Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Simulation Framework for Recommending Preambles for 4ab
Date Submitted: 23 August, 2022
Source: Vinod Kristem, Xiliang Luo, Moche Cohen (Apple Inc.)
Address: One Apple Park Way, Cupertino, CA 95104, USA
E-Mail: vinod.kristem@gmail.com

Abstract: This document proposes a simulation framework to evaluate the new preamble codes introduced in 4ab, and provides the performance of Golay codes

Purpose: To converge on a common framework to evaluate the new codes being proposed in 802.15.4ab

PAR Objective	Proposed Solution (how addressed)
Safeguards so that the high throughput data use cases will not cause significant disruption to low duty-cycle ranging use cases	
Interference mitigation techniques to support higher density and higher traffic use cases	Proposed sequences offer flexible multi-user interference mitigation
Other coexistence improvement	
Backward compatibility with enhanced ranging capable devices (ERDEVs)	
Improved link budget and/or reduced air-time	
Additional channels and operating frequencies	
Improvements to accuracy / precision / reliability and interoperability for high-integrity ranging	
Reduced complexity and power consumption	Proposed sequences allows efficient construction
Hybrid operation with narrowband signaling to assist UWB	
Enhanced native discovery and connection setup mechanisms	
Sensing capabilities to support presence detection and environment mapping	
Low-power low-latency streaming	
Higher data-rate streaming allowing at least 50 Mbit/s of throughput	
Support for peer-to-peer, peer-to-multi-peer, and station-to-infrastructure protocols	
Infrastructure synchronization mechanisms	

apEval Simulation Framework

apEval (4ab preamble Evaluation) Framework - 1

- INPUT
  - Set1: set of **target codes**
    - e.g. Set1 = {new preamble codes for 4ab}
  - Set2: set of **interfering codes**
    - e.g. Set2= {16 length-127 Ipatov codes} or {8 length-91 Ipatov codes} or the union of these
  - Number of preamble symbol repetitions (PSR) : R_1 for Set1, R_2 for Set2
    - Can set both to be the same by default. Allow to configure them differently for more checking
  - Gap of size: G
    - IntfGapFlag: 0: no gap for interference codes; 1: add gap to interference codes (only matter when interference code is also Golay)
  - Data/STS collision prob: p
  - Relative CFO: Δf_{max}
    - 40 ppm, channel 9
  - Spreading mode:
    - Common spreading: L_1=L_2=4
    - More spreading modes can be defined

- RUN Monto Carlo Sims
  - Details are in the following slide

- OUPUT
  - With a PSR value of R_1 for the target sequences, gap size G, and data collision probability p
    - 90-percentile cross-correlation for all sequences from Target codes (Set1) wrt the Interference codes (Union of Set1 and Set2)
    - 90-percentile cross-correlation for individual sequence in Target codes (Set1) wrt the Interference codes (Union of Set1 and Set2)

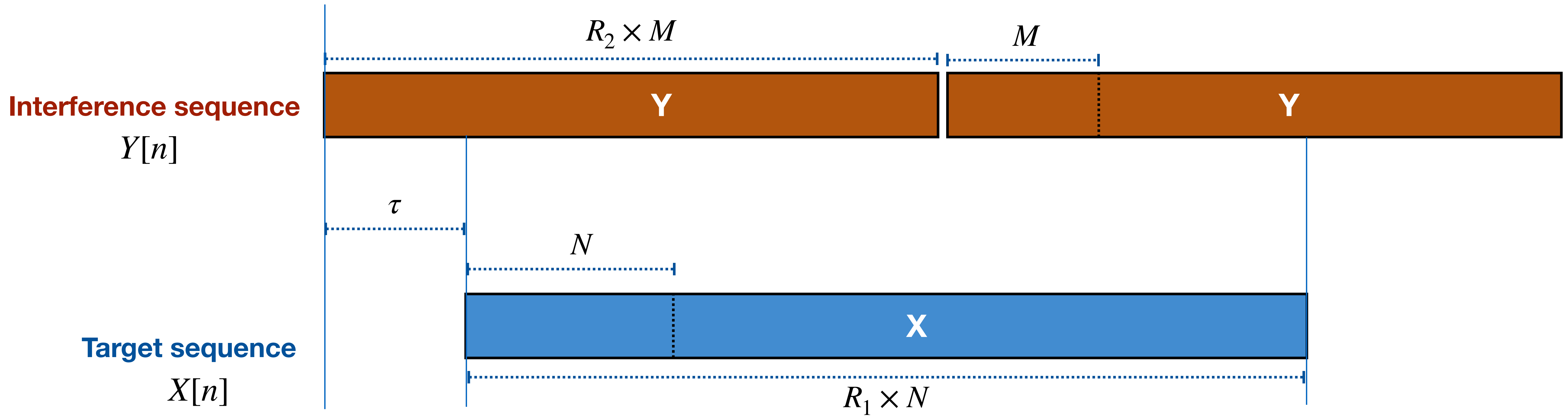
apEval Framework - 2

- For each x in the set: Set1, carry out the following Monto Carlo sims:
  - Construct a preamble symbol x' from x after spreading by L_1
    - A gap G is introduced before spreading when x is Golay
  - Construct the **target sequence** X by repeating the preamble symbol x' by R_1 times
  - FOR k=1:1000
    - Generate one uniformly distributed random number: $a \in [0,1]$
    - IF $a < p$
      - Generate a sequence Z containing random polarities with spreading factor of L_2
    - ELSE
      - Pick preamble symbol y ($y \neq x$) from the interference code set (Set1∪ Set2)
      - Construct y' by spreading y by a factor of L_2, then repeat symbol y' by R_2 times to get a sequence Z
        - If $\mathtt{IntfGapFlag} > 0$, a gap G is introduced before spreading when y is Golay
    - END IF
    - Generate CFO Δf, uniformly random in the interval $[-\Delta f_{\max}, \Delta f_{\max}]$
    - Apply CFO Δf to the sequence Z and get **interference sequence** Y
    - Compute the cross-correlation metric between $X[n]$ and $Y[n]$
  - END LOOP

Note:
The total number of sequences in both Set1 and Set2 is expected to be in the order of O(100)

apEval Framework - 3

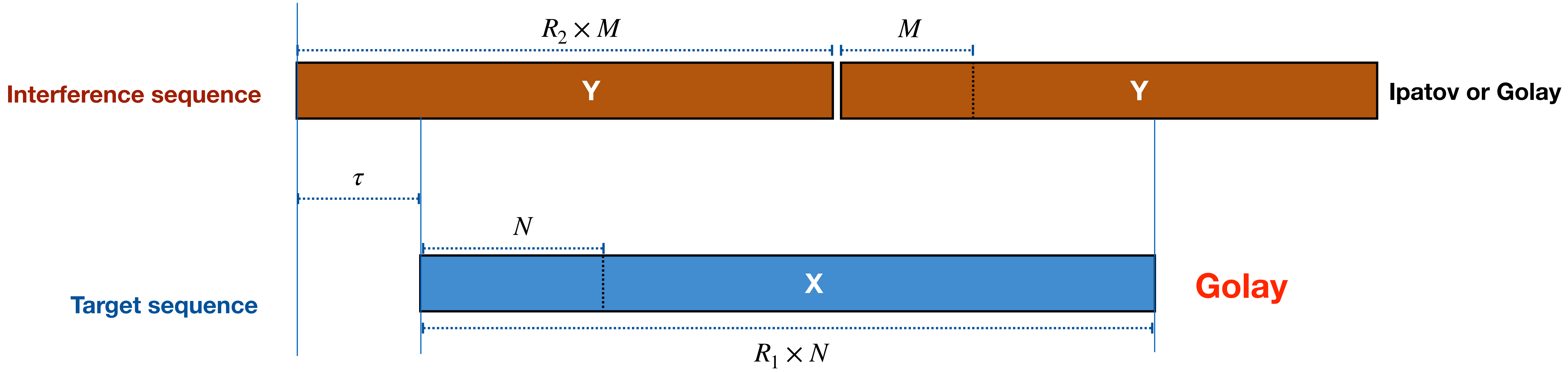
- Cross-Correlation Metric
  - Let N denote the length of x', the length of the **target sequence** $X[n]$ is $R_1 \times N$
  - Let M denote the length of y', the length of the **interference sequence** $Y[n]$ is $R_2 \times M$
  - Normalized Cross-Correlation metric is computed in dB scale as
    - $\max\limits_{\tau \in [0, R_2 M - 1]} \phi[\tau]$
      - where $\phi[\tau] := 20 \log_{10} \left| \dfrac{\sum_{n=0}^{R_1 N - 1} Y[\text{mod}(n+\tau, R_2 M)] \cdot X[n]}{\sum_{n=0}^{R_1 N - 1} X[n]^2} \right|$
      - Note: the range of τ to find the max of $\phi[\tau]$ could be reduced to $[0, M-1]$ when $Y[n]$ is periodic with period M
        - This will be the case when $\Delta f = 0$. When $\Delta f \neq 0$, the range needs to be $[0, R_2 M - 1]$



Note:
This wrap-around over interference enables simple treatment of mis-aligning during simulations!

Simulation Performance Highlight

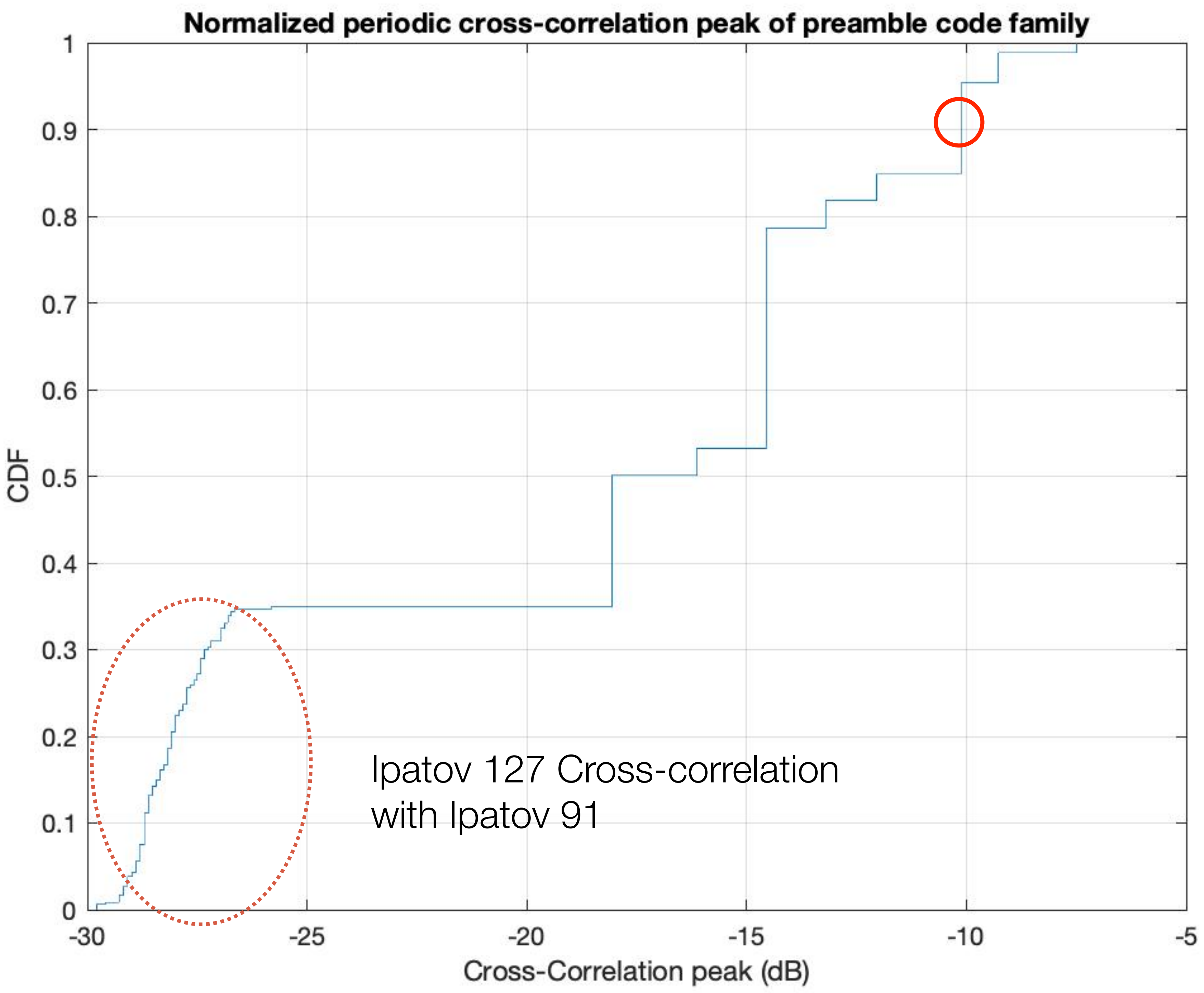
1. Performance of Proposed Golay Pairs



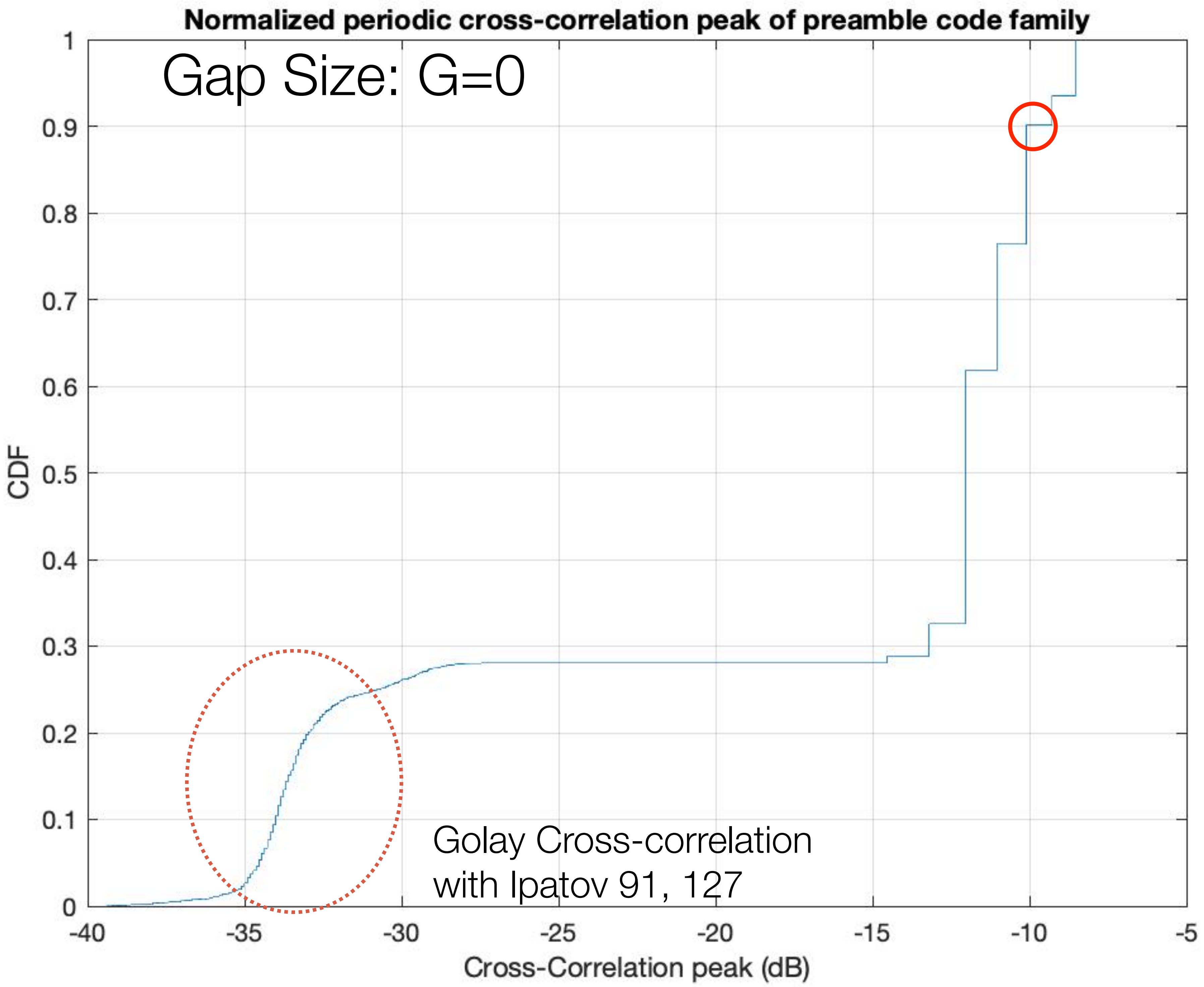
Results for Golay Pair: 64+64 (R_1,R_2=40, Δf_{max}=0, p=0, L_1,L_2 = 4)

Long-Term Correlation w/ PSR=40: No Gap in Target Sequence X

Target codes = {Ipatov 127: 16 codes}
Interfering codes = {Ipatov 91, Ipatov 127}



Target codes = {Golay 64+64: 64 codes}
Interfering codes = {Ipatov 91, Ipatov 127, Golay 64+64}

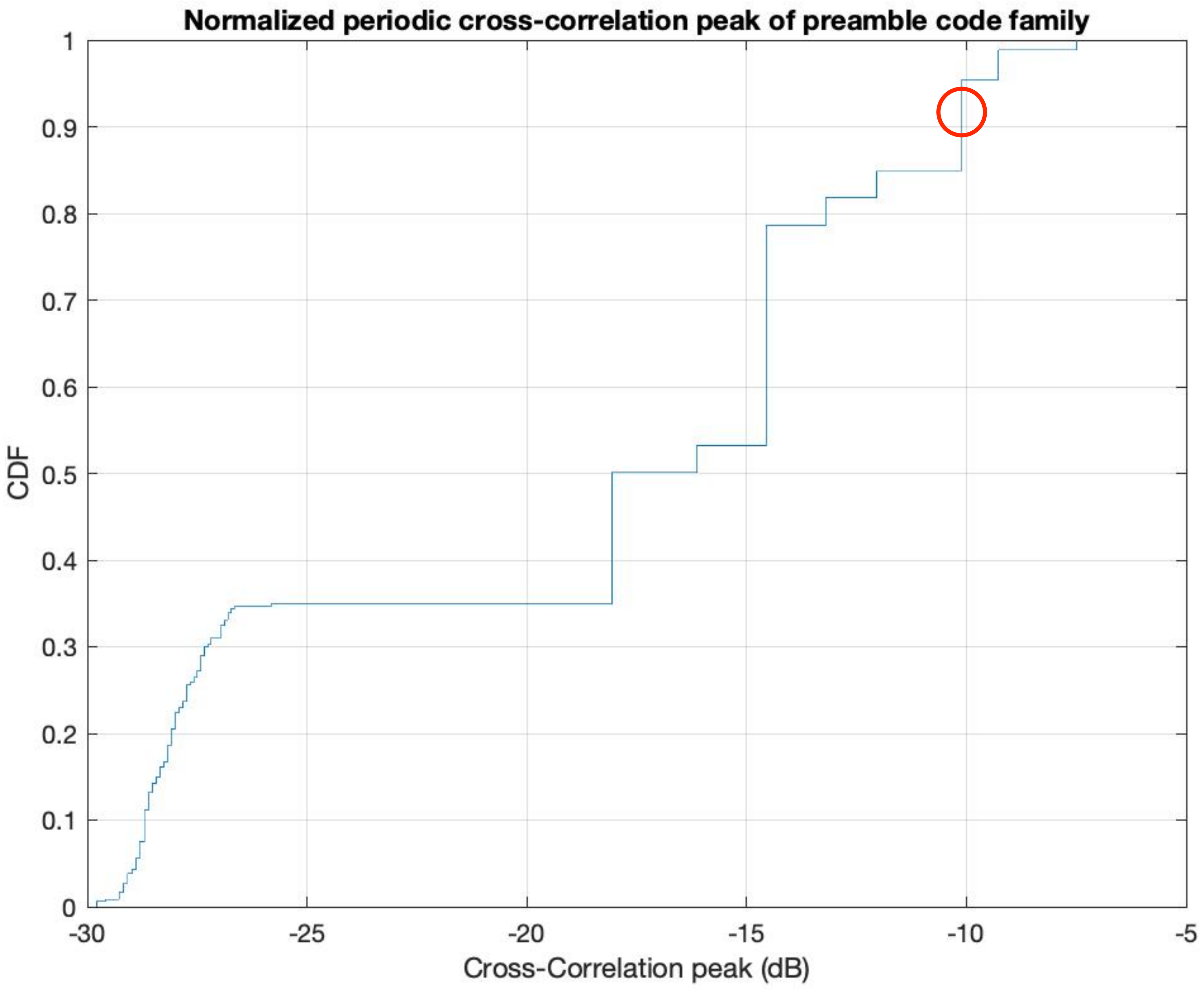


- Size 64 Golay set has similar/better cross-correlation than 4z Ipatov 127 set of size 16
    - Similar 90% CDF, but 1 dB better worst case cross-correlation with Golay 64+64
- Adding Golay (64+64) to the 4z-Ipatov family, does not make cross-correlation any worse

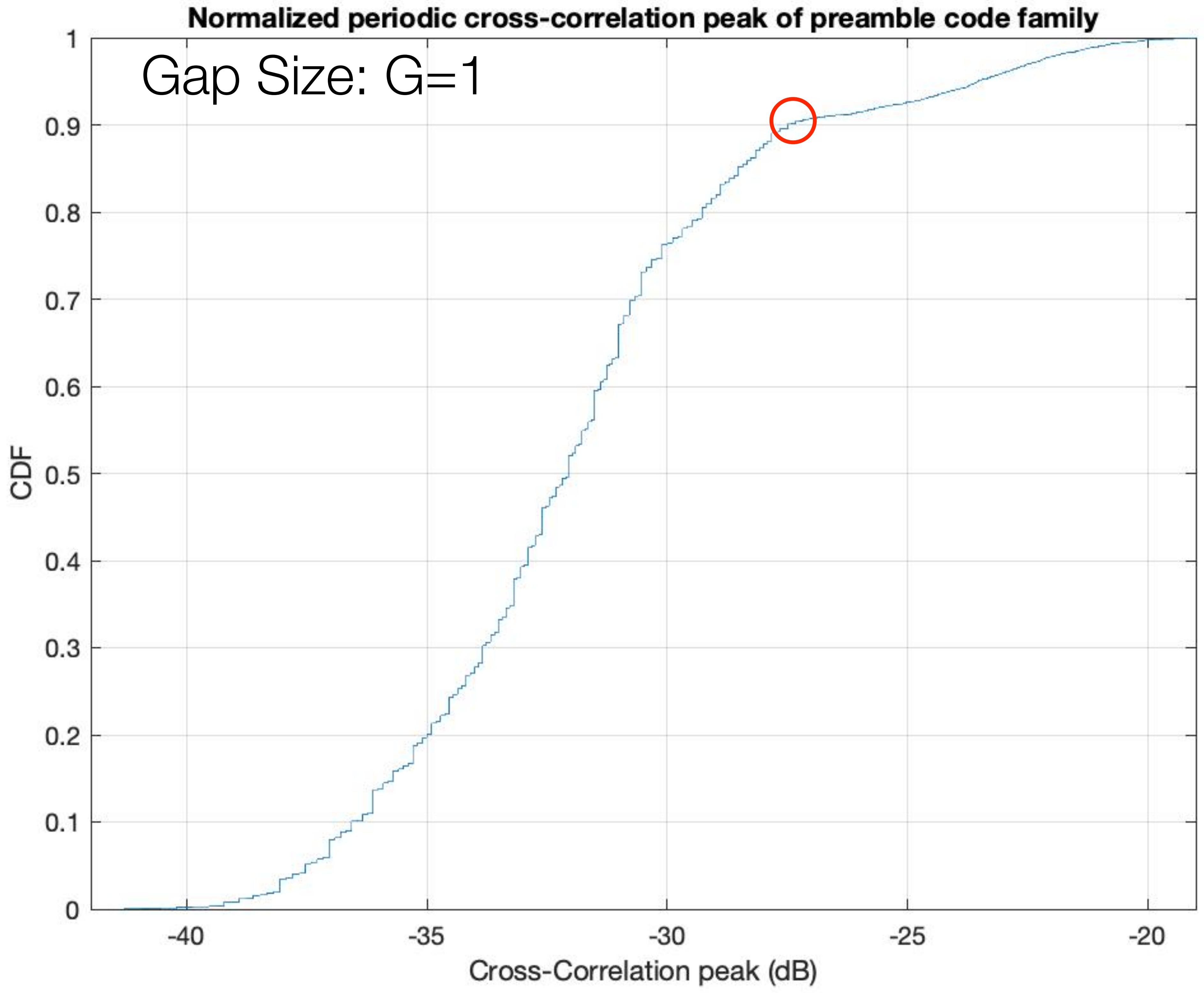
Results for Golay Pair: 64+64 (R_1,R_2=40, Δf_{max}=0, p=0, L_1,L_2 = 4)

Long-Term Correlation w/ PSR=40: Gap=1 in Target Sequence X

Target codes = {Ipatov 127: 16 codes}
Interfering codes = {Ipatov 91, Ipatov 127}



Target codes = {Golay 64+64: 64 codes}
Interfering codes = {Ipatov 91, Ipatov 127, Golay 64+64}

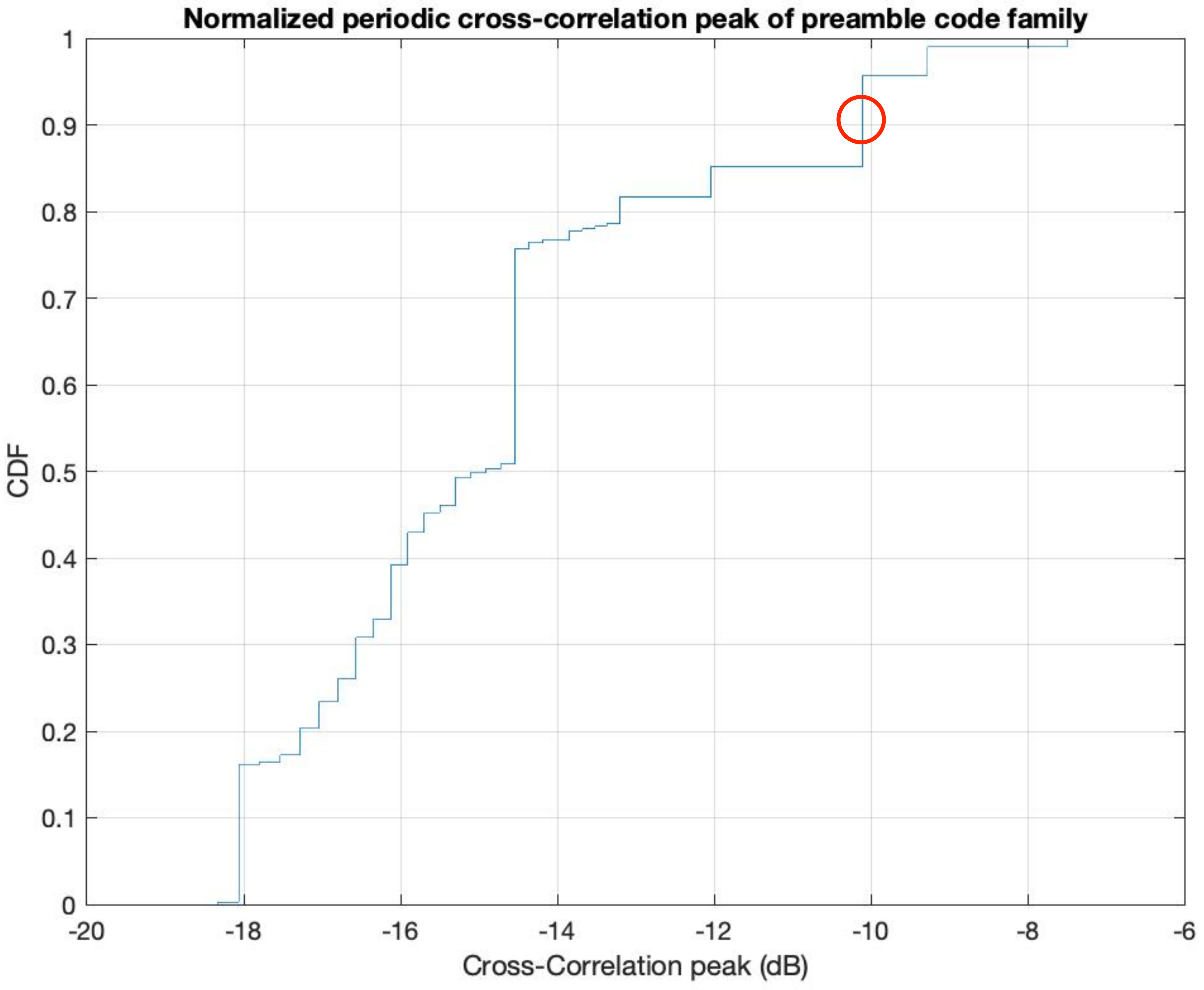


- Golay set with Gap: Adding just a gap of 1 chip improves the Golay cross-correlation by around >16 dB (Due to averaging of interference)

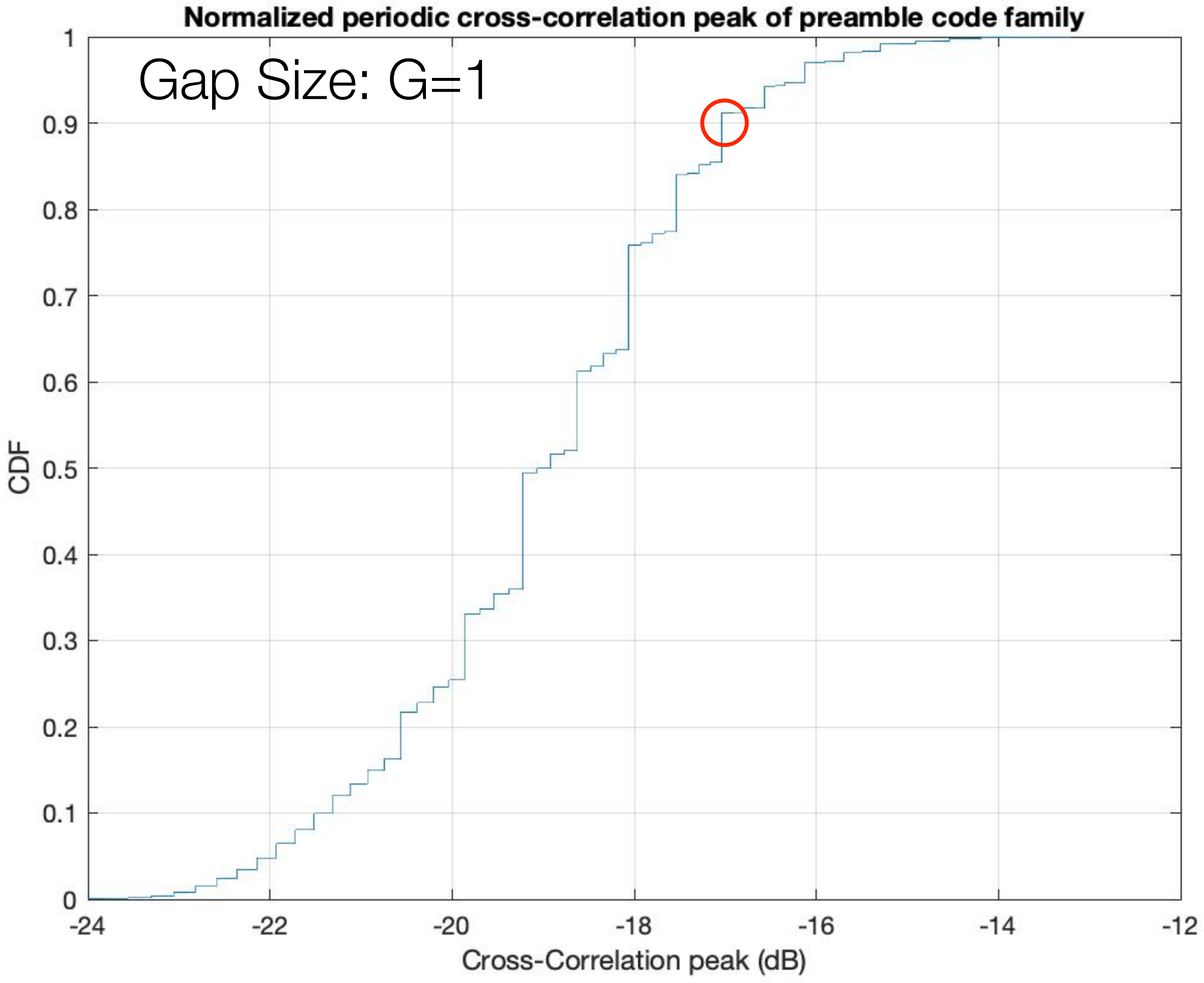
Results for Golay Pair: 64+64 (R_1,R_2=4, Δf_{max}=0, p=0, L_1,L_2 = 4)

Short-Term Correlation w/ PSR=4: Gap=1 in Target Sequence X

Target codes = {Ipatov 127: 16 codes}
Interfering codes = {Ipatov 91, Ipatov 127}

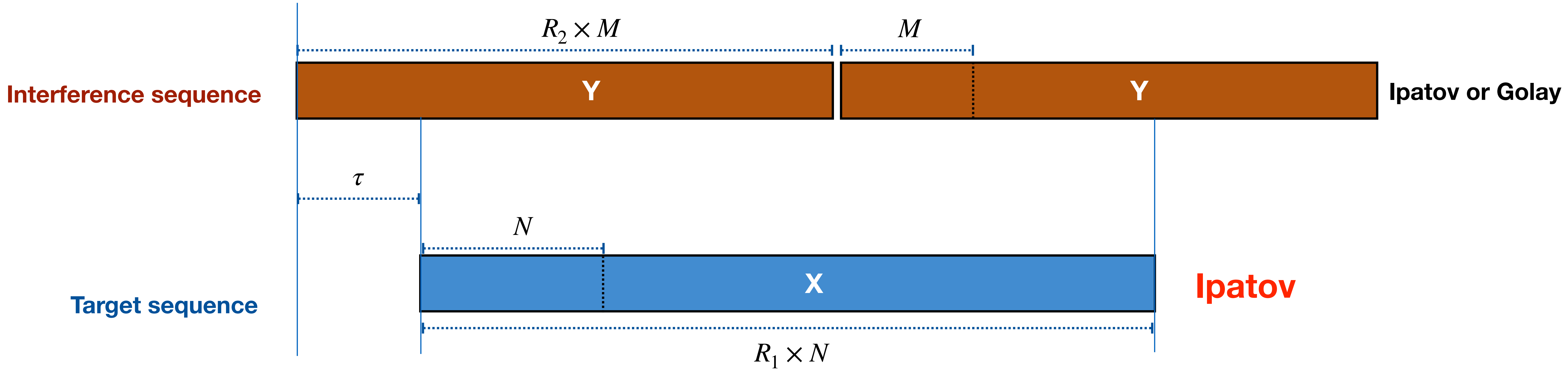


Target codes = {Golay 64+64: 64 codes}
Interfering codes = {Ipatov 91, Ipatov 127, Golay 64+64}



- Even with 4 preamble symbols (R=4), size 64 Golay set has better cross-correlation than 4z Ipatov 127 set of size 16
  - 7 dB better cross-correlation at 90% CDF

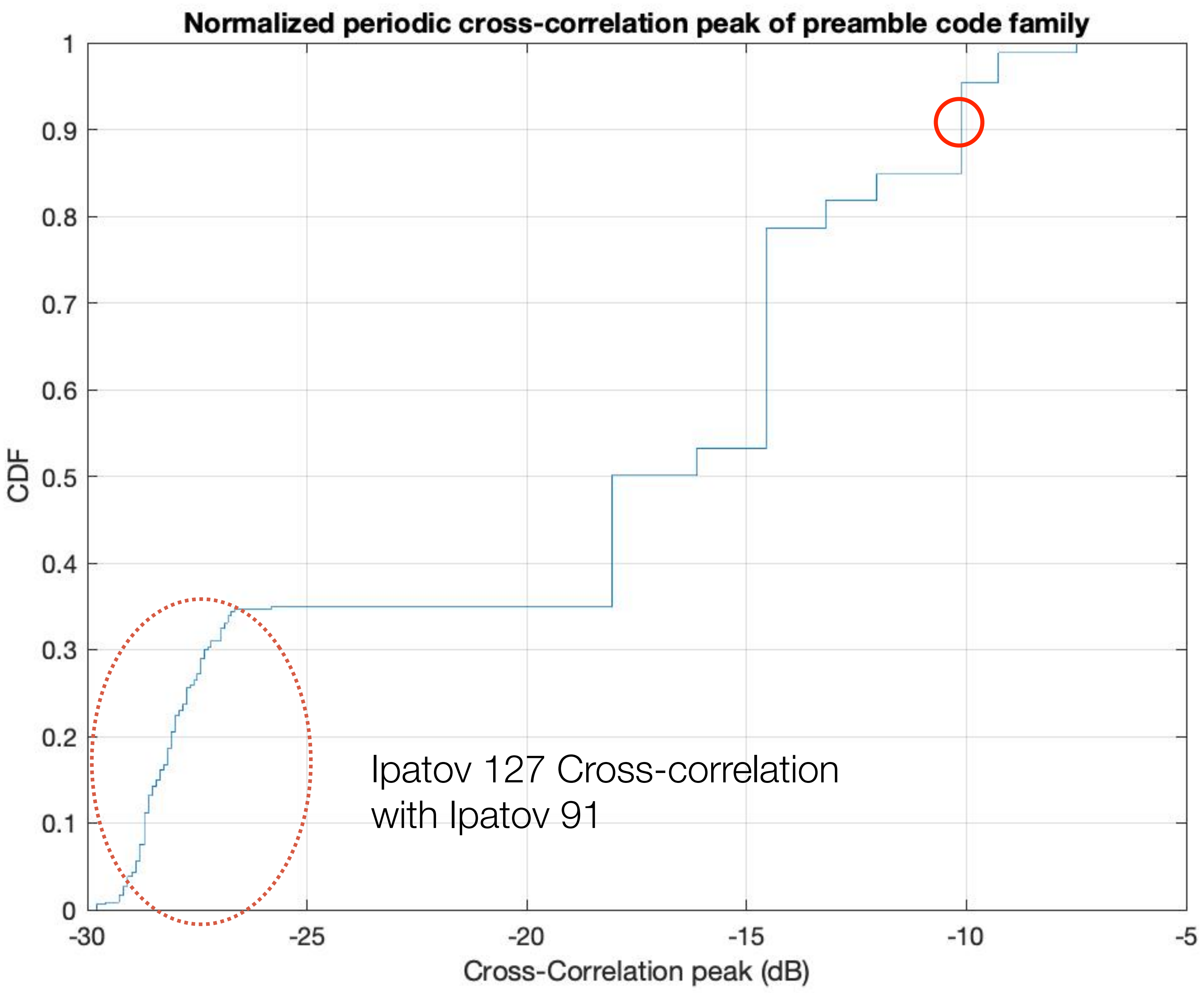
2. Performance of Legacy Ipatov due to new Golay Pairs



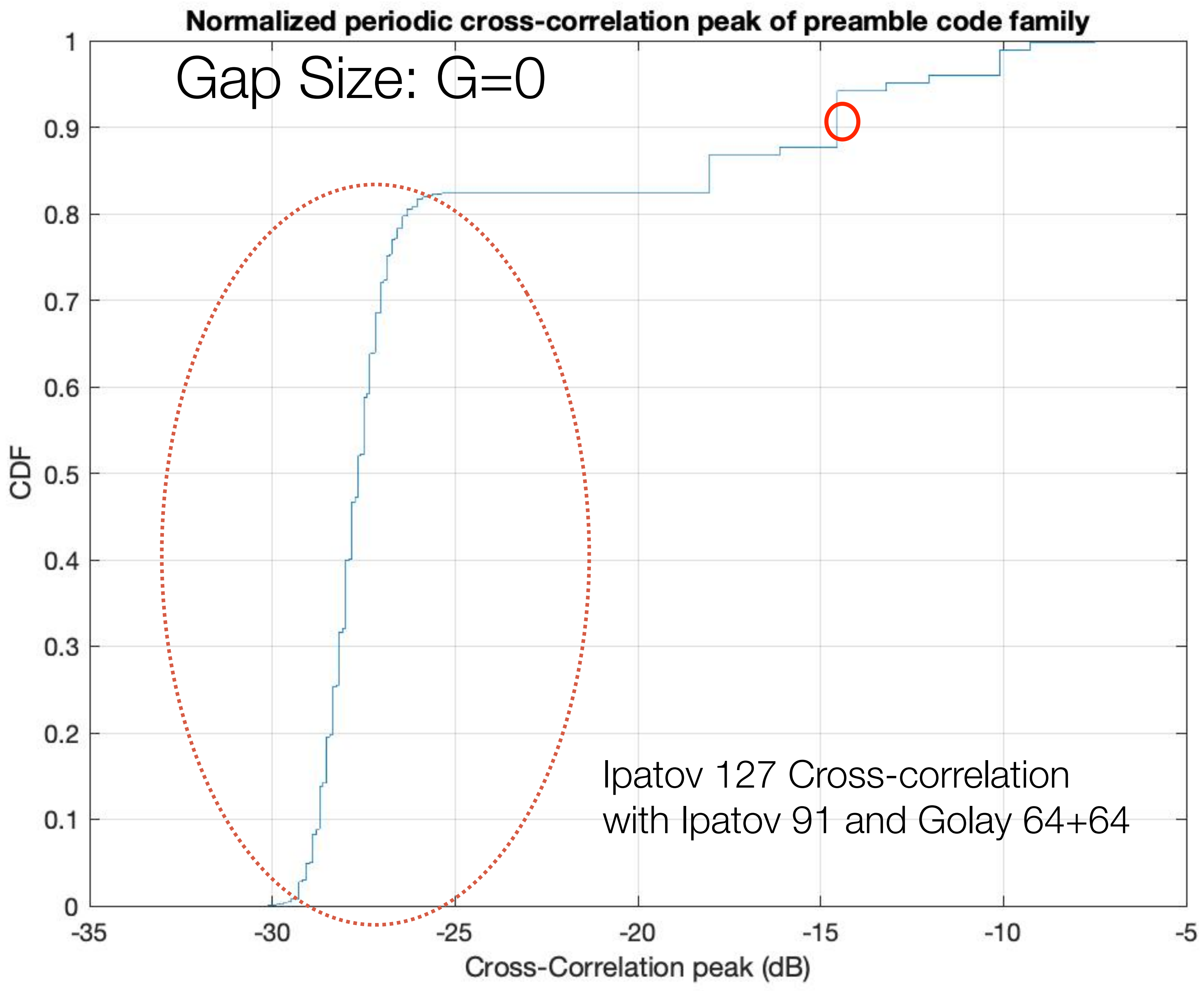
Impact on Legacy Ipatov (R_1,R_2=40, Δf_{max}=0, p=0, L_1,L_2 = 4)

Long-Term Correlation w/ PSR=40: No Gap in Interference Sequence Y

Target codes = {Ipatov 127: 16 codes}
Interfering codes = {Ipatov 91, Ipatov 127}



Target codes = {Ipatov 127: 16 codes}
Interfering codes = {Ipatov 91, Ipatov 127, Golay 64+64}

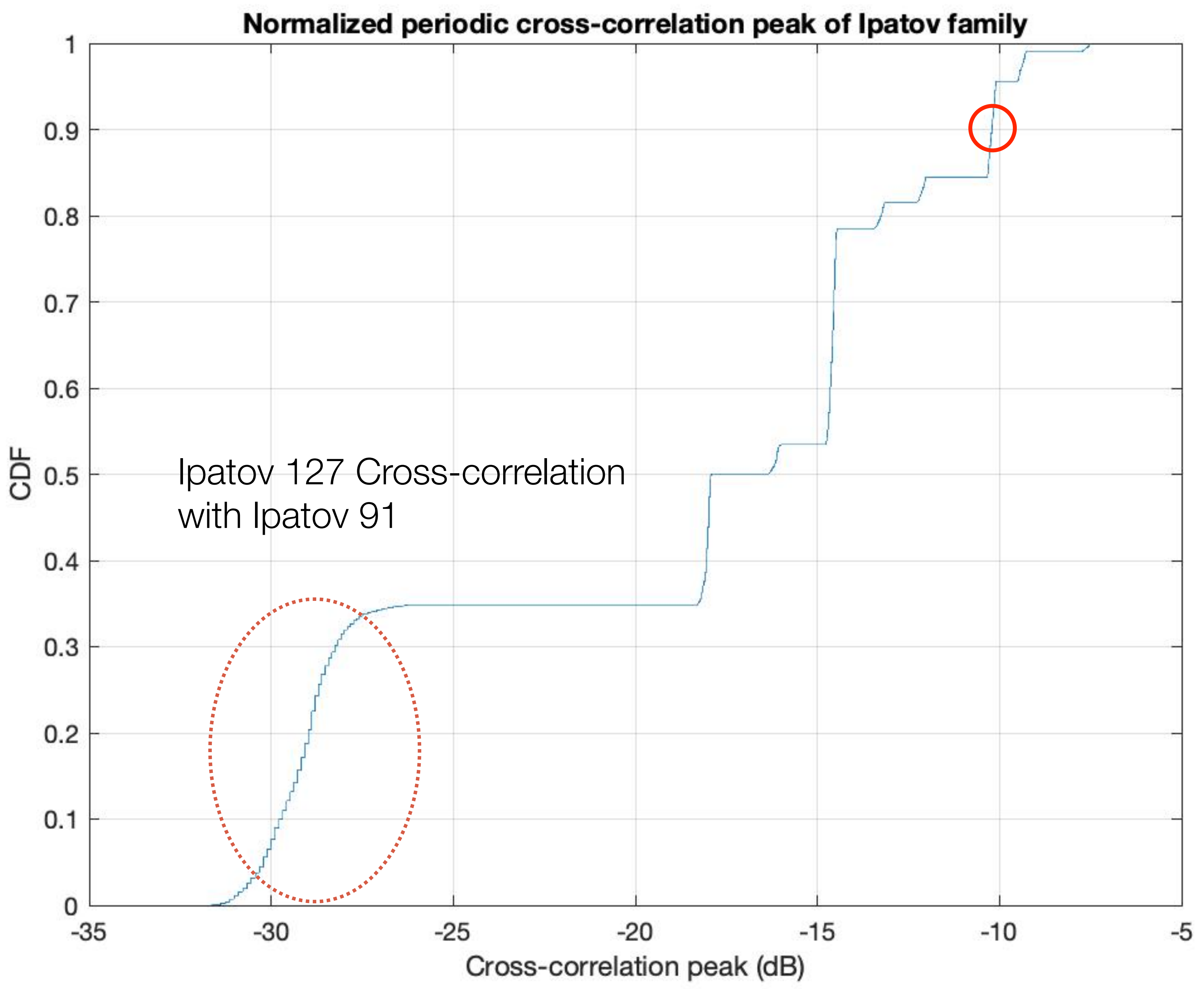


- Adding Golay (64+64) to the 4z-Ipatov family, does not make cross-correlation worse

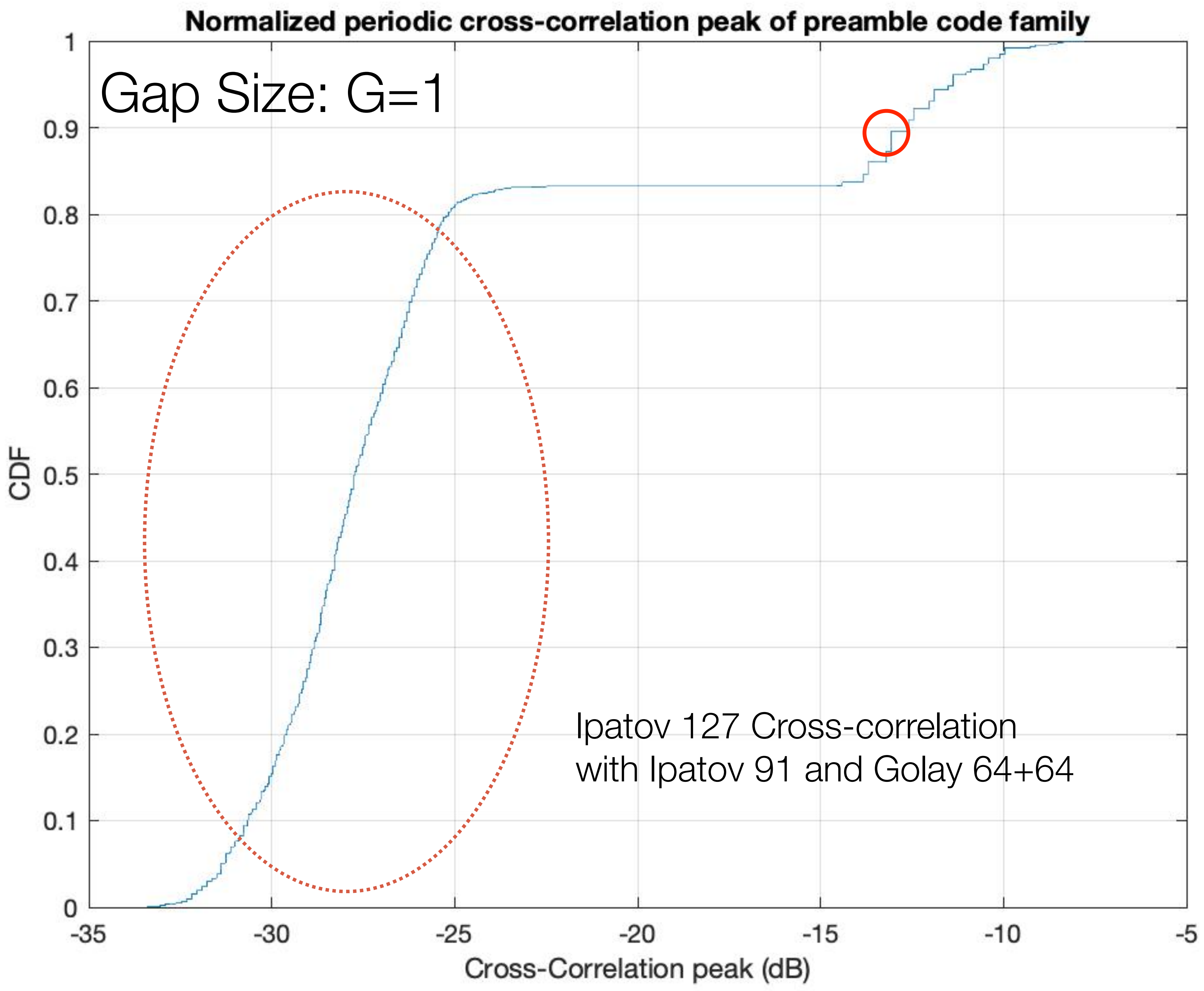
Impact on Legacy Ipatov (R_1,R_2=40, Δf_{max}=0, p=0, L_1,L_2 = 4)

Long-Term Correlation w/ PSR=40: Gap=1 in Golay Interference Sequence Y

Target codes = {Ipatov 127: 16 codes}
Interfering codes = {Ipatov 91, Ipatov 127}



Target codes = {Ipatov 127: 16 codes}
Interfering codes = {Ipatov 91, Ipatov 127, Golay 64+64}

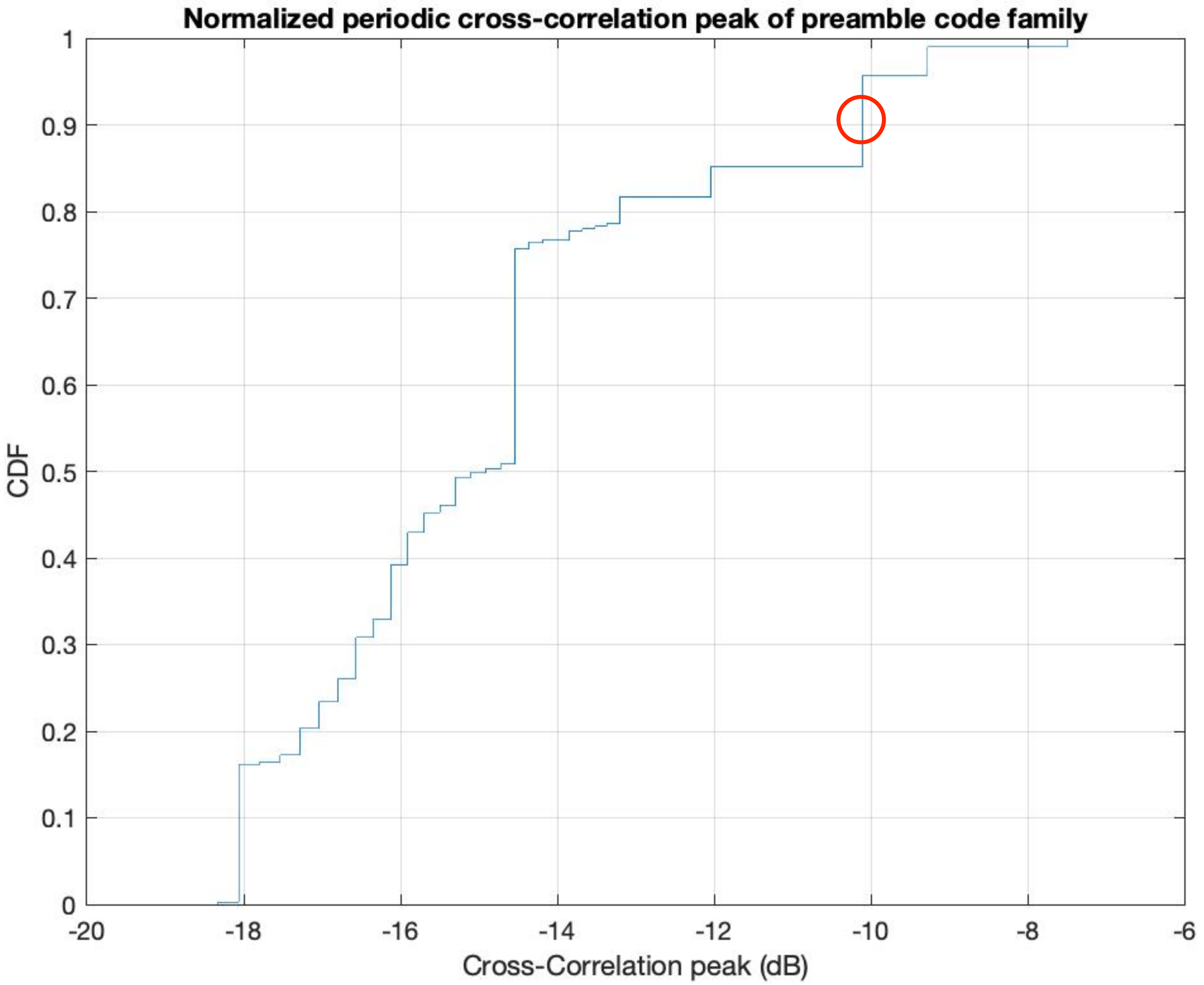


- Adding a Gap to Golay doesn't impact the cross-correlation observed by legacy 4z-Ipatov

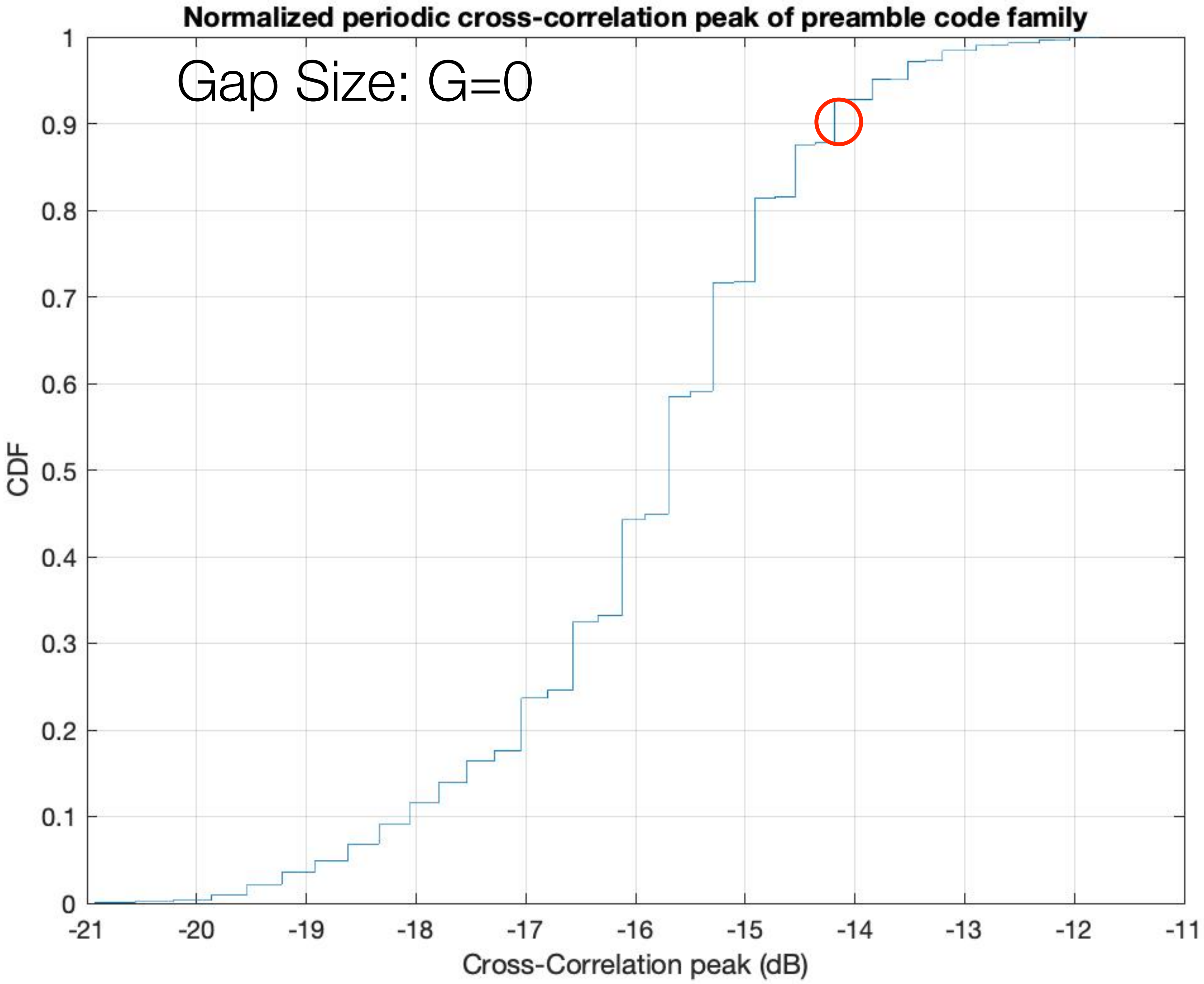
Impact on Legacy Ipatov (R_1,R_2=4, Δf_{max}=0, p=0, L_1,L_2 = 4)

Short-Term Correlation w/ PSR=4: No Gap in Interference Sequence Y

Target codes = {Ipatov 127: 16 codes}
Interfering codes = {Ipatov 91, Ipatov 127}



Target codes = {Ipatov 127: 16 codes}
Interfering codes = {Ipatov 91, Ipatov 127, Golay 64+64}



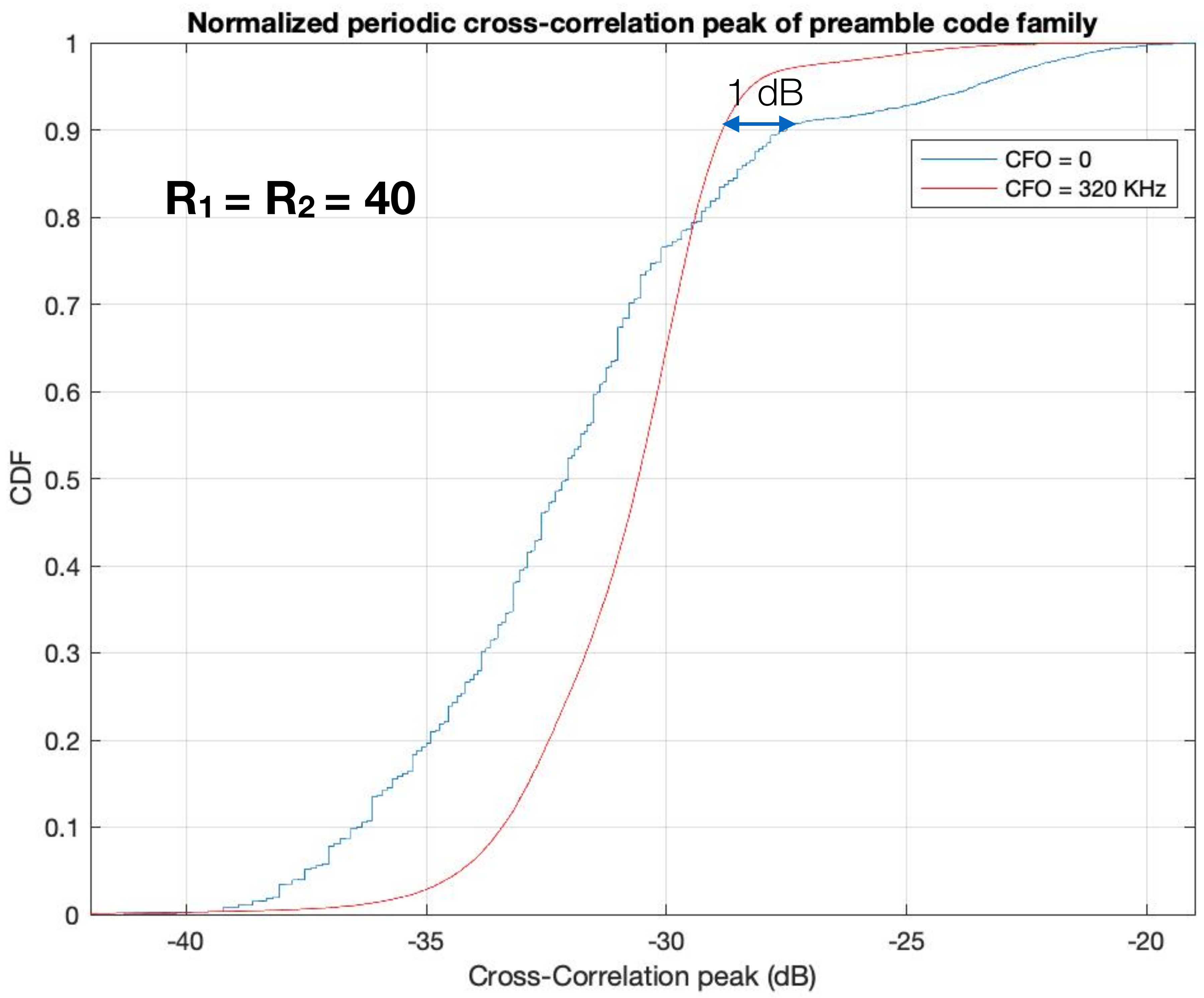
- Adding Golay (64+64) to the 4z-Ipatov family, does not make cross-correlation worse

Additional miscellaneous Results

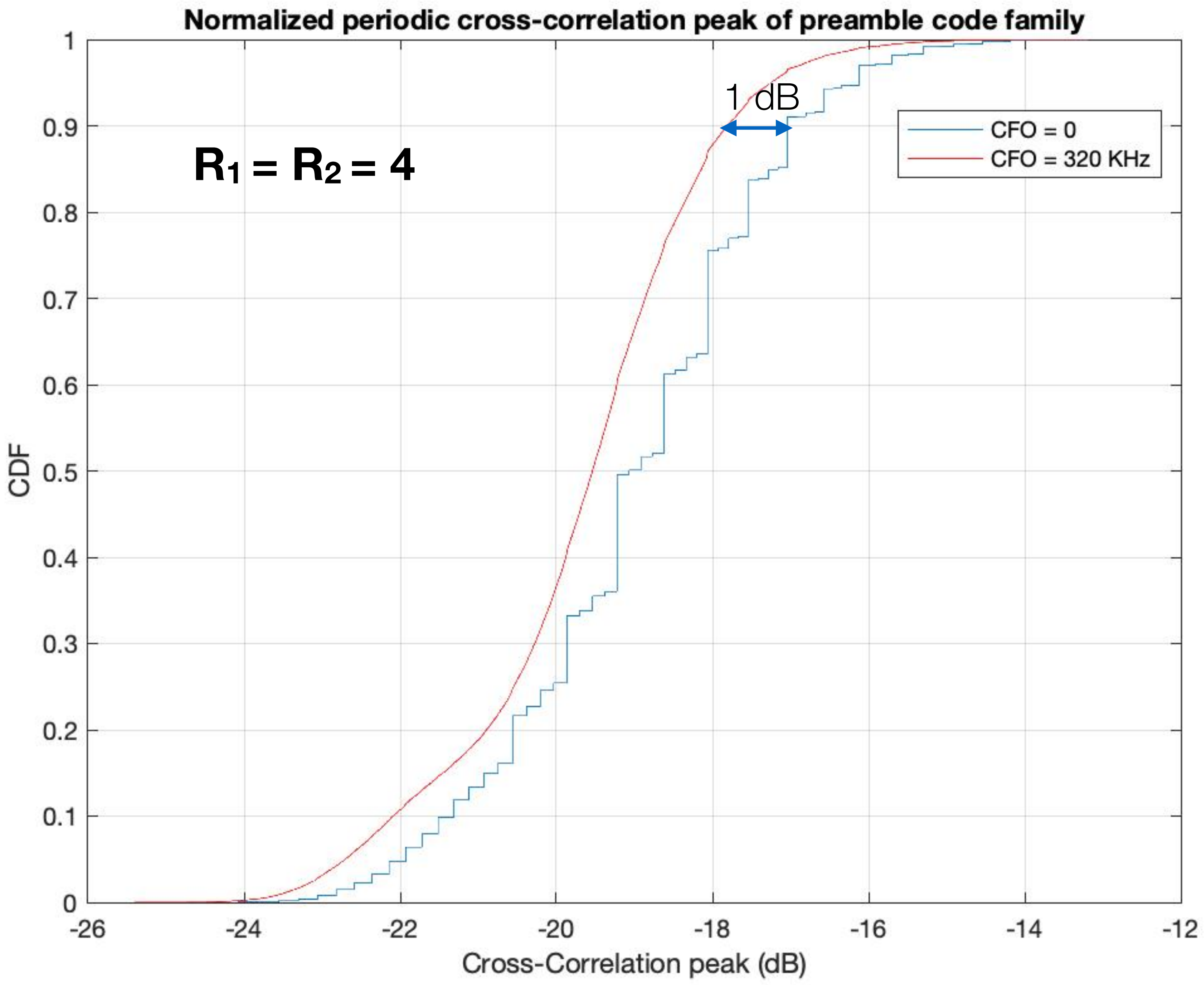
Results for Golay Pair, with CFO (Δf_{max}=320 KHz, p=0, L_1,L_2 = 4)

Gap=1 in Target Sequence X

Target codes = {Golay 64+64: 64 codes}
Interfering codes = {Ipatov 91, Ipatov 127, Golay 64+64}



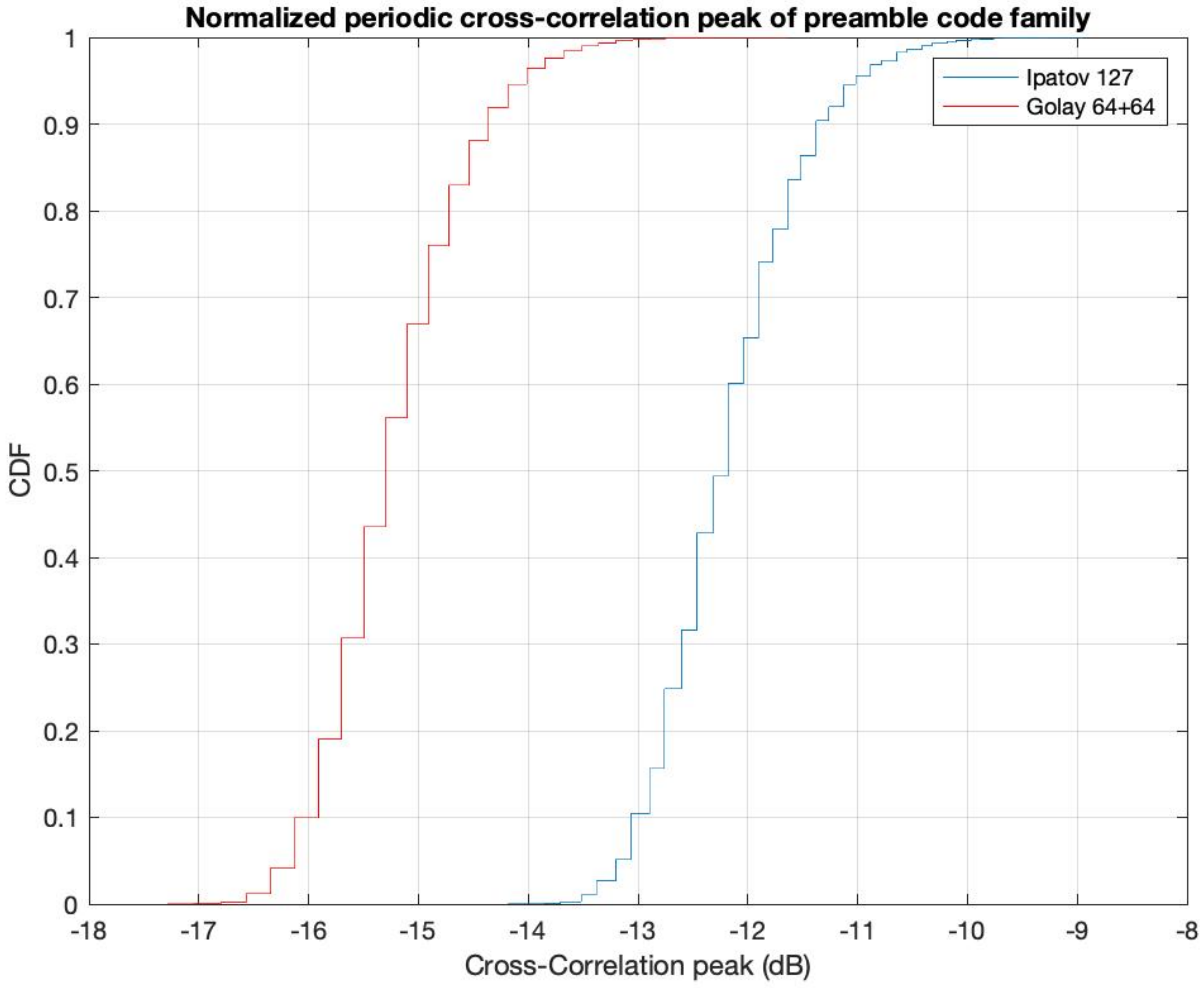
Target codes = {Golay 64+64: 64 codes}
Interfering codes = {Ipatov 91, Ipatov 127, Golay 64+64}



- CFO makes the cross-correlation better
  - 1 dB lower cross-correlation at 90% CDF

Results for Data/STS Collisions (R_1,R_2=4, Δf_{max}=0, p=1, L_1,L_2 = 4)

Short-Term Correlation w/ PSR=4: Gap=1 in Target Sequence X

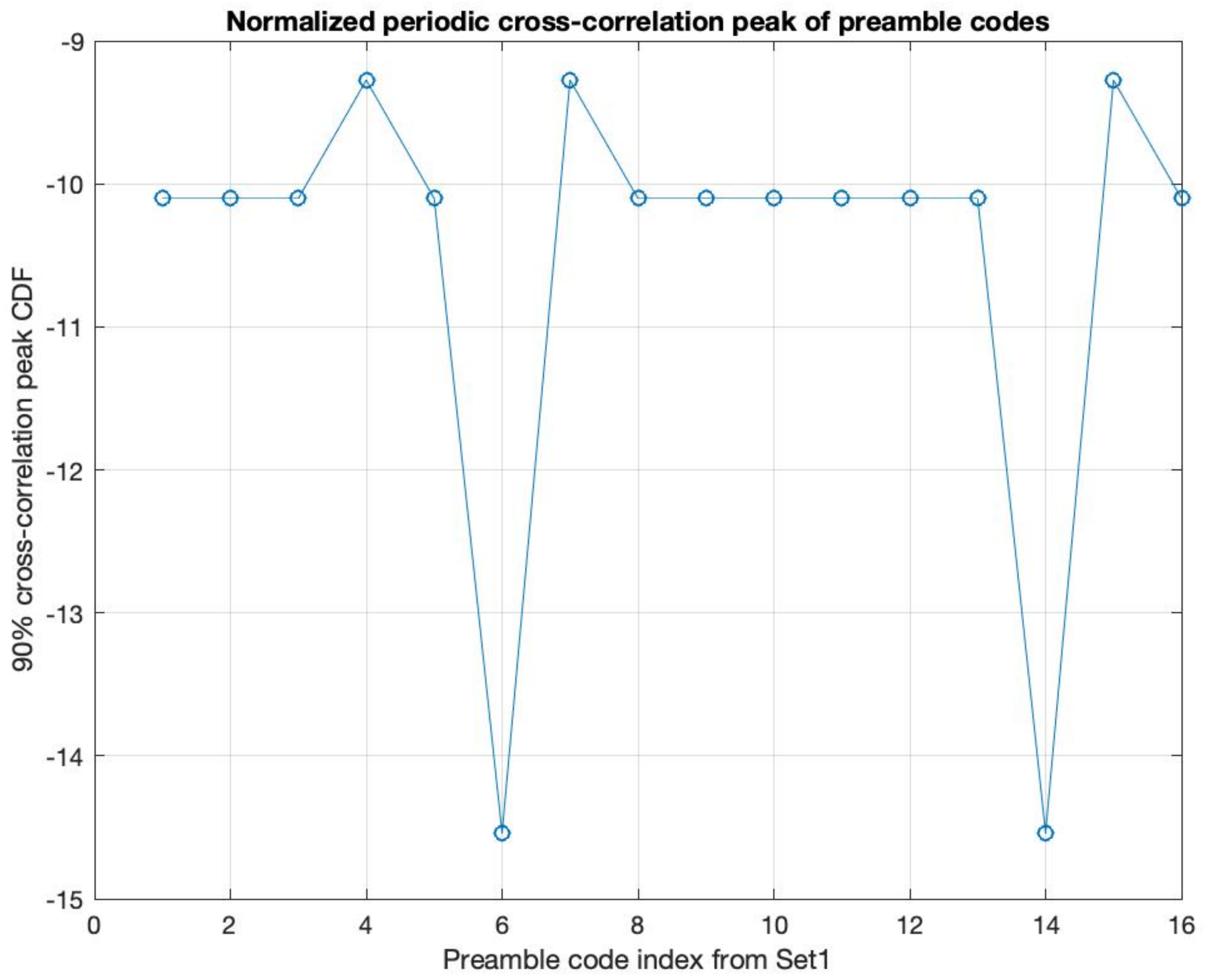


- Golay 64+64 set has lower cross-correlation with pulses with random polarity, due to higher mean PRF
    - 3 dB lower cross-correlation at 90% CDF

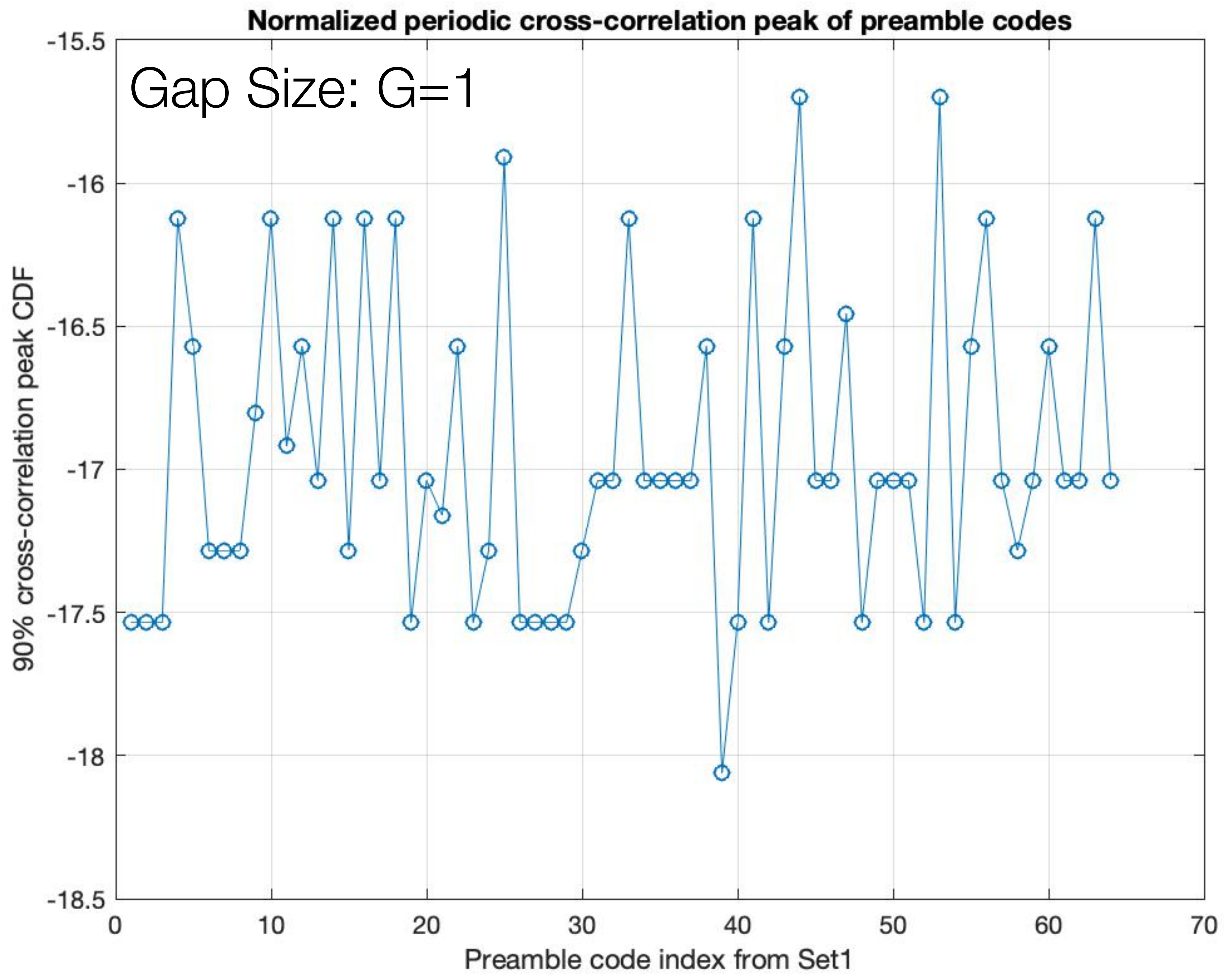
90% Cross-correlation Results for individual sequences (R_1,R_2=4, Δf_{max}=0, p=0, L_1,L_2 = 4)

Short-Term Correlation w/ PSR=4: Gap=1 in Target Sequence X

Target codes = {Ipatov 127: 16 codes}
Interfering codes = {Ipatov 91, Ipatov 127}



Target codes = {Golay 64+64: 64 codes}
Interfering codes = {Ipatov 91, Ipatov 127, Golay 64+64}

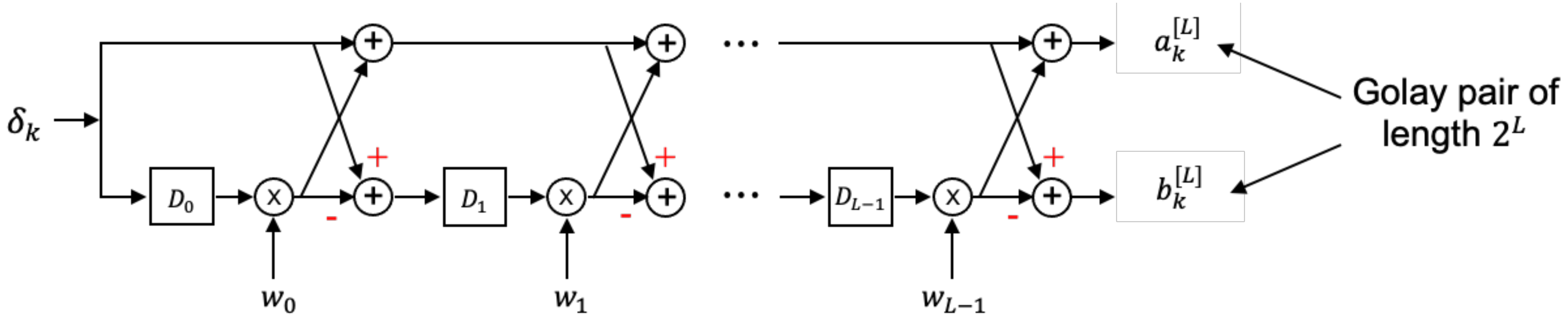


- All the 64 sequences from Golay set has similar 90% Cross-correlation CDF
  - All sequences have better 90% cross-correlation than Ipatov 127 set

More Information on Proposed (64, 64) Golay Pairs

Golay Generator from Seeds

Seed and Delay Vector Definitions

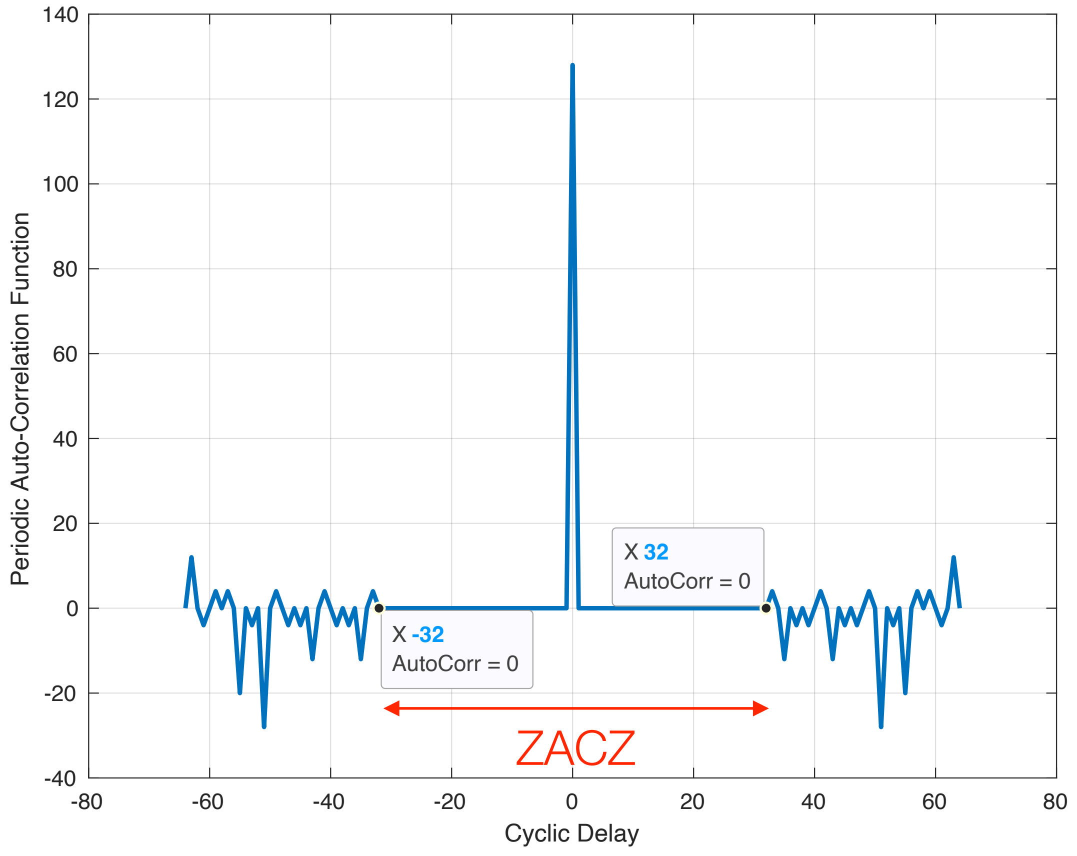


- $L = 6$
- Delay Vector:
  - $\mathbf{D} := [D_0, D_1, \ldots, D_{L-1}]$
  - $D_k \in \{2^0, 2^1, \ldots, 2^{L-1}\}, \forall k \in [0, L-1]$
- Weight Vector:
  - Seed $:= \sum_{i=0}^{L-1} \frac{1+w_i}{2} 2^i$

Golay Generator from Seeds

Seed and Delay Vector Configurations for 64 Golay (64, 64) Pairs

```
Seq. 1: Seed=40;  delay=[1   2  16   8   4  32];
Seq. 2: Seed=27;  delay=[2   1  16   8   4  32];
Seq. 3: Seed=7;   delay=[4   1  16   8   2  32];
Seq. 4: Seed=39;  delay=[1   8   4  16   2  32];
Seq. 5: Seed=61;  delay=[8   1  16   2   4  32];
Seq. 6: Seed=37;  delay=[4   1   2  16   8  32];
Seq. 7: Seed=63;  delay=[16   1   2   8   4  32];
Seq. 8: Seed=3;   delay=[4   2  16   8   1  32];
Seq. 9: Seed=58;  delay=[16   2   4   1   8  32];
Seq. 10: Seed=40; delay=[4   2  16   1   8  32];
Seq. 11: Seed=22; delay=[4   8   2   1  16  32];
Seq. 12: Seed=30; delay=[16   4   2   1   8  32];
Seq. 13: Seed=21; delay=[8   4  16   1   2  32];
Seq. 14: Seed=0;  delay=[4   2   1   8  16  32];
Seq. 15: Seed=47; delay=[4   8  16   2   1  32];
Seq. 16: Seed=59; delay=[2   8   1  16   4  32];
Seq. 17: Seed=42; delay=[1   2   8   4  16  32];
Seq. 18: Seed=61; delay=[1   8   2   4  16  32];
Seq. 19: Seed=52; delay=[1   4   8  16   2  32];
Seq. 20: Seed=47; delay=[1   4  16   2   8  32];
Seq. 21: Seed=58; delay=[16   8   1   2   4  32];
Seq. 22: Seed=39; delay=[8   1   4   2  16  32];
Seq. 23: Seed=53; delay=[8   4   2  16   1  32];
Seq. 24: Seed=50; delay=[2  16   8   4   1  32];
Seq. 25: Seed=52; delay=[1   8   2  16   4  32];
Seq. 26: Seed=9;  delay=[16   2   8   1   4  32];
Seq. 27: Seed=8;  delay=[16   1   2   8   4  32];
Seq. 28: Seed=9;  delay=[16   8   4   1   2  32];
Seq. 29: Seed=54; delay=[1   2  16   4   8  32];
Seq. 30: Seed=63; delay=[16   4   2   1   8  32];
Seq. 31: Seed=53; delay=[2  16   1   8   4  32];
Seq. 32: Seed=27; delay=[4  16   8   1   2  32];
Seq. 33: Seed=61; delay=[8   4   1   2  16  32];
Seq. 34: Seed=33; delay=[4  16   1   2   8  32];
Seq. 35: Seed=11; delay=[1   8   2   4  16  32];
Seq. 36: Seed=38; delay=[2   1   8   4  16  32];
Seq. 37: Seed=35; delay=[8   4  16   1   2  32];
Seq. 38: Seed=17; delay=[1   2   4  16   8  32];
Seq. 39: Seed=46; delay=[8   1   2  16   4  32];
Seq. 40: Seed=37; delay=[8  16   4   2   1  32];
Seq. 41: Seed=16; delay=[1  16   8   4   2  32];
Seq. 42: Seed=27; delay=[8   4   1  16   2  32];
Seq. 43: Seed=42; delay=[16   1   8   2   4  32];
Seq. 44: Seed=0;  delay=[1  16   8   4   2  32];
Seq. 45: Seed=8;  delay=[2  16   4   1   8  32];
Seq. 46: Seed=49; delay=[16   1   8   4   2  32];
Seq. 47: Seed=11; delay=[1  16   8   2   4  32];
Seq. 48: Seed=27; delay=[4   2   8  16   1  32];
Seq. 49: Seed=7;  delay=[8   4  16   1   2  32];
Seq. 50: Seed=62; delay=[2   8   1   4  16  32];
Seq. 51: Seed=36; delay=[2   8   4   1  16  32];
Seq. 52: Seed=15; delay=[2  16   8   1   4  32];
Seq. 53: Seed=30; delay=[1   8   4  16   2  32];
Seq. 54: Seed=11; delay=[2   4   8  16   1  32];
Seq. 55: Seed=61; delay=[2   4  16   1   8  32];
Seq. 56: Seed=54; delay=[2   4   8   1  16  32];
Seq. 57: Seed=1;  delay=[2   1   4  16   8  32];
Seq. 58: Seed=27; delay=[1   2  16   4   8  32];
Seq. 59: Seed=13; delay=[16   2   8   1   4  32];
Seq. 60: Seed=44; delay=[8   4   1   2  16  32];
Seq. 61: Seed=35; delay=[8   2   1   4  16  32];
Seq. 62: Seed=61; delay=[4   2   1   8  16  32];
Seq. 63: Seed=28; delay=[1   8   2   4  16  32];
Seq. 64: Seed=39; delay=[2   1   8  16   4  32];
```



Note: corresponding sequences are also available in the shared codes for apEval: Doc#: 15-22-0447-01-04ab-apEval_framework.m

- Each of the recommended Golay pair exhibits a ZACZ of 2x32 as illustrated in the top right figure (before spreading, in the absence a gap)