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

Submission Title: [**Proposal of SUN OFDM LR for 802.15.4ad**]
Date Submitted: 29 July 2024
Source: Hiroshi Harada and Goro Kawabuchi (Kyoto University)
Address Yoshidahonmachi. Sakyo, Kyoto, 606-8501, Japan
Voice: +81-75-753-5317 , E-Mail: hiroshi.harada@i.kyoto-u.ac.jp

Re: [Wireless Next Generation, Long Range extension enhancements to 802.15.4-2020]

Abstract: Propose of 802.15.4 SUN OFDM Low Rate (LR) for 802.15.4ad. A part of this contribution supported from the commissioned research (No. JPJ012368C05101) by National Institute of Information and Communications Technology (NICT) , Japan is included.

Purpose:

Proposal of SUN OFDM LR for 802.15.4ad

July 29, 2025

Hiroshi Harada, Ph.D., IEEE fellow,
and Goro Kawabuchi

Kyoto University

Background

- We have already proposed IEEE 802.15.4 SUN OFDM LR in 15-25/0035r0.
- This proposal was an SC-OFDM (Single Carrier OFDM) system that first selects a frequency using frequency hopping and then transmits a block consisting of a pilot signal and information symbols at the selected frequency.
- We have demonstrated the transmission characteristics of the proposed SC-OFDM system under AWGN and multipath fading environments and interference noise conditions in 15-25/0158r3 and 15-25/0262r0.
- Additionally, we have proposed SHR in 15-0325r1.
- This contribution document summarizes our proposed OFDM LR and its basic transmission characteristics.

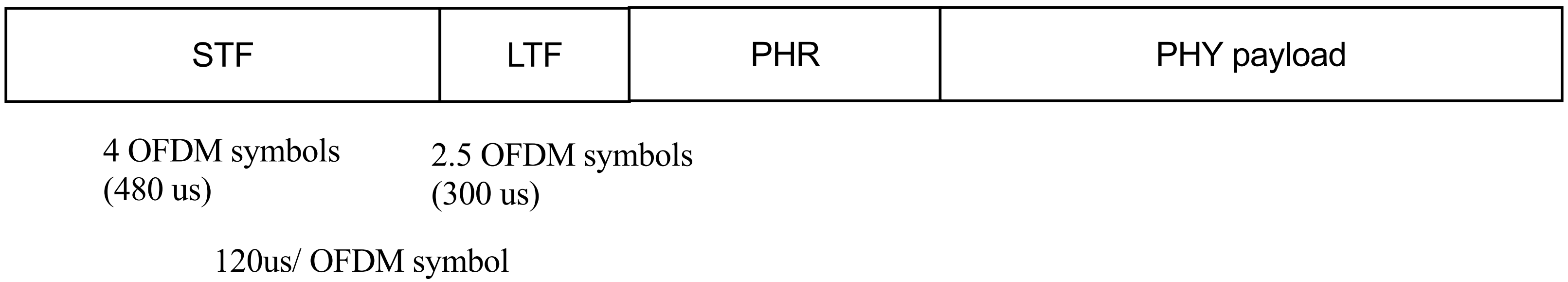
Proposed 802.15.4 SUN-OFDM LR (15-25/0035r0, 15-25/0262r0)

		Option LR1	Option LR2	Option LR3	Option LR4*
Channel spacing		200 kHz			800 kHz
Subcarrier spacing		31.25/3 kHz			
DFT size		16	16	16	64
Number of subcarriers used		14	14	14	52
Num. of data-subcarriers		12	6	1	1
OFDM symbol duration		120 us			
Guard interval		24 us			
Primary modulation scheme		BPSK			
Coding Scheme and rate		Convolutional code (Constraint length: 7) Coding rate1/2			
Spreading factor		8 (MCS 0), 4 (MCS1), 2(MCS 2)			
Data rate for PSDU (kb/s)	MCS 0	6.25		0.260	0.260
	MCS 1		6.25	0.694	0.694
	MCS 2			1.667	1.667
	MCS 3			3.704	3.704

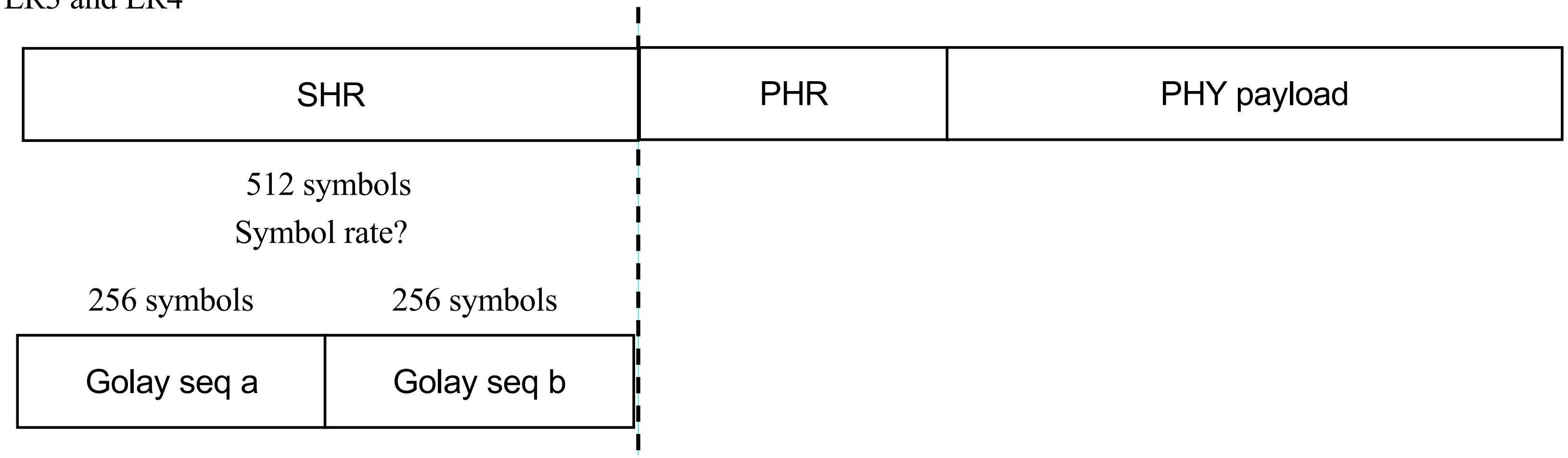
LR4: for FCC 15.247

Frame format SUN-OFDM LR (15-25/0035r0, 15-25/0158r3, 15-25/0262r0, 15-0325r1)

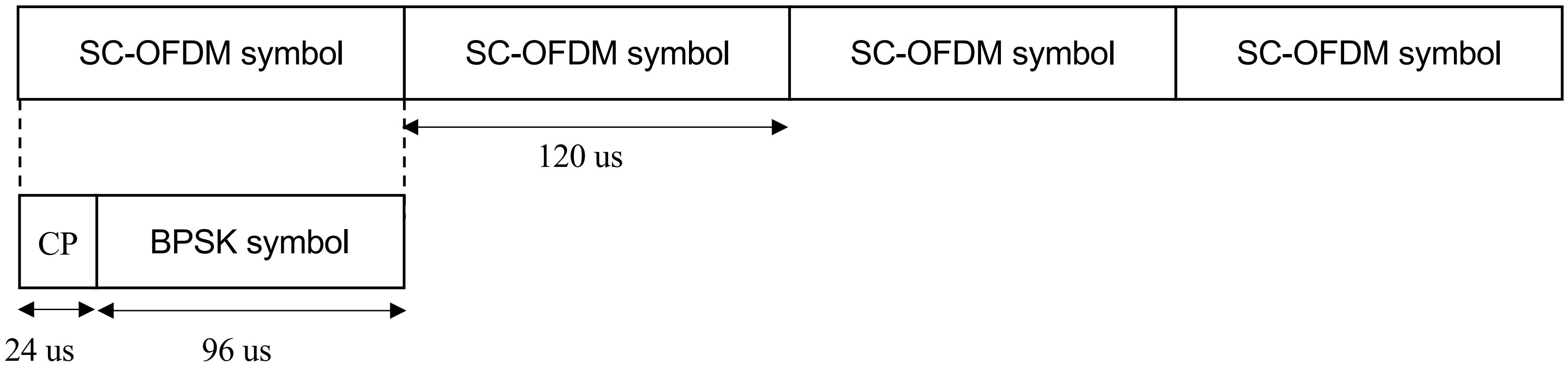
OFDM LR1 and LR2 (Same as SUN-OFDM option 4)



OFDM LR3 and LR4

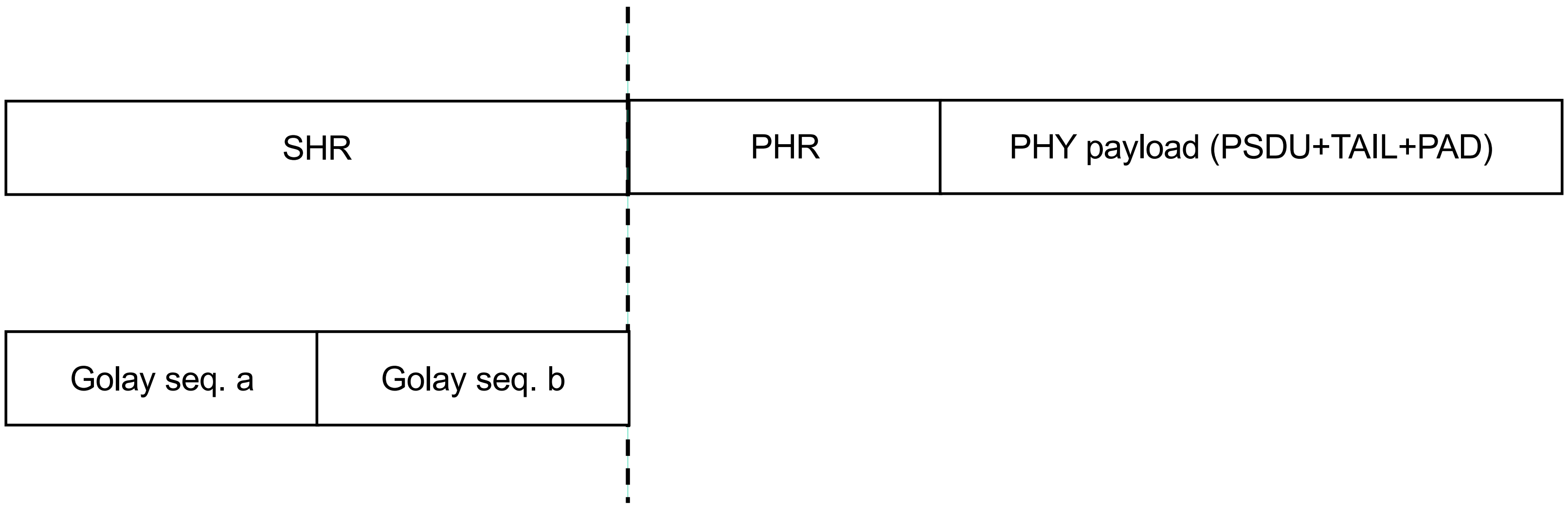


PHR & PHY payload of SUN-OFDM LR1 and LR3 (15−25/0035r0)



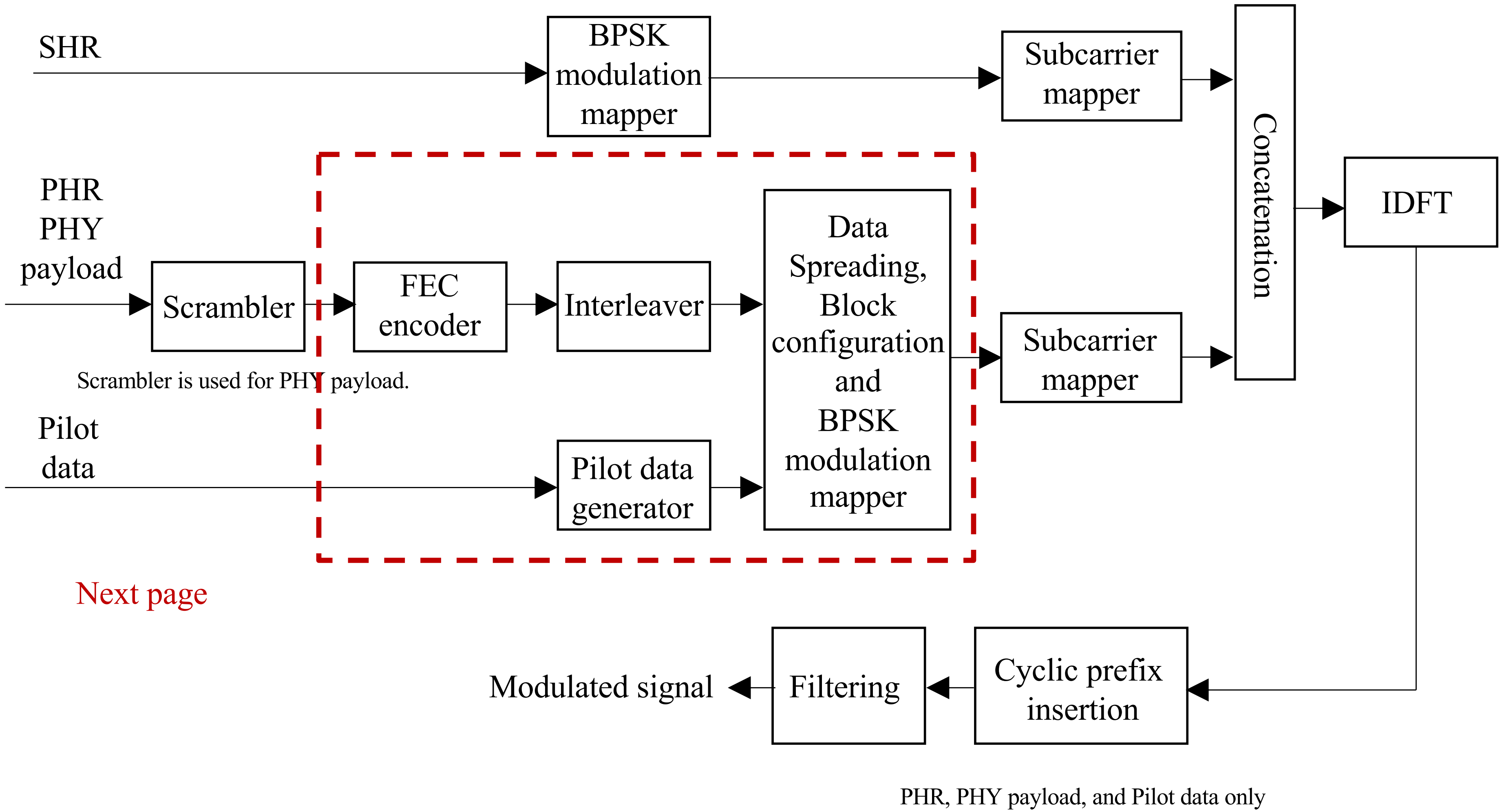
Proposed SUN OFDM LR3 (SC-OFDM)

Frame configuration of proposed SC-OFDM (15-25/0035r0, 15-25/0158r3, 15-25/0262r0, 15-0325r1)

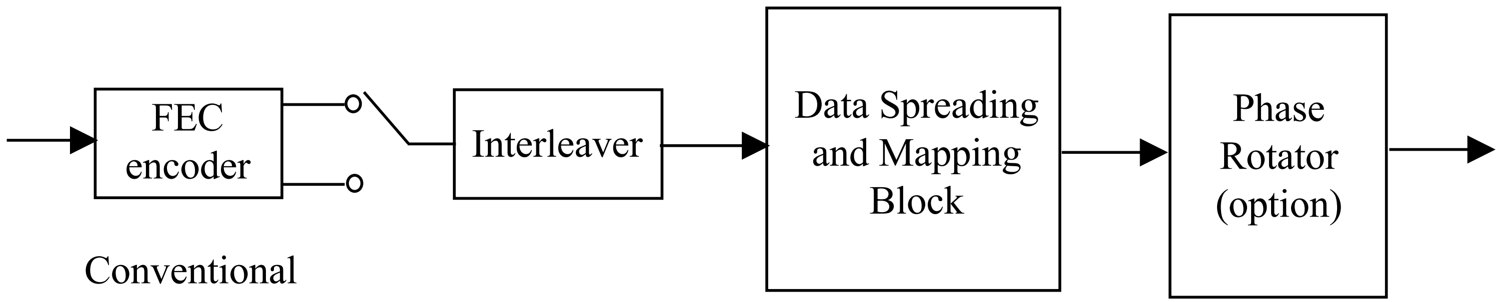


- In this SC-OFDM, SHR consists of two Golay sequences a and b of equal length.
- This is because the PHR and PHY payload parts are transmitted in blocks, and pilot data is stored in each block.

Reference modulator diagram



Modulation and coding scheme



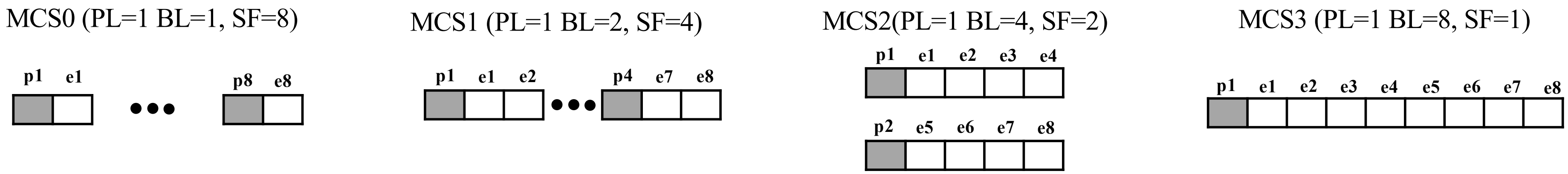
Conventional convolutional code for OFDM SUN (R=1/2, K=7)

P_j: PN9 $\quad j=1,\cdots$

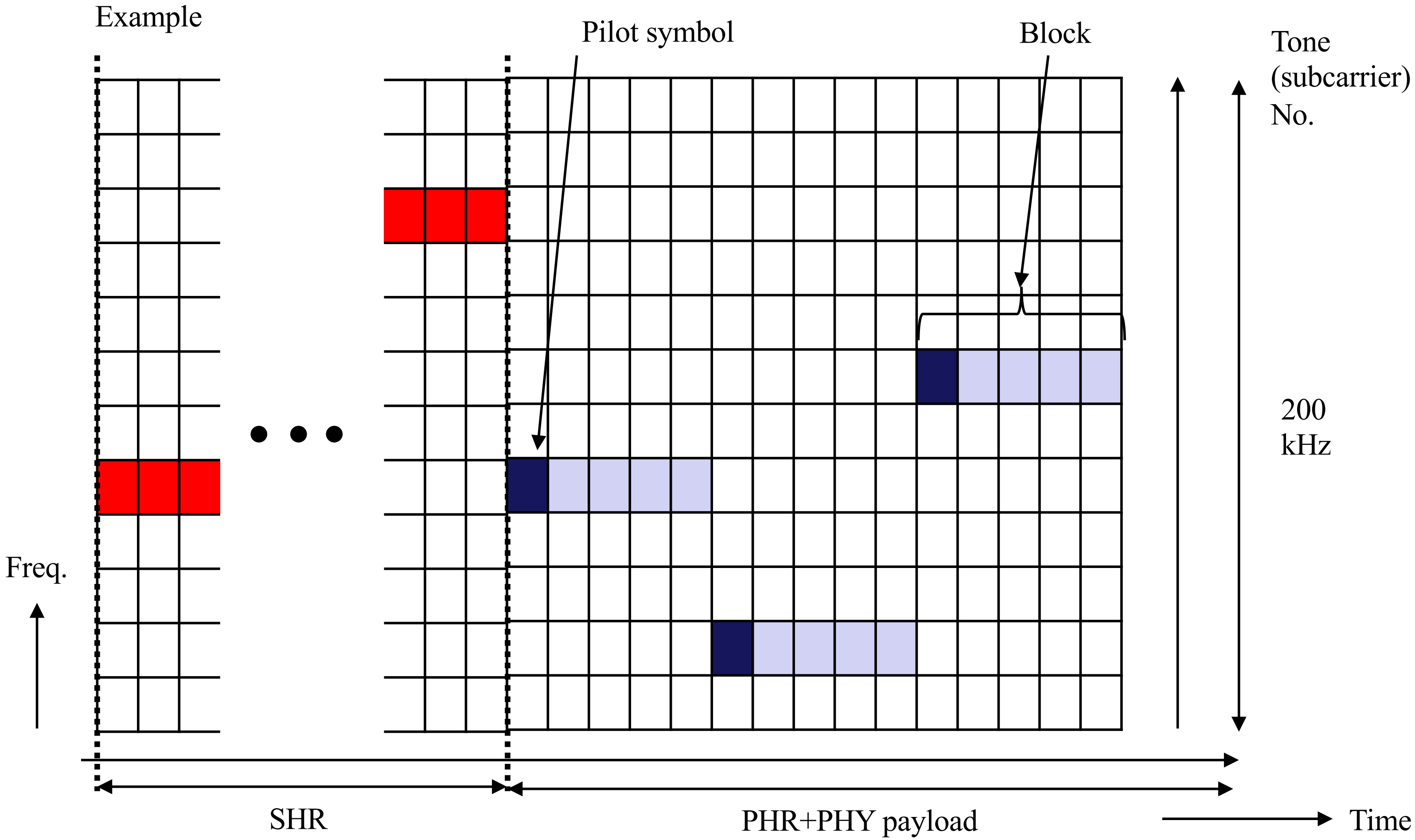
$e_{(k-1)\times \mathrm{SF}+i} = d_k \quad 1 \le i \le \mathrm{SF}$

PL: the number of pilot data
BL: the number of information data in a block
SF: the number of repetitions of interleaved data d_k.

Example of block mapped

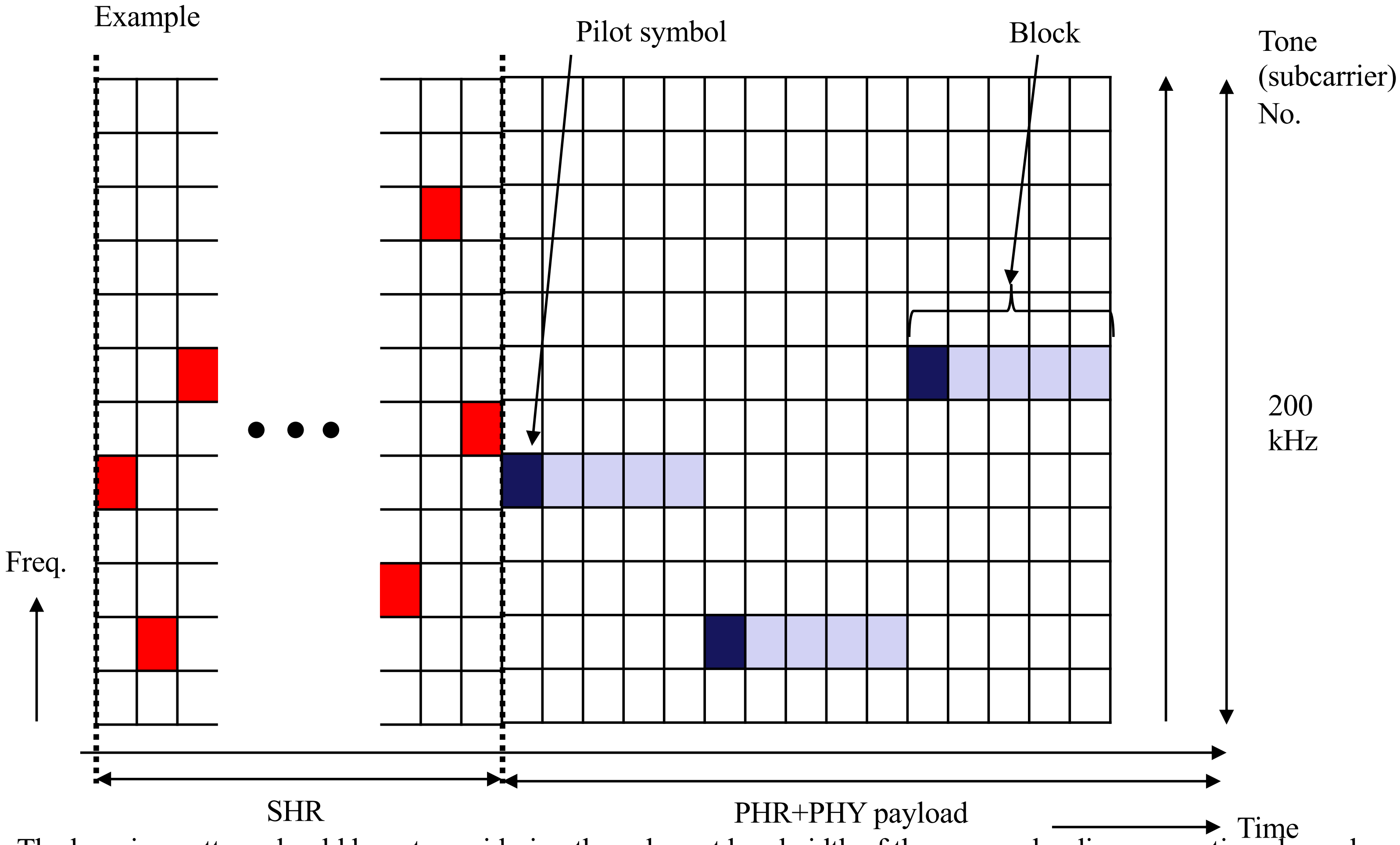


Frame construction and frequency hopping examples for Proposed SC-OFDM (Hopping case 1)



- The hopping pattern must be set considering the coherent bandwidth of the assumed wireless transmission channel.
- In this case, frequency hopping for the SHR section is performed in Golay sequence units.
- SHR may be transmitted at a single frequency without hopping..

Frame construction and frequency hopping examples for Proposed SC-OFDM (Hopping case 2)



- The hopping pattern should be set considering the coherent bandwidth of the assumed radio propagation channel.
- In this proposal, hopping is performed for each symbol of the Golay sequence.
- SHR may be transmitted at a single frequency without hopping.

PER under AWGN and multipath fading environments

Simulation parameters

- MCS 0-4
- Packet size: 20 byte
- Interleave size: 16 (4x4)
- Evaluation index: Packet Error Rate (PER)
- Padding bit: 2 bit
- Tail bit: 6 bit
- Gurad interval: ¼
- Perfect synchronization

MCS0: PL1, BL1: SF 8
MCS1: PL1, BL2: SF 4
MCS2: PL1, BL4: SF 2
MCS3: PL1, BL8: SF 1

PL: the number of pilot data
BL: the number of information data in a block
SF: the number of repetitions of interleaved data d_k.

Simulation parameters

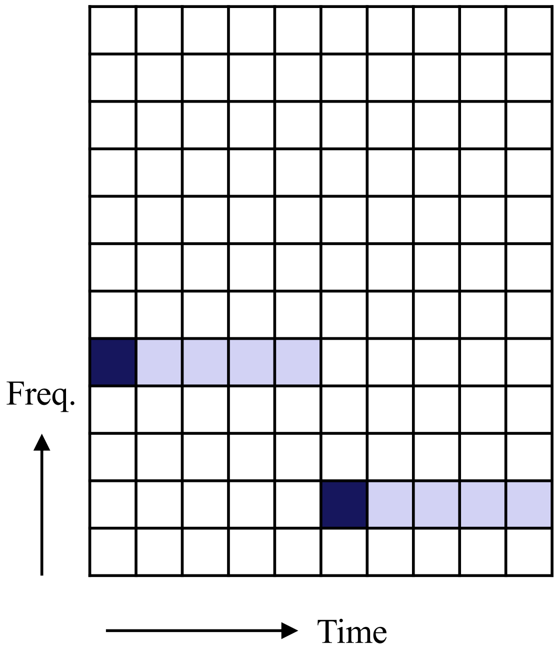
- Block structure
  - MCS0: PL1, BL1: SF 8
  - MCS1: PL1, BL2: SF 4
  - MCS2: PL1, BL4: SF 2
  - MCS3: PL1, BL8: SF 1

PL: the number of pilot data
BL: the number of information data in a block
SF: the number of repetitions of interleaved data d_k.

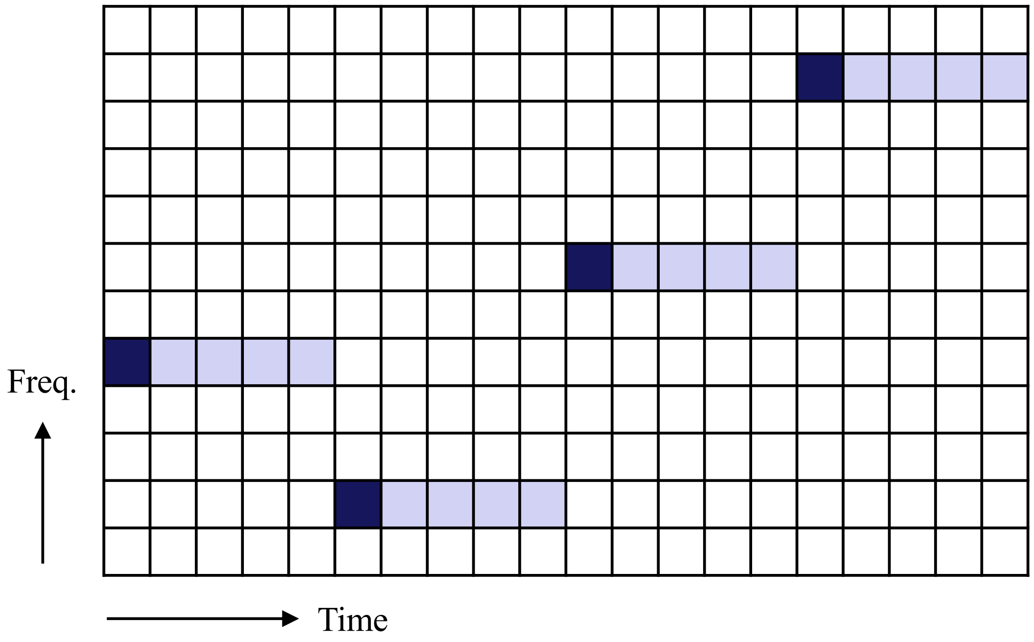
- Of the 14 subcarriers (Option 4), the subcarriers that each user selects as FH(Frequency Hopping)
  - Nsub 2: 2 subcarriers
  - Nsub 4: 4subcarriers
  - Nsub 8: 8 subcarriers
  - Nsub14: 14 subcarriers
- In this simulation, the subcarriers selected as FH are randomly selected from among 14 subcarriers.
- Each block does not overlap on the time axis.
- After estimating the propagation characteristics using the pilot symbol at the beginning of each block, the data in each block is demodulated.

Example of frame construction

BL=4, Nsub=2



BL=4, Nsub=4

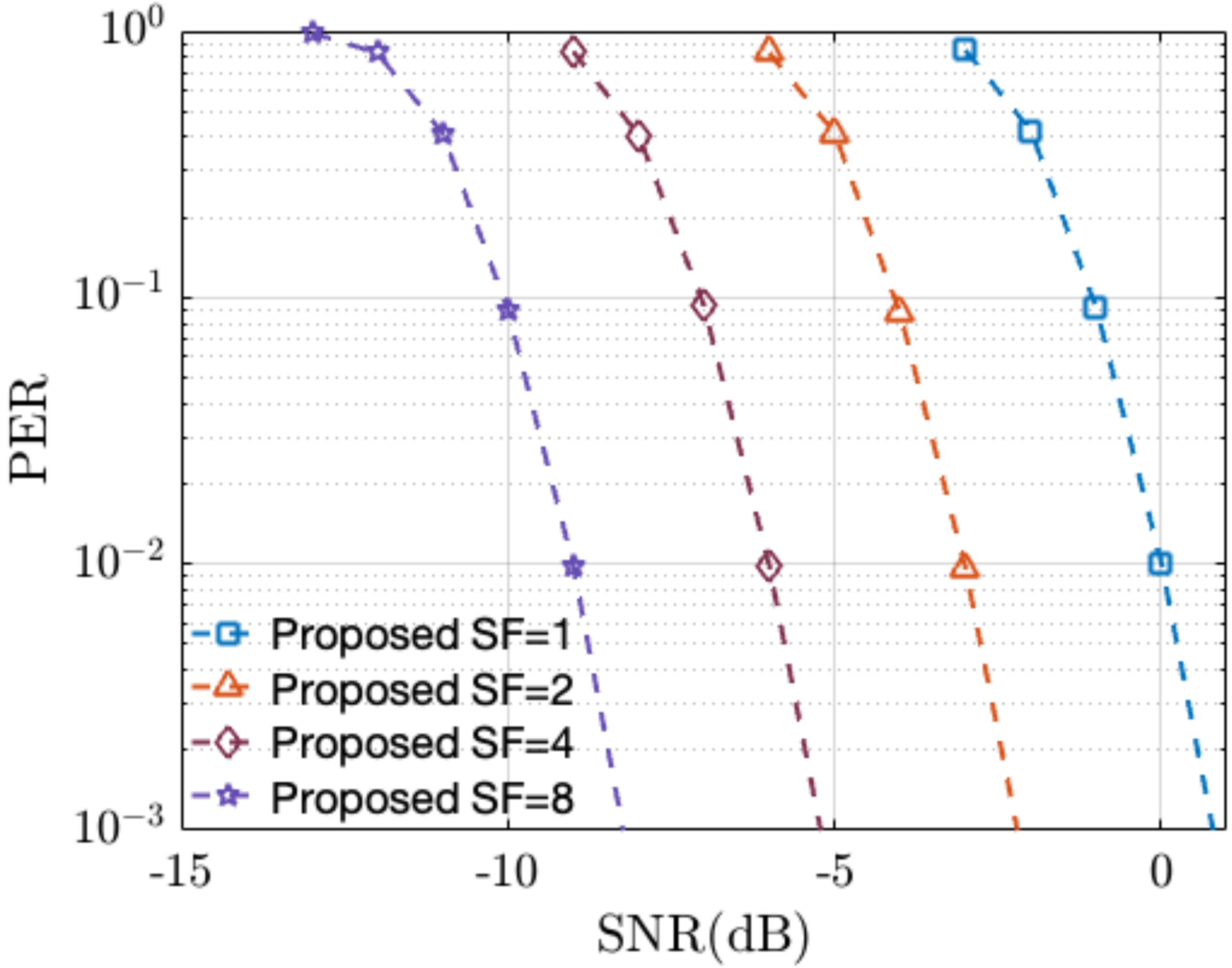


SNR, CIR and received signal power conversion

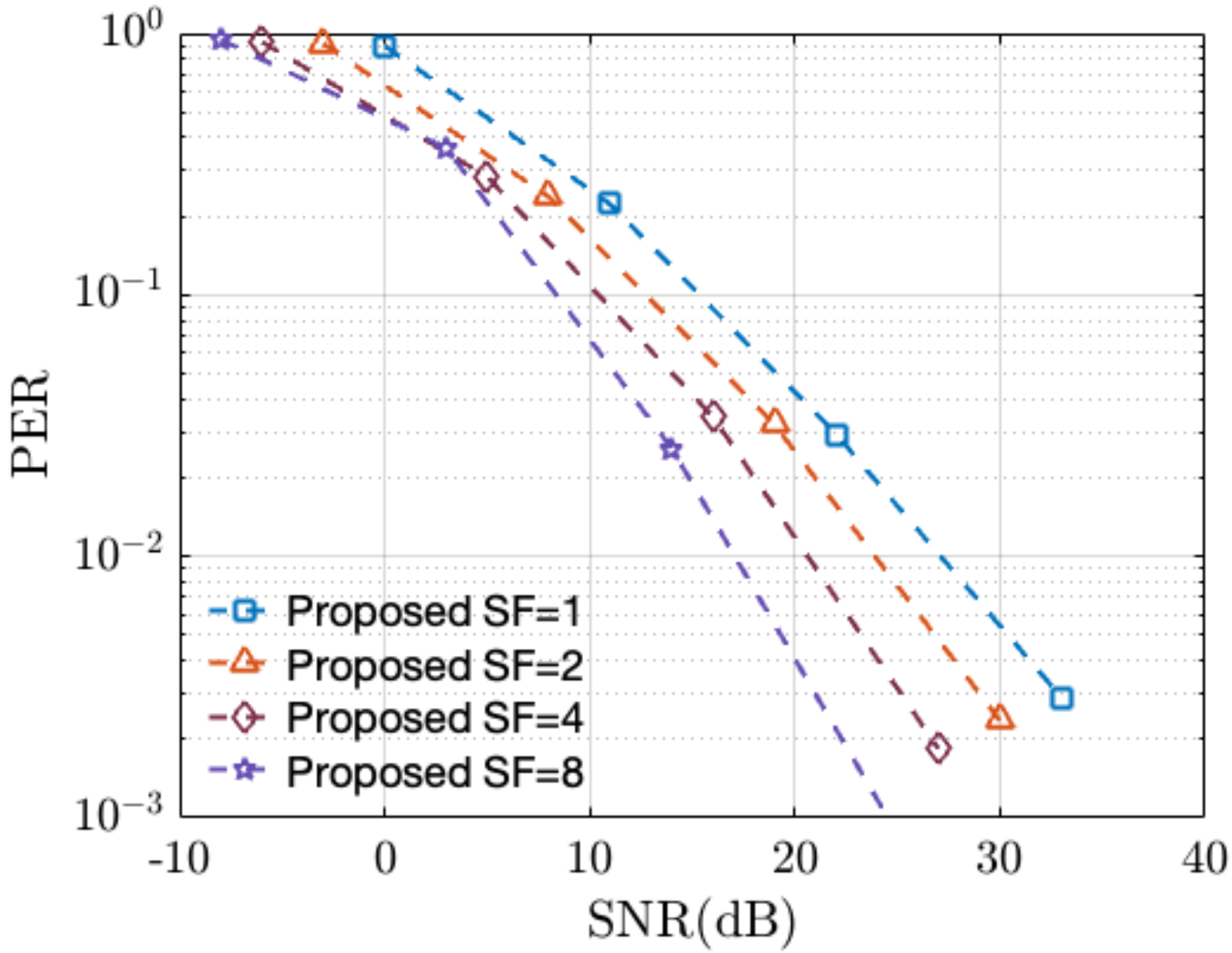
- In the case of Noise Figure (NF) =0dB and bandwidth =31.25/3 kHz, noise power should be -133.8 dB
- For SNR, each active tone in the symbol is treated as the signal (S).
- For CIR, the entire subcarrier bandwidth is considered as the carrier (C).

SNR(dB)	CIR(dB)	Received power (dBm)
-10	-22.0	-143.8 dBm
-5	-17.0	-138.8 dBm
0	-12.0	-133.8 dBm
5	-7.0	-128.8 dBm
10	-2.0	-123.3 dBm

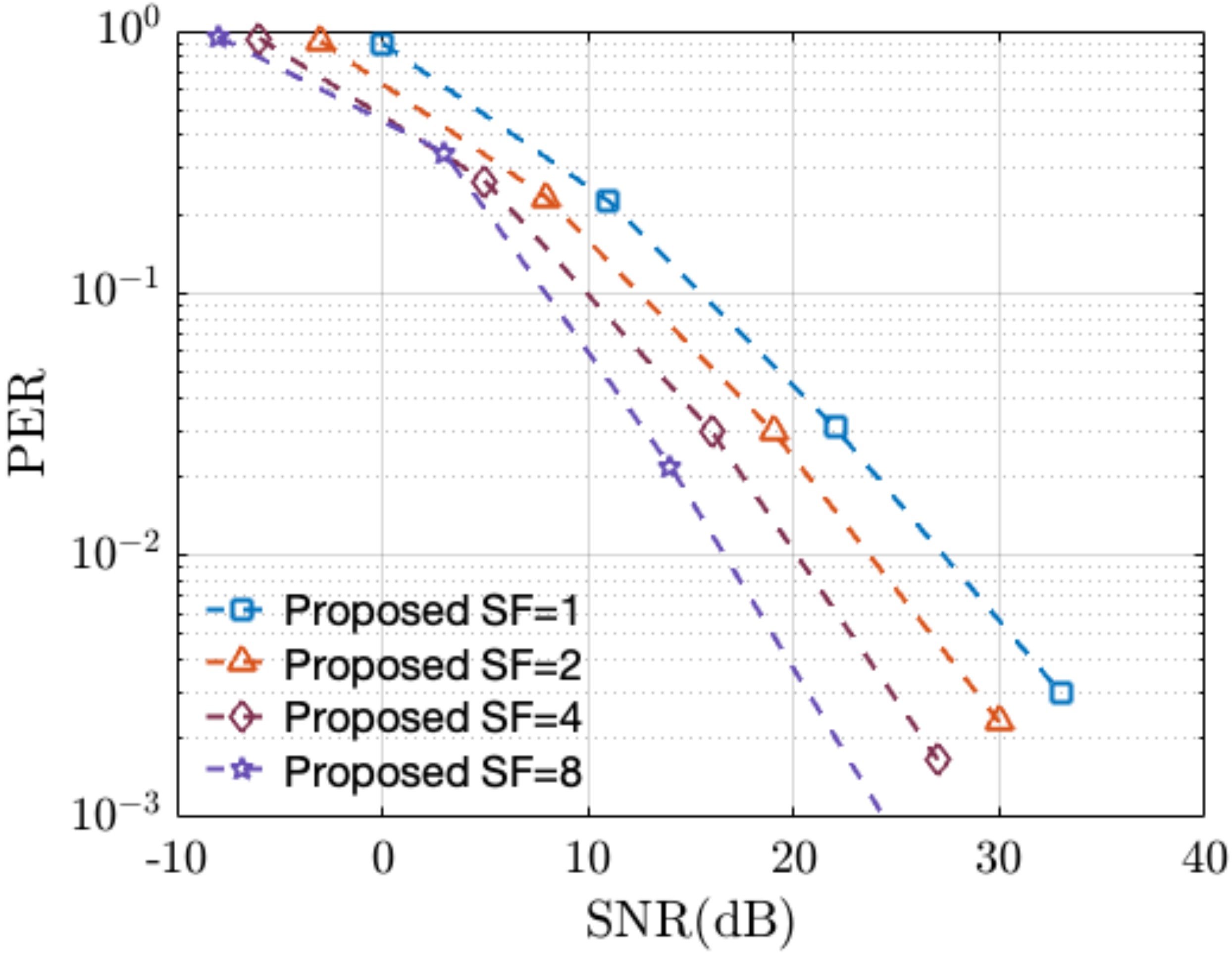
PER under AWGN (Nsub=14)



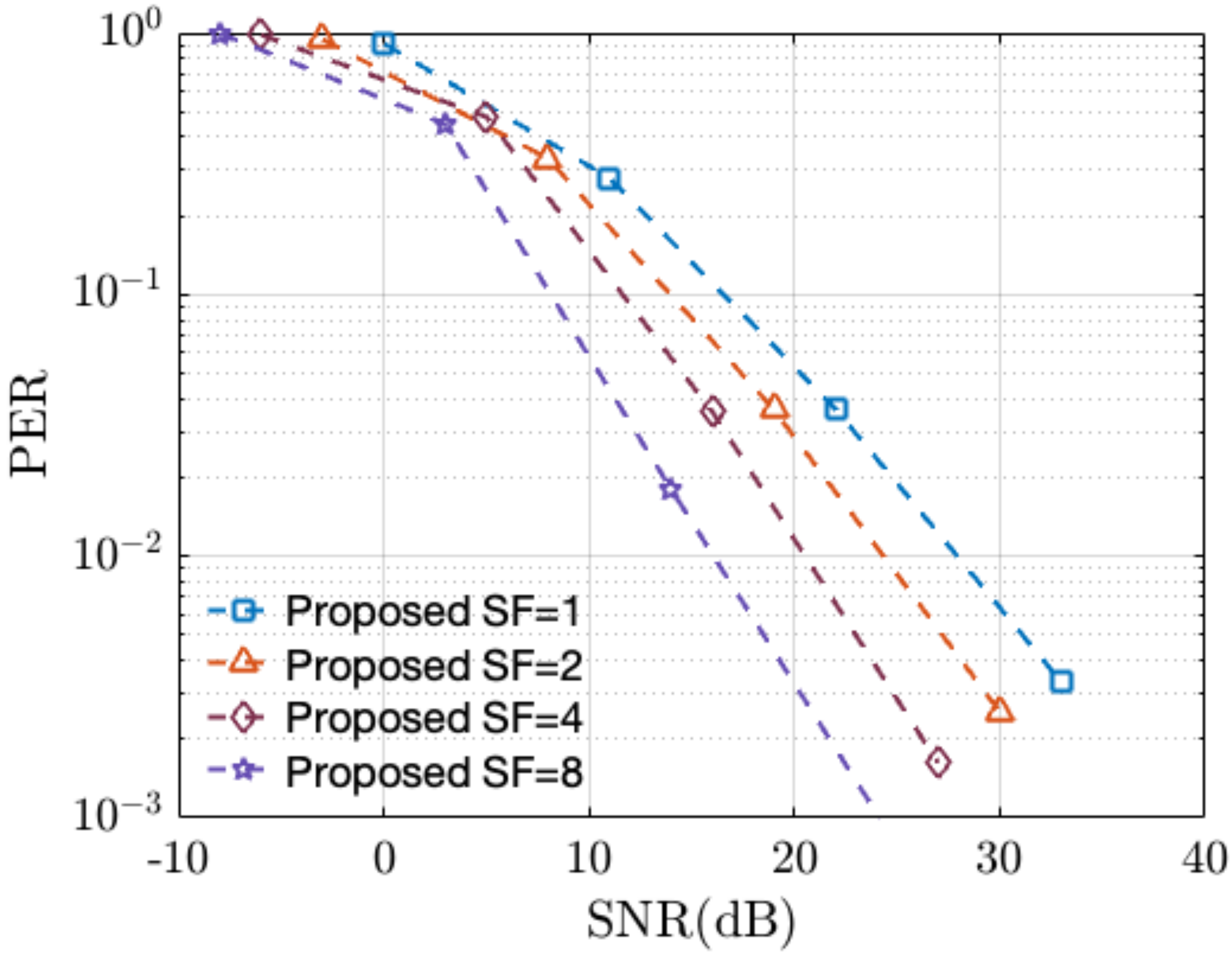
PER under GSM Typical Urban (fd=0.6Hz, Nsub=14)



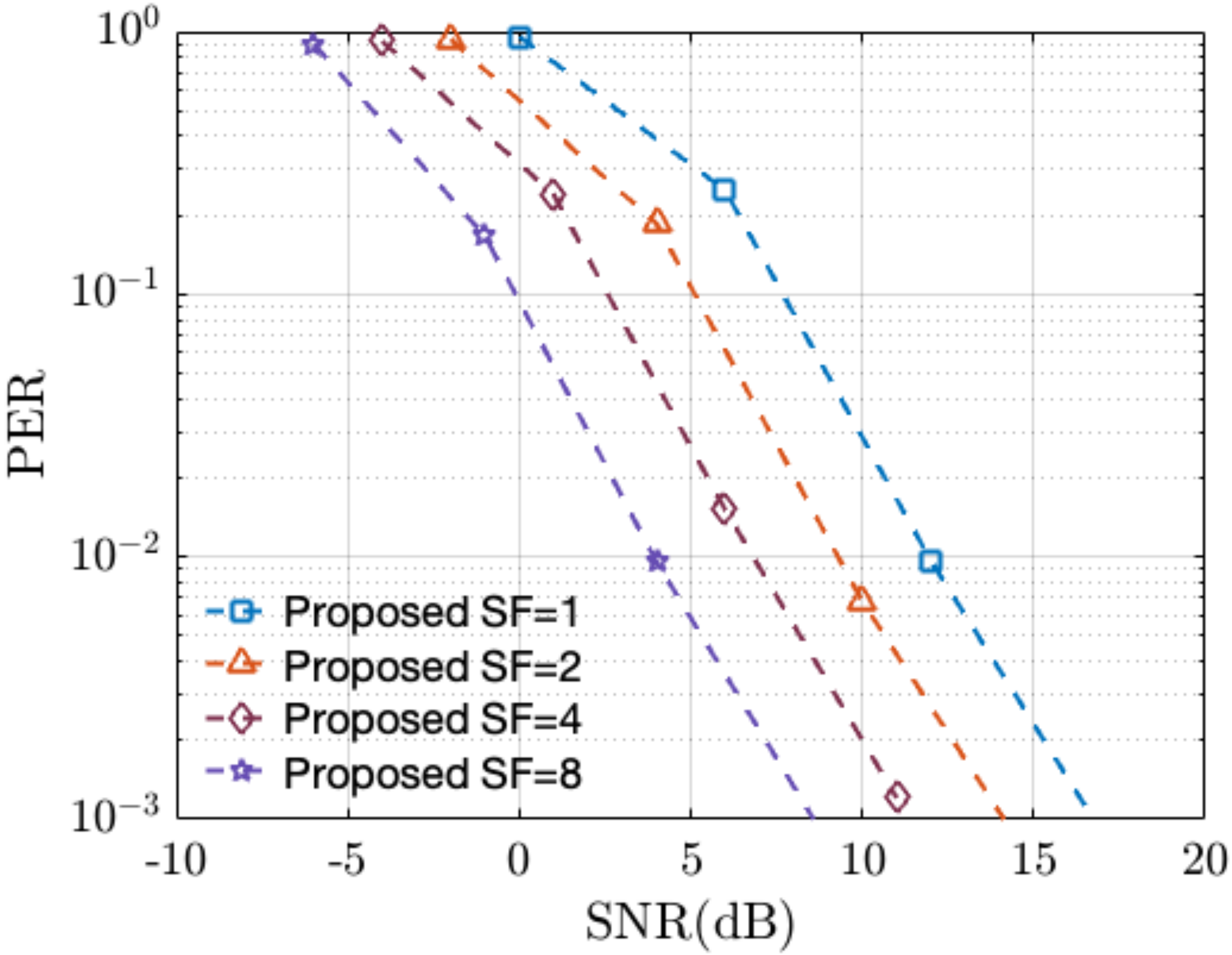
PER under IEEE 802.22 Profile A (fd=0.6Hz, Nsub=14)



PER under TDL-B (fd=2.5Hz, Nsub=14)



PER under TDL-D (fd=2.5Hz, Nsub=14)



Summary: Required SNR and power to achieve required PER (Payload part)

Channel model	MCS	SF	Doppler frequency(Hz)	Required PER	Required power(dBm)
AWGN	0	8	N/A	10^{-2}	-142.8
	1	4	N/A	10^{-2}	-139.8
	2	2	N/A	10^{-2}	-136.8
	3	1	N/A	10^{-2}	-133.8
COST 207 TU (GSM TU)	0	8	0.6	10^{-2}	-116.7
	1	4	0.6	10^{-2}	-113.2
	2	2	0.6	10^{-2}	-109.9
	3	1	0.6	10^{-2}	-106.7
802.22 profile A	0	8	0.6	10^{-2}	-117.2
	1	4	0.6	10^{-2}	-113.6
	2	2	0.6	10^{-2}	-110.1
	3	1	0.6	10^{-2}	-106.5

Summary: Required SNR and power to achieve required PER (Payload part, cont’)

Channel model	MCS	SF	Doppler frequency(Hz)	Required PER	Required power(dBm)
TDL-B	0	8	2.5	10^{-2}	-117.7
	1	4	2.5	10^{-2}	-113.3
	2	2	2.5	10^{-2}	-109.5
	3	1	2.5	10^{-2}	-105.9
TDL-D	0	8	2.5	10^{-2}	-129.9
	1	4	2.5	10^{-2}	-127.0
	2	2	2.5	10^{-2}	-124.5
	3	1	2.5	10^{-2}	-121.9

Required power to achieve required synchronization error(15-25/0325r1)

	Environment	Required error rate	Required power(dBm)
SC-OFDM	AWGN	10^{-2}	-145.8
	802.22 profile A	10^{-2}	-130.5
	Interference (BW : 10 kHz td : 5 ms)	10^{-2}	-157.6

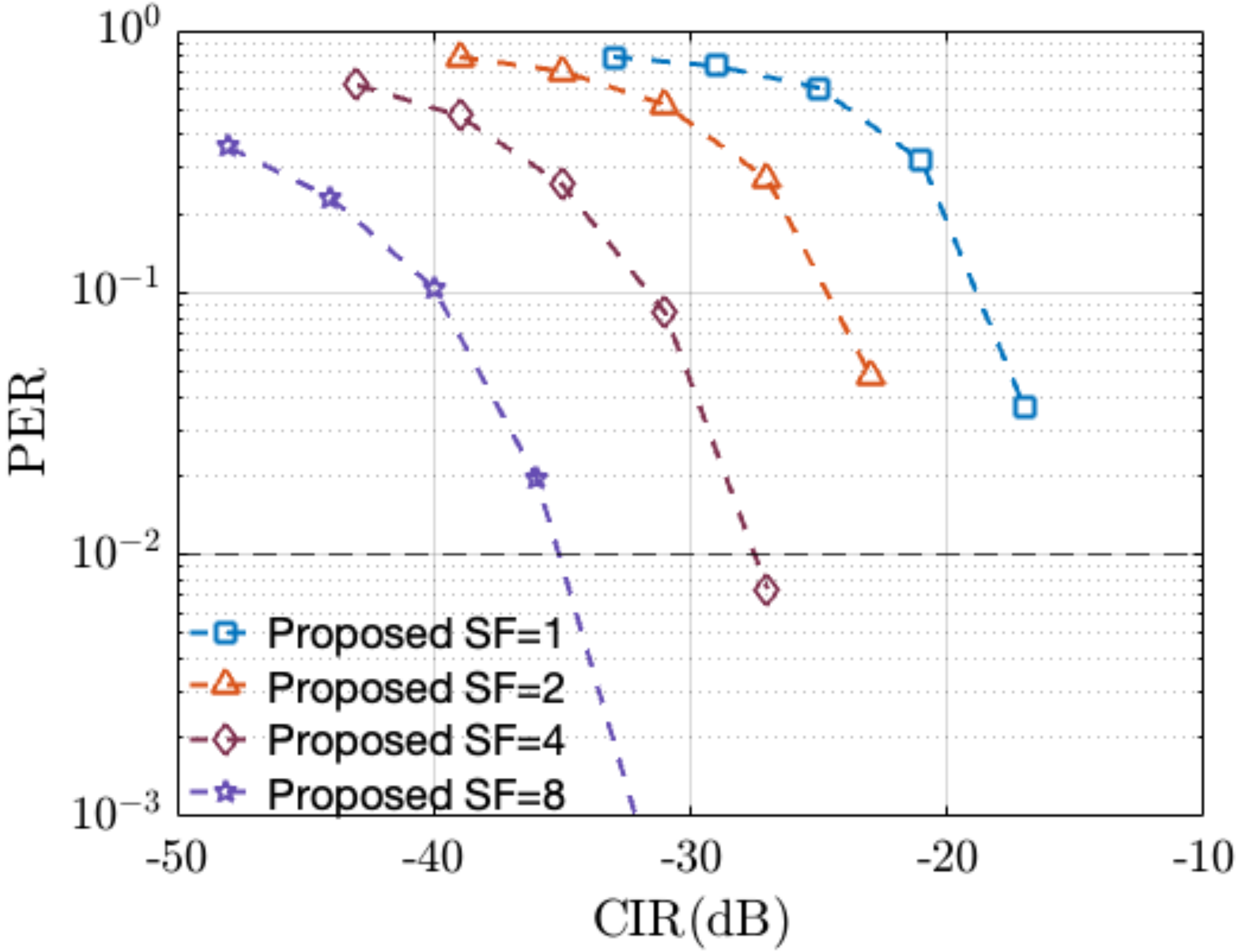
The synchronization characteristics of the proposed SHR have a margin compared to PER..

PER under interference environments

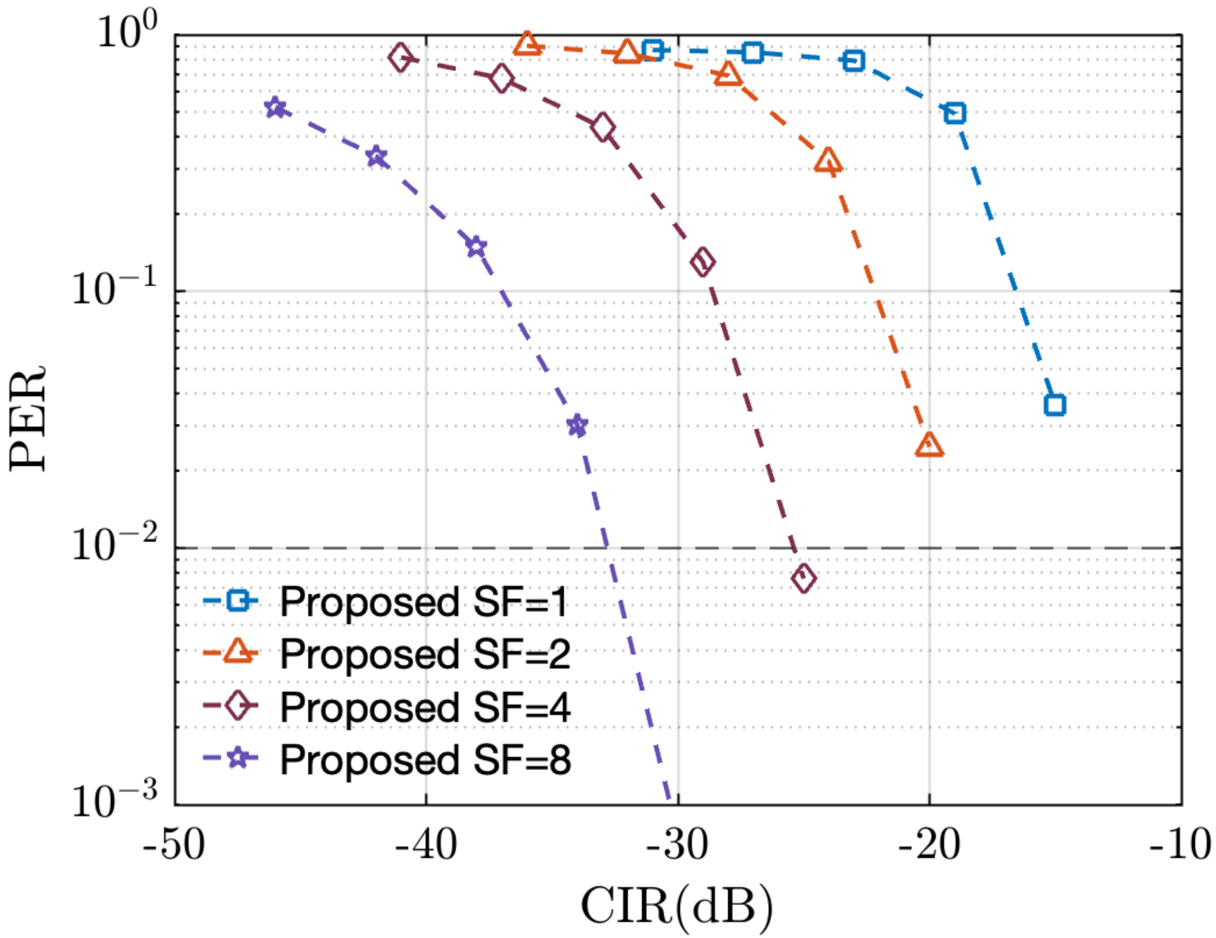
Simulation parameters (interference)

- Bandwidth (BW): : 125 kHz, time duration (td): 5ms
- BW: 2000 kHz, td: 5ms
- BW: 10 kHz, td: same as packet

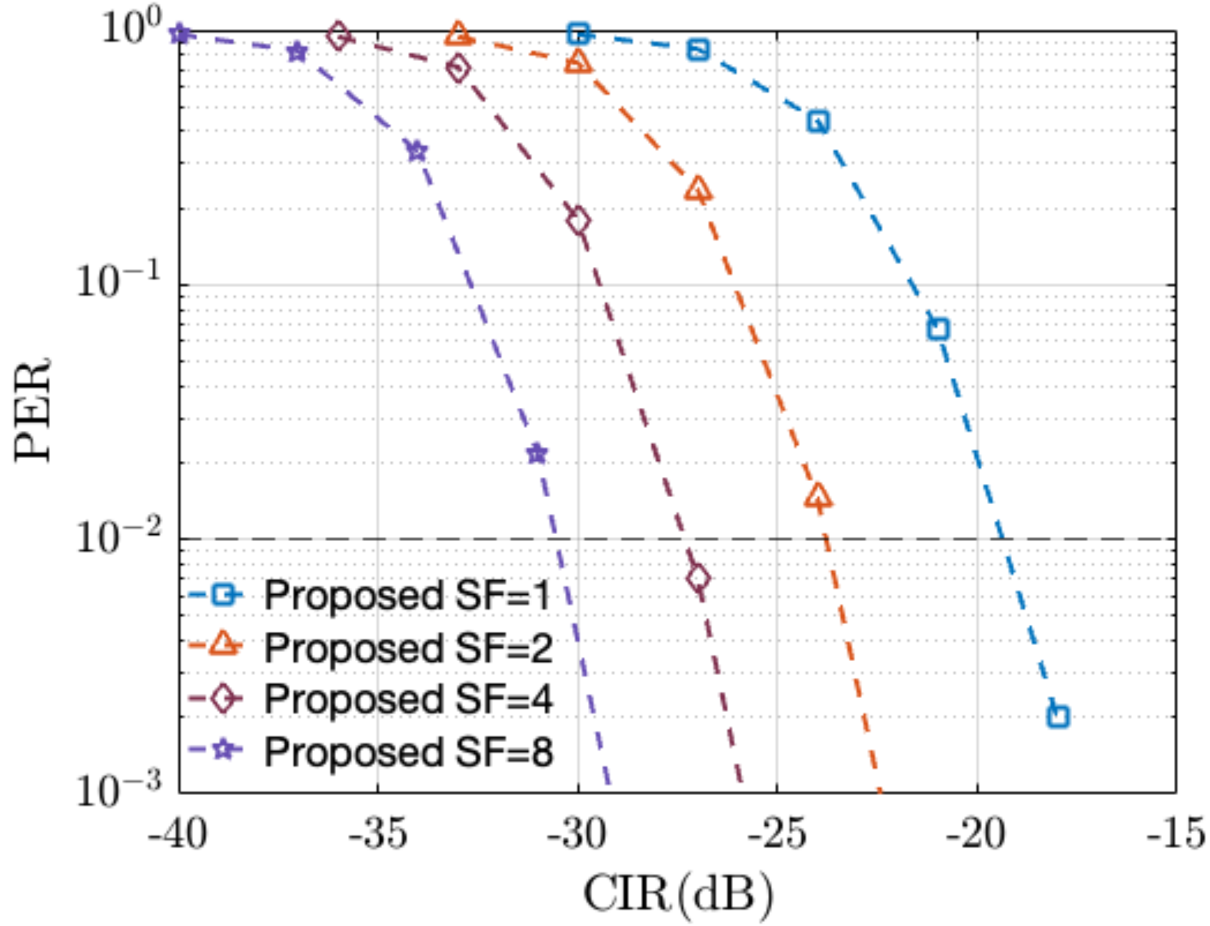
BW: 125 kHz, td: 5ms (Nsub=14)



BW: 2000 kHz, td: 5ms (Nsub=14)



BW: 10 kHz, td: same as packet (Nsub=14)



Summary: Required SNR and power

Interference BW (kHz)	Interference td (ms)	MCS	SF	Required PER	Required power(dBm)
125	5	0	8	10^{-2}	-156.9
		1	4	10^{-2}	
		2	2	10^{-2}	
		3	1	10^{-2}	
2000	5	0	8	10^{-2}	-154.6
		1	4	10^{-2}	-147.2
		2	2	10^{-2}	
		3	1	10^{-2}	
10	Same as packet	0	8	10^{-2}	-152.3
		1	4	10^{-2}	-149.1
		2	2	10^{-2}	-145.6
		3	1	10^{-2}	-141.2

Reference
(from 15-25/0158r3)

Example of spreading + phase rotation (Payload)

$$d_k = \begin{cases} 1 \\ -1 \end{cases} \text{(k=1,2,3,4,5,6,….)} \quad \Rightarrow \quad e_k \text{ (k=1,2,3,4,5,6,….)}$$

Option	$N_{Data\ Tones}$
1	12
2	24
3	48
4	96

Spreading factor:2

Data:4(input)×2(Spreading)
Pilot:2

$$e_{2k-1} = d_k \exp\left(j\frac{2\pi(2\times mod(k, N_{Data\ Tones}/2) - 1)}{4}\right)$$
$$e_{2k} = d_k$$

Spreading factor:4

Data:2×4
Pilot:4

$$e_{4k-3} = d_k \exp(j\frac{2\pi(2\times mod(k, N_{Data\ Tones}/4) - 1)}{4})$$
$$e_{4k-2} = d_k \exp\left(j\frac{2\pi(3\times mod(k, N_{Data\ Tones}/4) - 1)}{4}\right)$$
$$e_{4k-1} = d_k$$
$$e_{4k} = d_k \exp(j\frac{2\pi(mod(k, N_{Data\ Tones}/4) - 1)}{4})$$

Spreading factor:8

Data:1×8
Pilot:8

$$e_{8k-7} = d_k \exp(j\frac{2\pi(2\times mod(k, N_{Data\ Tones}/4) - 1)}{4} + j\pi)$$
$$e_{8k-6} = d_k \exp\left(j\frac{2\pi(3\times mod(k, N_{Data\ Tones}/4) - 1)}{4} + j\pi\right)$$
$$e_{8k-5} = d_k \exp(j\pi)$$
$$e_{8k-4} = d_k \exp(j\frac{2\pi(mod(k, N_{Data\ Tones}/4) - 1)}{4} + j\pi)$$
$$e_{8k-3} = d_k \exp(\frac{j2\pi(2 * mod(k, N_{Data\ Tones}/4) - 1)}{4})$$
$$e_{8k-2} = d_k \exp\left(\frac{j2\pi(3 * mod(k, N_{Data\ Tones}/4) - 1)}{4}\right)$$
$$e_{8k-1} = d_k$$
$$e_{8k} = d_k \exp(\frac{j2\pi(mod(k, N_{Data\ Tones}/4) - 1)}{4})$$

Example of spreading + phase rotation (Payload)

$$d_k = \begin{cases} 1 \\ -1 \end{cases} \text{(k=1,2,3,4,5,6,….)} \Rightarrow e_k \text{ (k=1,2,3,4,5,6,….)}$$

option	$N_{Data\ Tones}$
1	12
2	24
3	48
4	96

Spreading factor:2

Data:4(input)×2(SF)
Pilot:2

$$e_{2k-1} = d_k \exp\left(j\frac{2\pi(2\times mod(k, N_{Data\ Tones}/2) - 1)}{4}\right)$$

$$e_{2k} = d_k$$

$d_k, d_{k+1}, d_{k+2}, d_{k+3} \Rightarrow$

p_{2l-1}	e_{2k-1}	e_{2k}	e_{2k+1}	e_{2k+2}	p_{2l}	e_{2k+3}	e_{2k+4}	e_{2k+5}	e_{2k+6}

Spreading factor:4

Data:2×4
Pilot:4

$$e_{4k-3} = d_k \exp(j\frac{2\pi(2\times mod(k, N_{Data\ Tones}/4) - 1)}{4})$$

$$e_{4k-2} = d_k \exp\left(j\frac{2\pi(3\times mod(k, N_{Data\ Tones}/4) - 1)}{4}\right)$$

$$e_{4k-1} = d_k$$

$$e_{4k} = d_k \exp(j\frac{2\pi(mod(k, N_{Data\ Tones}/4) - 1)}{4})$$

$d_k, d_{k+1} \Rightarrow$

p_{4l-3}	e_{8k-7}	e_{8k-6}	p_{4l-2}	e_{8k-5}	e_{8k-4}	p_{4l-1}	e_{8k-3}	e_{8k-2}	p_{4l}	e_{8k-1}	e_{8k}

Spreading factor:8

Data:1×8
Pilot:8

$$e_{8k-7} = d_k \exp(j\frac{2\pi(2\times mod(k, N_{Data\ Tones}/4) - 1)}{4} + j\pi)$$

$$e_{8k-6} = d_k \exp\left(j\frac{2\pi(3\times mod(k, N_{Data\ Tones}/4) - 1)}{4} + j\pi\right)$$

$$e_{8k-5} = d_k \exp(j\pi)$$

$$e_{8k-4} = d_k \exp(j\frac{2\pi(mod(k, N_{Data\ Tones}/4) - 1)}{4} + j\pi)$$

$$e_{8k-3} = d_k \exp(\frac{j2\pi(2 * mod(k, N_{Data\ Tones}/4) - 1)}{4})$$

$$e_{8k-2} = d_k \exp\left(\frac{j2\pi(3 * mod(k, N_{Data\ Tones}/4) - 1)}{4}\right)$$

$$e_{8k-1} = d_k$$

$$e_{8k} = d_k \exp(\frac{j2\pi(mod(k, N_{Data\ Tones}/4) - 1)}{4})$$

$d_k \Rightarrow$

p_{8l-7}	e_{8k-7}	p_{8l-6}	e_{8k-6}	p_{8l-5}	e_{8k-5}	p_{8l-4}	e_{8k-4}	p_{8l-3}	e_{8k-3}	p_{8l-2}	e_{8k-2}	p_{8l-1}	e_{8k-1}	p_{8l}	e_{8k}

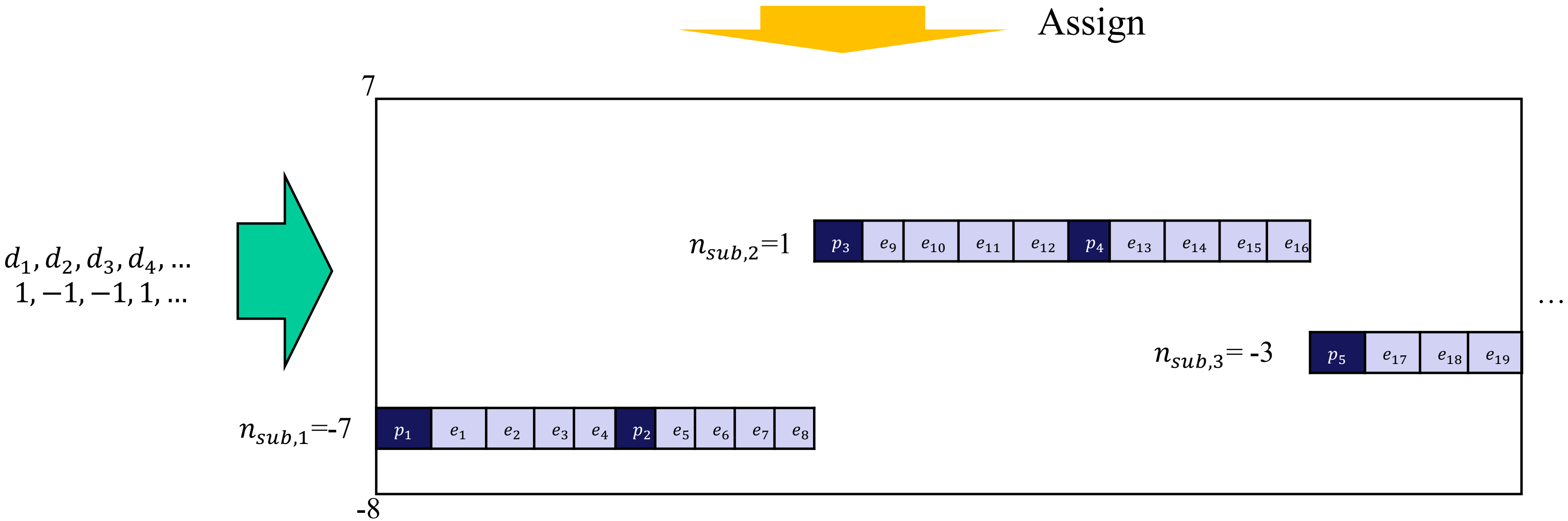
Example of spreading + phase rotation (Payload, PL=1, BL=4, SF=2)

Input $d_1,\ d_2,\ d_3,\ d_4, \ldots. = 1,\ -1,\ -1,\ 1,\ \ldots$

Spreading $e_1, e_2,\ e_3, e_4,\ e_5, e_6,\ e_7, e_8, \ldots. = 1j, 1,\ \ 1j, -1,\ \ -1j, -1,\ \ -1j, 1, \ldots$ $\left\{ \begin{array}{l} e_{2k-1} = d_k \exp\left(j\dfrac{2\pi(2\times mod(k, N_{Data\ Tones}/2) - 1)}{4}\right) \\ e_{2k} = d_k \end{array} \right\}$

Pilot $p_1, p_2, p_3, p_4, p_5, p_6, \ldots = -1, -1, -1, -1, 1, 1, \ldots$ $\{\ \text{PN9}_N\ \}$

Subcarrier $n_{sub,i}$=-7,1,-3,…



Subcarrier mapping scheme

- There are various methods of block mapping based on Nsub.
  - Random mapping： One subcarrier is selected from among the available subcarriers at each time.
  - Non-Random mapping: Mapping is performed based on a mapping scheme.

A proposal of subcarrier mapping scheme (Nsub=14)

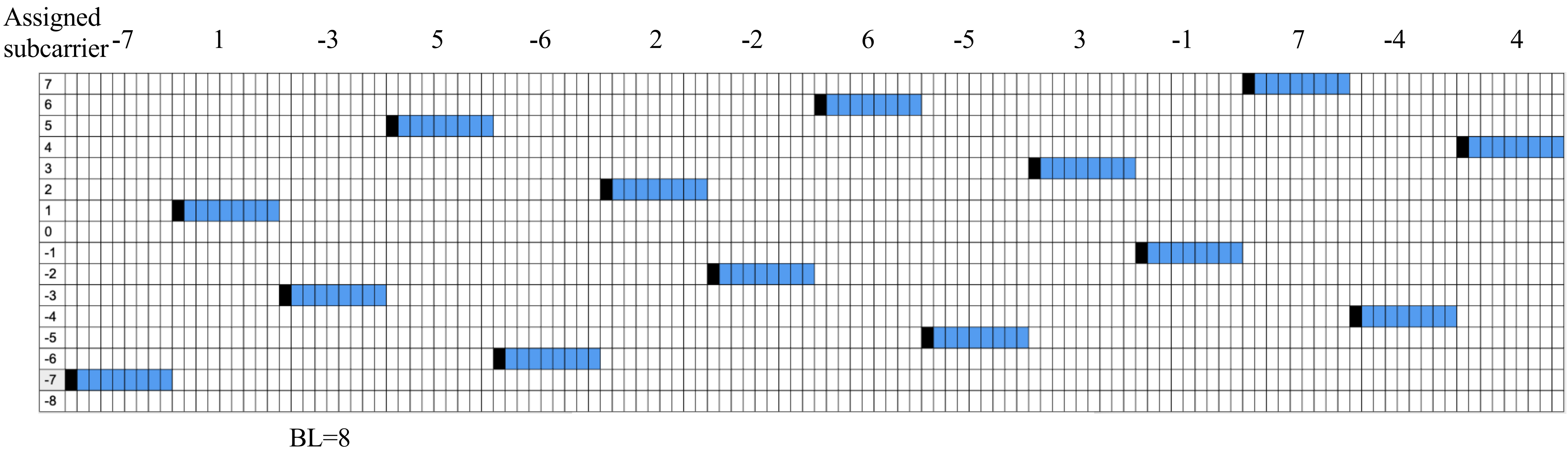
The tone(subcarrier) number assigned to each blocks: $-\frac{N_{FFT}}{2}, -\frac{N_{FFT}}{2}+1, \dots, \frac{N_{FFT}}{2}-1 \quad (i = 1,2,3, \dots)$

$$n_{sub,i} = \frac{N_{FFT}}{2} \times \mathrm{mod}(i-1,2) + \frac{N_{FFT}}{4} \times \mathrm{mod}\left(floor\left(\frac{i-1}{2}\right), 2\right) + \mathrm{mod}\left(floor\left(\frac{i-1}{4}\right), \frac{N_{FFT}}{4}\right) + 1 - \frac{N_{FFT}}{2}$$

Inactive subcarriers are excluded.

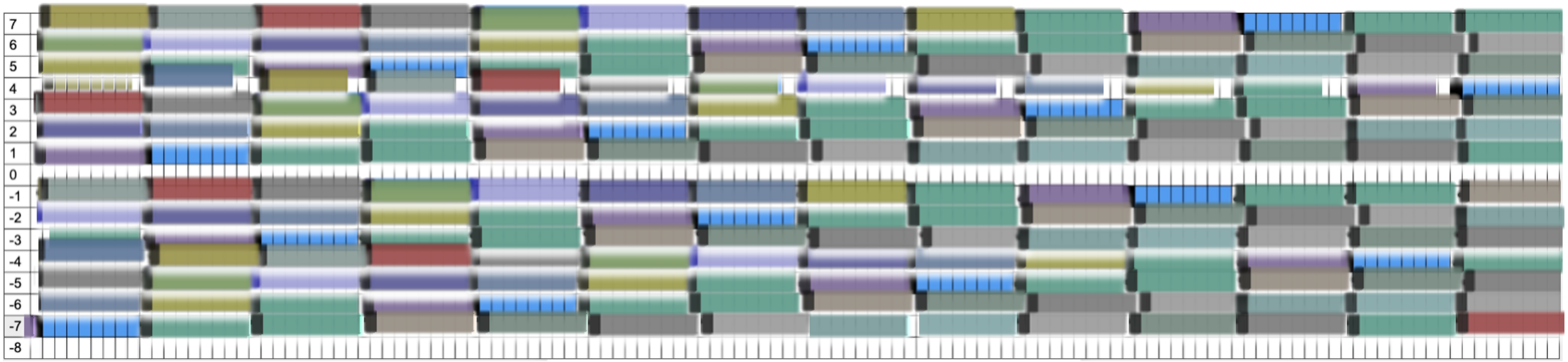
In the case of Option4 (N_{FFT}=16), the subcarriers selected in the i-th block are as follows.

$n_{sub,i}$=-7,1,-3,5,-6,2,-2,6,-5,3,-1,7,-4,4, -7,1,-3,5,-6,2,-2,6,-5,3,-1,7,-4,4, …



Subcarrier mapping scheme

- By arranging the subcarriers in a cyclical pattern, multiple transmitters can use the bandwidth efficiently (without overlap)
- The same number of transmitters as the number of active subcarriers can be accommodated in the same bandwidth with minimal interference
- For example, one possible method would be to assign a cyclic shift of one subcarrier on the frequency axis to the subcarriers allocated and used in Slide 19, and then assign the pattern to other user.



Pilot Generator

Use the existing pilot generation method as is

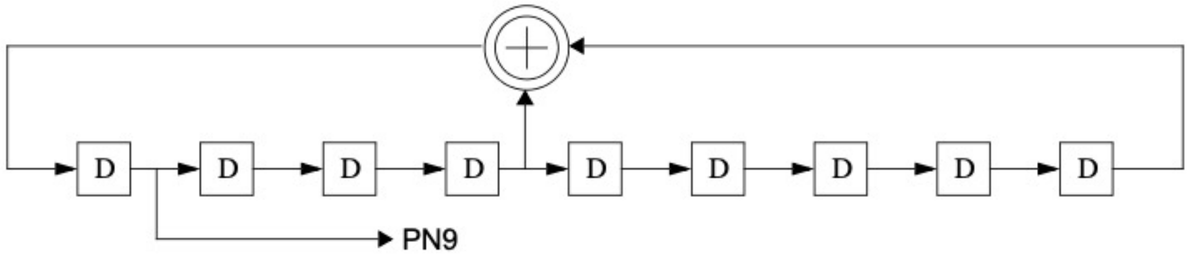


Figure 16-2—Schematic of the PN generator

The seed in the PN9 shall be all ones: "1 1 1 1 1 1 1 1 1." The PN9 shall be reinitialized to the seed after each packet (either transmit or receive).

The PN9 generator is clocked using the seed as the starting point and enabled after the first clock cycle. For example, the first 30 bits out of the PN9, once it is enabled, would be as follows:

$$PN9_n = 0_0\ 0_1\ 0_2\ 0_3\ 1_4\ 1_5\ 1_6\ 1_7\ 0_8\ 1_9\ 1_{10}\ 1_{11}\ 0_{12}\ 0_{13}\ 0_{14}\ 0_{15}\ 1_{16}\ 0_{17}\ 1_{18}\ 1_{19}\ 0_{20}\ 0_{21}\ 1_{22}\ 1_{23}\ 0_{24}\ 1_{25}\ 1_{26}\ 0_{27}\ 1_{28}\ 1_{29}$$

Ref.: IEEE Std 802.15.4-2020, p.524

Example: $p_1, p_2, p_3, p_4, p_5, p_6, \ldots = -1, -1, -1, -1, 1, 1, \ldots$