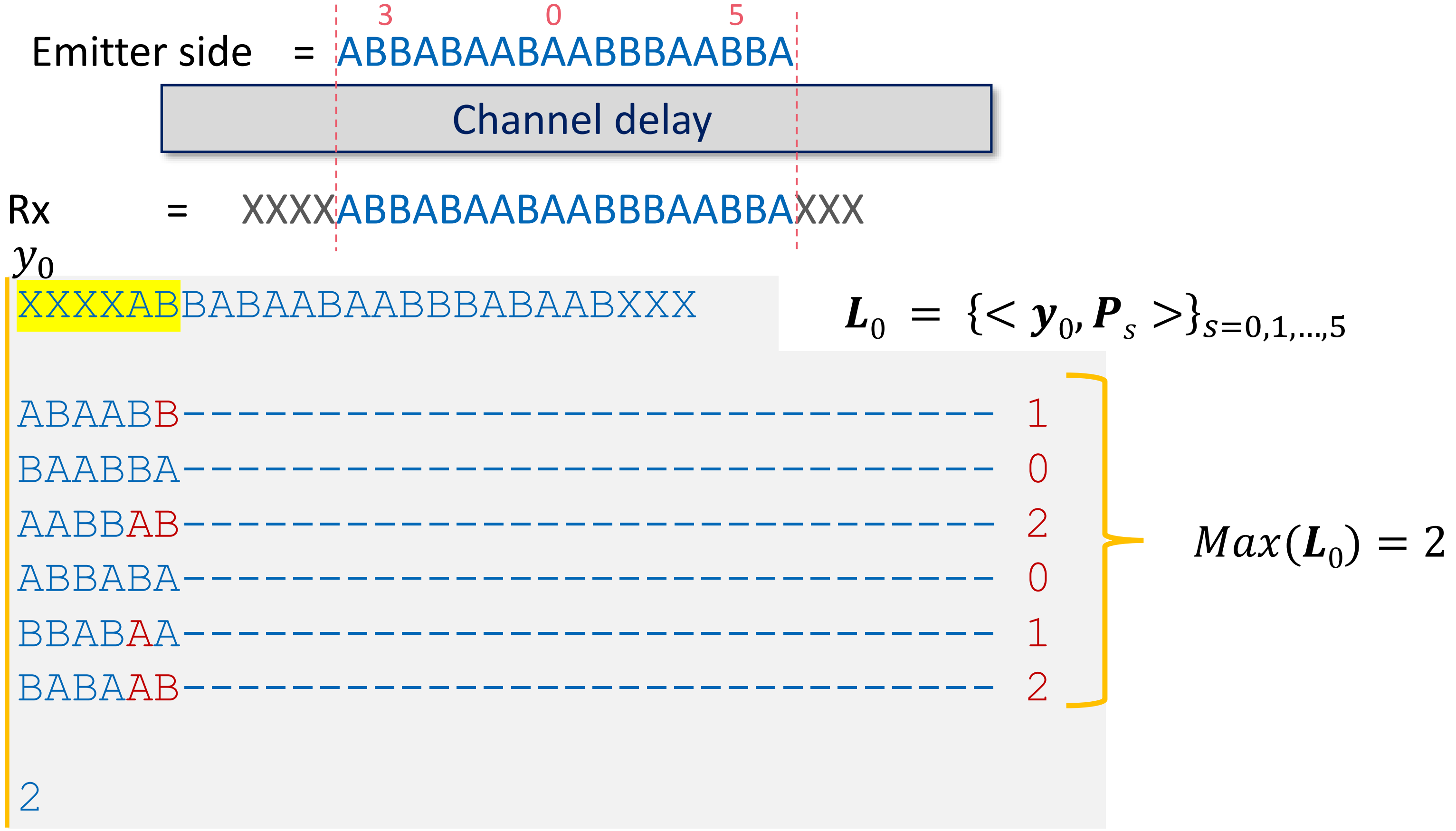
Rx = XXXXABBABAABAABBBAABBAXXX

CCSK based detection: Toy example

P_0 = ABAABB

Message = {3,0,5}

CCSK Frame = {ABBABA, ABAABB, BAABBA}



Emitter side = ABBABAABAABBBAABBA

Rx = XXXXABBABAABAABBBAABBAXXX

y_0

XXXXABBABAABAABBBABAABXXX

$L_0 = \{< y_0, P_s >\}_{s=0,1,\ldots,5}$

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

2

$Max(L_0) = 2$

CCSK based detection: Toy example

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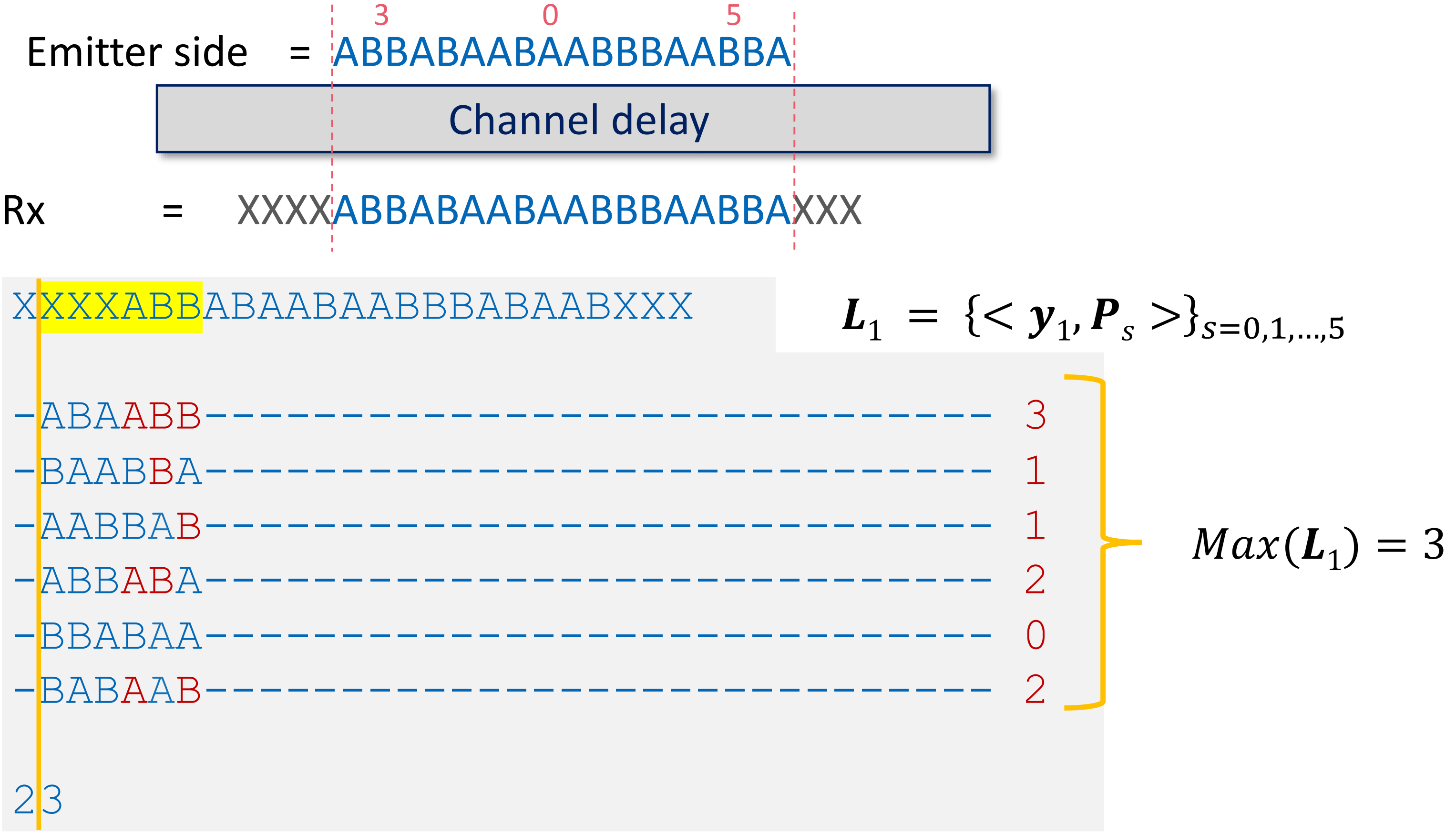
Message = {3,0,5}

CCSK Frame = {ABB**A**BA, **A**BAABB, BAABB**A**}



Emitter side = ABBABAABAABBBAABBA

Rx = XXXXABBABAABAABBBAABBAXXX

```
XXXXABBABAABAABBBABAABXXX

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

23
```

$L_1 = \{< y_1, P_s >\}_{s=0,1,\dots,5}$

$Max(L_1) = 3$

CCSK based detection: Toy example

$\boldsymbol{P}_0$ = **A**BAABB

Message = {3,0,5}

CCSK Frame = {ABB**A**BA, **A**BAABB, BAABB**A**}

Emitter side = ABBABAABAABBBAABBA (3, 0, 5)

Channel delay

Rx = XXXXABBABAABAABBBAABBAXXX

```
XXXXABBABAABAABBBABAABXXX

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


234
```

$$\boldsymbol{L}_2 = \{<\boldsymbol{y}_2, \boldsymbol{P}_s>\}_{s=0,1,\ldots,5}$$

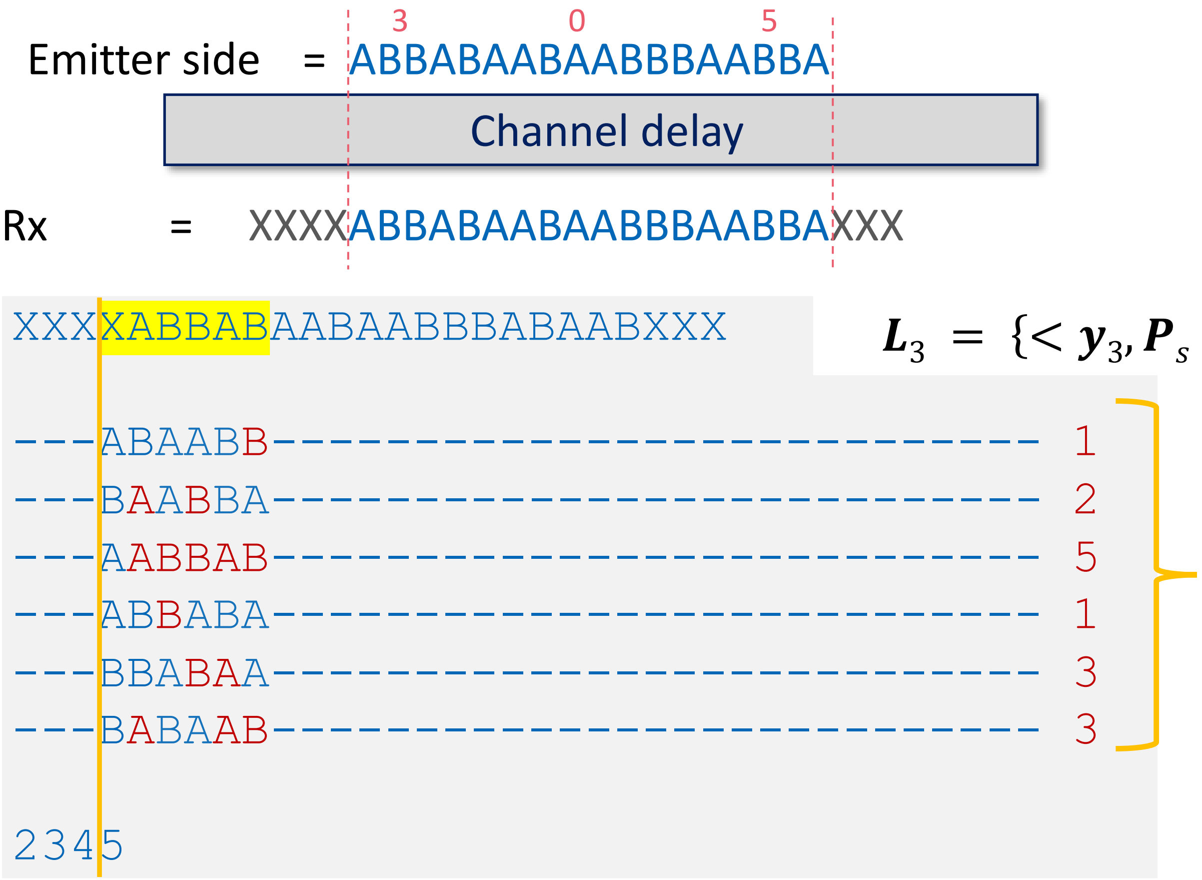
$$Max(\boldsymbol{L}_2) = 4$$

CCSK based detection: Toy example

$\boldsymbol{P}_0$ = **A**BAABB

Message = {3,0,5}

CCSK Frame = {ABB**A**BA, **A**BAABB, BAABB**A**}



Emitter side = ABBABAABAABBBAABBA

Channel delay

Rx = XXXXABBABAABAABBBAABBAXXX

```
XXXXABBABAABAABBBABAABXXX

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

2345
```

$$\boldsymbol{L}_3 = \{<\boldsymbol{y}_3, \boldsymbol{P}_s>\}_{s=0,1,\ldots,5}$$

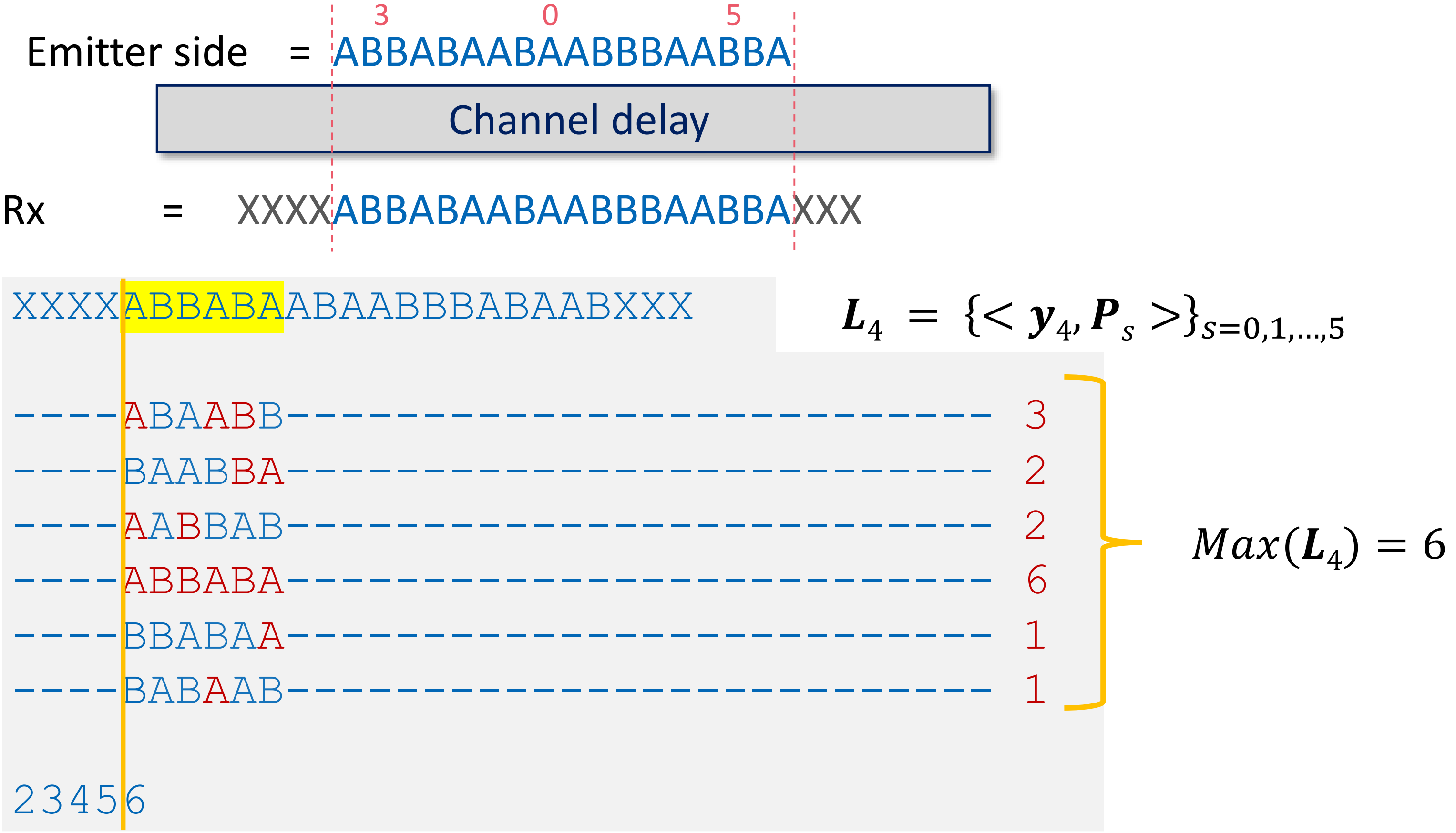
$$Max(\boldsymbol{L}_3) = 5$$

CCSK based detection: Toy example

P_0 = **A**BAABB

Message = {3,0,5}

CCSK Frame = {ABB**A**BA, **A**BAABB, BAABB**A**}



3 0 5

Emitter side = ABBABAABAABBBAABBA

Channel delay

Rx = XXXXABBABAABAABBBAABBAXXX

```
XXXXABBABAABAABBBABAABXXX

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

23456
```

$L_4 = \{< y_4, P_s >\}_{s=0,1,\ldots,5}$

$Max(L_4) = 6$

CCSK based detection: Toy example

General context
System model
Detection
○●○○○○○
Synchronization
QCSP performance
GNU Radio
Conclusion and Perspectives

$\boldsymbol{P}_0$ = **A**BAABB

Message = {3,0,5}

CCSK Frame = {ABB**A**BA, **A**BAABB, BAABB**A**}

Emitter side = ABBABAABAABBBAABBA

3 0 5

Channel delay

Rx = XXXXABBABAABAABBBAABBAXXX

```
XXXXABBABAABAABBBABAABXXX

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

23456 ... 6
```

$\boldsymbol{L}_{10} = \{<\boldsymbol{y}_{10}, \boldsymbol{P}_s>\}_{s=0,1,\ldots,5}$

$Max(\boldsymbol{L}_{10}) = 6$

CCSK based detection: Toy example

P_0 = **A**BAABB

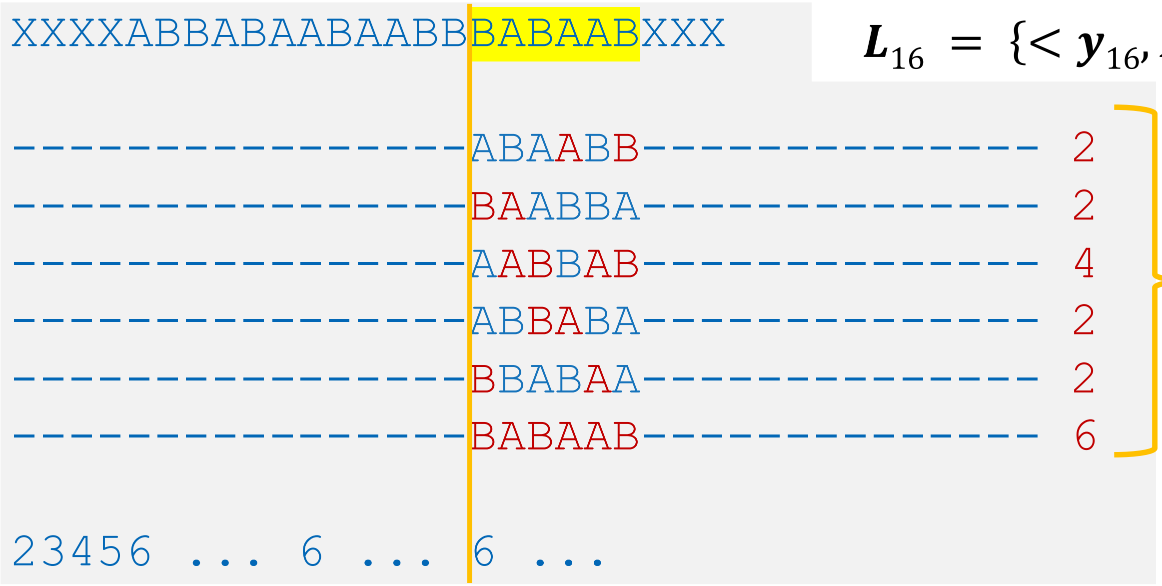
Message = {3,0,5}

CCSK Frame = {ABB**A**BA, **A**BAABB, BAABB**A**}

Emitter side = ABBABAABAABBBAABBA (3, 0, 5)

Channel delay

Rx = XXXXABBABAABAABBBAABBAXXX



```
XXXXABBABAABAABBBABAABXXX

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

23456 ... 6 ... 6 ...
```

$$L_{16} = \{<\boldsymbol{y}_{16}, \boldsymbol{P}_s>\}_{s=0,1,\ldots,5}$$

$$Max(\boldsymbol{L}_{16}) = 6$$

CCSK based detection: Toy example

General context
System model
Detection
○●○○○○○
Synchronization
QCSP performance
GNU Radio
Conclusion and Perspectives

P_0 = **A**BAABB

Message = {3,0,5}

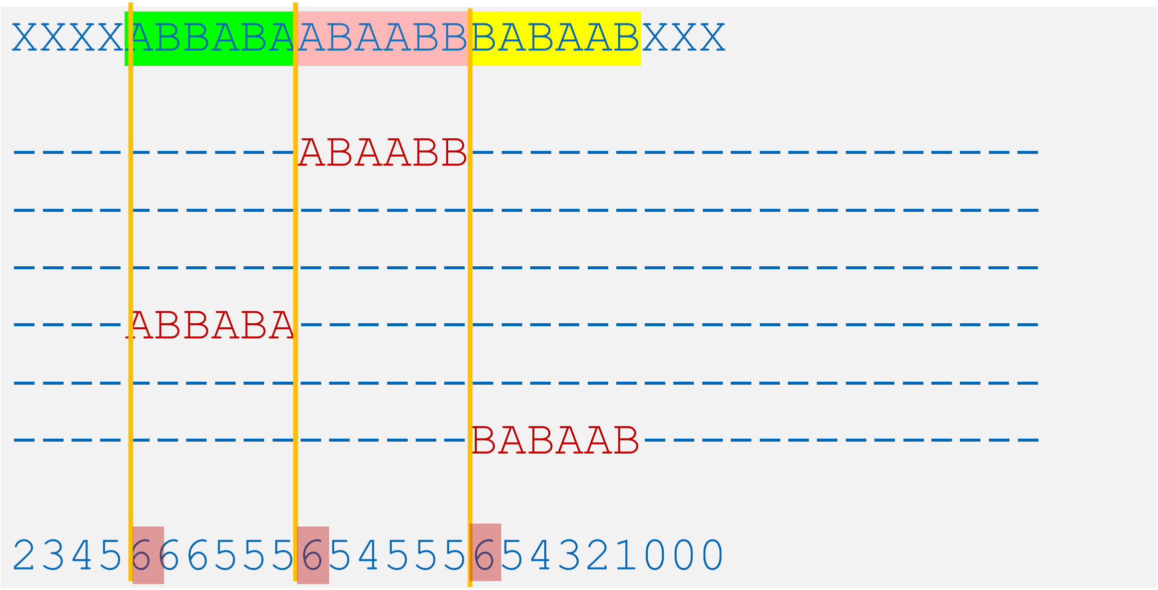
CCSK Frame = {ABB**A**BA, **A**BAABB, BAABB**A**}

3 0 5

Emitter side = ABBABAABAABBBAABBA

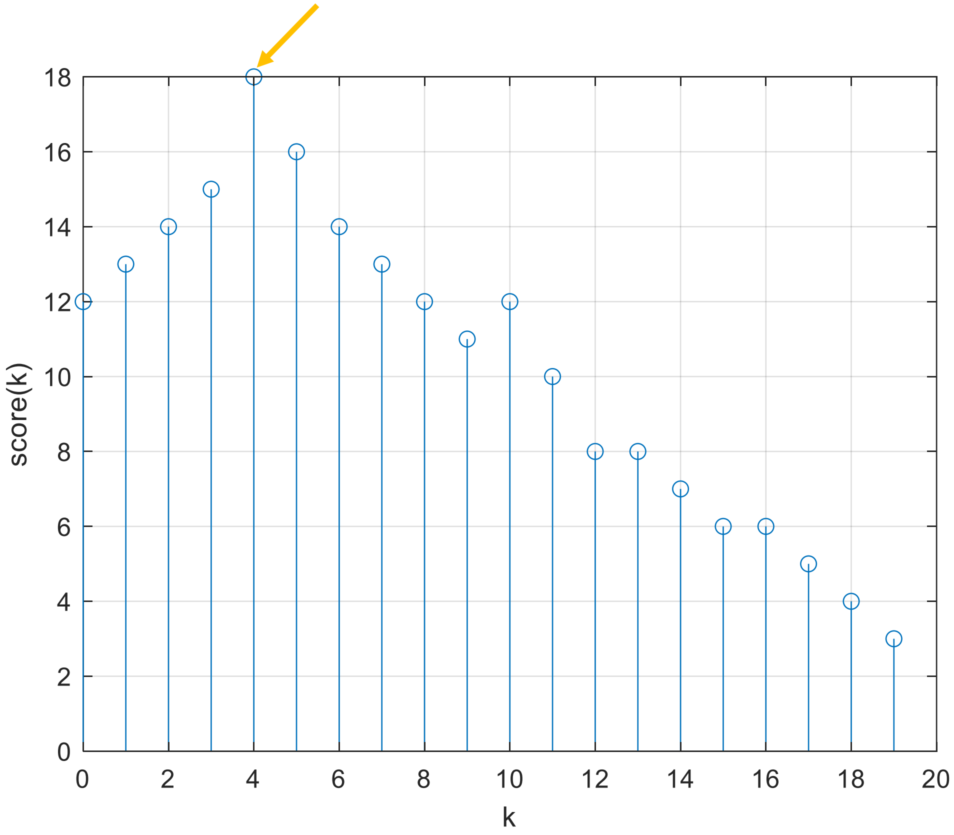
Channel delay

Rx = XXXXABBABAABAABBBAABBAXXX



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

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



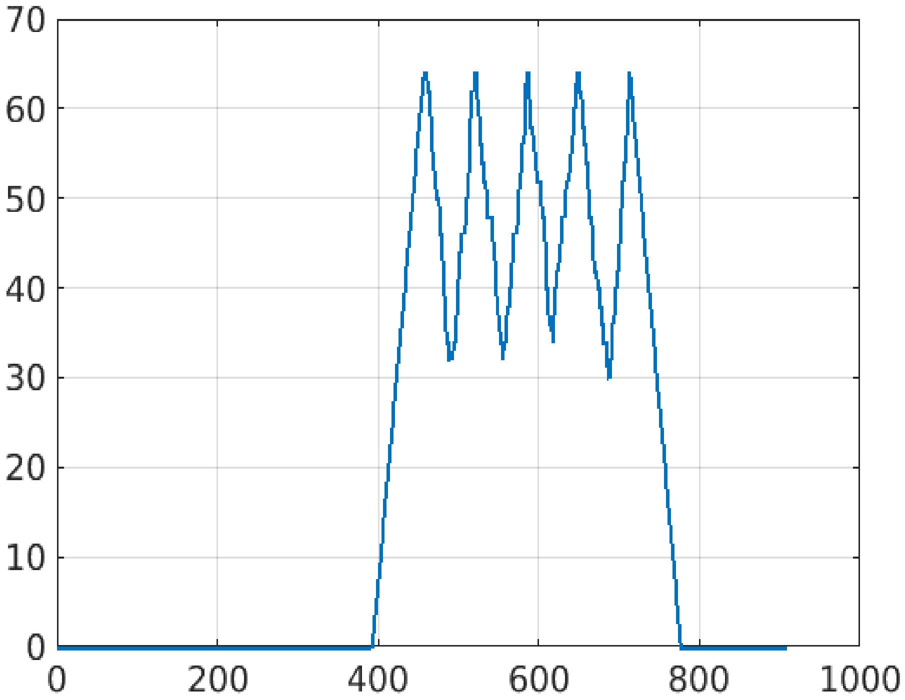
CCSK based detection: General case

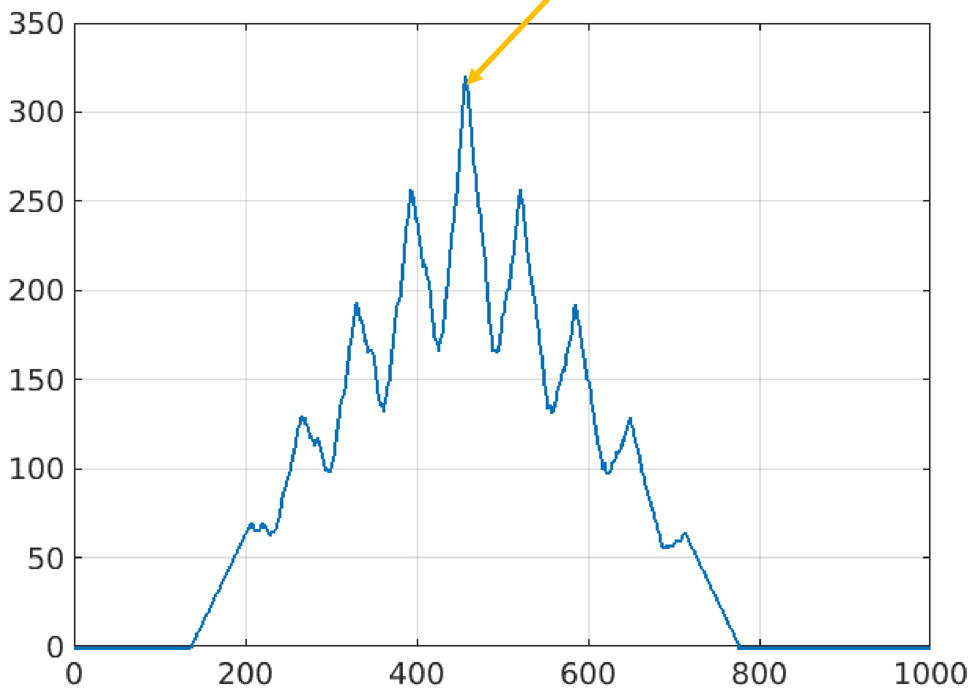
- N = 5, q=64, no noise

Correct synchronization:
$S = 64 \times 5 = 320$

$\max(|L_k|)$

$S_k(Y) = \sum_{i=0}^{4} \max(|L_{k+64i}|)$



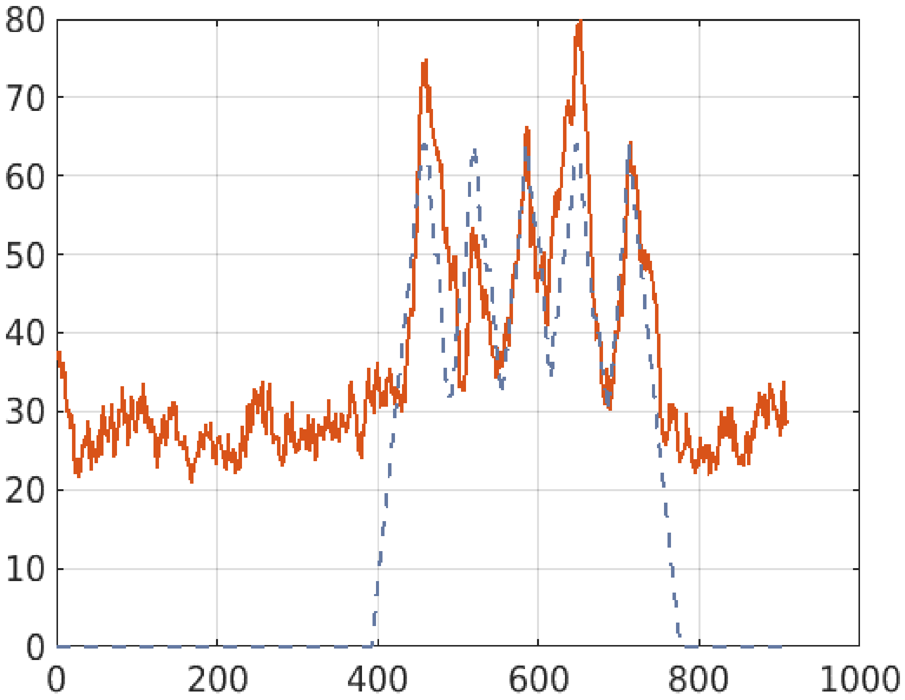


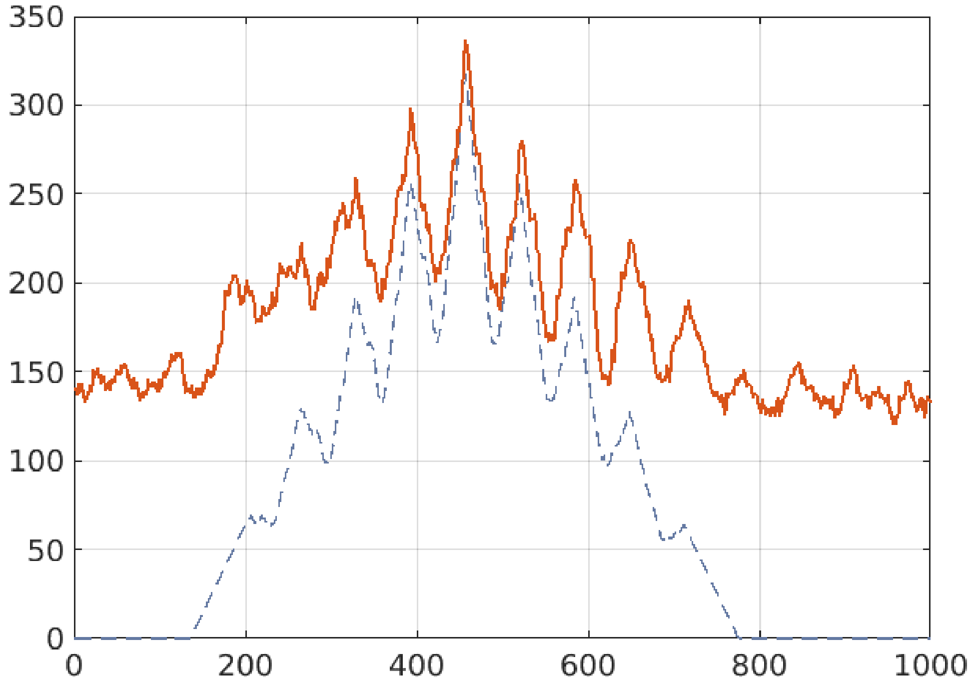
CCSK based detection: General case

- N = 5, q=64, with noise

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

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





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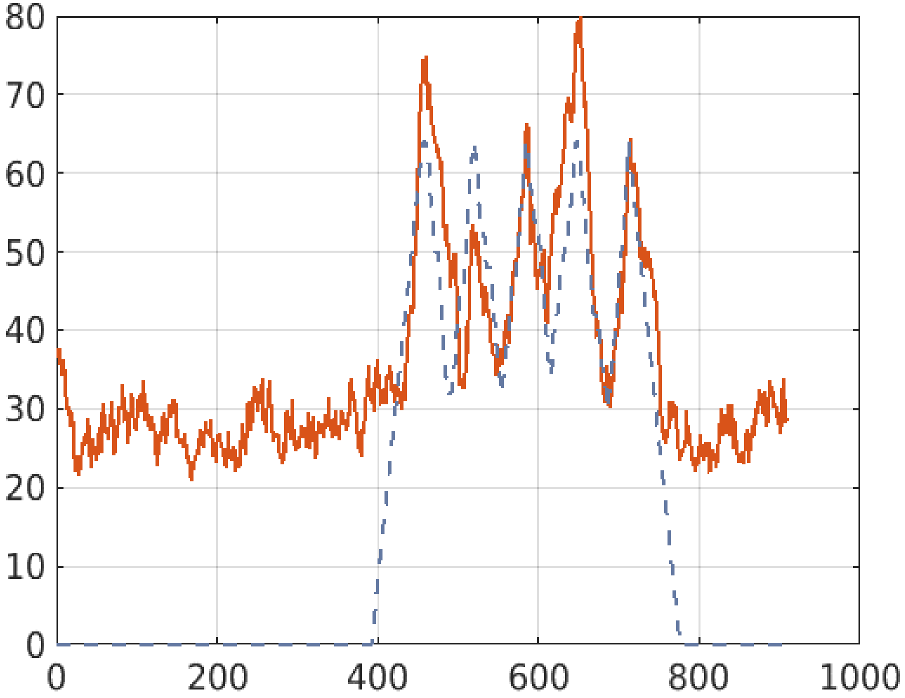
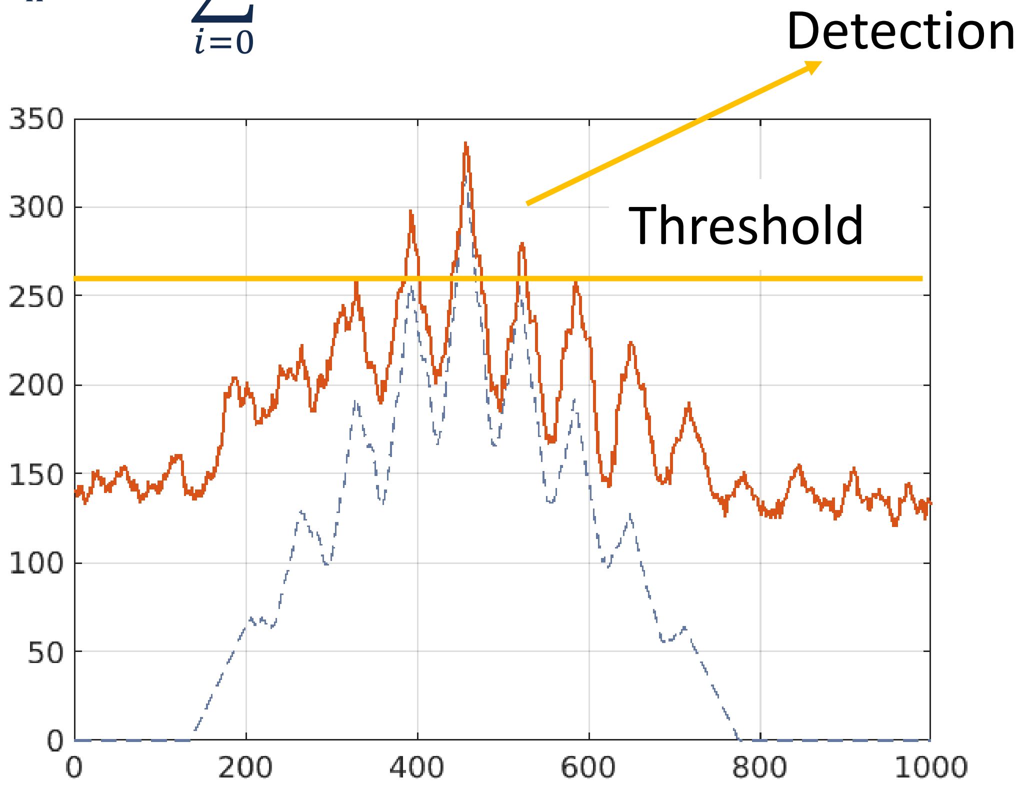
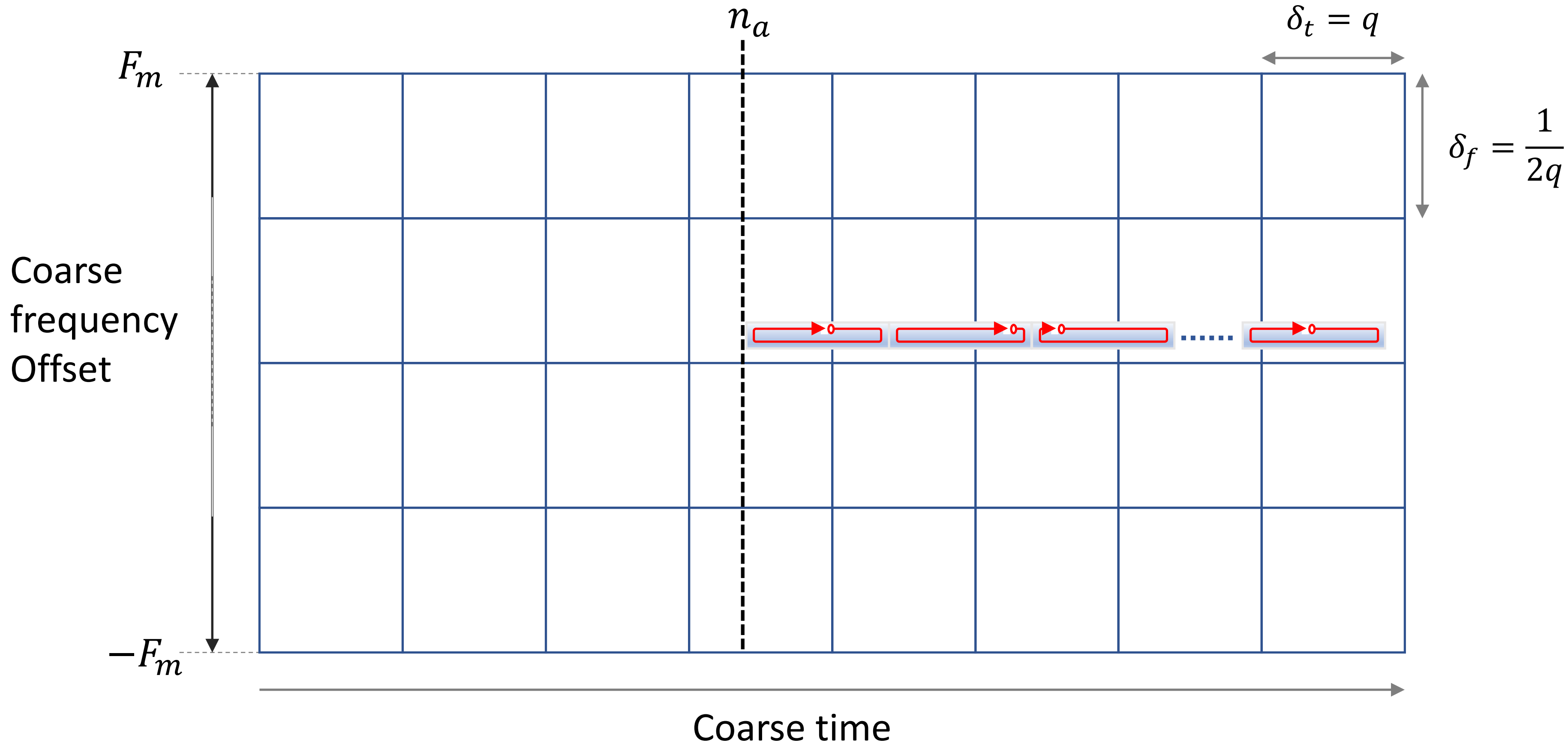
$$S_k(Y) = \sum_{i=0}^{4} \max(|L_{k+64i}|)$$

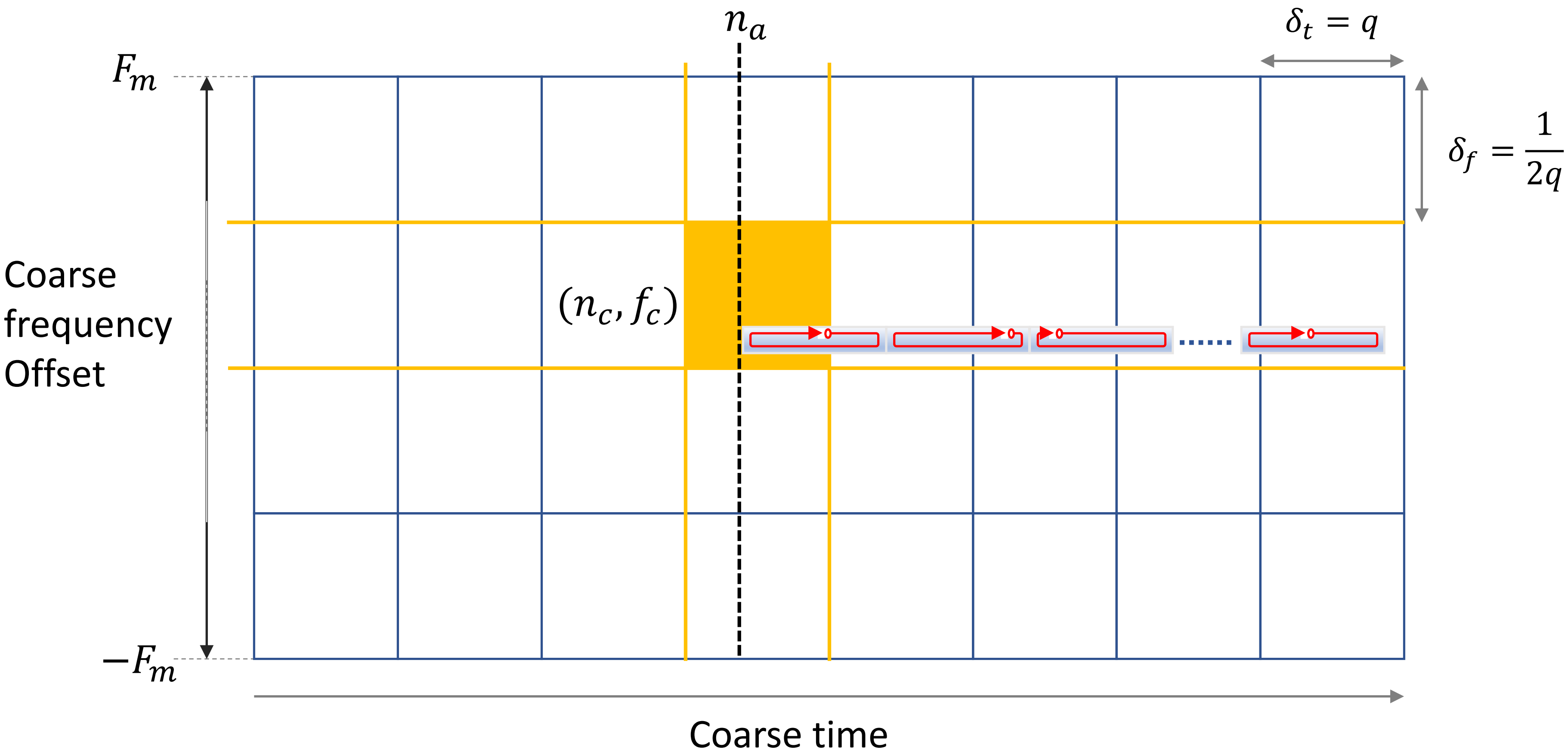




Time-frequency decomposition



Time-frequency decomposition

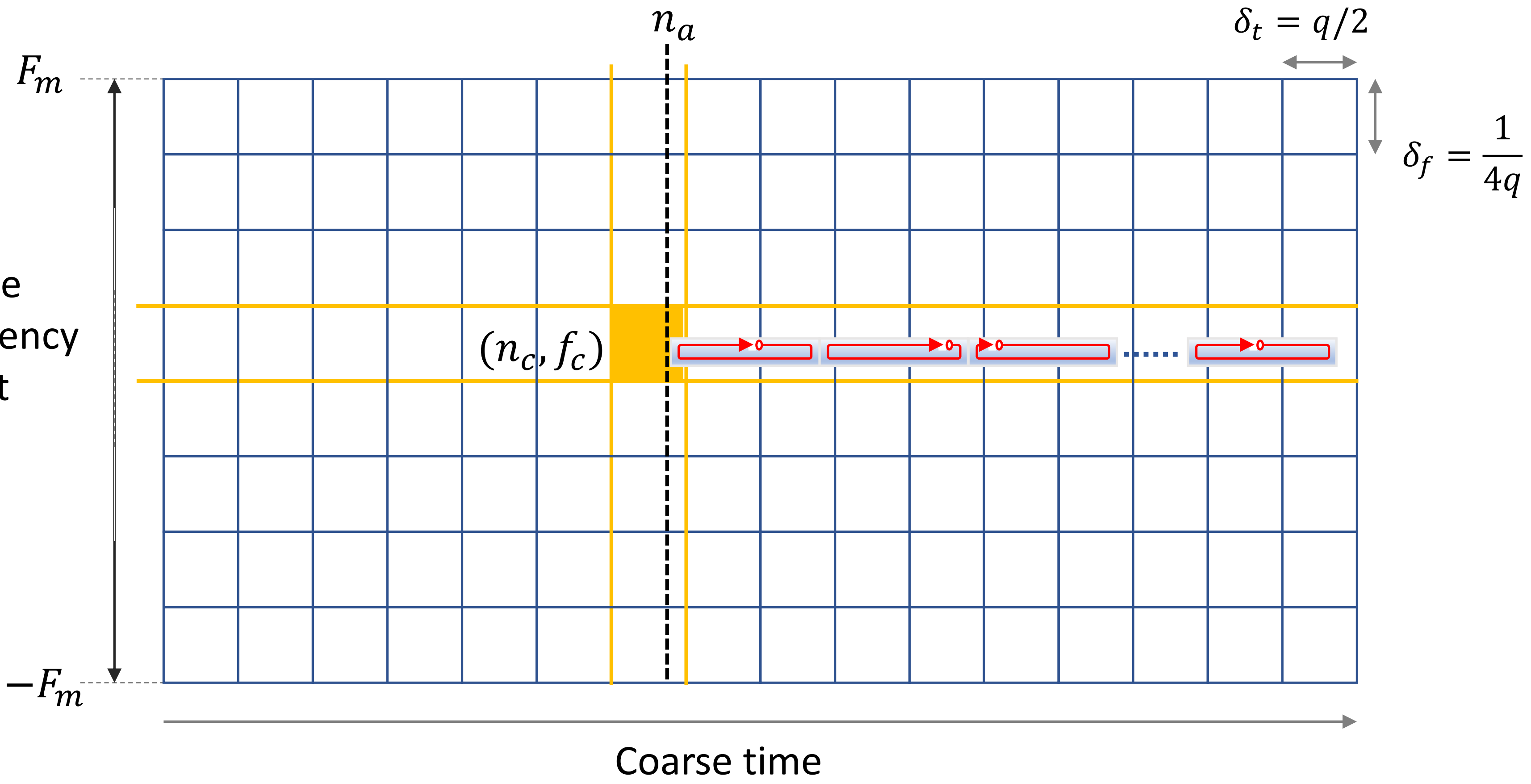


$N = 120, q = 64$

Coarse Precisions

- ➢ Reliable detection is achieved at SNR = -9 dB.
- ➢ n_c and f_c are coarse time and frequency offsets.
- ➢ n_a and f_o limited to $q/2$ and $1/4q$ respectively

Time-frequency decomposition



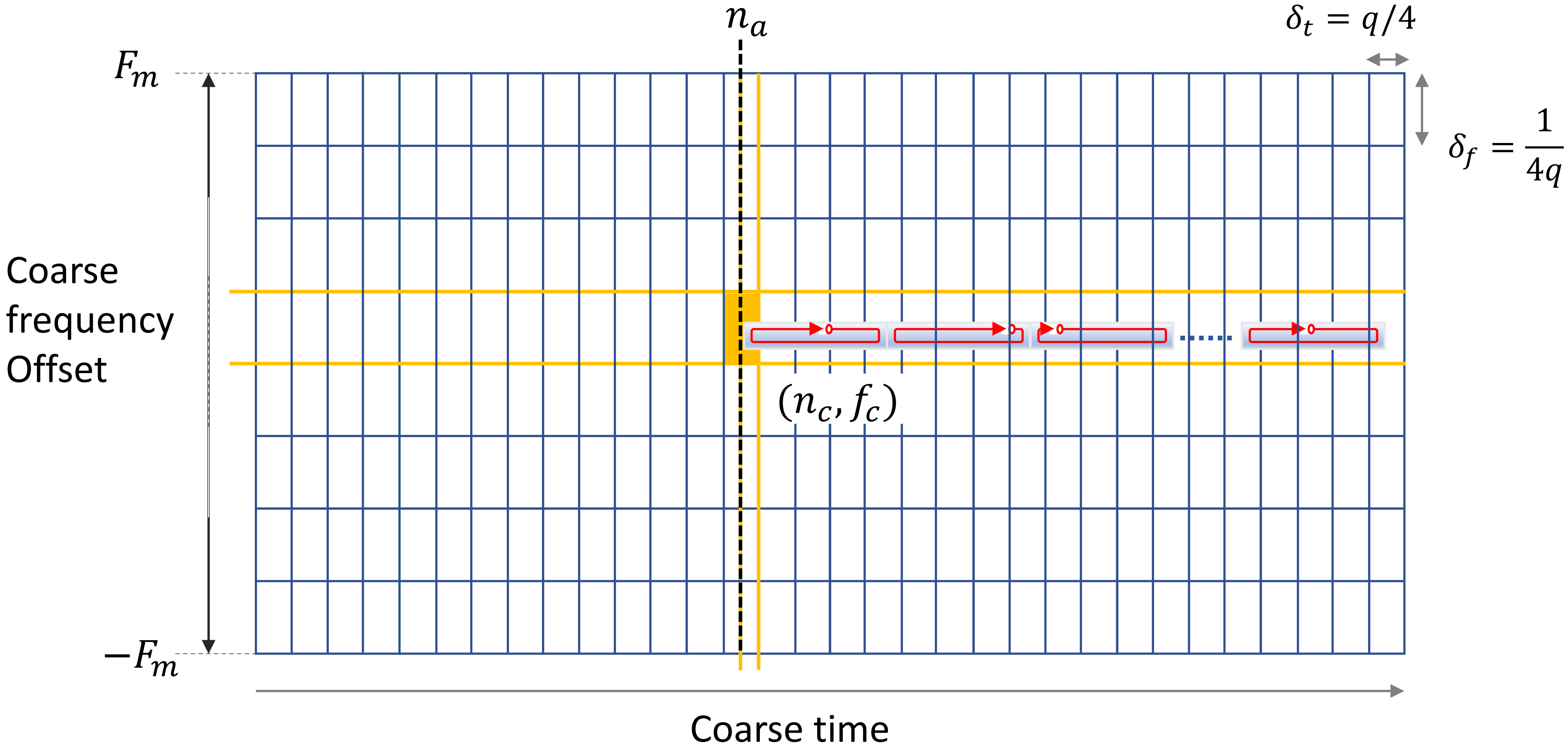
$N = 120, q = 64$

Coarse Precisions

- Reliable detection is achieved at SNR = -10.4 dB.
- n_c and f_c are coarse time and frequency offsets.
- n_a and f_o limited to $q/4$ and $1/8q$ respectively

Complexity × 4

Time-frequency decomposition



$N = 120, q = 64$

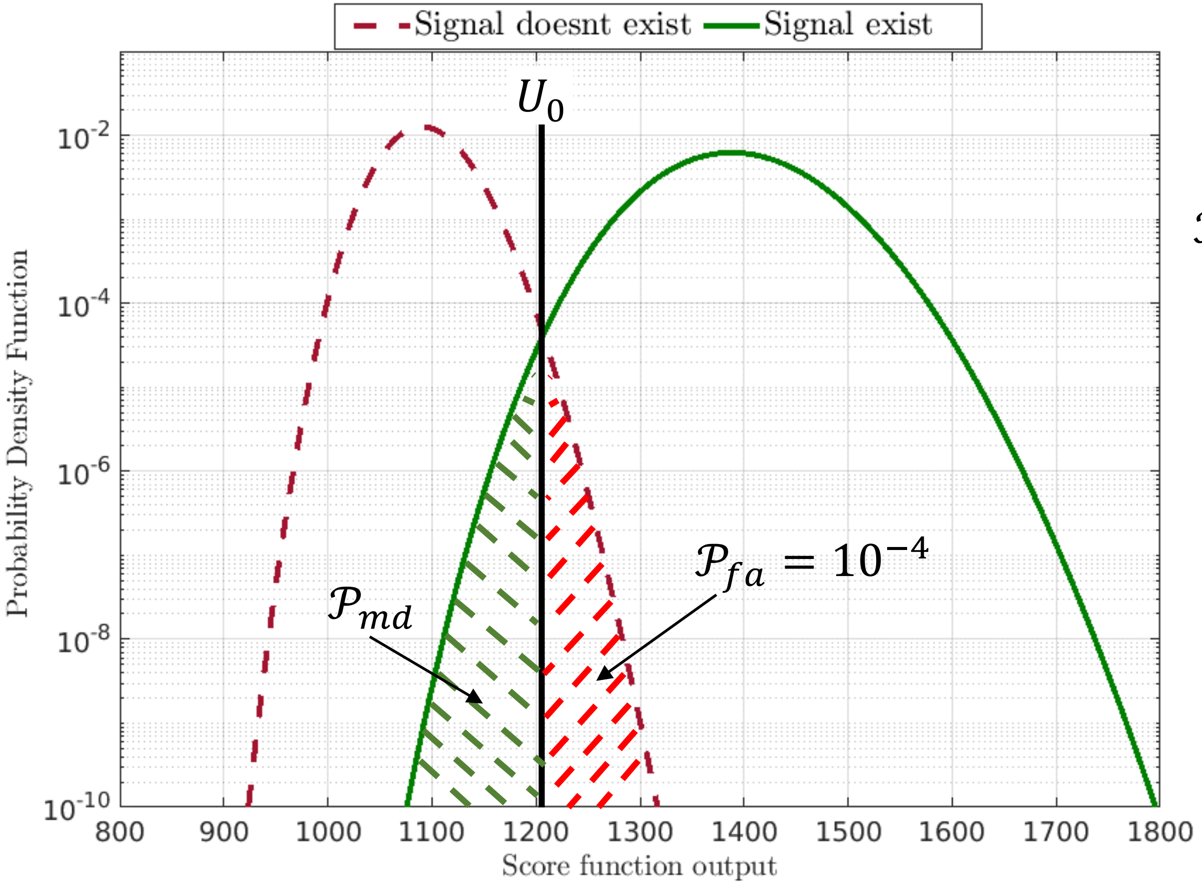
Coarse Precisions

- ➢ Reliable detection is achieved at SNR = -11.8 dB.
- ➢ n_c and f_c are coarse time and frequency offsets.
- ➢ n_a and f_o limited to $q/16$ and $1/8q$ respectively

Complexity × 8

Score function distributions

- ➢ Distribution of the score function output for given parameters, when signal does exist or not.
- ➢ Illustration of the detection problem.



$\mathcal{P}_{fa}$: Probability false alarm

$\mathcal{P}_{md}$: Probability miss detection

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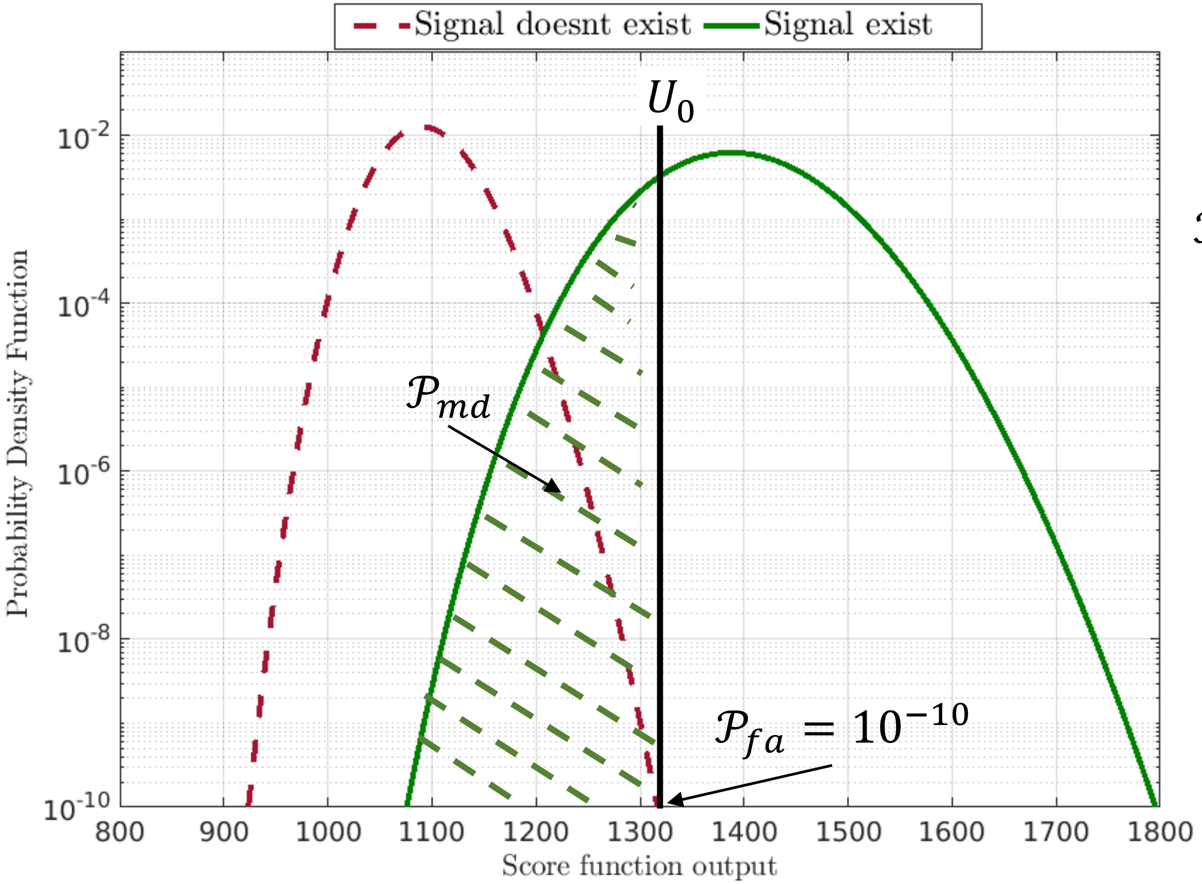


$\mathcal{P}_{fa}$: Probability false alarm

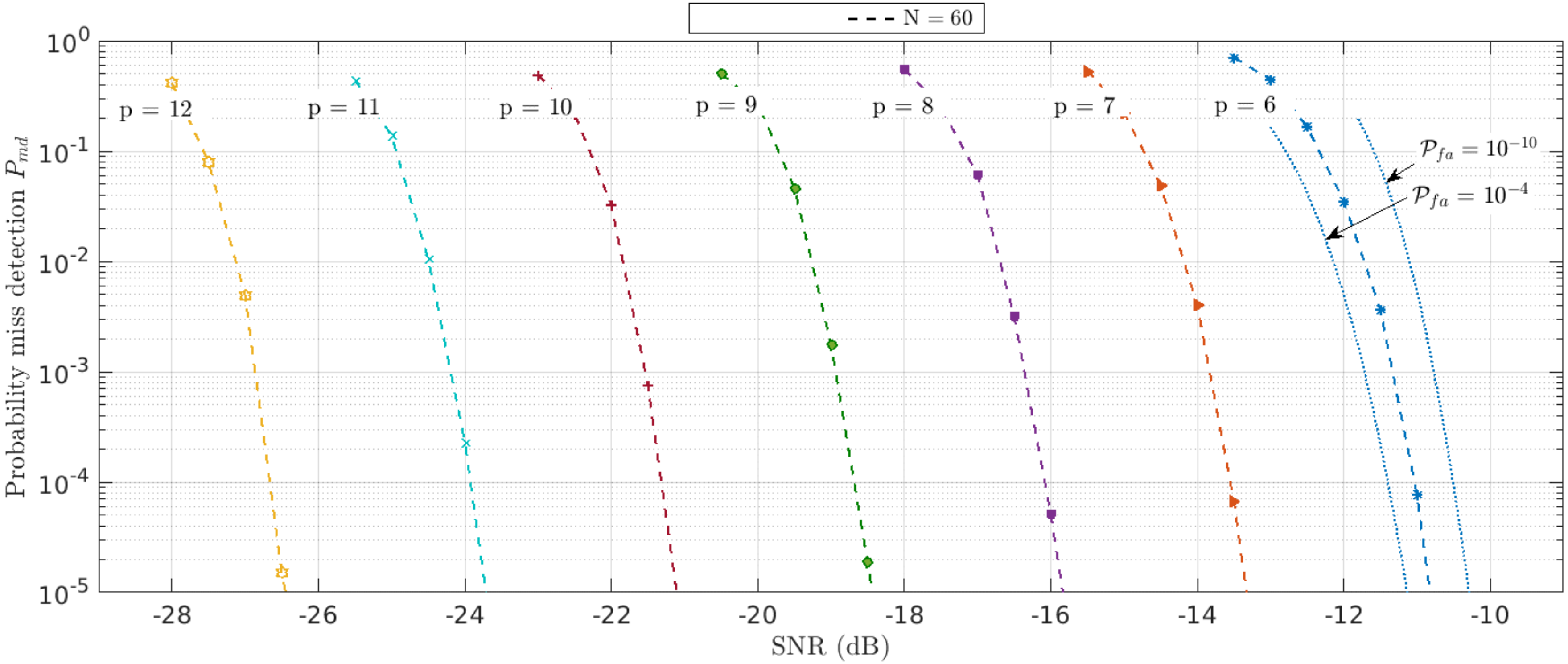
$\mathcal{P}_{md}$: Probability miss detection

Detection performance:

Effect of GF(q) order and N

$\mathcal{P}_{md}$ as function of SNR for $q = 2^p$, from $p = 6$ to $p = 12$ according to the following parameters:

- Number of CCSK symbols N: $N = 60$ and $N = 120$.
- Threshold value U_0 corresponding to $\mathcal{P}_{fa} = 10^{-6}, \mathcal{P}_{fa} = 10^{-4}$ and $\mathcal{P}_{fa} = 10^{-10}$.
- Perfect time and frequency synchronization.



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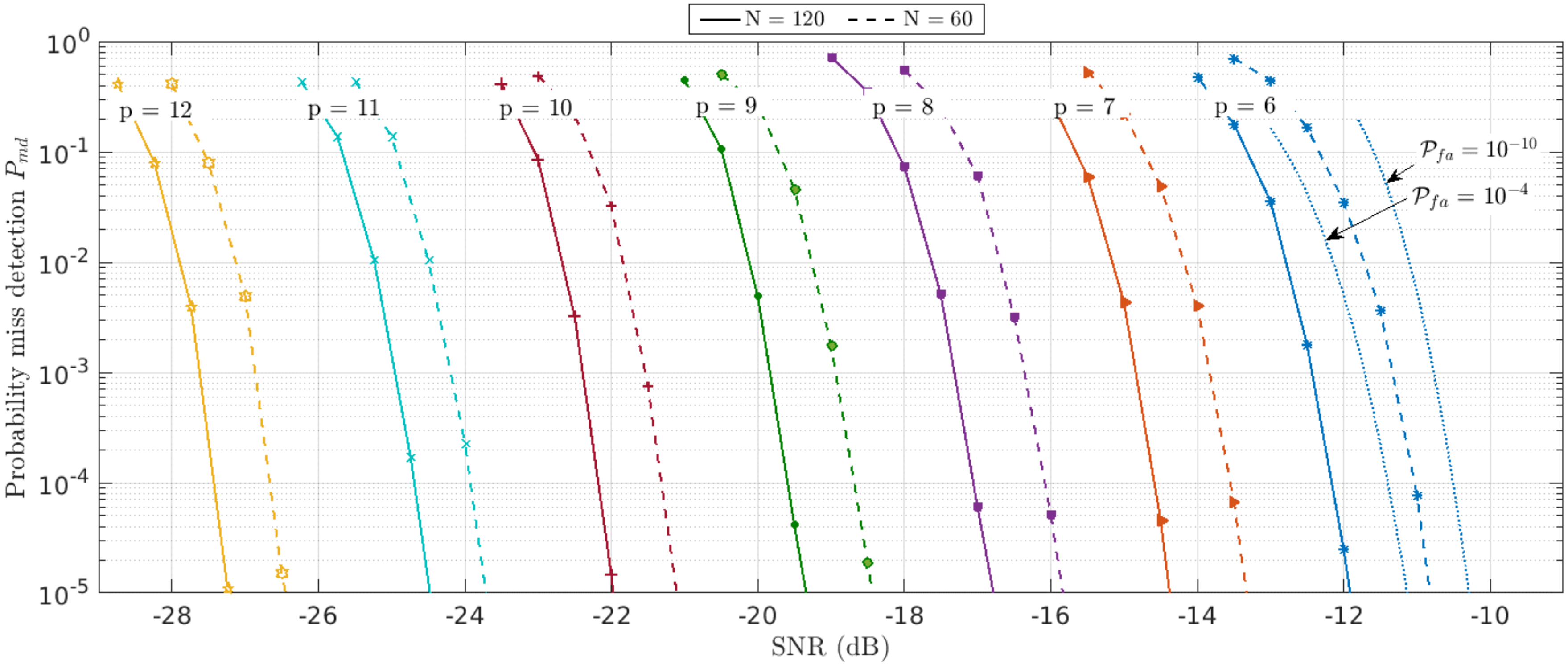

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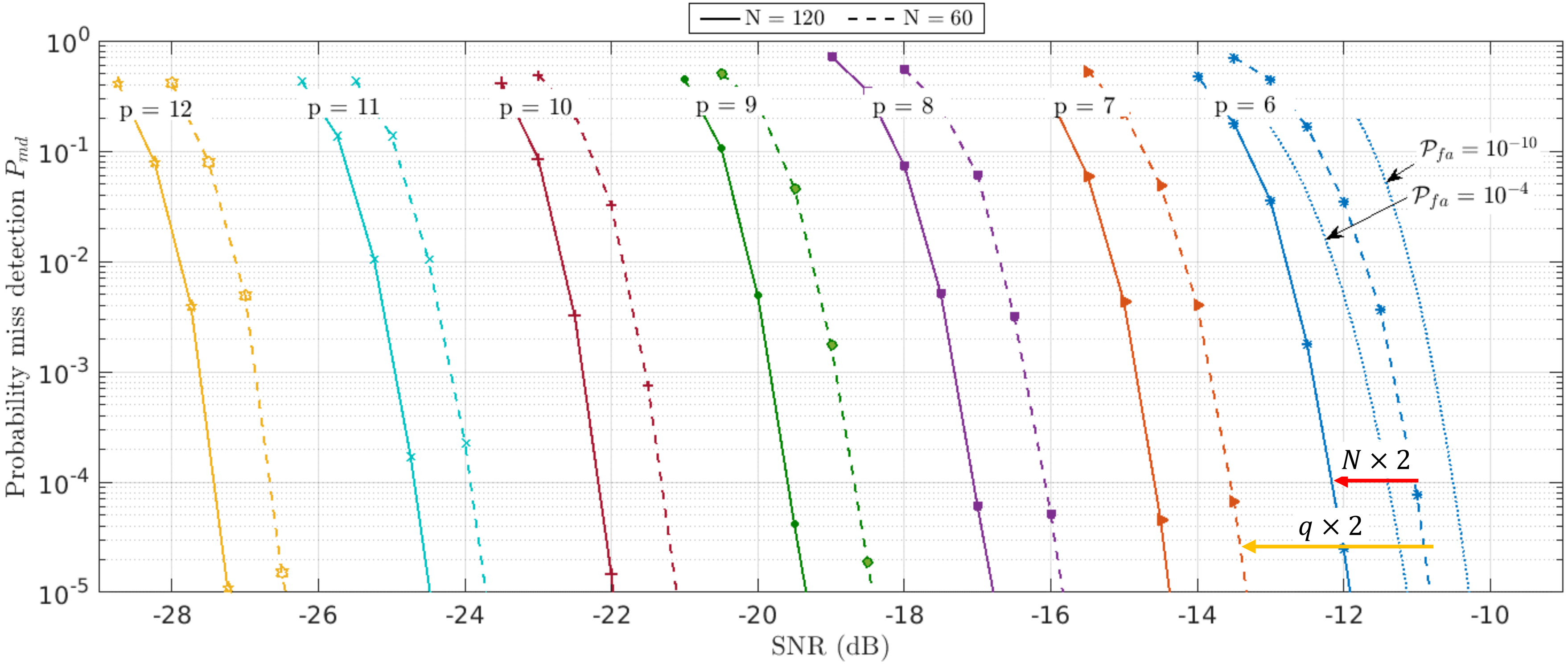

Detection performance:

Effect of GF(q) order and N

General context

System model

Detection

○○○○○○●○

Synchronization

QCSP performance

GNU Radio

Conclusion and Perspectives

$\mathcal{P}_{md}$ as function of SNR for $q = 2^p$, from $p = 6$ to $p = 12$ according to the following parameters:

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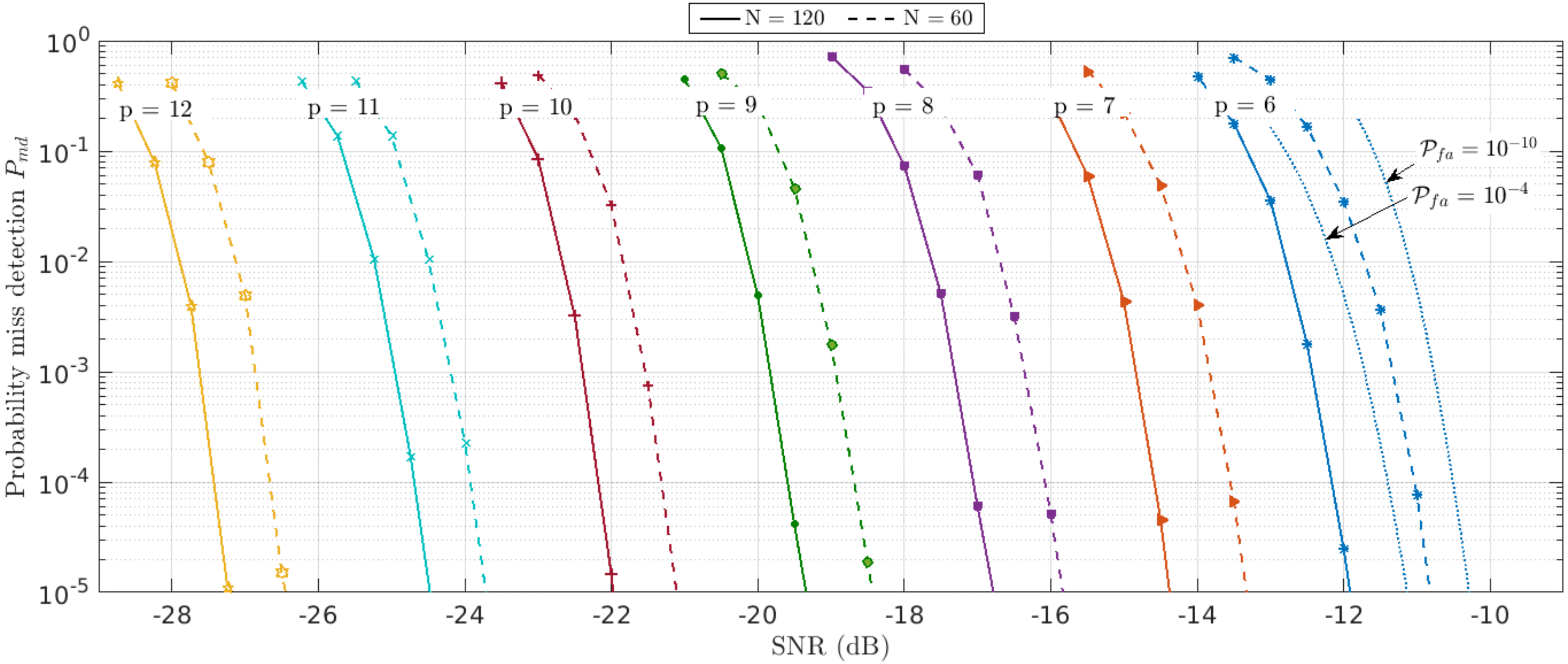
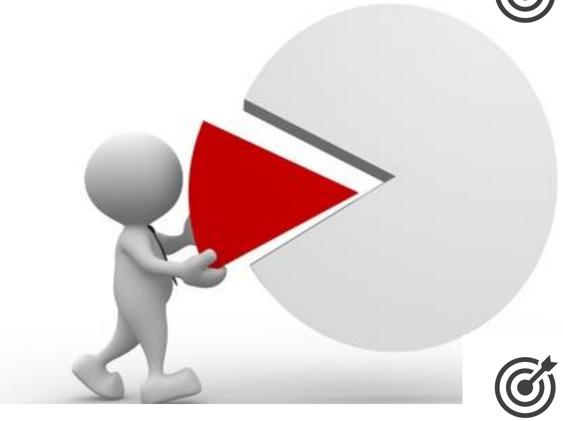


Theoretical model is also developed and validated through Monte-Carlo simulation

Contributions

Detection



- From proof of concept to a final specification ready to demonstration
- Derivation of a theoretical model for the proposed algorithm in AWGN channel
- Assessment of global detection performance

Published in:

[Pub 1]: K. Saied, A. Al Ghouwayel, and E. Boutillon, "Quasi Cyclic Short Packet for Asynchronous Preamble-Less Transmission in Very LowSNRs", *in* ***IEEE Transaction journal on Wireless Communication (IEEE TWC)****, March 2022, p. 1 - 13*.

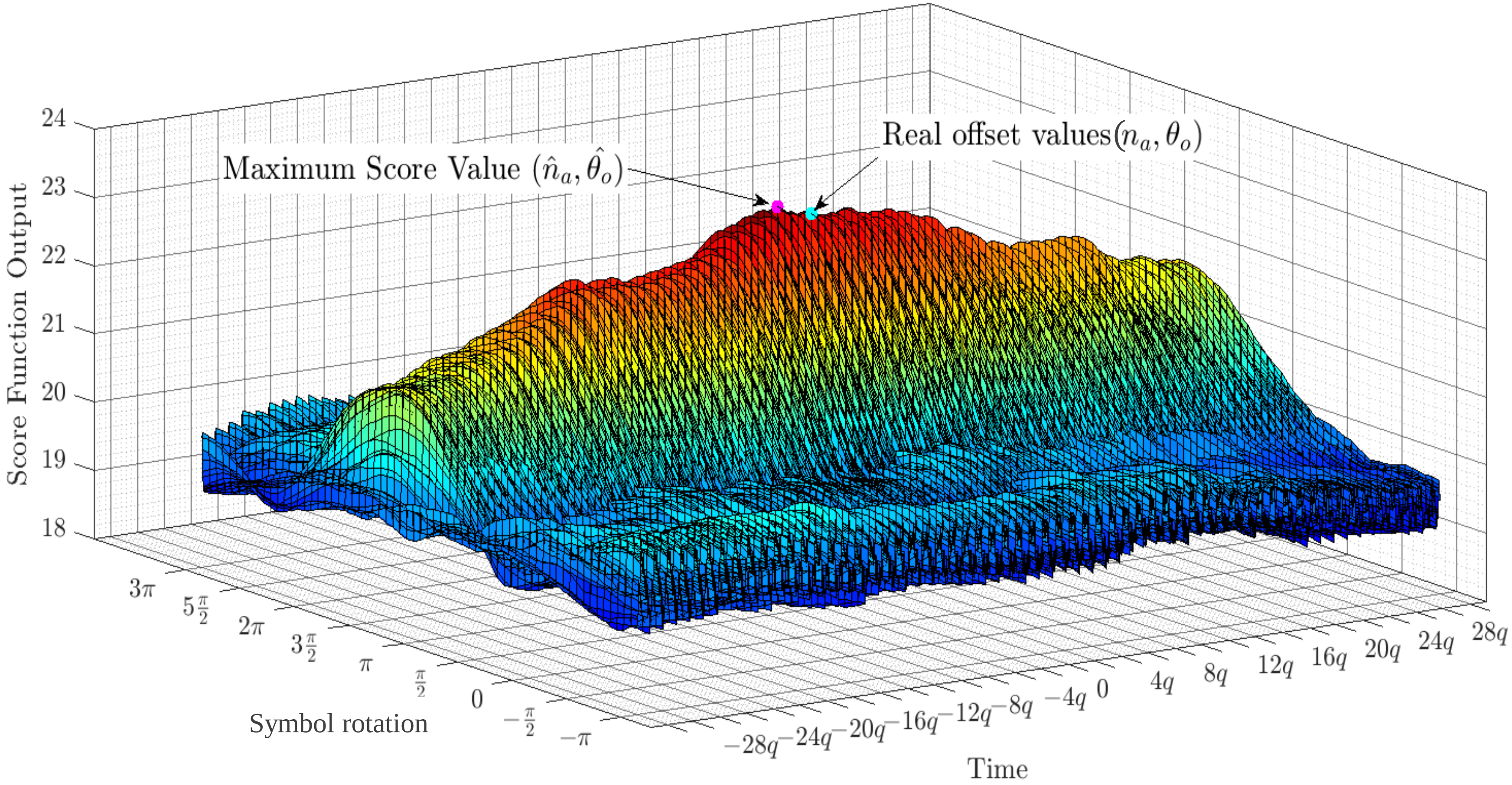
[Pub 2]: C. Moniere, K. Saied, B. Legal, and E. Boutillon, "Time sliding window for the detection of CCSK frames", *in the* ***IEEE Workshop on Signal Processing Systems*** *(SiPS'2021)*, Oct. 2021, Combria, Portugal.

Outline

- QCSP system model
- Blind detection algorithm for QCSP
- **Self synchronization algorithm for QCSP**
- QCSP system performance
- Conclusion and perspectives

Problem statement

- S_n^θ values in 3D grid where N $= 60$, $q = 64$ and affected by $n_a = 20, f_o = 0.00875$ ($\theta = 2\pi q f_o = 1.12\,\pi$) and SNR = -10 dB.



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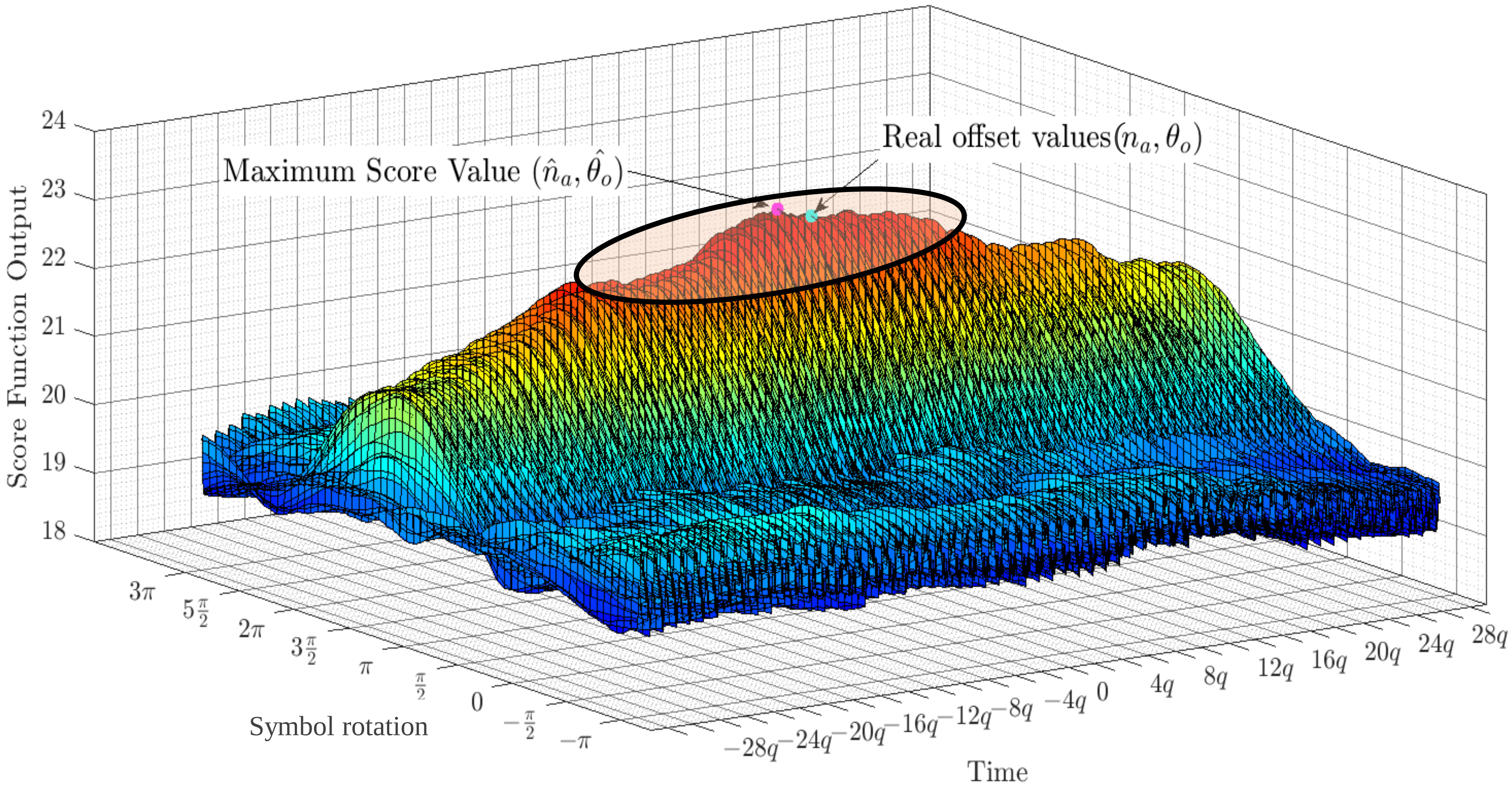
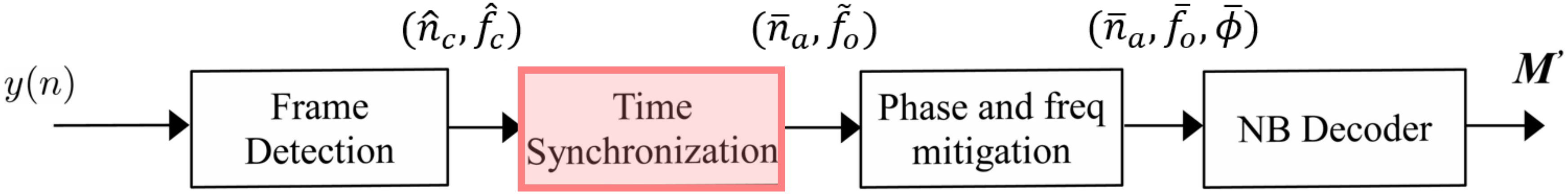
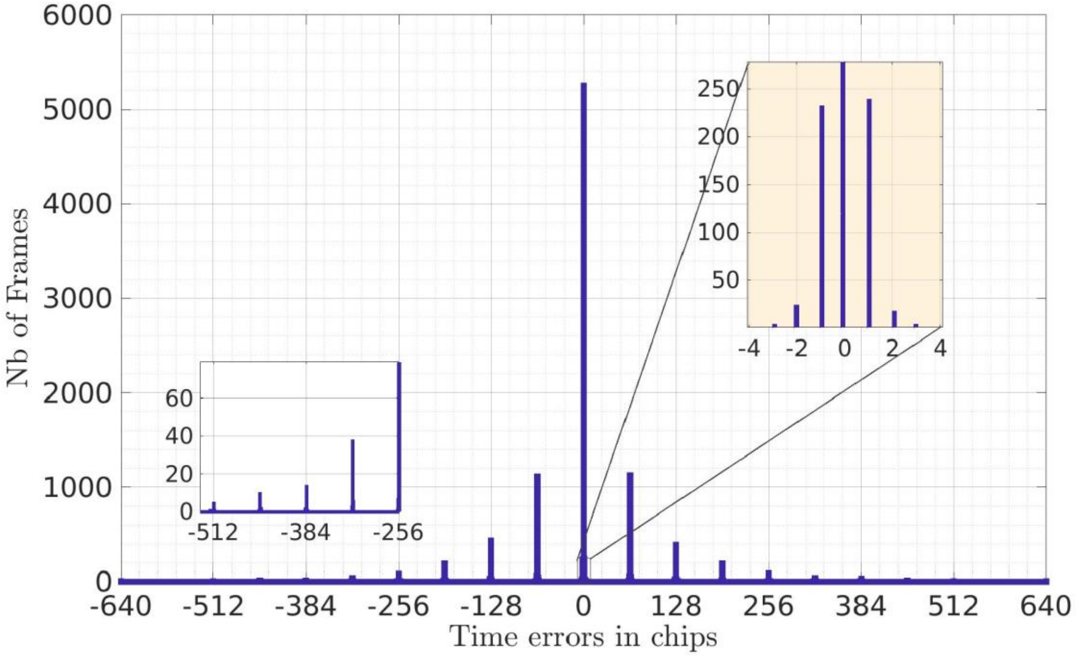


Time Synchronization



- Chip errors for 10^4 detected QCSP frames of length N = 60 and $\boldsymbol{P}_0$ sequence of length q = 64 chips, at SNR = -10 dB.

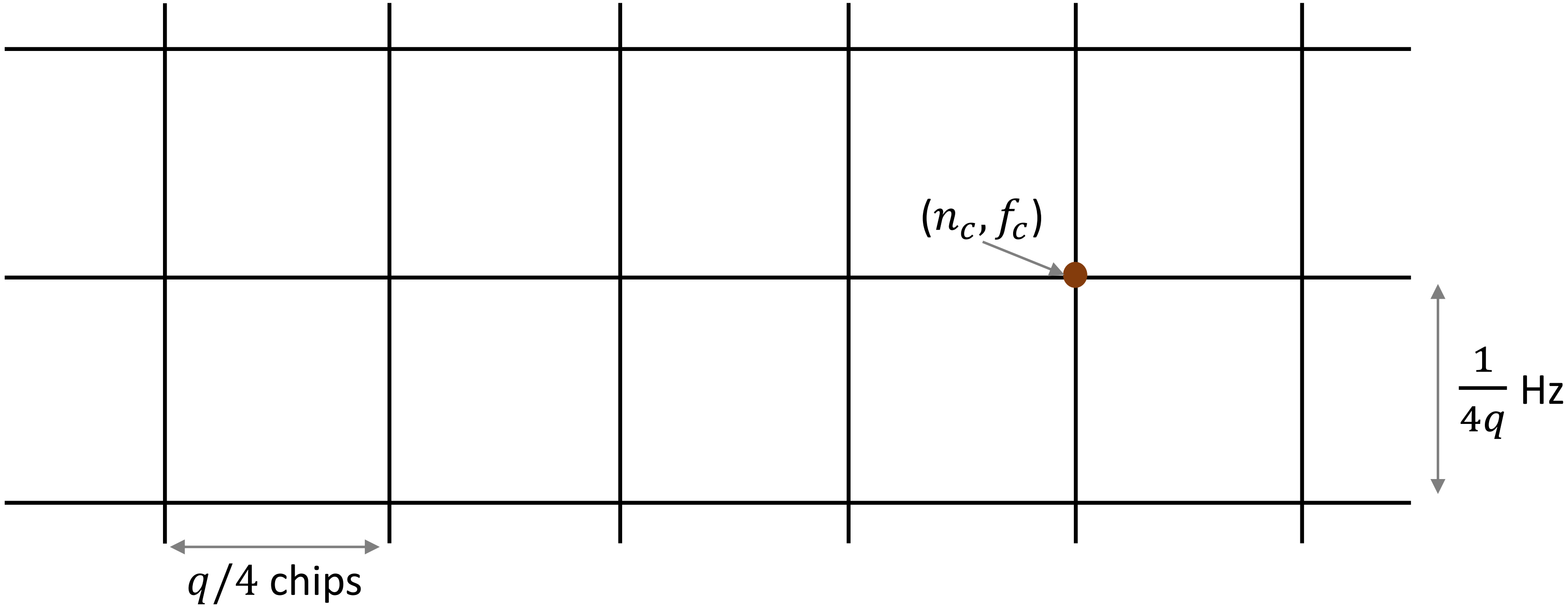


Type of time errors

- Errors at symbol level.
- Errors at chip level.

Proposed solution

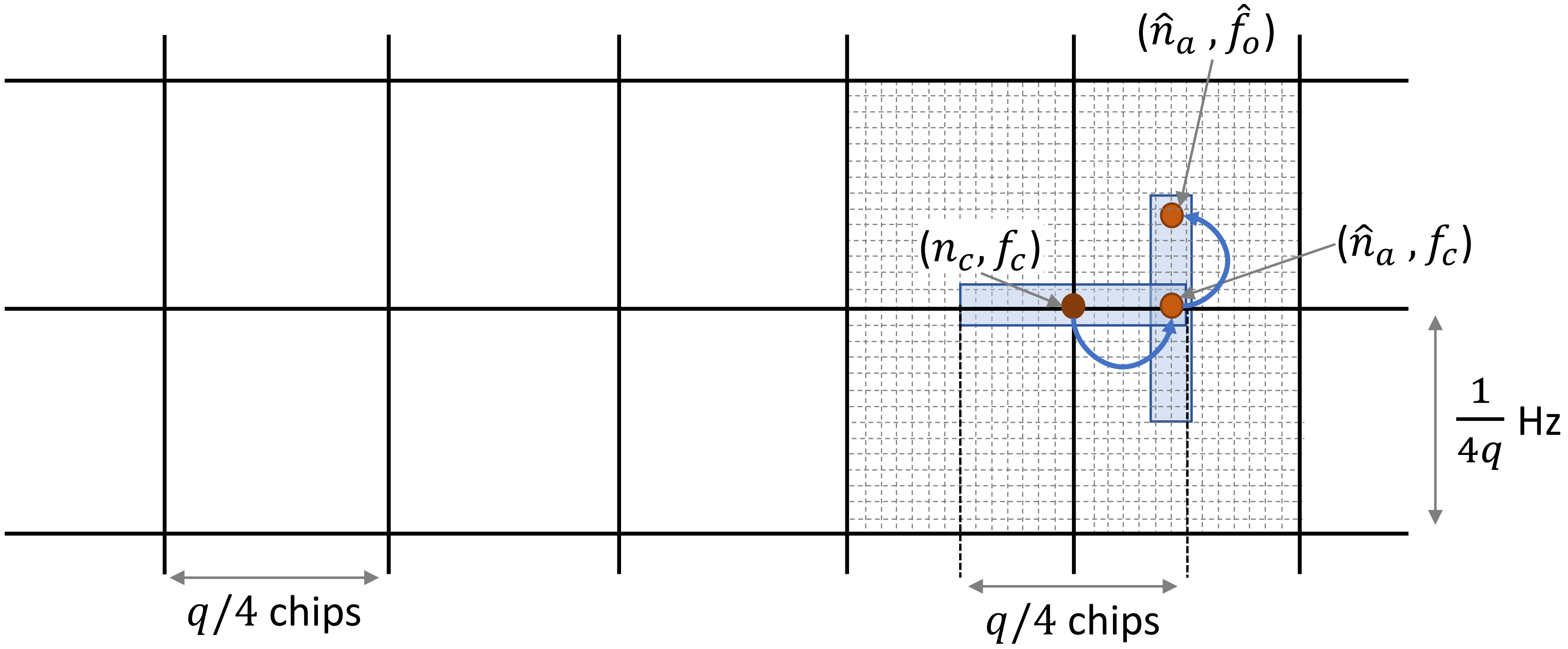
1- Time-frequency grid and detection output



Proposed solution

1- Time-frequency grid and detection output

2- Finer time-frequency grid and apply detection method to decrease the synchronization errors.

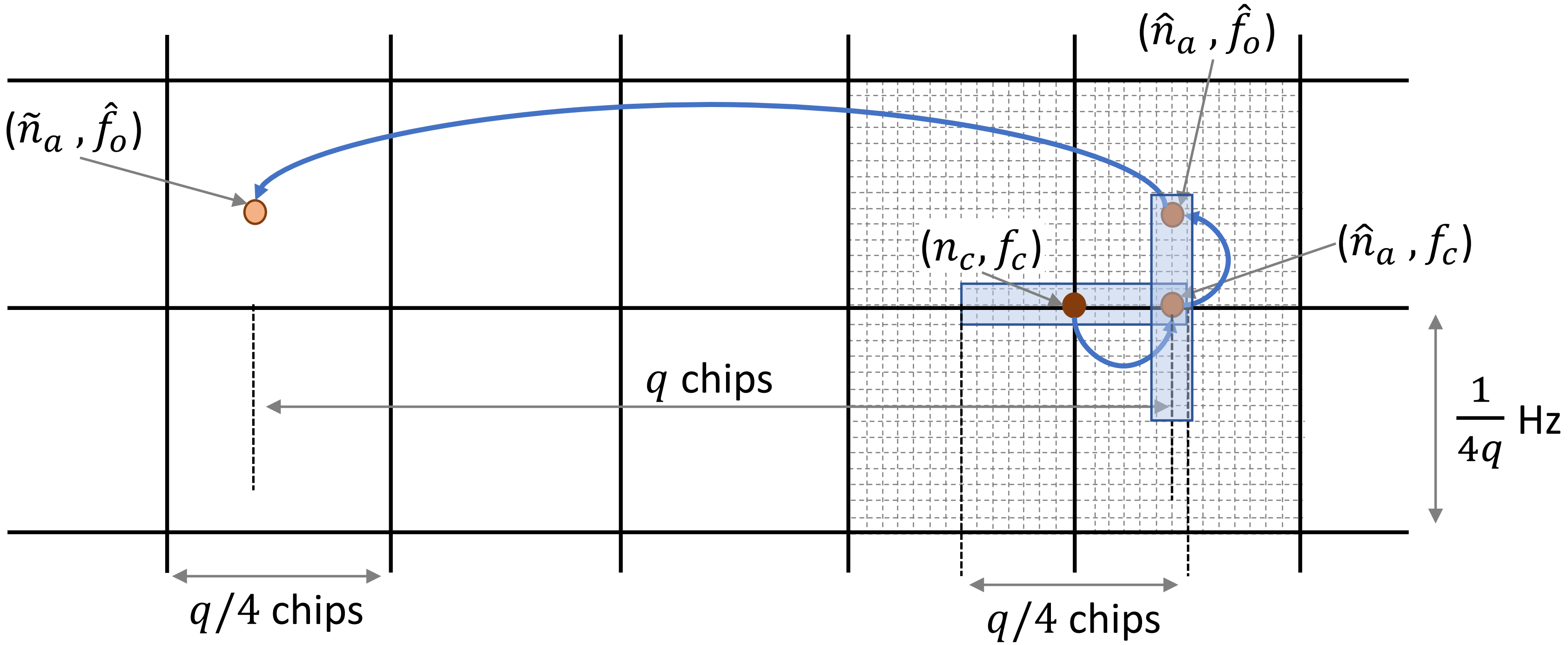


Proposed solution

1- Time-frequency grid and detection output

2- Finer time-frequency grid and apply detection method to decrease the synchronization errors.

3- Time synchronization at the symbol level thanks to Weighted Over Modulation (WOM) method.



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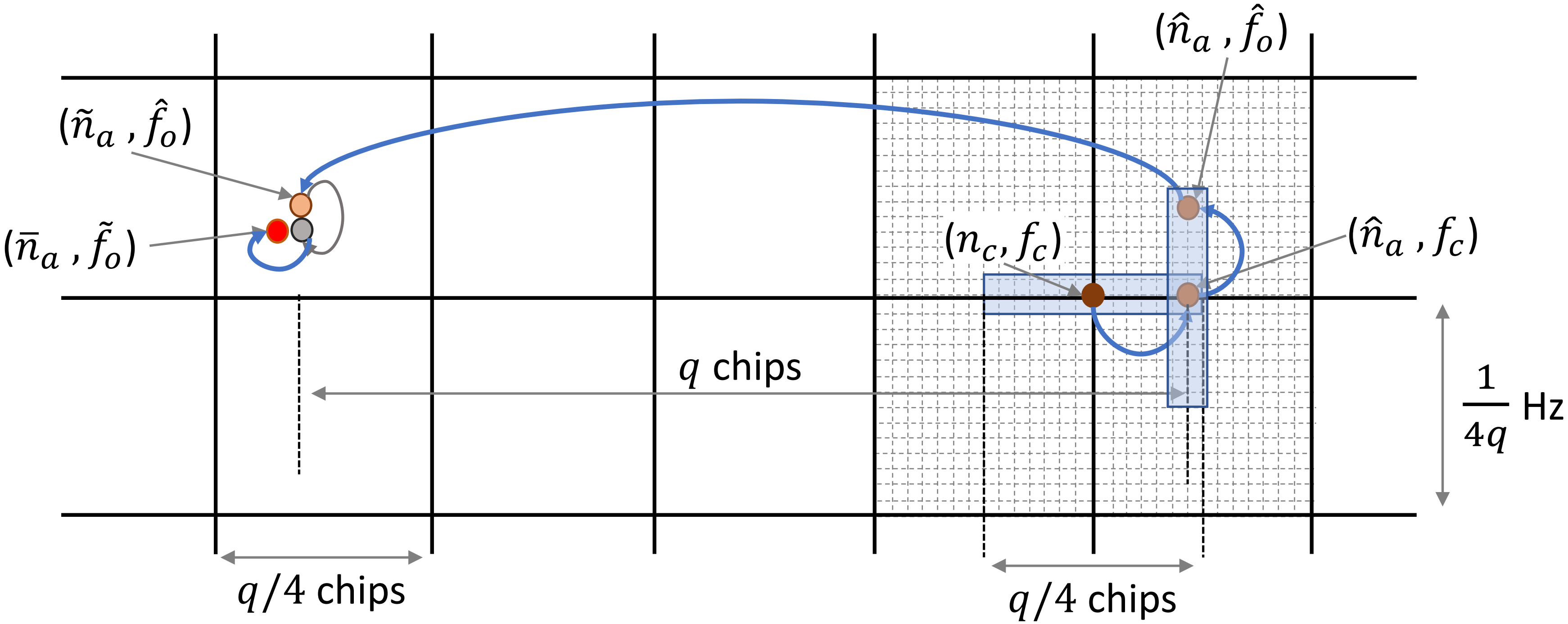
3- Time synchronization at the symbol level thanks to Weighted Over Modulation (WOM) method.

4- Time synchronization at the chip level thanks to NB-LDPC structure.



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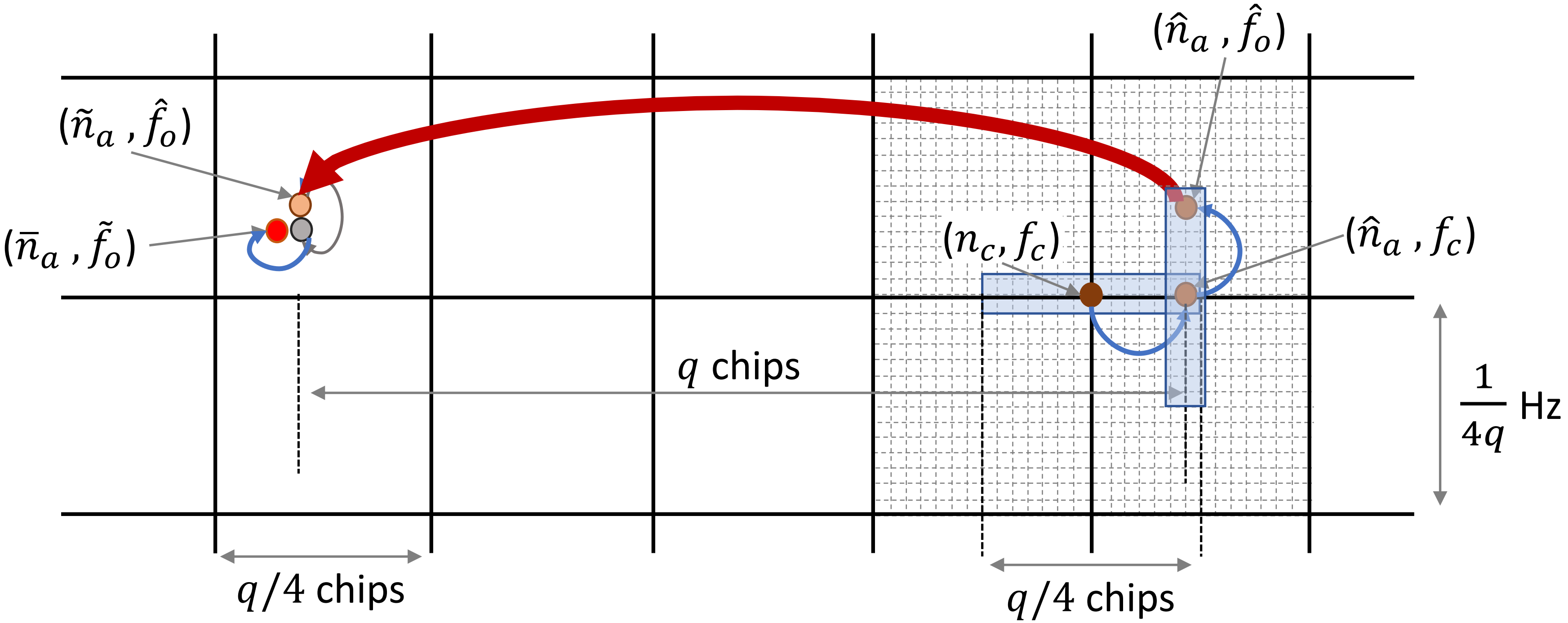

Over-Modulation (OM)

- OM generates a pre-defined phase pattern (a known sequence of ±1: +1 no phase change, and -1 (rotation)) within the sequence of the symbols being transmitted.

OM definition

- Sequence $\boldsymbol{B} = [b_0, b_1, \dots, b_{N-1}]$ with $b_k \in \{-1, 1\}$ and have good auto-correlation properties.
- QCSP frame defined as:

$$\boldsymbol{F} = [b_0 \boldsymbol{P}_{c_0}, b_1 \boldsymbol{P}_{c_1}, \dots, b_{N-1} \boldsymbol{P}_{c_{N-1}}]$$

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- OM toy example:

OM sequence B			**1**	**1**	**1**	**-1**	**1**	**-1**	**1**	**-1**	**-1**	**-1**	
Correlation output	0	0	q	q	q	-q	q	-q	q	-q	-q	-q	
Dot product	0	0	q	q	q	q	q	q	q	q	q	q	$=10q$

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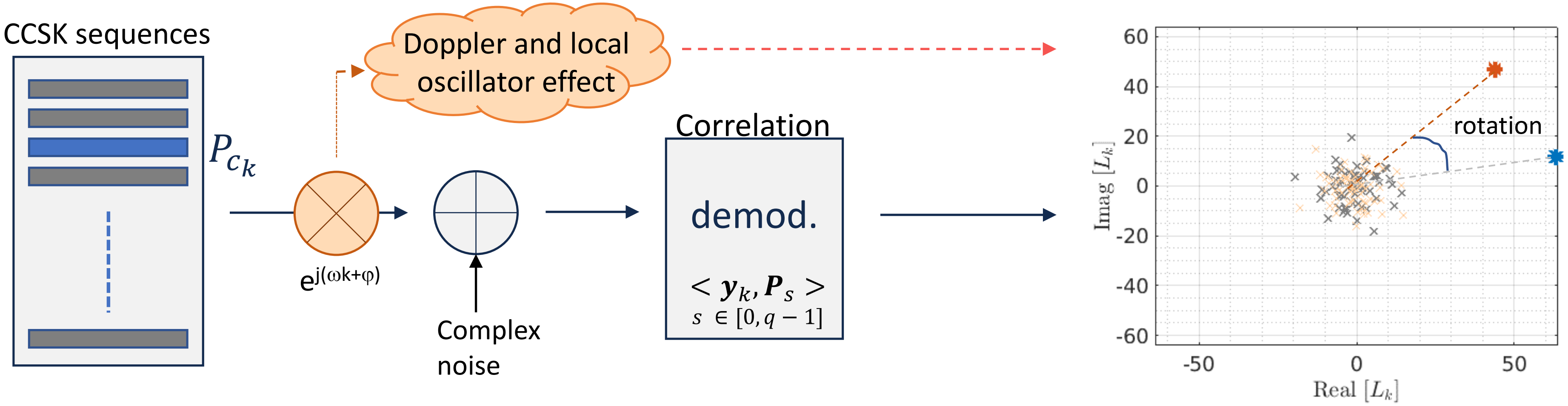
- OM toy example:

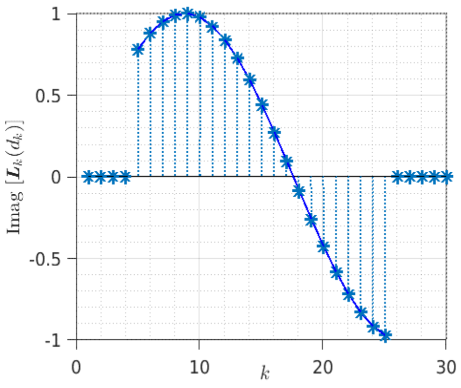
	OM sequence B			1	1	1	-1	1	-1	1	-1	-1	-1	
	Correlation output	0	0	q	q	q	$-q$	q	$-q$	q	$-q$	$-q$	$-q$	
	Dot product	0	0	q	q	q	q	q	q	q	q	q	q	$=10q$
1 symbol shift	Correlation output	0	q	q	q	$-q$	q	$-q$	q	$-q$	$-q$	$-q$	0	
	Dot product	0	0	q	q	$-q$	$-q$	$-q$	$-q$	$-q$	q	q	0	$= -q$
2 symbol shift	Correlation output	q	q	q	$-q$	q	$-q$	q	$-q$	$-q$	$-q$	0	0	
	Dot product	0	0	q	$-q$	q	q	$-q$	q	$-q$	q	0	0	$= 2q$

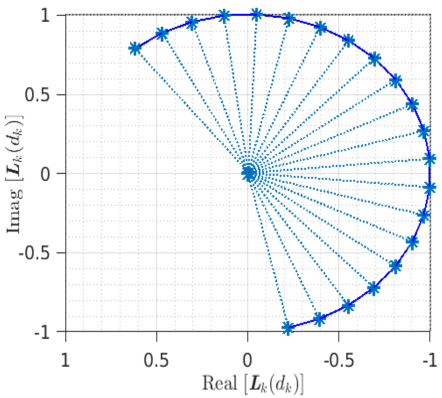
Correlation output

- Correlation output between each of the received symbols $\boldsymbol{y}_k$ and the q CCSK sequences $\boldsymbol{P}_s$



- **Pattern** of the maxima of the CCSK correlation values of each received symbol, **Synchronized** and **No noise**

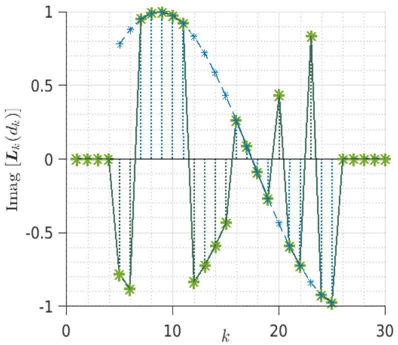


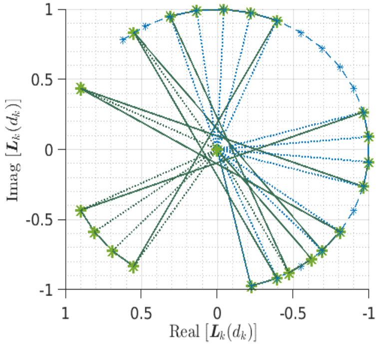


CCSK-OM correlation output pattern

OM sequence **B**																				
-1	**-1**	**1**	**1**	**1**	**1**	**1**	**-1**	**-1**	**-1**	**-1**	**1**	**1**	**1**	**1**	**-1**	**1**	**1**	**-1**	**1**	**1**

- **Pattern** of $L_k(d_k)$ values when CCSK-**OM** sequence is transmitted

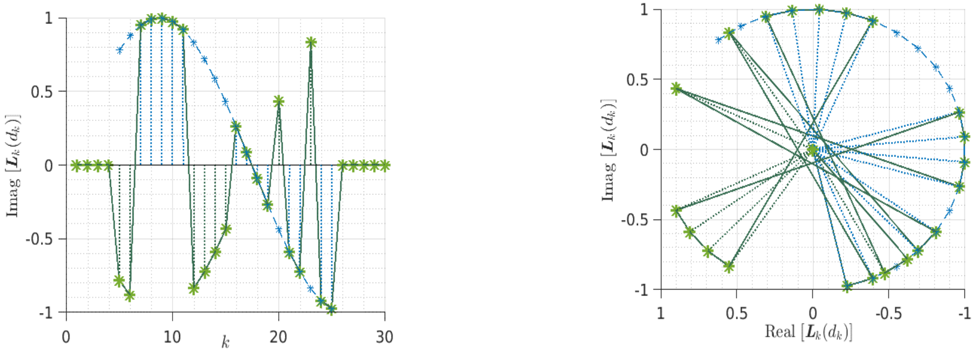




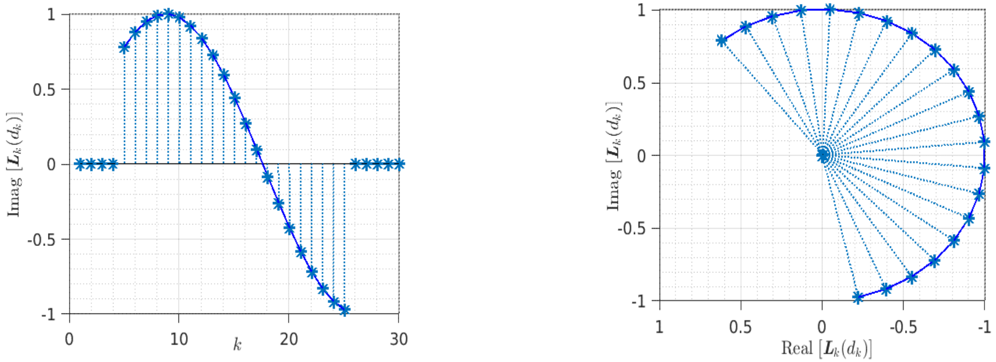
CCSK-OM correlation output pattern

OM sequence **B**	**-1**	**-1**	**1**	**1**	**1**	**1**	**1**	**-1**	**-1**	**-1**	**-1**	**1**	**1**	**1**	**1**	**-1**	**1**	**1**	**-1**	**1**	**1**

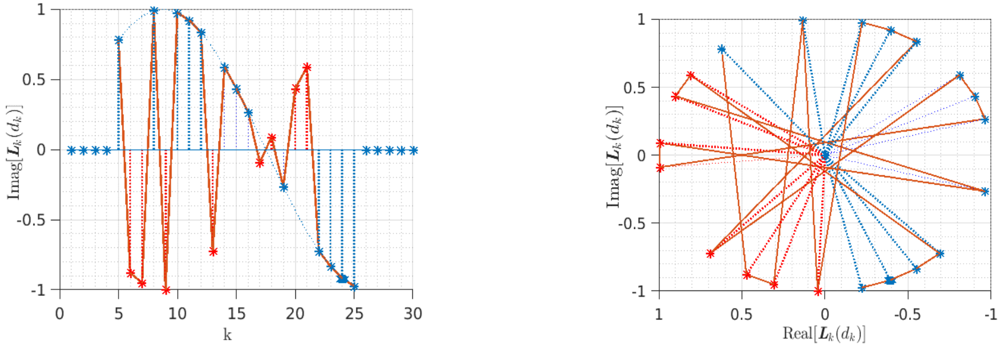
- **Pattern** of $L_k(d_k)$ values when CCSK-**OM** sequence is transmitted



- **Pattern** of the point-by-point multiplication of $\boldsymbol{L_k(d_k)}$ and ***B(k)*** - **Correct** hypothesis



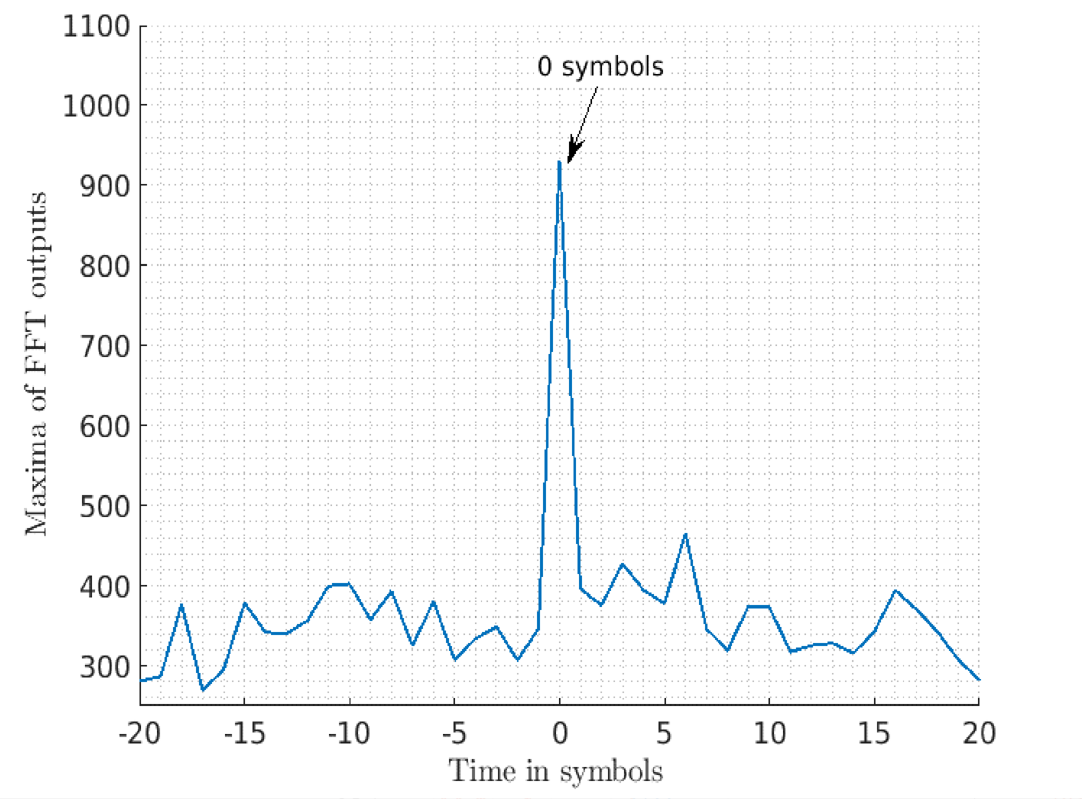
- **Pattern** of the point-by-point multiplication of $\boldsymbol{L_k(d_k)}$ and ***B(k)*** - **Wrong** hypothesis



CCSK-OM correlation output pattern

OM sequence **B**	-1	-1	1	1	1	1	1	-1	-1	-1	-1	1	1	1	1	-1	1	1	-1	1	1

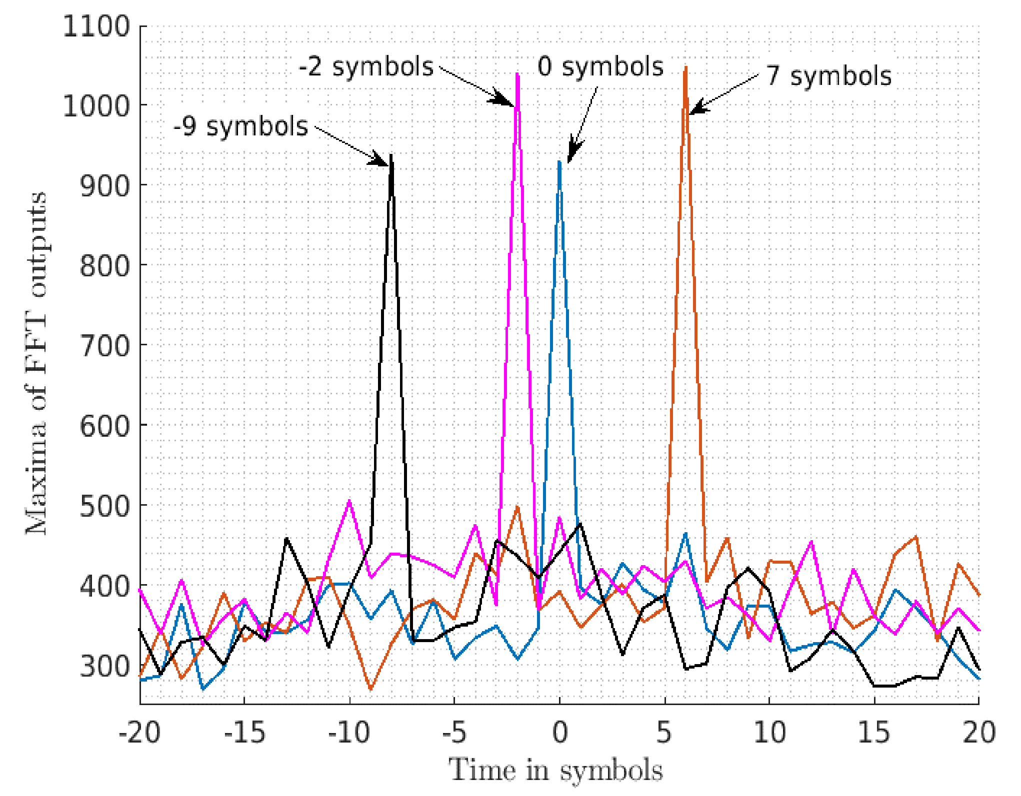
- **Pattern** of $L_k(d_k)$ values when CCSK-**OM** sequen is transmitted
- **Pattern** of the point-by-p multiplication of $L_k(d_k)$ and ***B(k)*** - **Correct** hypoth
- **Pattern** of the point-by-p multiplication of $L_k(d_k)$ and ***B(k)*** - **Wrong** hypothe



CCSK-OM correlation output pattern

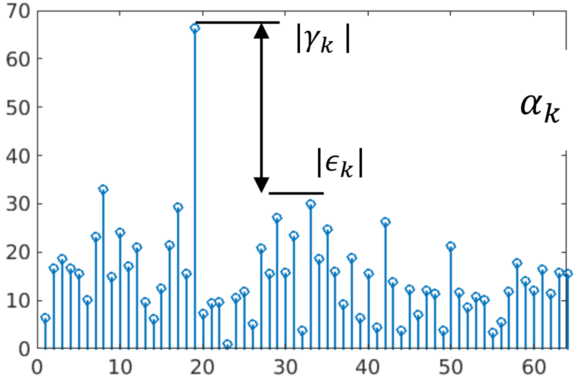
OM sequence **B**																				
-1	-1	1	1	1	1	1	-1	-1	-1	-1	1	1	1	1	-1	1	1	-1	1	1

- **Pattern** of $L_k(d_k)$ values when CCSK-**OM** sequen is transmitted
- **Pattern** of the point-by-p multiplication of $L_k(d_k)$ and ***B(k)*** - Correct hypoth
- **Pattern** of the point-by-p multiplication of $L_k(d_k)$ and ***B(k)*** - Wrong hypothe



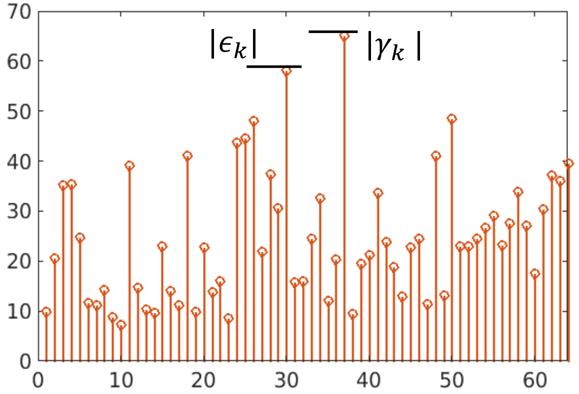
CCSK additional information

- Output of the correlation is weighted by a coefficient α_k that indicates the reliability of the decision of CCSK demodulation. ➔ **Weighted OM (WOM)** algorithm



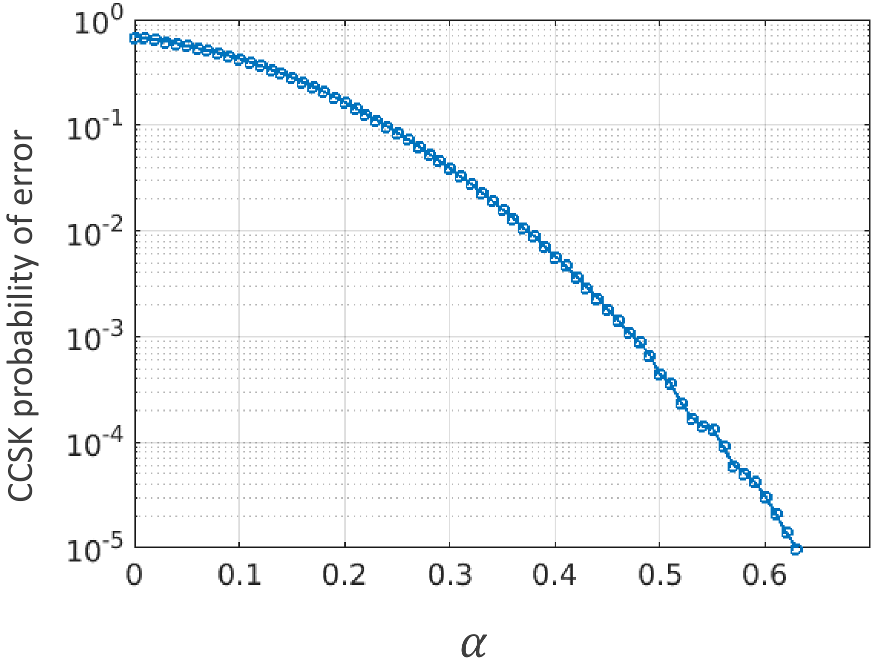
Case 1: Reliable

$$\alpha_k = \frac{|\gamma_k| - |\epsilon_k|}{|\gamma_k|}$$



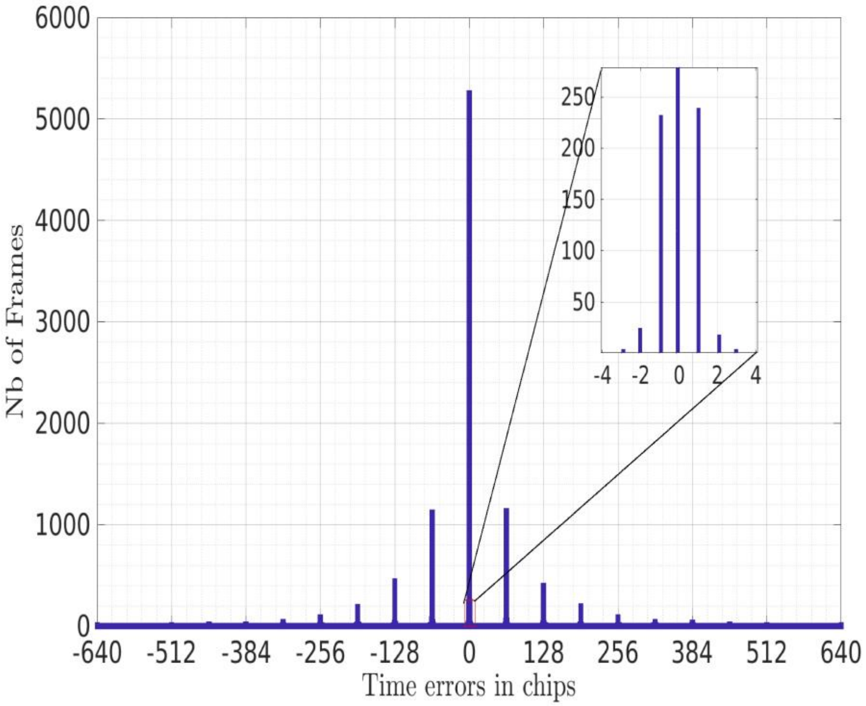
Case 2: Unreliable

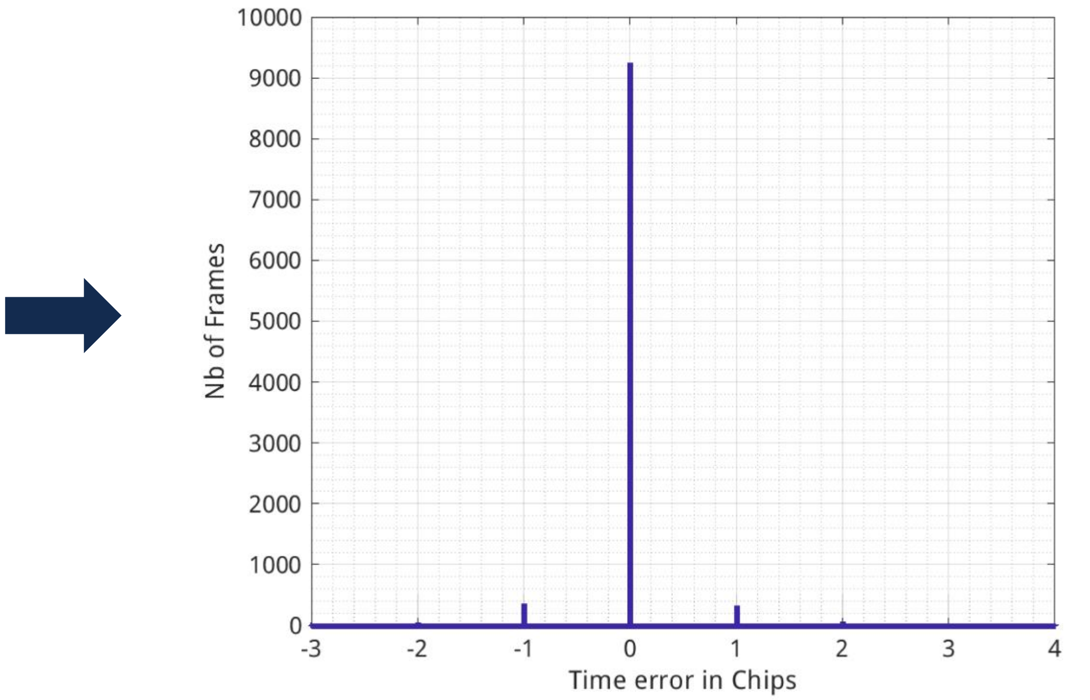
Probability of error from the CCSK demodulation as function of coefficient α



OM results

- Chip errors for 10^4 detected QCSP frames of length N = 60 and $\boldsymbol{P}_0$ sequence of length q = 64 chips, at SNR = -10 dB.





- Before symbol synchronization
- After symbol synchronization

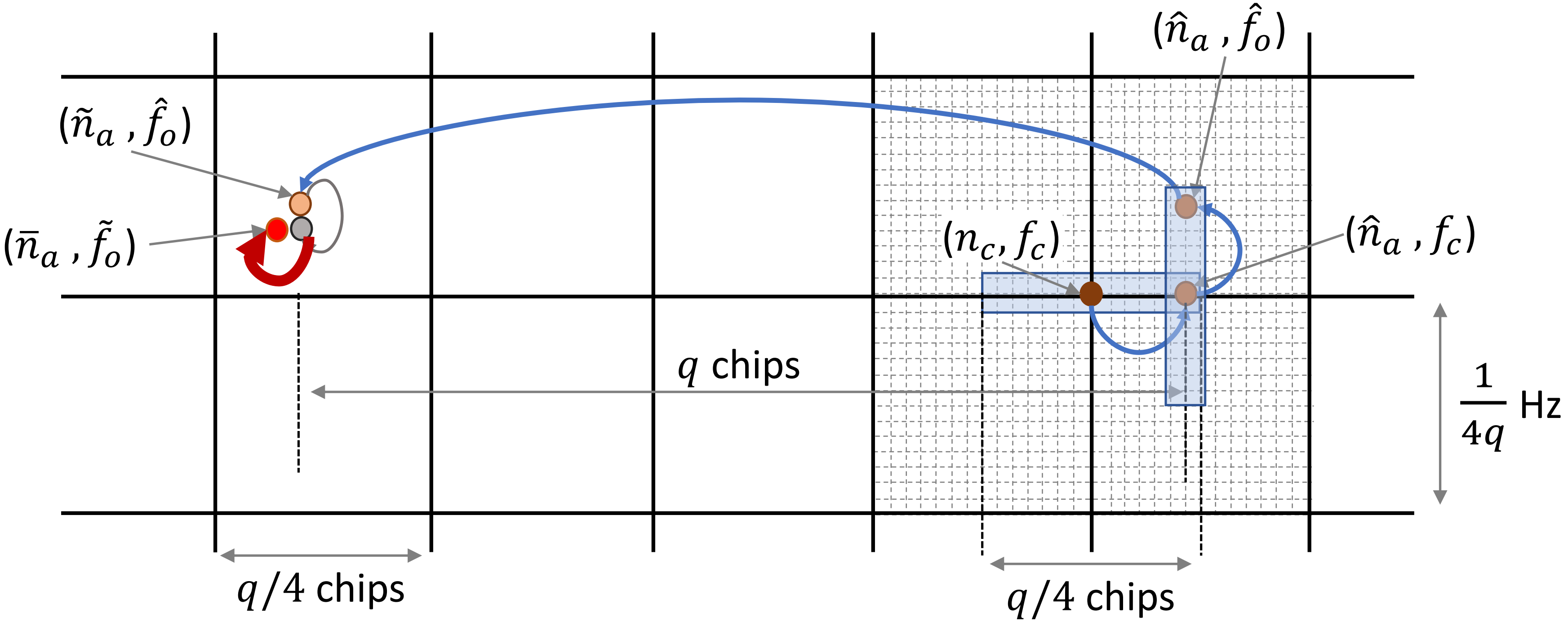
Proposed solution

1- Time-frequency grid and detection output

2- Finer time-frequency grid and apply detection method to decrease the synchronization errors.

3- Time synchronization at the symbol level thanks to Weighted Over Modulation (WOM) method.

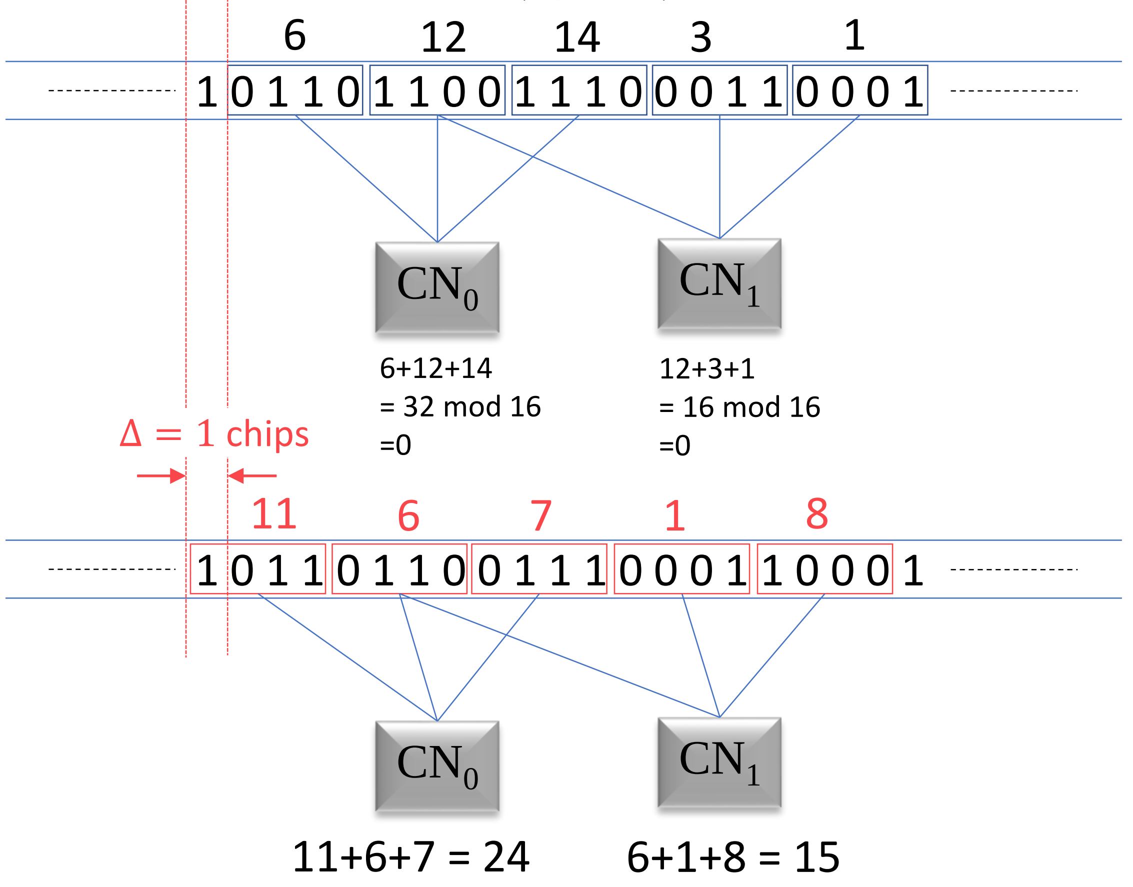
4- Time synchronization at the chip level thanks to NB-LDPC structure.



Chip synchronization: PC concept

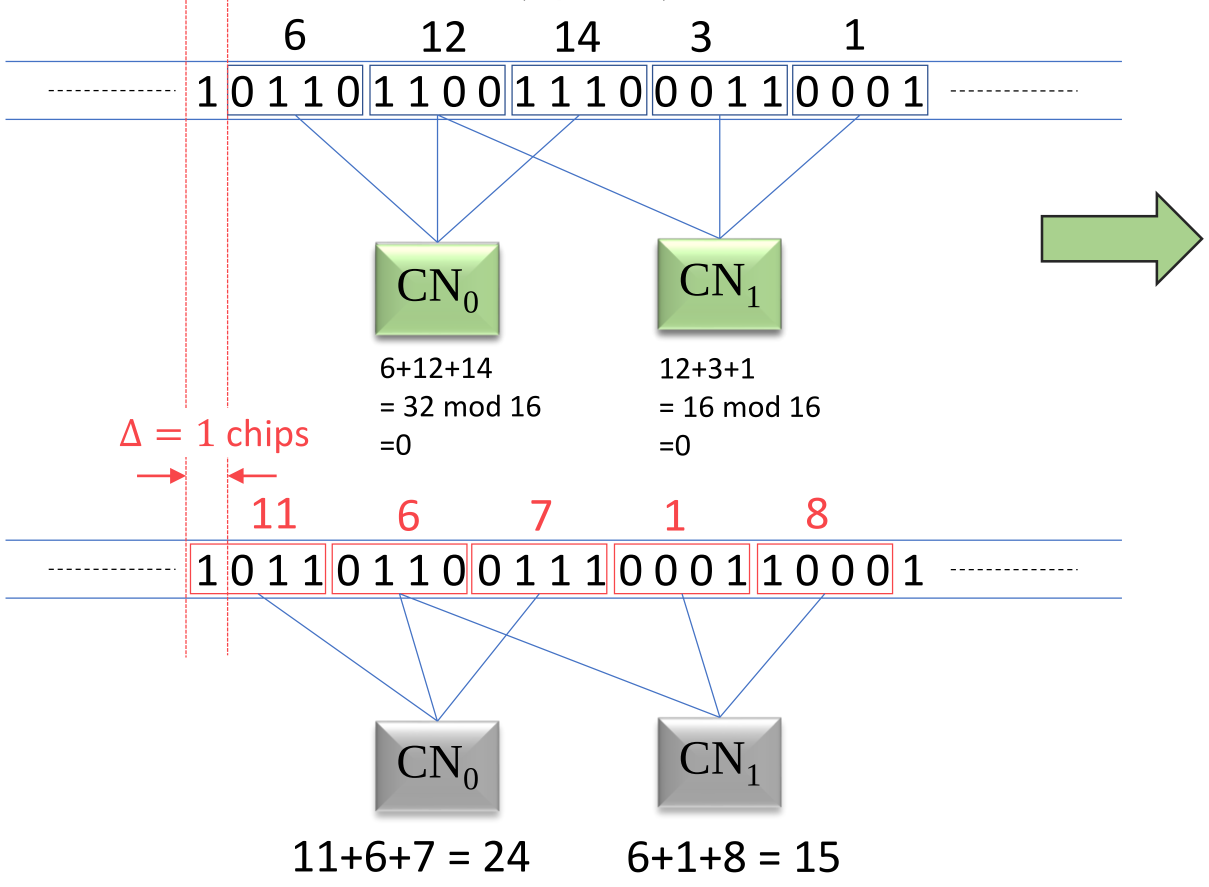
A brief Toy example in the Group $(\mathbb{Z}/16\mathbb{Z})$:

CN_1 Check Node
$\sum$ input mod 16



Chip synchronization: PC concept

A brief Toy example in the Group $(\mathbb{Z}/16\mathbb{Z})$:



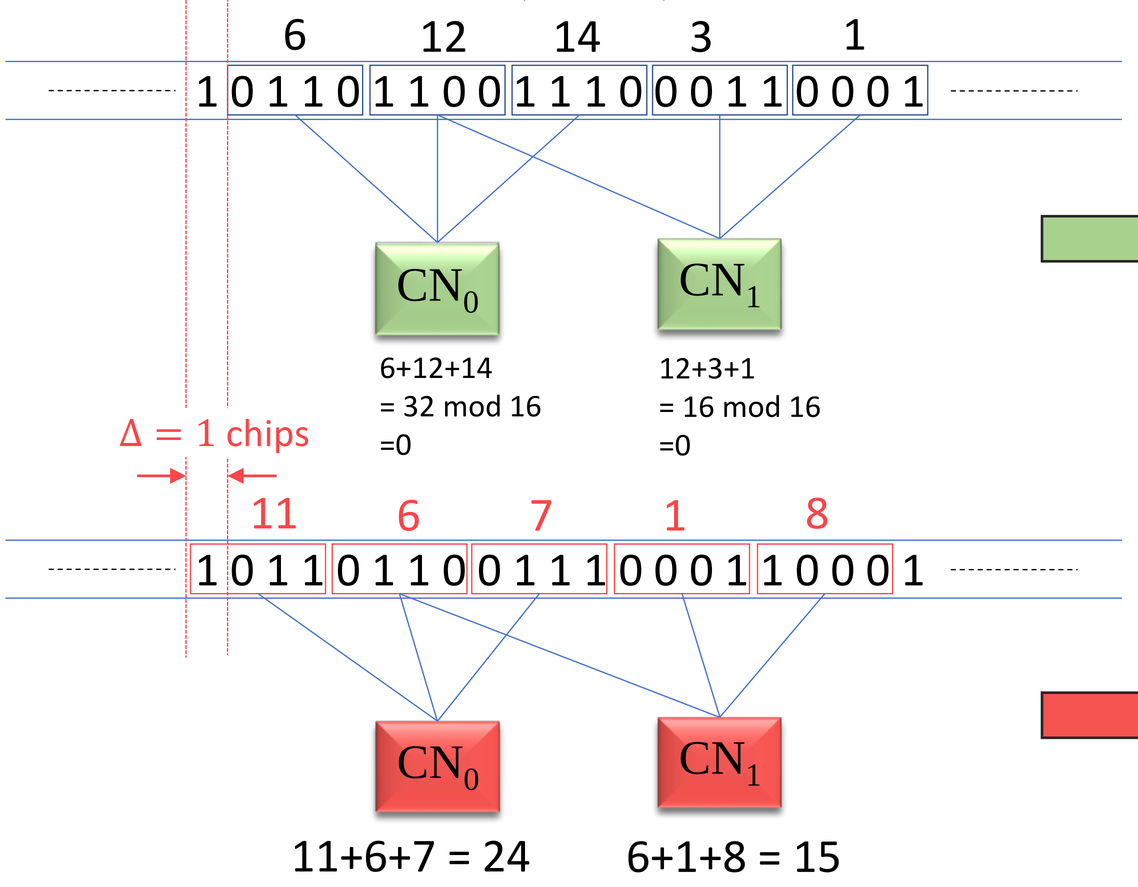
CN_1 Check Node
$\sum$ input mod 16

All PCs are fulfilled
$\sum$ input = 0 mod 16

Chip synchronization: PC concept

A brief Toy example in the Group $(\mathbb{Z}/16\mathbb{Z})$:

CN_1 Check Node
$\sum$ input mod 16

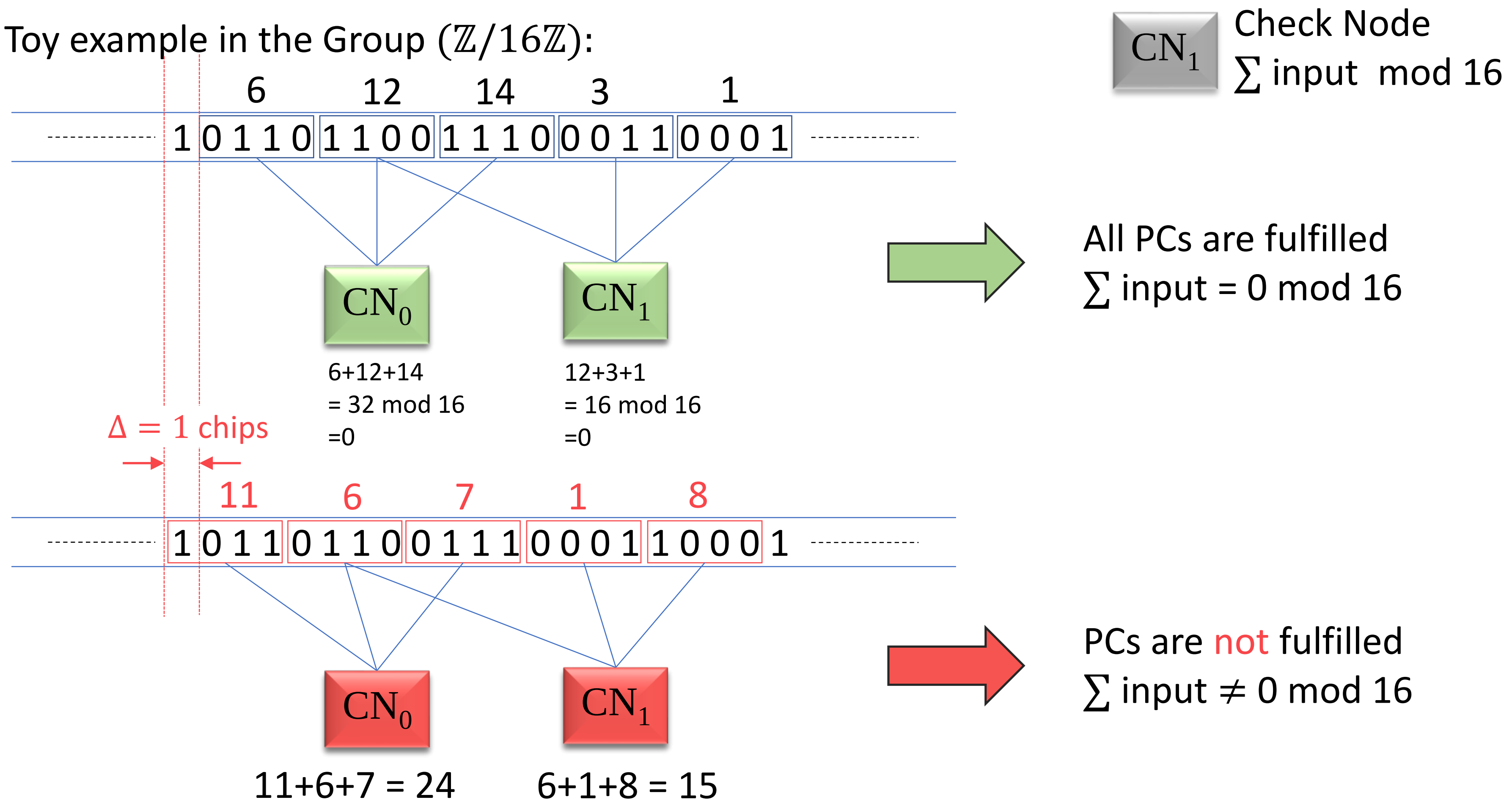


All PCs are fulfilled
$\sum$ input = 0 mod 16

PCs are not fulfilled
$\sum$ input $\neq$ 0 mod 16

Chip synchronization: PC concept

A brief Toy example in the Group $(\mathbb{Z}/16\mathbb{Z})$:



CN$_1$ Check Node
$\sum$ input mod 16

6 12 14 3 1

1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 1 1 0 0 0 1

CN$_0$ CN$_1$

6+12+14
= 32 mod 16
=0

12+3+1
= 16 mod 16
=0

All PCs are fulfilled
$\sum$ input = 0 mod 16

$\Delta = 1$ chips

11 6 7 1 8

1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 1 1 0 0 0 1

CN$_0$ CN$_1$

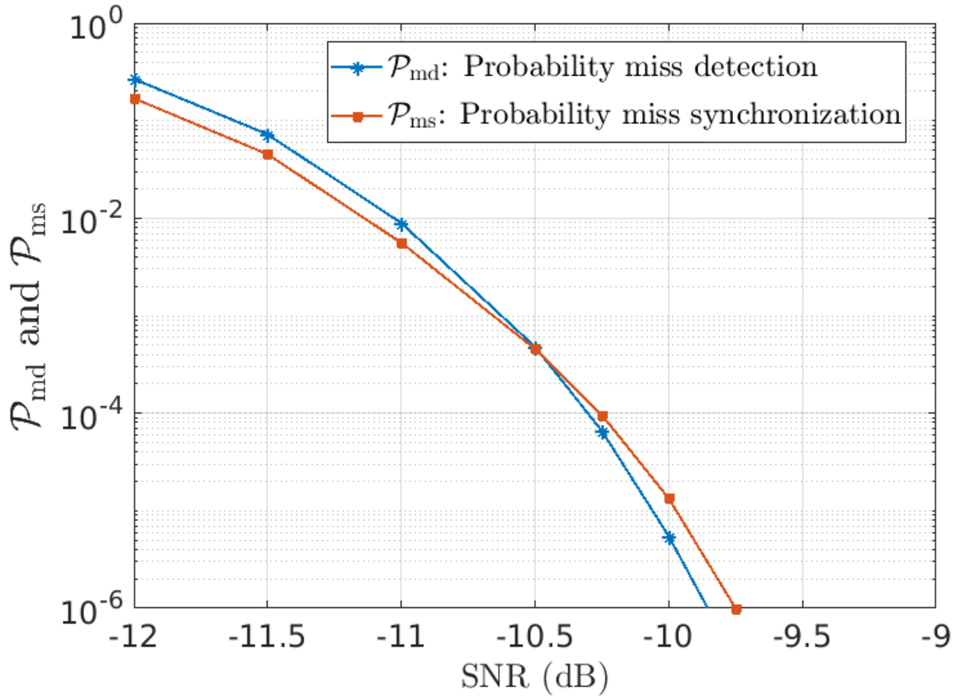
11+6+7 = 24 6+1+8 = 15

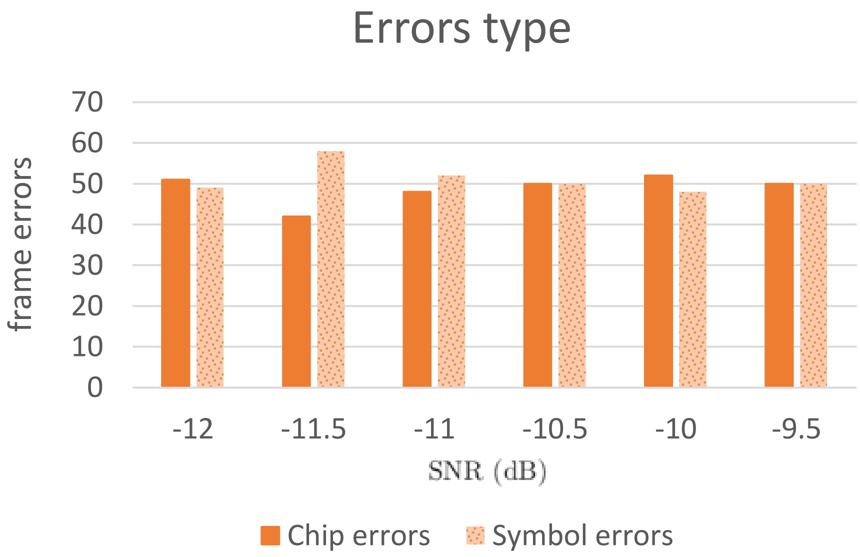
PCs are not fulfilled
$\sum$ input $\neq$ 0 mod 16

- Same concept on the complicated NB-codes.
- Test several hypothesis and keep the best one.
- In case of NB-LDPC code, reduction in the decoding algorithm is performed.

Time synchronization results

- Detection grid $(q/4, \pi/2)$
- $N = 60$ QCSP symbols
- NB-LDPC $R_c = 1/3, q = 64$
- Asynchronous AWGN channel
- Time and frequency shifts are uniformly randomly distributed.





Contributions

Synchronization in time

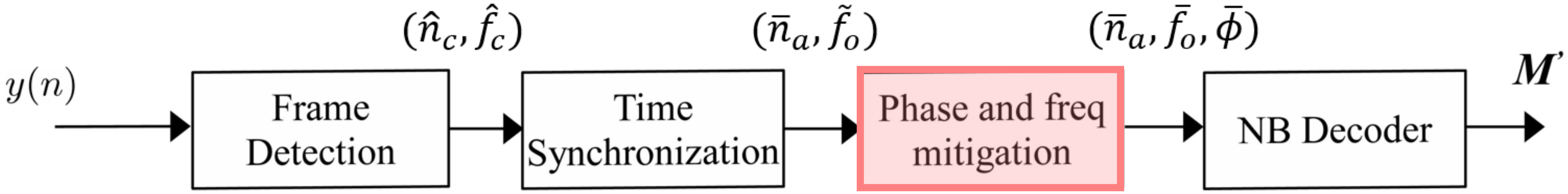
- Characterization and identification of time synchronization errors
- Proposition of a global time synchronization algorithm at very low SNRs
- Utilization of the weighted over-modulation for the symbol synch.
- Utilization of the NB-LDPC code for the chip synchronization with complexity reduction

Published in:

[Pub 3]: K. Saied, A. Al Ghouwayel, and E. Boutillon, "Blind Time-Synchronization of CCSK Short Frames", *in The 17th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob21)*, Oct. 2021, Bologna, Italy.

[Patent 1]: E. Boutillon and K. Saied, "A method for a transmitter to transmit a signal to a receiver in a communication system, and its corresponding receiving method", July 2021.

Phase synchronization



$y(n)$

Frame Detection

$(\hat{n}_c, \hat{f}_c)$

Time Synchronization

$(\bar{n}_a, \tilde{f}_o)$

Phase and freq mitigation

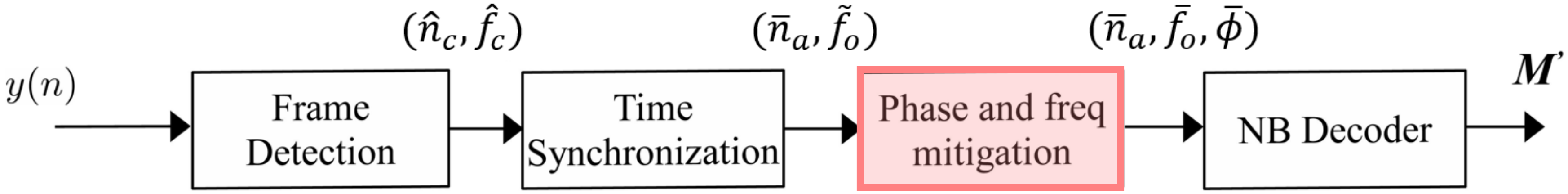
$(\bar{n}_a, \bar{f}_o, \bar{\phi})$

NB Decoder

M'

- Detection and time-synchronization are not the end of the story.
- Phase offset has a big impact on the generation of the LLRs.

Phase synchronization



- Detection and time-synchronization are not the end of the story.
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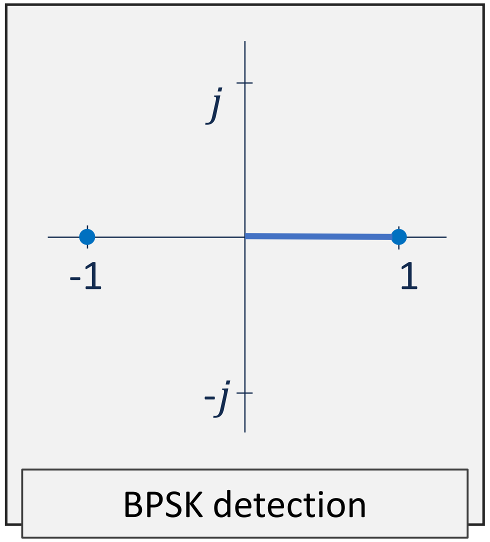
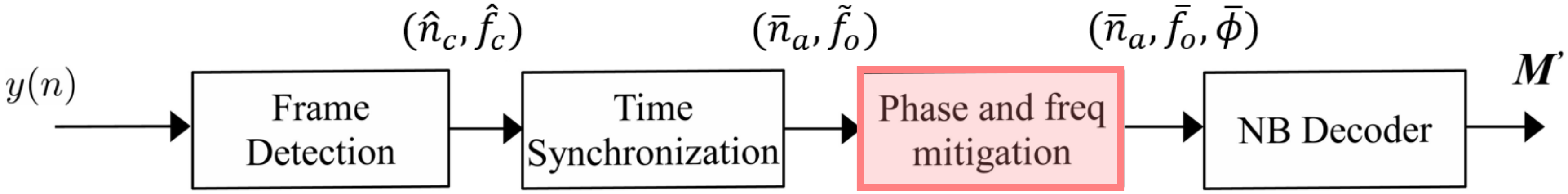


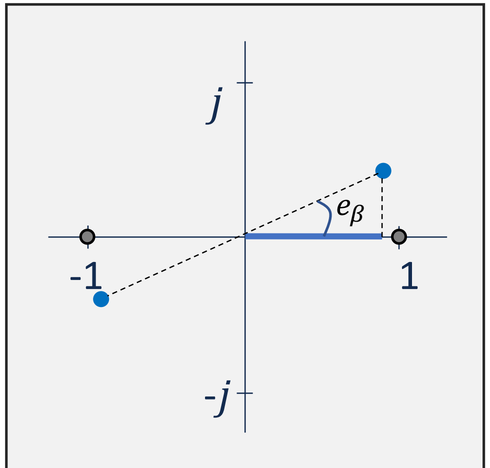
LLR generation: $\mathrm{Real}(\mathrm{IFFT}(\mathrm{FFT}(\boldsymbol{y})^* \odot \mathrm{FFT}(\boldsymbol{P}_0)))$

Phase synchronization



$y(n)$ → Frame Detection → $(\hat{n}_c, \hat{f}_c)$ → Time Synchronization → $(\bar{n}_a, \tilde{f}_o)$ → Phase and freq mitigation → $(\bar{n}_a, \bar{f}_o, \bar{\phi})$ → NB Decoder → $\boldsymbol{M'}$

- Detection and time-synchronization are not the end of the story.
- Phase offset has a big impact on the generation of the LLRs.



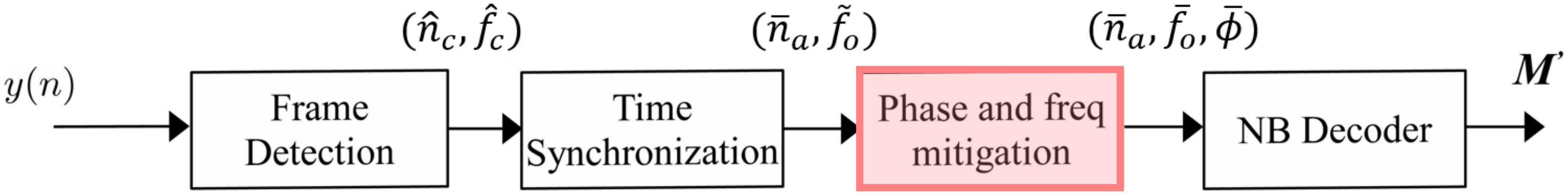
Phase error $e_\beta = \pi/6$

SNR degradation due to e_β

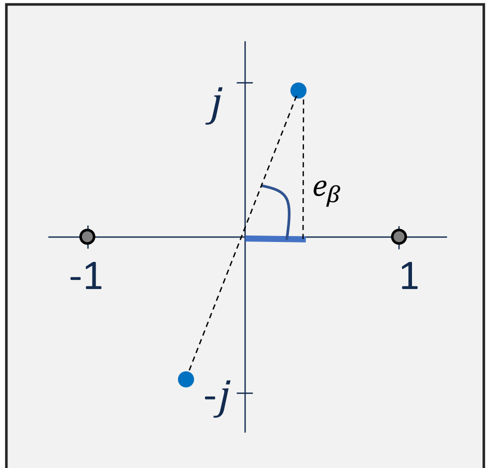
SNR degradation = $10\log_{10}(\cos(e_\beta)^2)$

LLR generation: $\mathrm{Real}(\mathrm{IFFT}(\mathrm{FFT}(\boldsymbol{y})^* \odot \mathrm{FFT}(\boldsymbol{P}_0)))$

Phase synchronization



- ➢ Detection and time-synchronization are not the end of the story.
- ➢ Phase offset has a big impact on the generation of the LLRs.



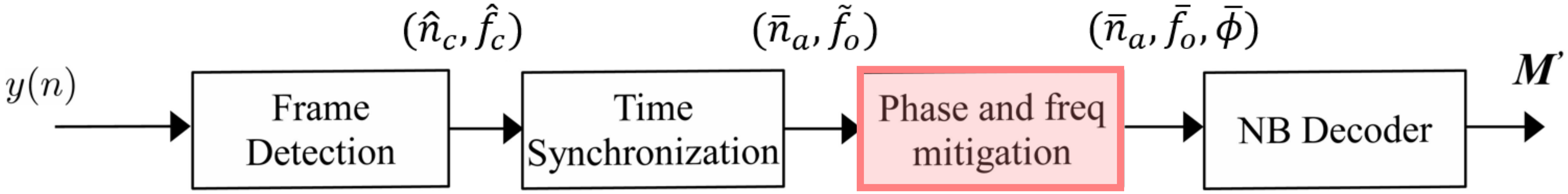
Phase error $e_\beta = \pi/3$

SNR degradation due to e_β

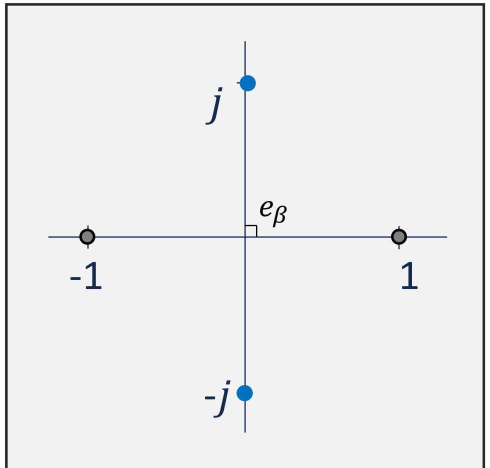
SNR degradation = $10\log_{10}(\cos(e_\beta)^2)$

LLR generation: $\mathrm{Real}(\mathrm{IFFT}(\mathrm{FFT}(\boldsymbol{y})^* \odot \mathrm{FFT}(\boldsymbol{P}_0)))$

Phase synchronization



- ➢ Detection and time-synchronization are not the end of the story.
- ➢ Phase offset has a big impact on the generation of the LLRs.



Phase error $e_\beta = \pi/2$

SNR degradation due to e_β

SNR degradation = $10 \log_{10}(\cos(e_\beta)^2)$

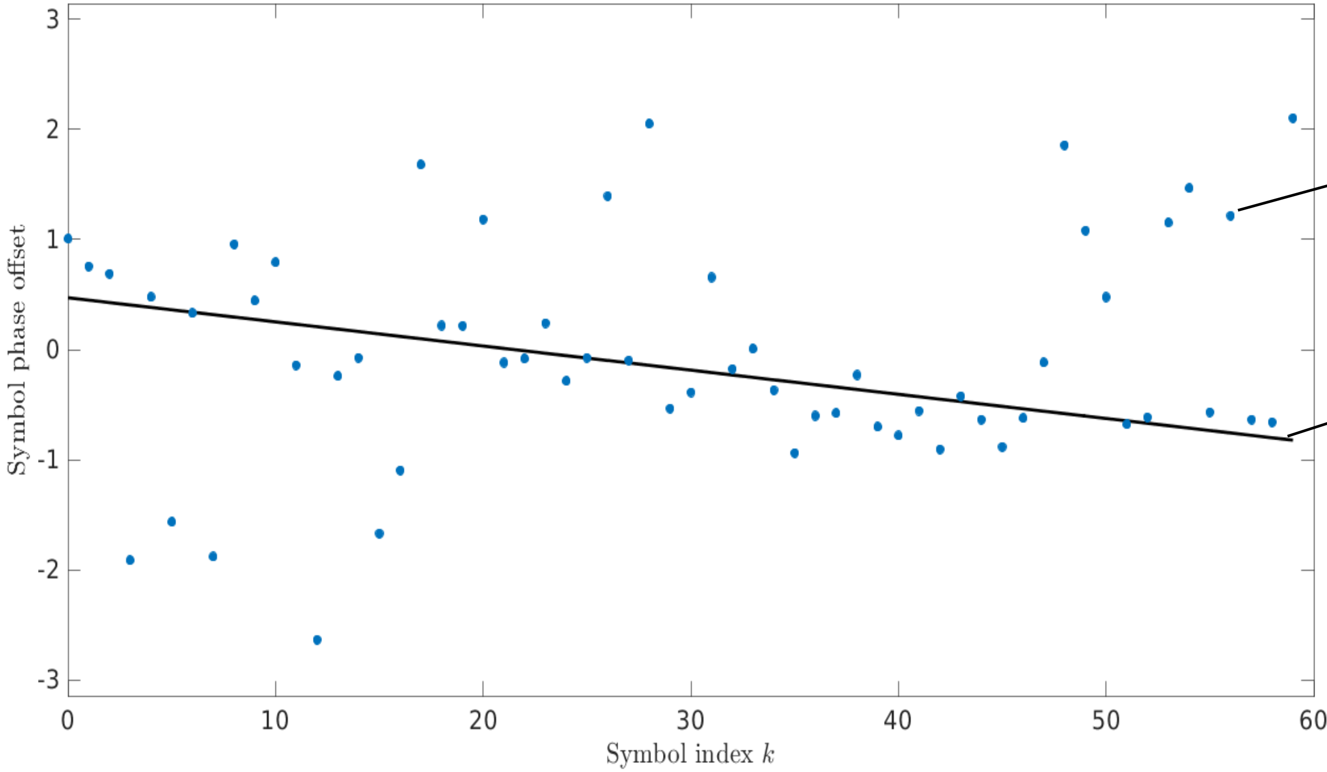
LLR generation: $\text{Real}(\text{IFFT}(\text{FFT}(\boldsymbol{y})^* \odot \text{FFT}(\boldsymbol{P}_0)))$

Phase in QCSP frame

Correlation output

$L(k) = e^{j(\omega k + \theta)} A + Z(k)$ where $\omega = 2\pi f_r q$ and $\theta = \varphi_0 + \pi f_r (q-1)$

➔ Phase = $\omega k + \theta + noise$



Obtained phase (noisy):
$\omega k + \theta + noise$

Real phase offsets: $\omega k + \theta$

Phase in QCSP frame

Correlation output

$L(k) = e^{j(\omega k + \theta)} A + Z(k)$ where $\omega = 2\pi f_r q$ and $\theta = \varphi_0 + \pi f_r (q-1)$

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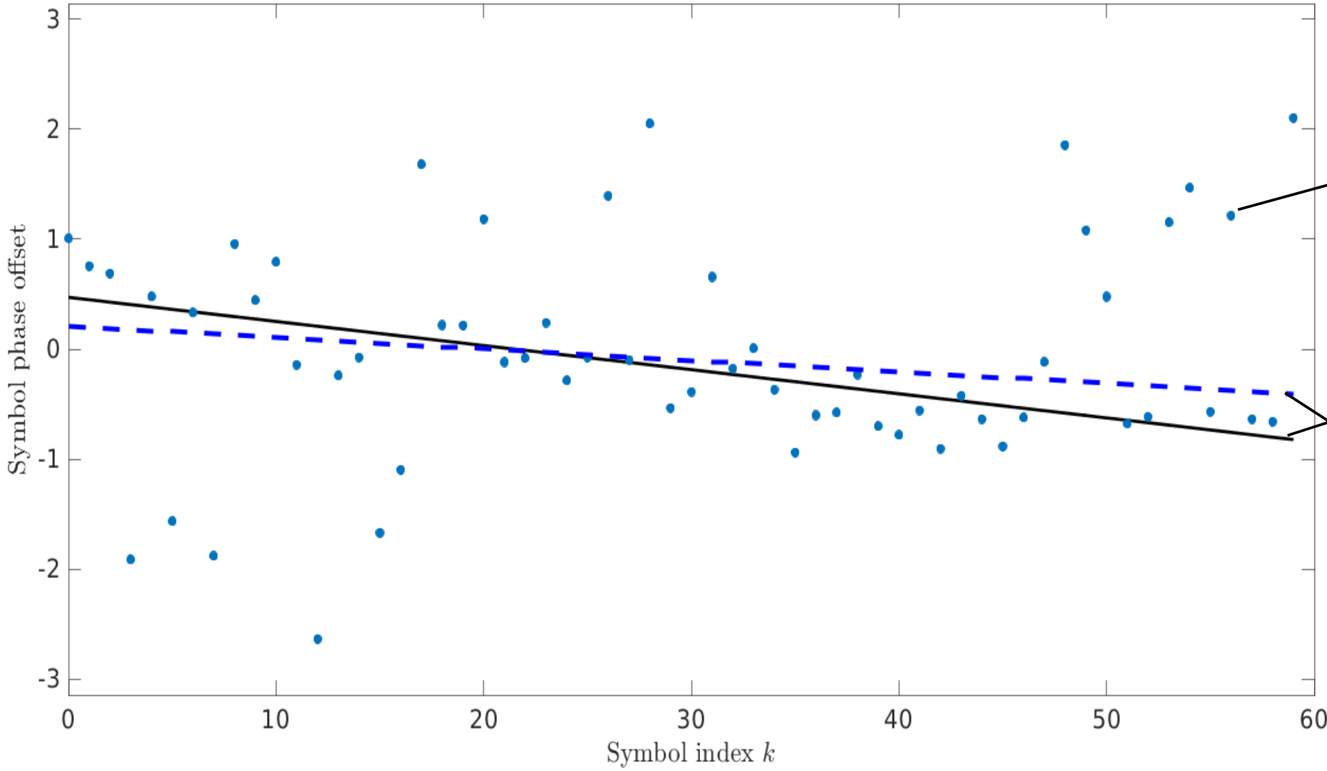


Obtained phase (noisy): $\omega k + \theta + noise$

Real phase offsets: $\omega k + \theta$

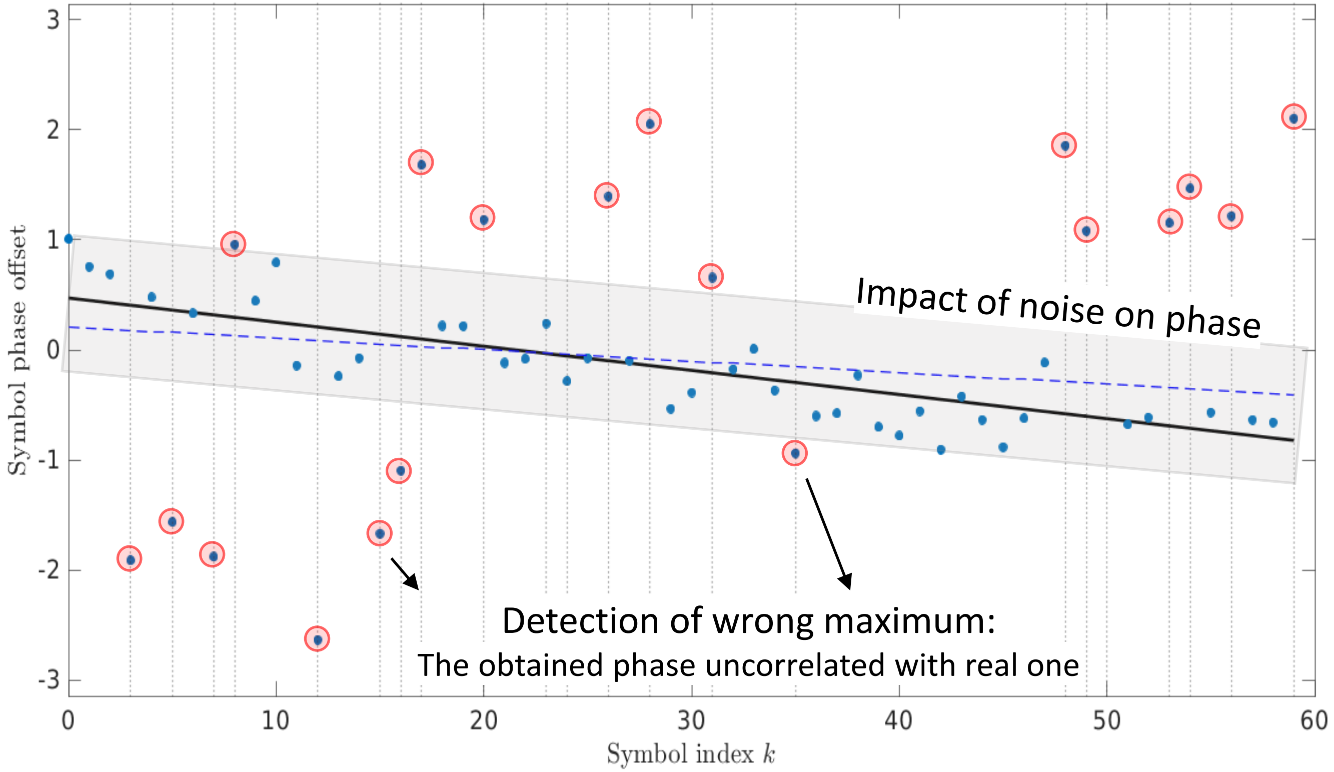
Phase estimation using direct FFT method

Phase in QCSP frame

Correlation output

$L(k) = e^{j(\omega k+\ \theta)}A + Z(k)$ where $\omega = 2\pi f_r q$ and $\theta = \varphi_0 + \pi f_r (q-1)$

➔ Phase = $\omega k + \ \theta + noise$

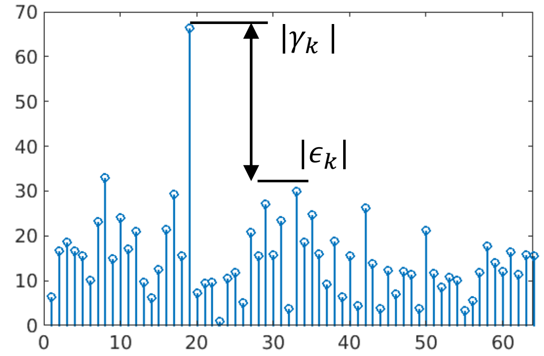


Impact of noise on phase

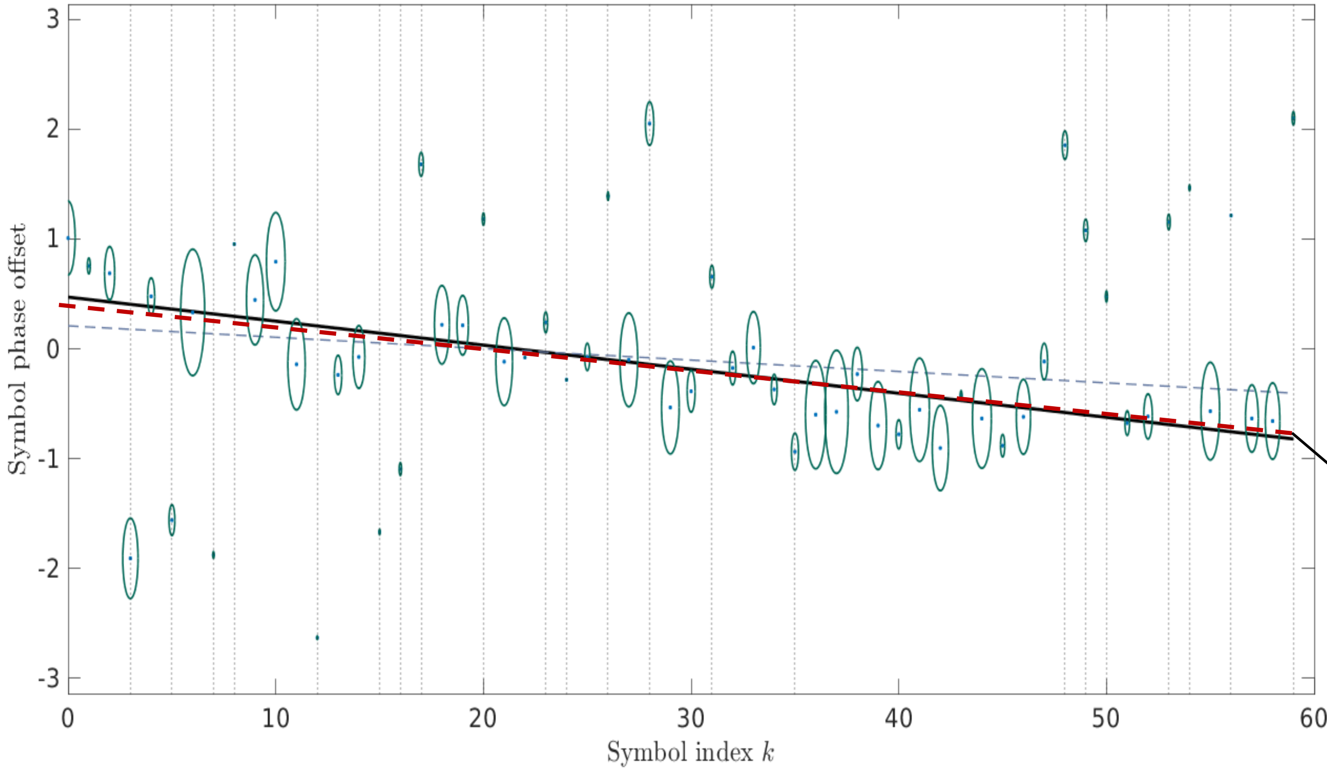
Detection of wrong maximum:
The obtained phase uncorrelated with real one

Phase in QCSP frame: Side information

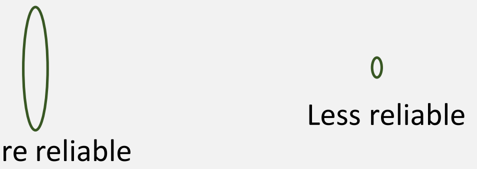
- Estimation using the side information coming from:
  1) **Soft demodulation of the CCSK.**
  2) Error control code



$$\alpha_k = \frac{|\gamma_k| - |\epsilon_k|}{|\gamma_k|}$$



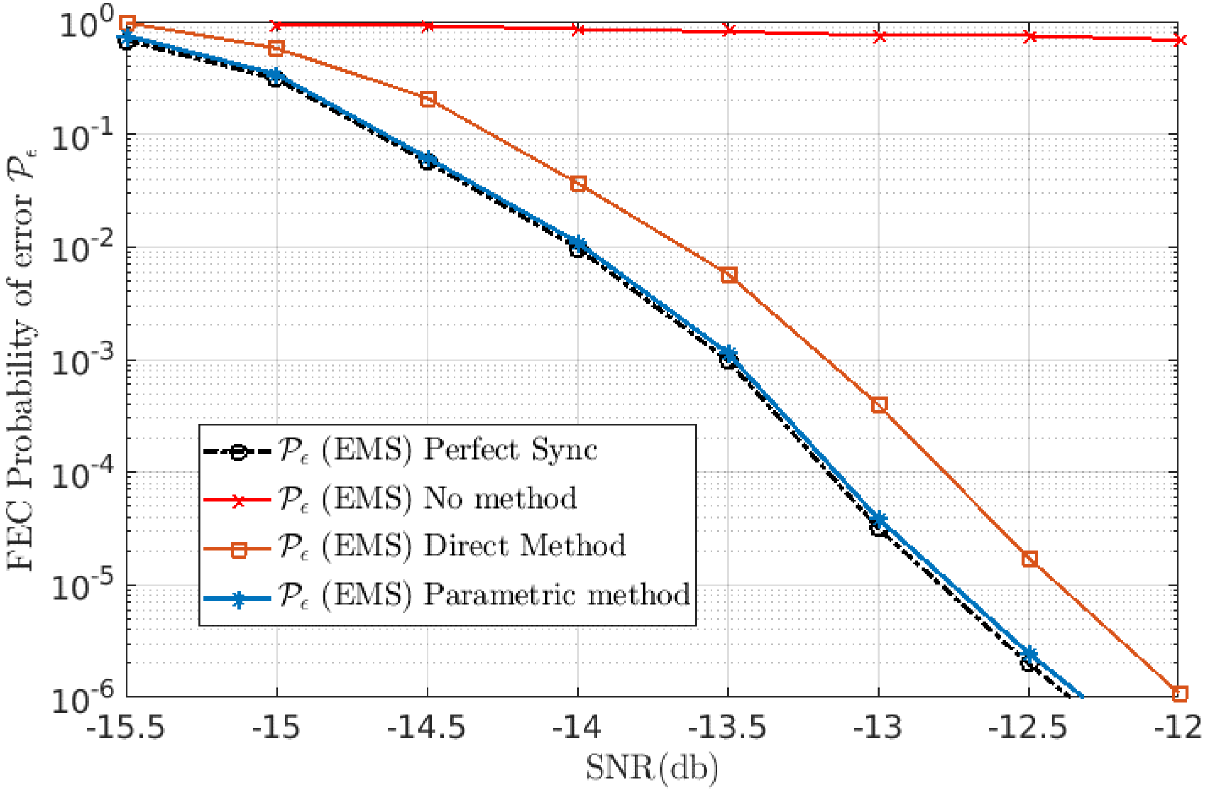
Diameter of the circle is α_k



Phase estimation using direct weighted FFT method by 1) and 2)

Phase synchronization

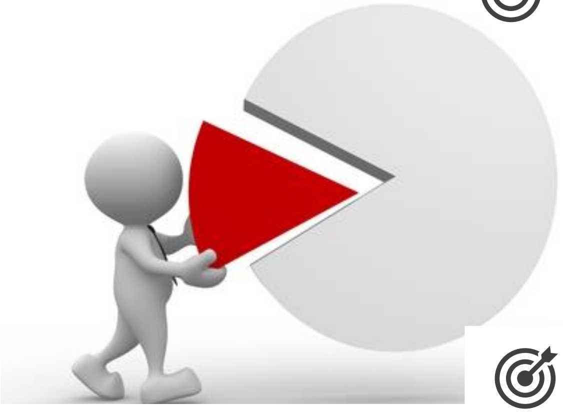
NB-LDPC performance in an AWGN channel with CCSK modulation. QCSP frame $K = 20$ symbols, $R_c = 1/3, q = 64$. The decoding algorithm used is the EMS with 30 decoding iterations.



[Ref 5]: Saied, K., Ghouwayel, A. & Boutillon, E., *Phase Synchronization for NB-LDPC Coded CCSK Short Frames in Submitted to the 2022 IEEE Vehicular Technology Conference VTC2022*

Contributions

Synchronization in phase



◎ Proposition of phase and frequency synchronization methods for QCSP

◎ Estimation using FFT with weighted coefficients

◎ Proposition of a parametric method based on the Maximum-likelihood estimation using the parametric probability density function

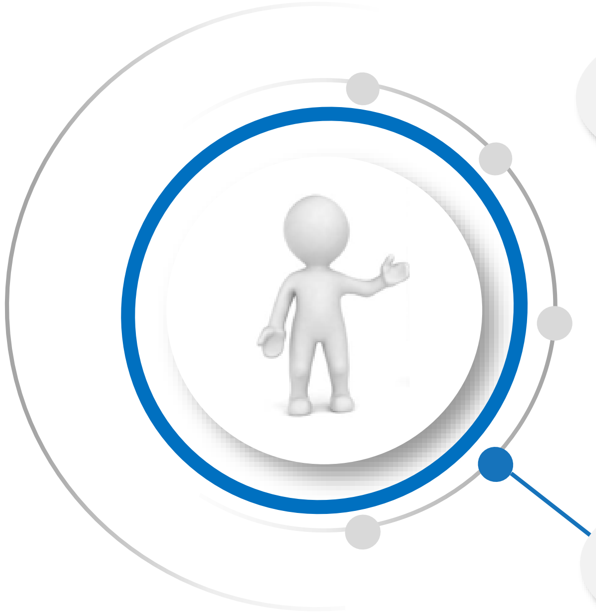
Published in:

[Pub 4]: K. Saied, A. Al Ghouwayel, and E. Boutillon, "Phase Synchronization for Non-Binary Coded CCSK Short Frames", *accepted in the 2022 IEEE 95th Vehicular Technology Conference: VTC2022-Spring*.

[Deliv 2]: K. Saied and E. Boutillon.”Blind Synchronization Algorithm for QCSP Frames”. [Online]. Available: https://qcsp.univ-ubs.fr/wp-content/uploads/2022/01/QCSP_Synchronization.pdf

Outline

- General context
- System model
- Detection
- Synchronization
- **QCSP performance** ○○
- GNU Radio
- Conclusion and Perspectives



QCSP system model

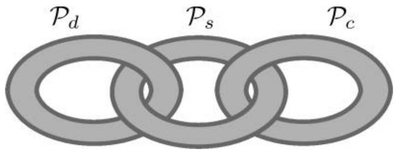
Blind detection algorithm for QCSP

Self synchronization algorithm for QCSP

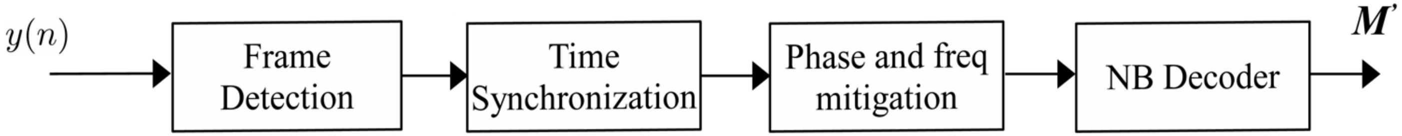
QCSP system performance

Conclusion and perspectives

QCSP system performance



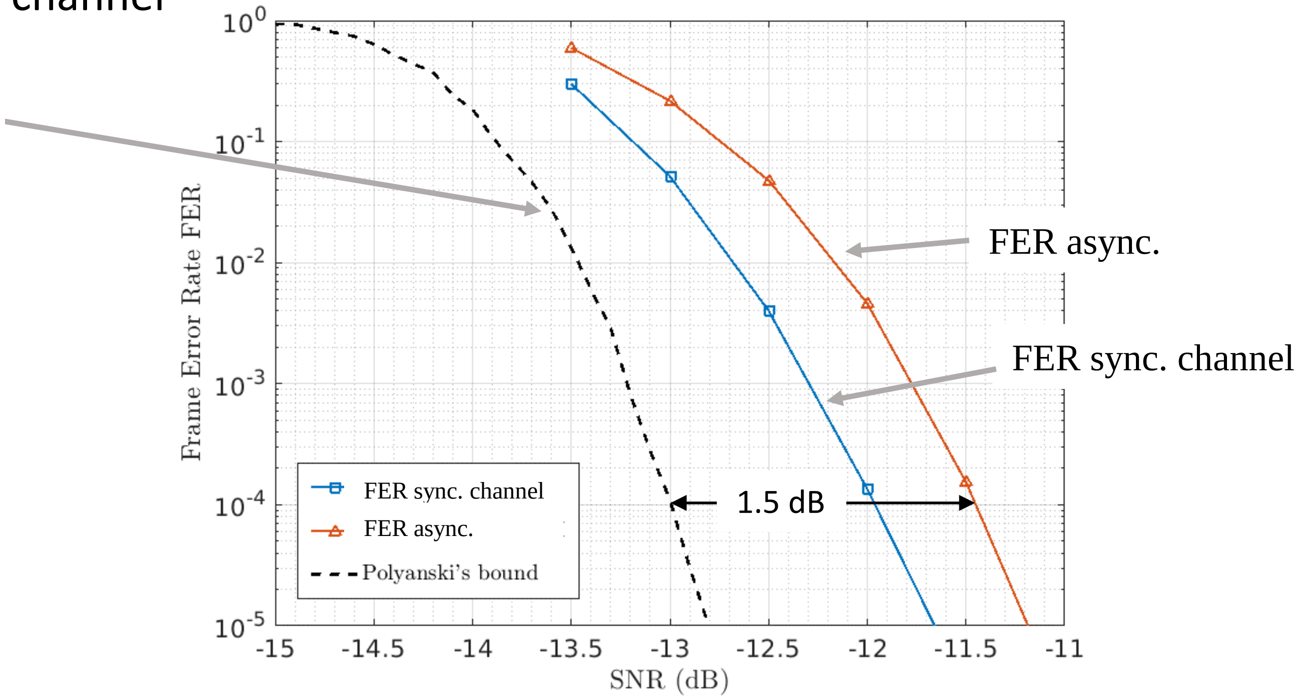
Overall probability at the receiver side



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

Asynchronous AWGN channel

Theoretical Lower bound [ref 6,ref 7]



FER async.

FER sync. channel

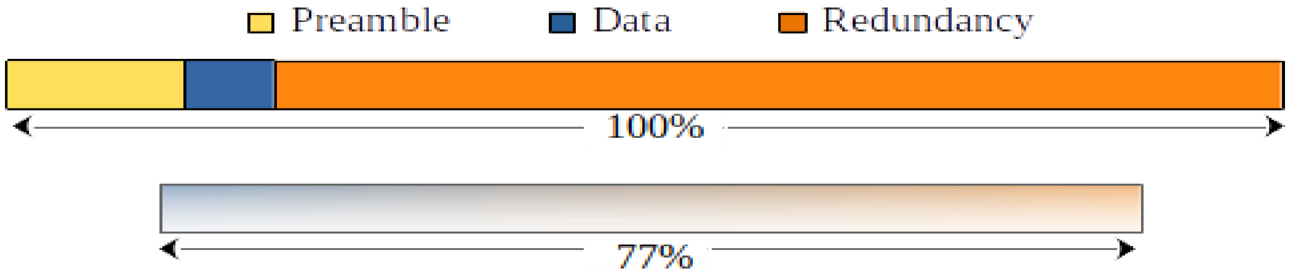
[Ref 6]: Polyanskiy, Y., Poor, H. V. & Verdu, S., Channel Coding Rate in the Finite Blocklength Regime, *IEEE Transactions on Information Theory* **56,** 2307–2359, issn: 1557-9654 (May 2010).
[Ref 7]: Savin, V., *Non-Binary Polar Codes for Spread-Spectrum Modulations in 2021 11th International Symposium on Topics in Coding (ISTC)* (2021), 1–5.

Comparison with a classical frame

Detection-correction with optimal synchronization

Aiming to do the comparison with up-to-date codes, we build an adhoc solution taking elements from the Narrowband IoT (NB-IoT) 3GPP standard [ref 8].

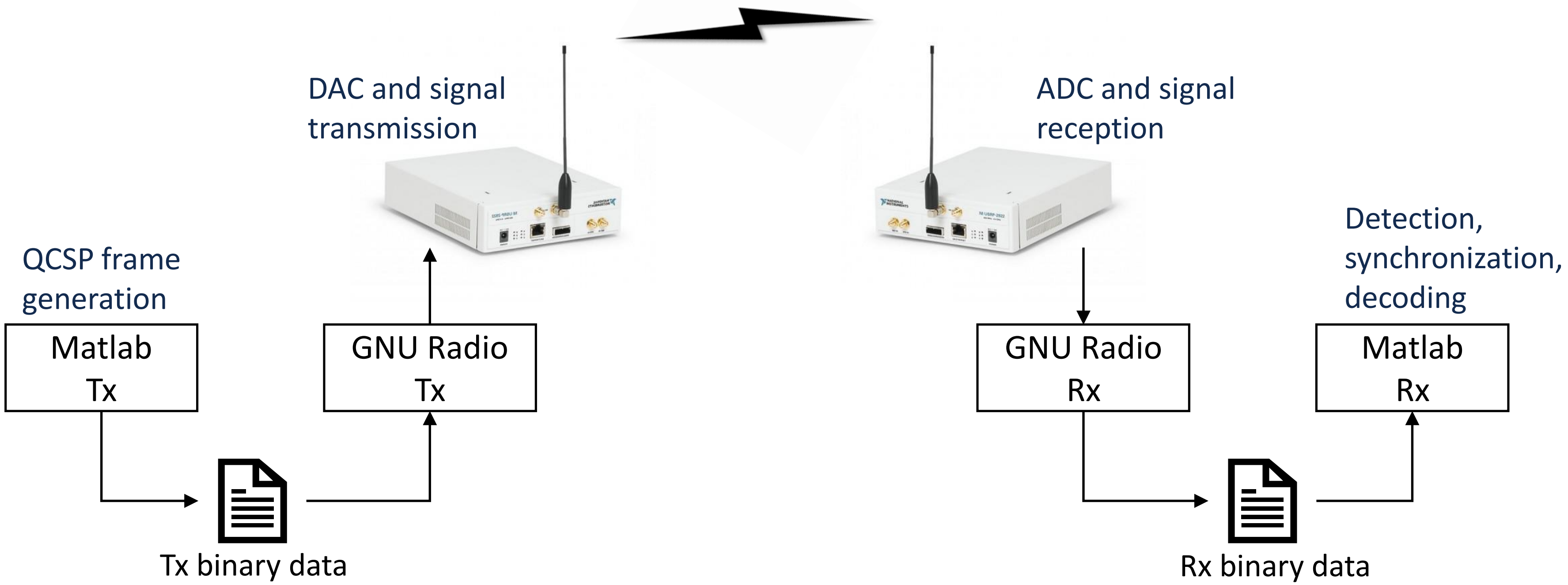
- At SNR ≈ -12 dB:
  - Preamble *p* = 793 Zadoff–Chu sequence to guarantee $\mathcal{P}_{md} = 10^{-4}$ and $\mathcal{P}_{fa} = 10^{-6}$.
  - For *k* = 360 bits (60 symbols) frame length with a classical solution is 9973 symbols.
  - perfectly synchronized.
- The size of the proposed QCSP sequence is 7680 (60 × 2 × 64).
- Using QCSP frame provides a frame size reduced by 23%.
- This 23% saving translates directly into an increase of the wireless channel capacity and in energy saving for the wireless sensors.



[Ref 8]: 43GPP. *Performance evaluation of LDPC codes for NR eMBB data*. Discussion and decision R1-1713740. Version 6.1.4.1.6. 3rd Generation Partnership Project (3GPP), 2017

Proof of Concept: GNU radio

Offline experimental set-up

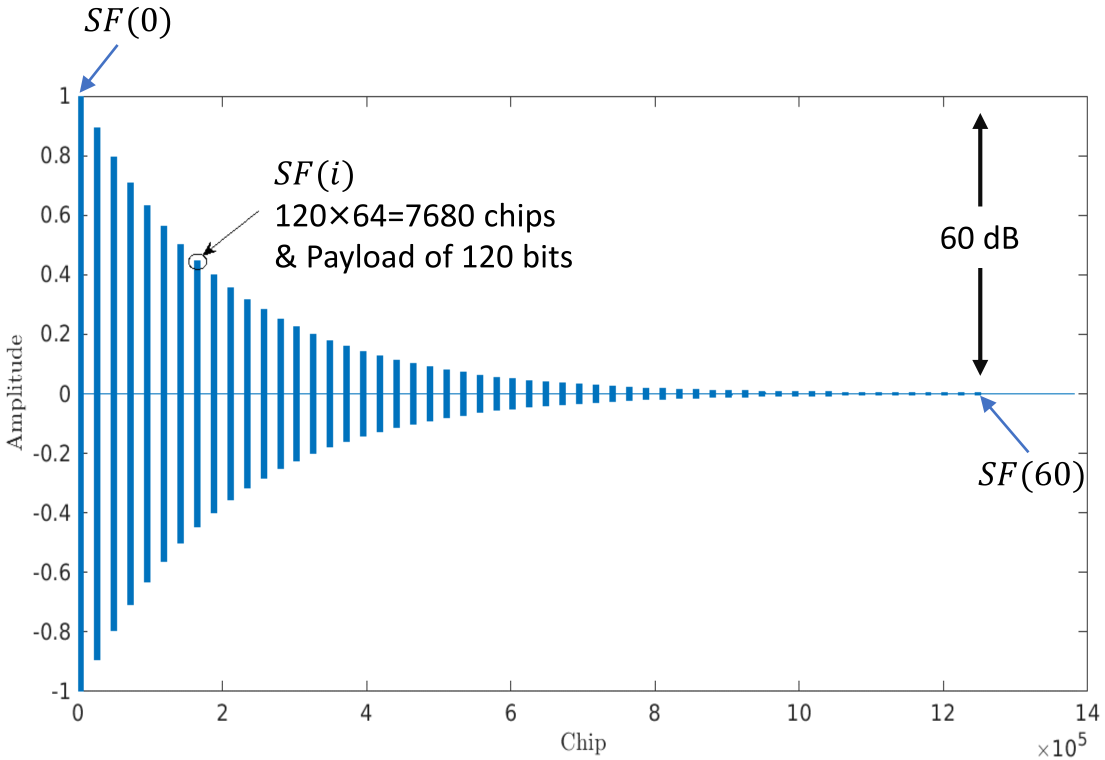


Notes

- ➢ Indoor test across 2 different rooms.
- ➢ Raised cosine filter (0.35).

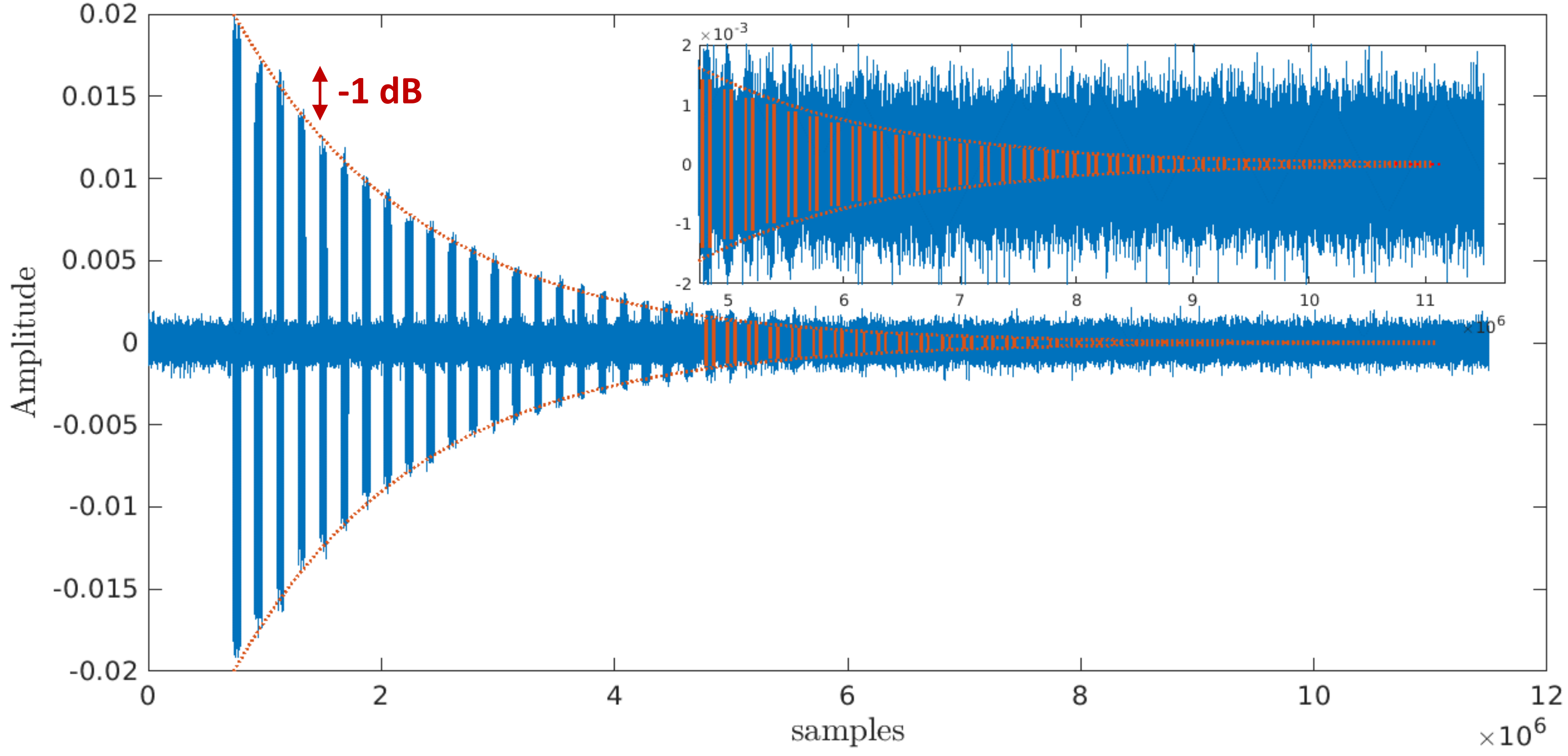
Transmitter: Super-Frame structure

$$\boldsymbol{SF} = \left[\boldsymbol{F} \quad \boldsymbol{Z} \quad \frac{\boldsymbol{F}}{10^{1/20}} \quad \boldsymbol{Z} \quad \frac{\boldsymbol{F}}{10^{2/20}} \quad \boldsymbol{Z} \ \ldots \ \boldsymbol{Z} \quad \frac{\boldsymbol{F}}{10^{60/20}} \right]$$



- Super-Frame (SF) composed of 60 QCSP frames.
- QCSP frame: $N = 120, q = 64$ chips and $R_c = 1/2$ NB-LDPC code over GF(64).
- -1 dB of energy between two consecutive frames

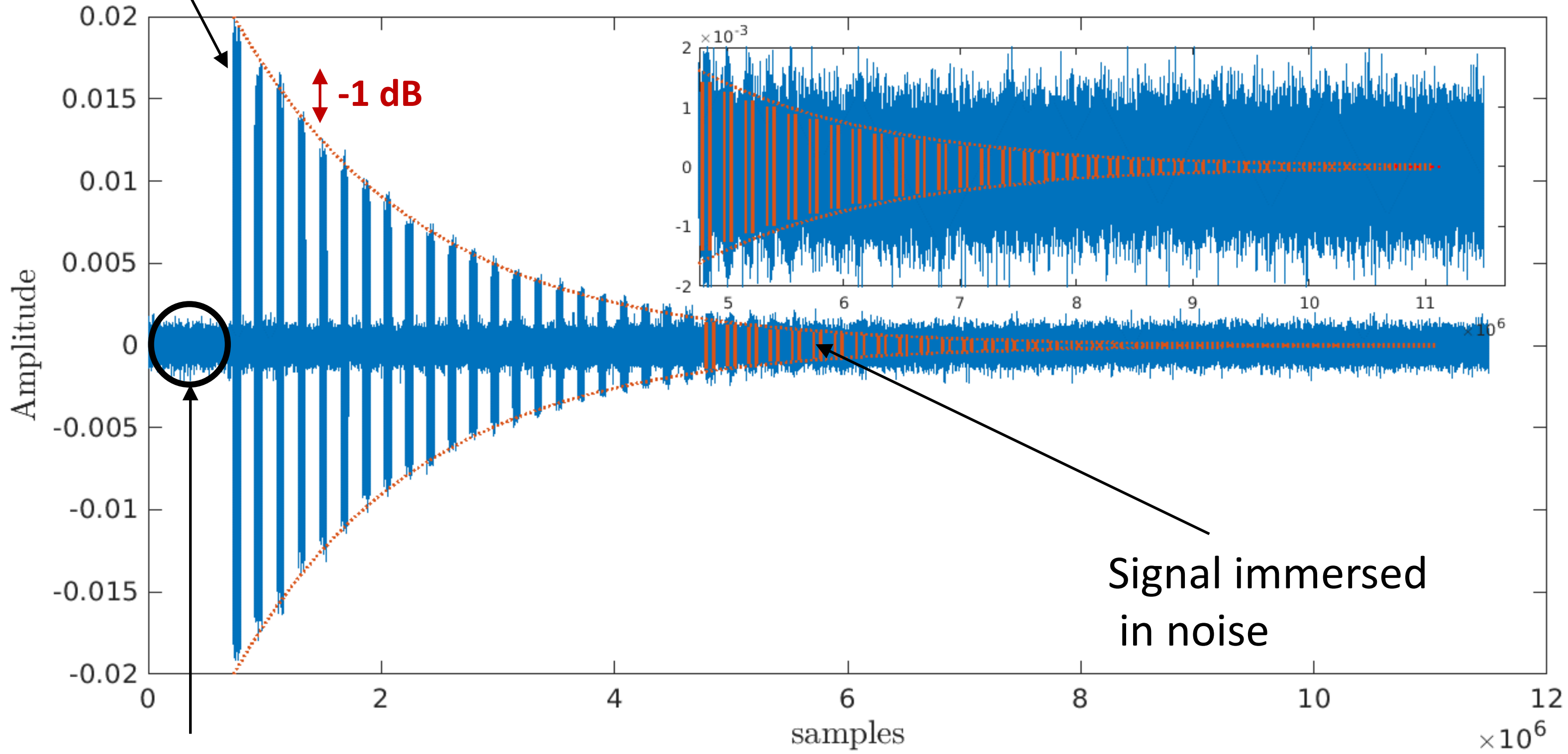
Receiver side



Receiver side

$$\text{SNR} = \frac{P_r - P_n}{P_n}$$

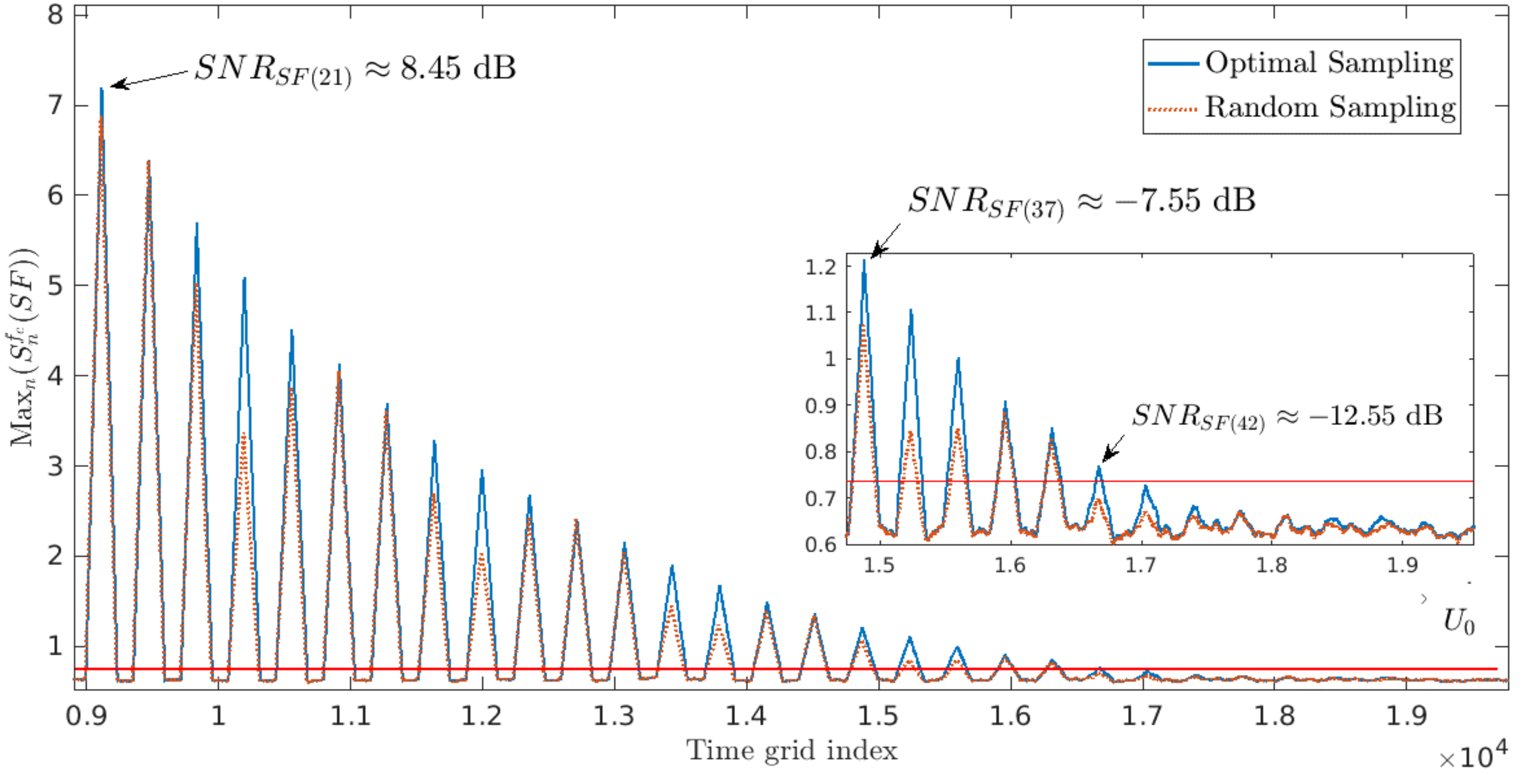
Calculation of power received signal P_r



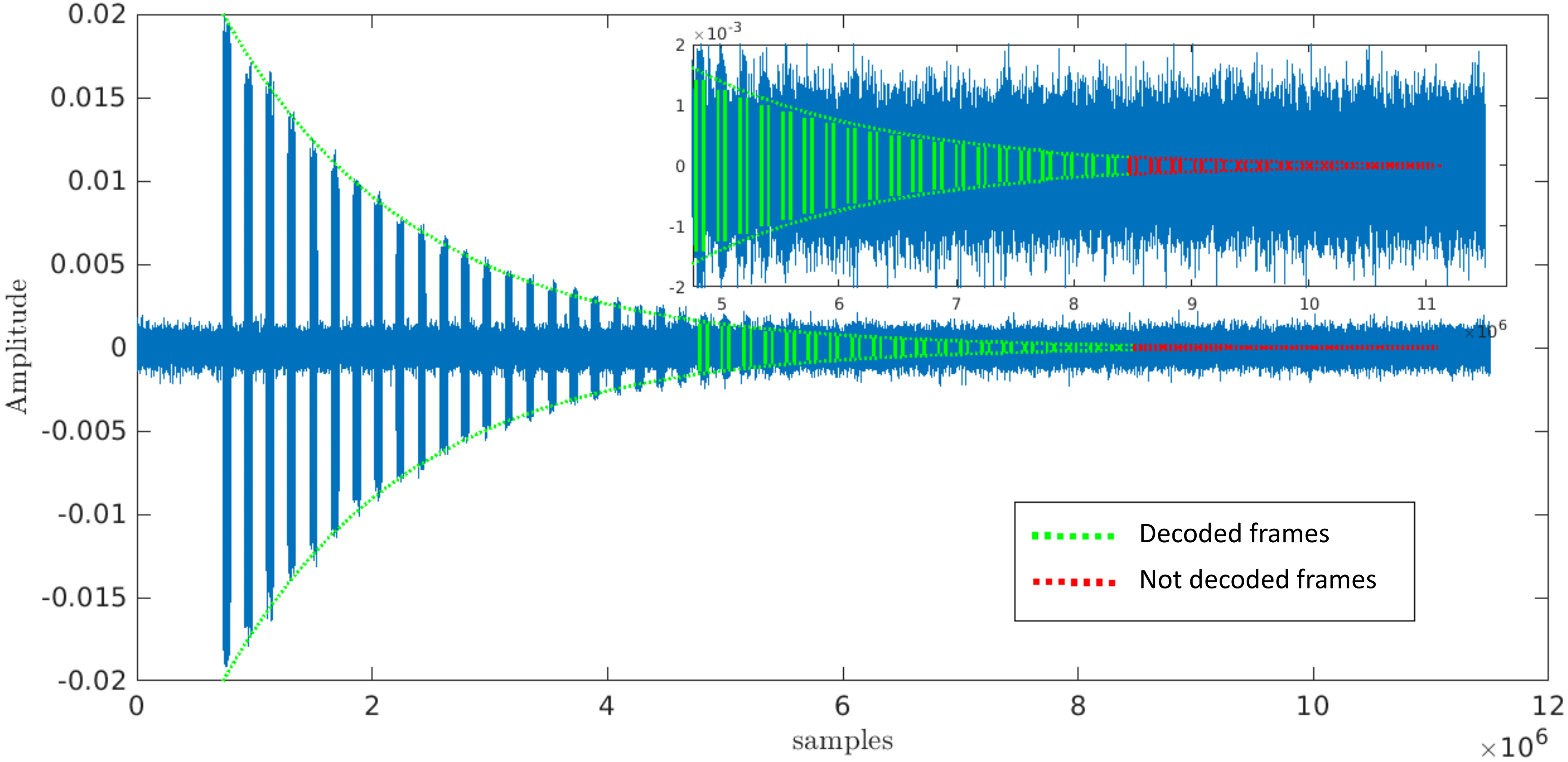
Signal immersed in noise

Calculation of power of noise P_n

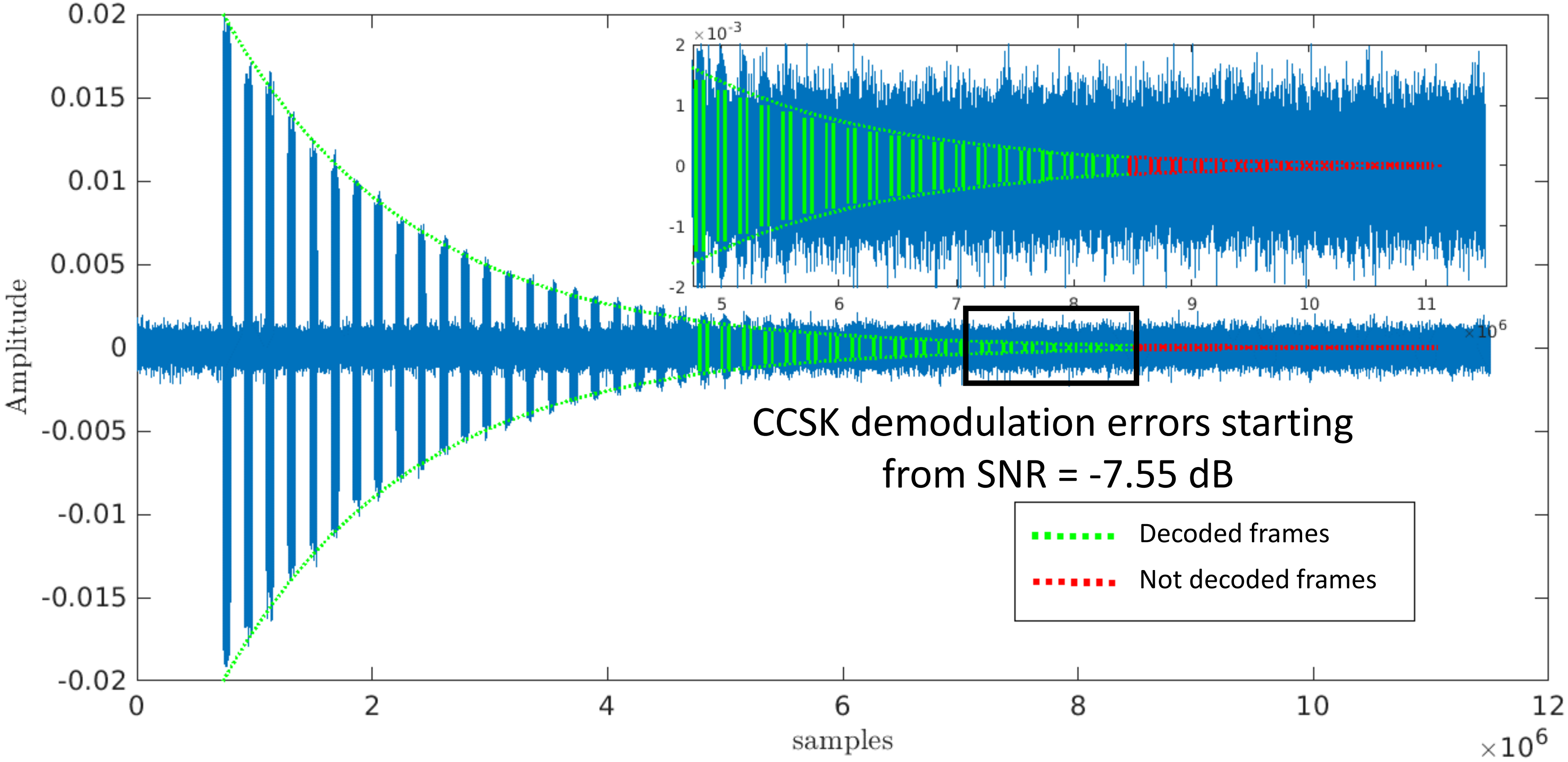
Output of detection filter



Results

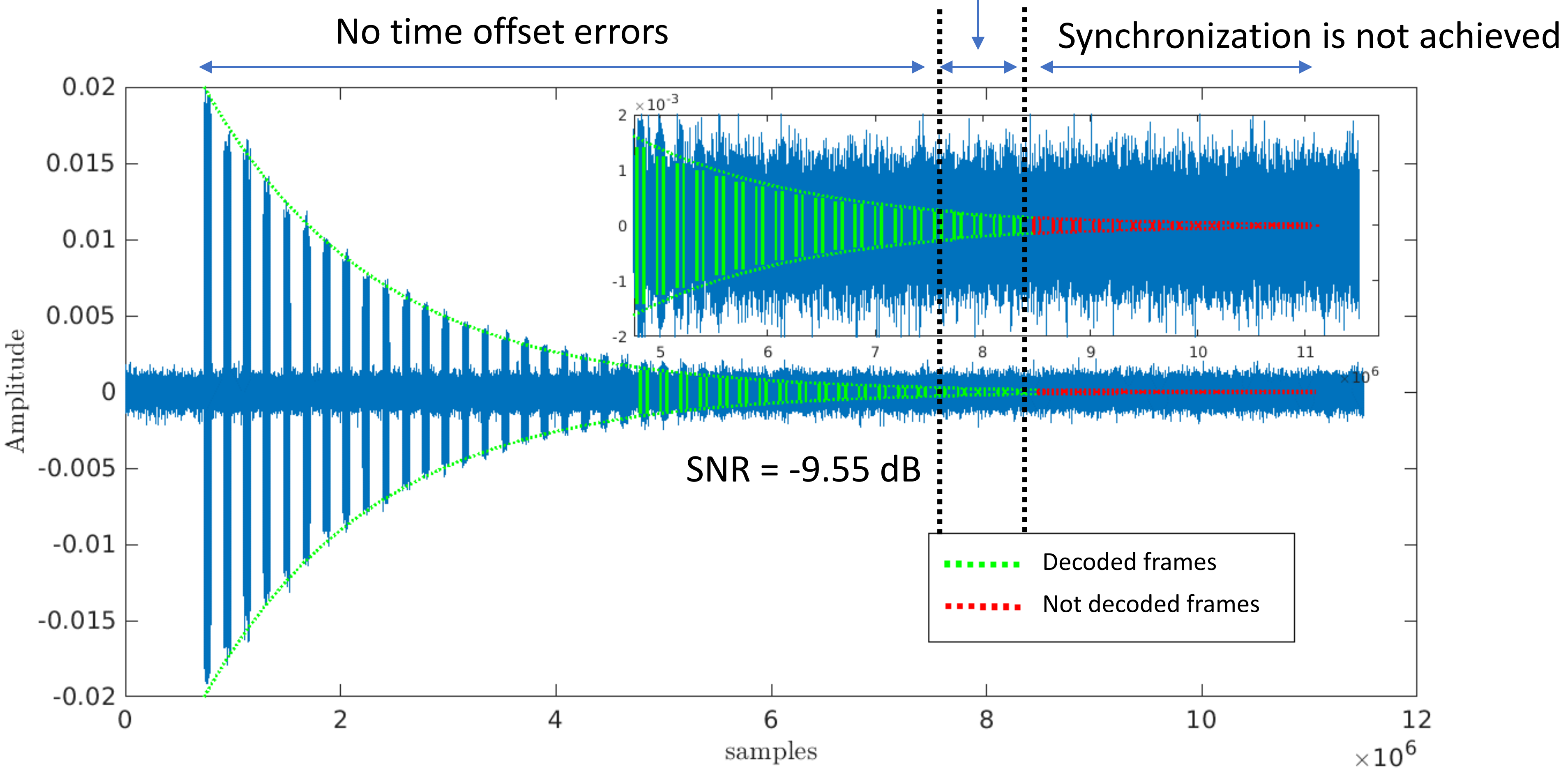

Amplitude
samples
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
0
2
4
6
8
10
12
$\times10^6$
$\times10^{-3}$
2
1
0
-1
-2
5
6
7
8
9
10
11
$\times10^6$
Decoded frames
Not decoded frames

Results



CCSK demodulation errors starting from SNR = -7.55 dB

Results



Synchronization using the proposed methods

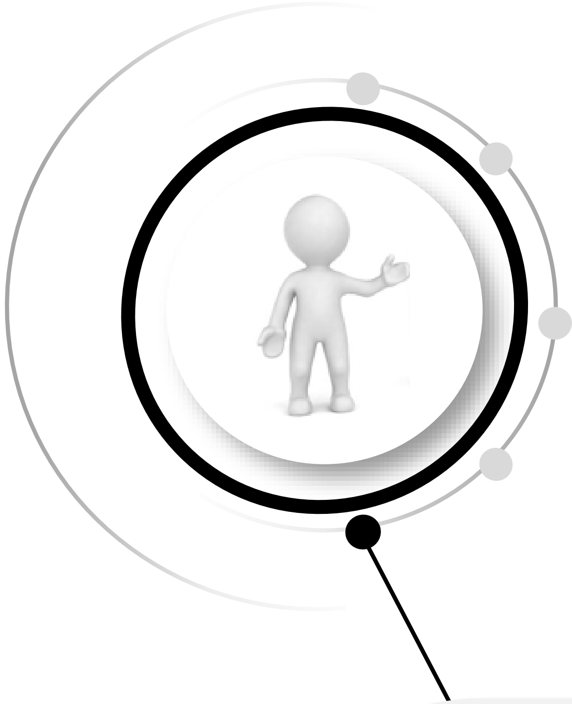
No time offset errors

Synchronization is not achieved

SNR = -9.55 dB

Outline

General context
System model
Detection
Synchronization
QCSP performance
GNU Radio
Conclusion and Perspectives



- QCSP system model
- Blind detection algorithm for QCSP
- Self synchronization algorithm for QCSP
- QCSP system performance
- **Conclusion and perspectives**

Conclusion

Preamble-less frames for short packet transmission at very low SNRs

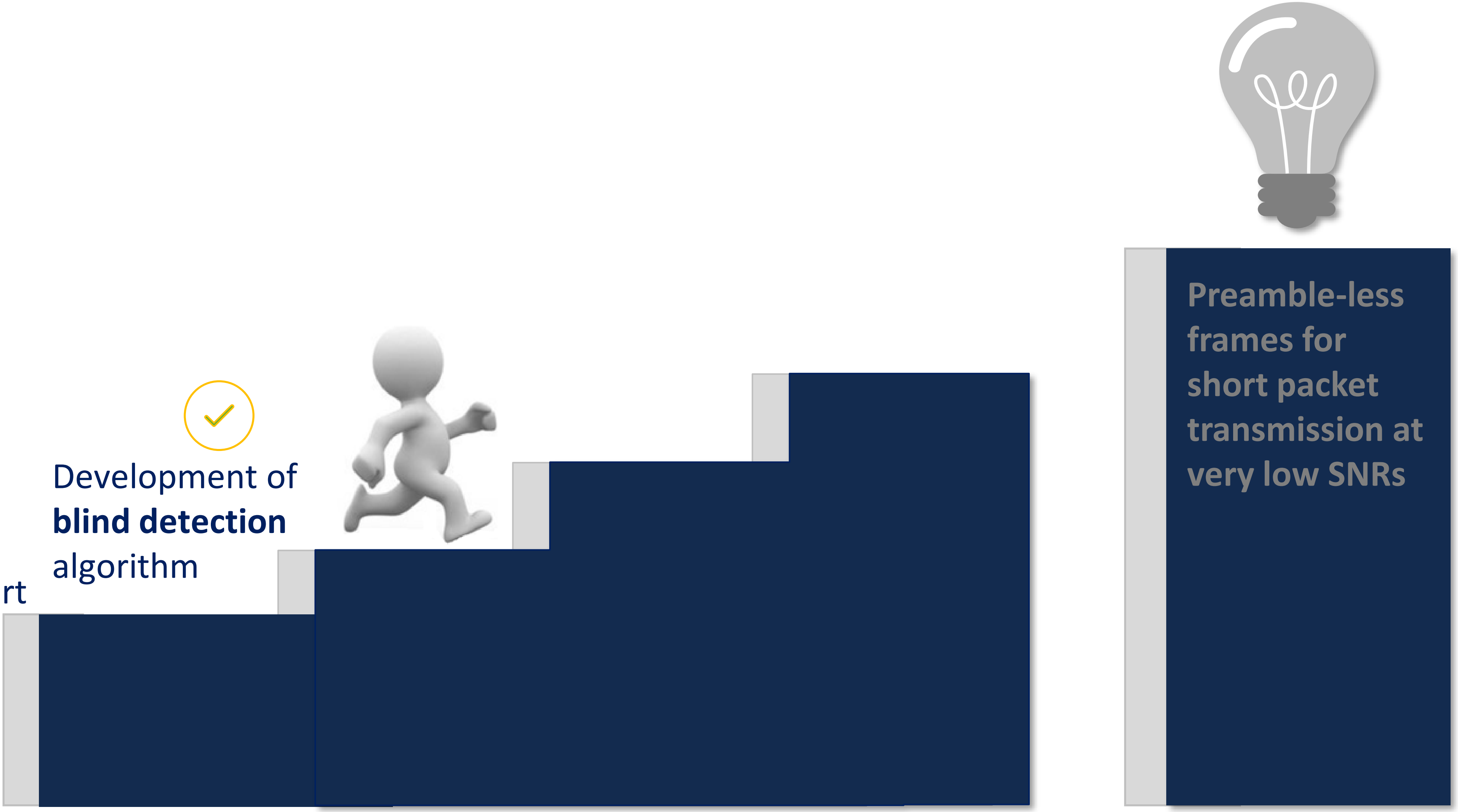
Conclusion

✓

Quasi-Cyclic Short Packet (QCSP) Validation

Preamble-less frames for short packet transmission at very low SNRs

Conclusion



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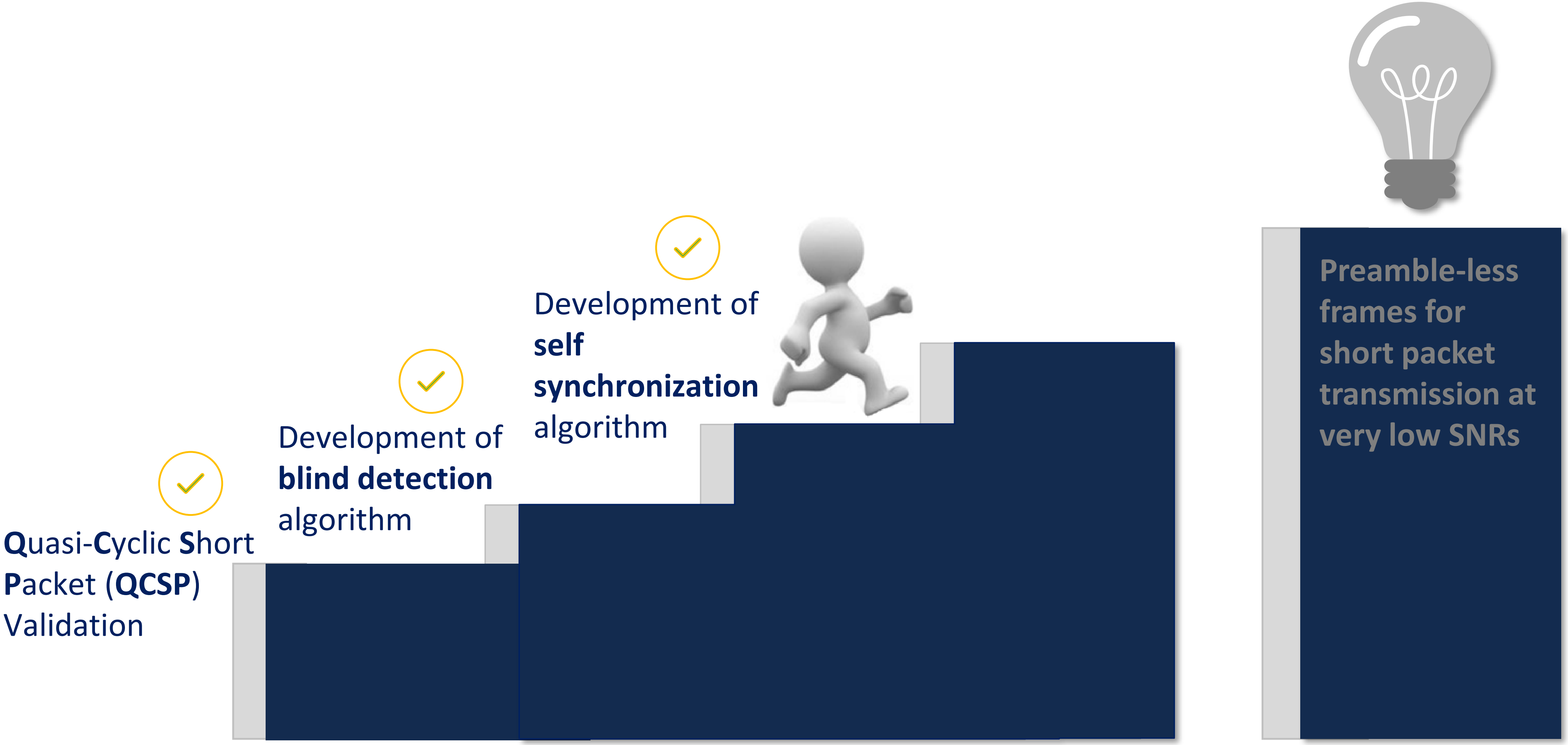
Development of **blind detection** algorithm

Preamble-less frames for short packet transmission at very low SNRs

Conclusion



✓

Quasi-**C**yclic **S**hort **P**acket (**QCSP**) Validation

✓

Development of **blind detection** algorithm

✓

Development of **self synchronization** algorithm

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Conclusion

✓

Quasi-**C**yclic **S**hort **P**acket (**QCSP**) Validation

✓

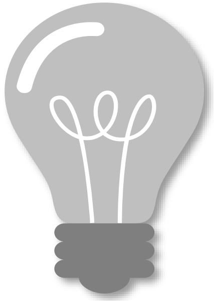
Development of **blind detection** algorithm

✓

Development of **self synchronization** algorithm

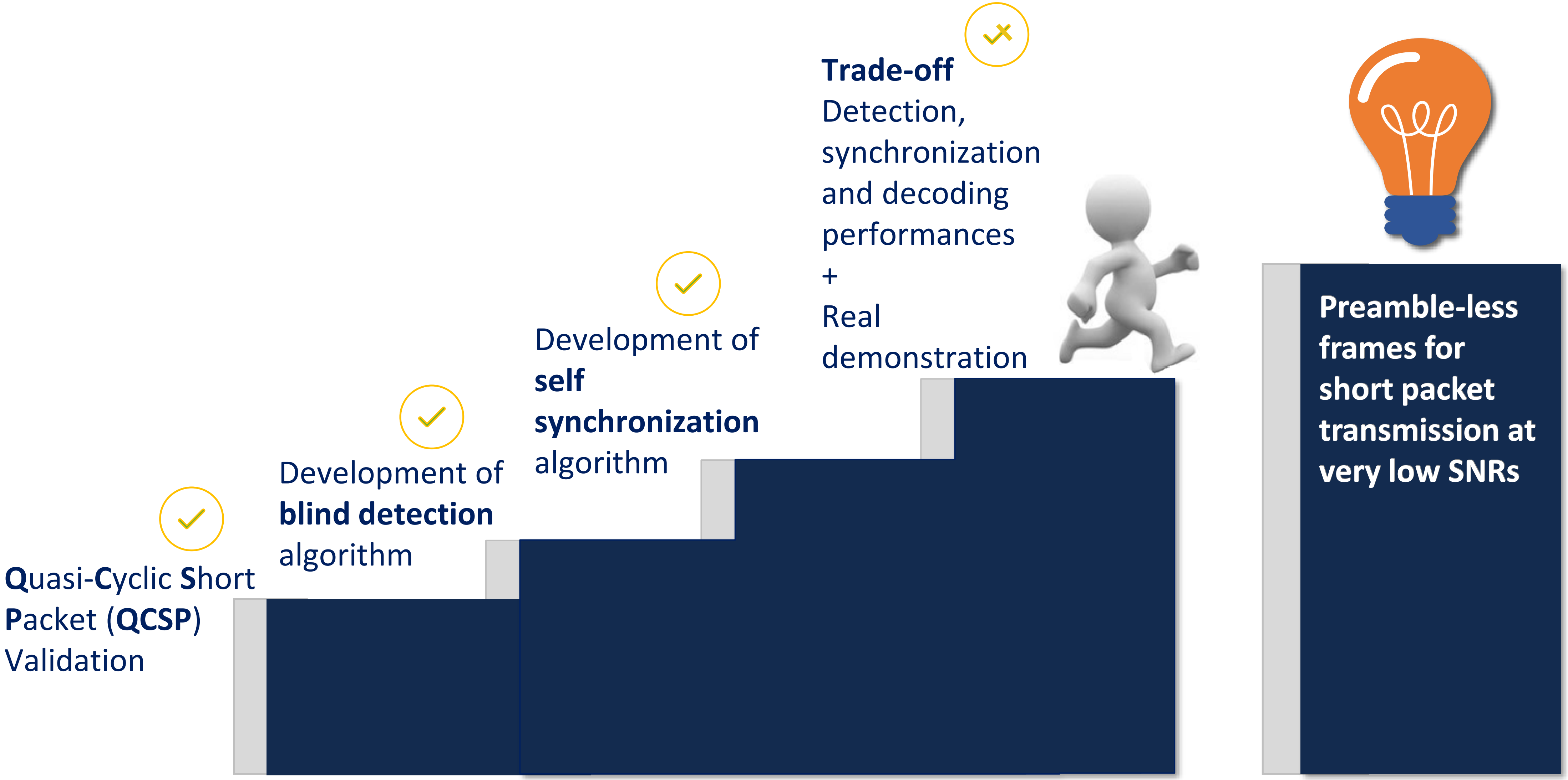
✓✗

Trade-off
Detection, synchronization and decoding performances
+
Real demonstration



Preamble-less frames for short packet transmission at very low SNRs

Conclusion



✓ Quasi-Cyclic Short Packet (**QCSP**) Validation

✓ Development of **blind detection** algorithm

✓ Development of **self synchronization** algorithm

✓ **Trade-off** Detection, synchronization and decoding performances + Real demonstration

Preamble-less frames for short packet transmission at very low SNRs

Perspectives

General context

System model

Detection

Synchronization

QCSP performance

GNU Radio

Conclusion and Perspectives

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Improving point to point communication (use of Zadoff-Chu sequence, use of NB-Turbo codes, OM in detection, …)

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Experimentation of QCSP in the context of **IoT multi-user access** and **LTE channel**.

(CortexLab enviroment)

Perspectives:

Toward the multi-user context

QCSP frame offers many degree of diversity

- Generic diversity:
  - → Time, frequency, space diversity (using MIMO).
- Specific diversity:
  - → Phase (two frames in quadrature are orthogonal).
  - → Spreading sequence of the CCSK modulation.
  - → Overmodulation sequence of the frame.
  - → Error control code associated to each user.

Experimentation of QCSP in the context of **IoT multi-user access** and **LTE channel**.

How to take maximum profit of the available diversity?

Publications

- **Patent:**

  -E. Boutillon and K. Saied, "A method for a transmitter to transmit a signal to a receiver in a communication system, and its corresponding receiving method", July 2021.

- **Journals:**

  -K. Saied, A. Al Ghouwayel, and E. Boutillon, "Quasi Cyclic Short Packet for Asynchronous Preamble-Less Transmission in Very LowSNRs", *in IEEE Transaction journal on Wireless Communication (TWC), March 2022, p. 1 - 13*.

  -C. Moniere, K. Saied, B. Legal, and E. Boutillon, extention of "Time sliding window for the detection of CCSK frames", *to be submitted to IEEE Open Journal of the Computer Society (OJCS) –**To be submitted soon***.

- **Conferences:**

  -K. Saied, A. Al Ghouwayel, and E. Boutillon, "Blind Time-Synchronization of CCSK Short Frames", *in The 17th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob21)*, Oct. 2021, Bologna, Italy.

  -C. Moniere, K. Saied, B. Legal, and E. Boutillon, "Time sliding window for the detection of CCSK frames", *in the IEEE Workshop on Signal Processing Systems (SiPS'2021)*, Oct. 2021, Combria, Portugal.

  -K. Saied, A. Al Ghouwayel, and E. Boutillon, "Phase Synchronization for Non-Binary Coded CCSK Short Frames", *accepted in the 2022 IEEE 95th Vehicular Technology Conference: VTC2022-Spring*. **(Accepted)**

  -L. Camacho, K. SAIED, and E. Boutillon, "QCSP detection using Over-Modulation at very low SNRs".**(in progress)**

- **Deliverables to ANR**

  -K. Saied and E. Boutillon."Blind Detection Algorithm for QCSP Frames". [Online]. Available: https://qcsp.univ-ubs.fr/wp content/uploads/2022/01/QCSP_Detection-1.pdf

  -K. Saied and E. Boutillon."Blind Synchronization Algorithm for QCSP Frames". [Online]. Available: https://qcsp.univ-ubs.fr/wp-content/uploads/2022/01/QCSP_Synchronization.pdf

Thank you !