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

Submission Title: [**Transmission characteristics of 802.15.4ad SUN OFDM LR based on SC-OFDM**]

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

Abstract: Propose 802.15.4ad SUN OFDM LR scheme based on SC-OFDM. 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: Discuss technical specification based on SC-OFDM for 802.15.4ad Low Rate (LR) system.

Transmission characteristics of 802.15.4ad SUN OFDM LR based on SC-OFDM

May 15, 2025

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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 used frequency hopping to first select a frequency and then transmit a block consisting of a pilot signal and information symbols at that selected frequency
- We have demonstrated the transmission characteristics of this proposed SC-OFDM system in AWGN and multipath fading environments in 15-25/0158r3
- In this contribution, we have further evaluated the transmission characteristics of the proposed SC-OFDM system in AWGN and multipath fading environments and under the interference noise conditions specified in the technical requirements document

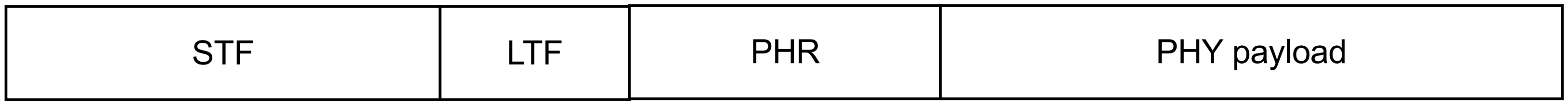
Proposed 802.15.4 SUN-OFDM LR

		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		0.521	0.521
	MCS 1		6.25	1.041	1.041
	MCS 2			2.083	2.083

LR4: for FCC 15.247

Frame format SUN-OFDM LR

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

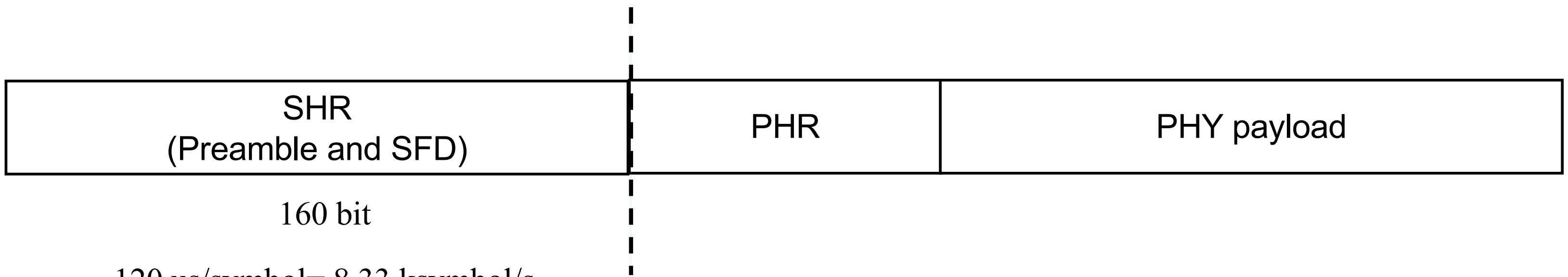


4 OFDM symbols (480 us)

2.5 OFDM symbols (300 us)

120us/ OFDM symbol

OFDM LR3

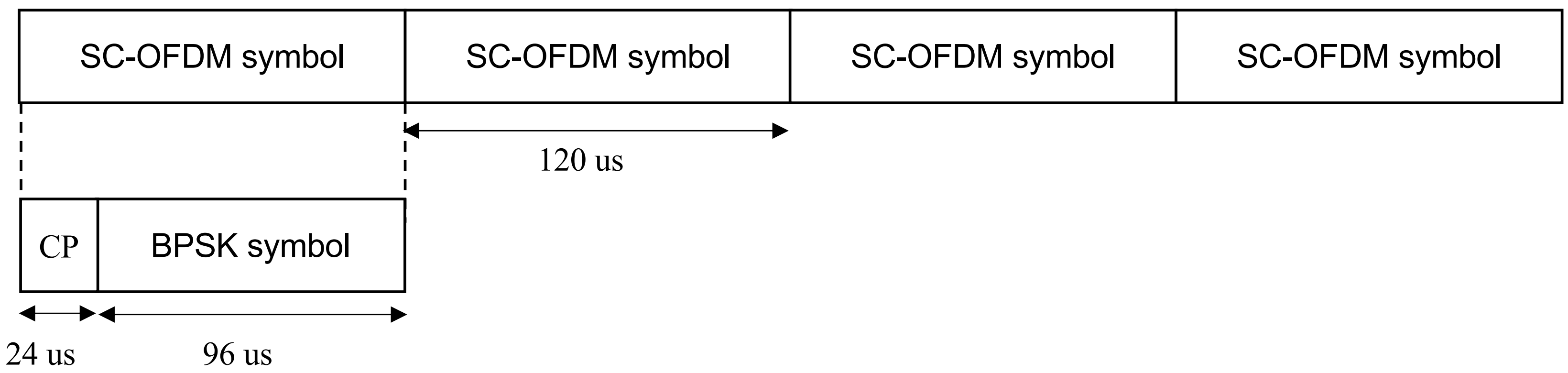


160 bit

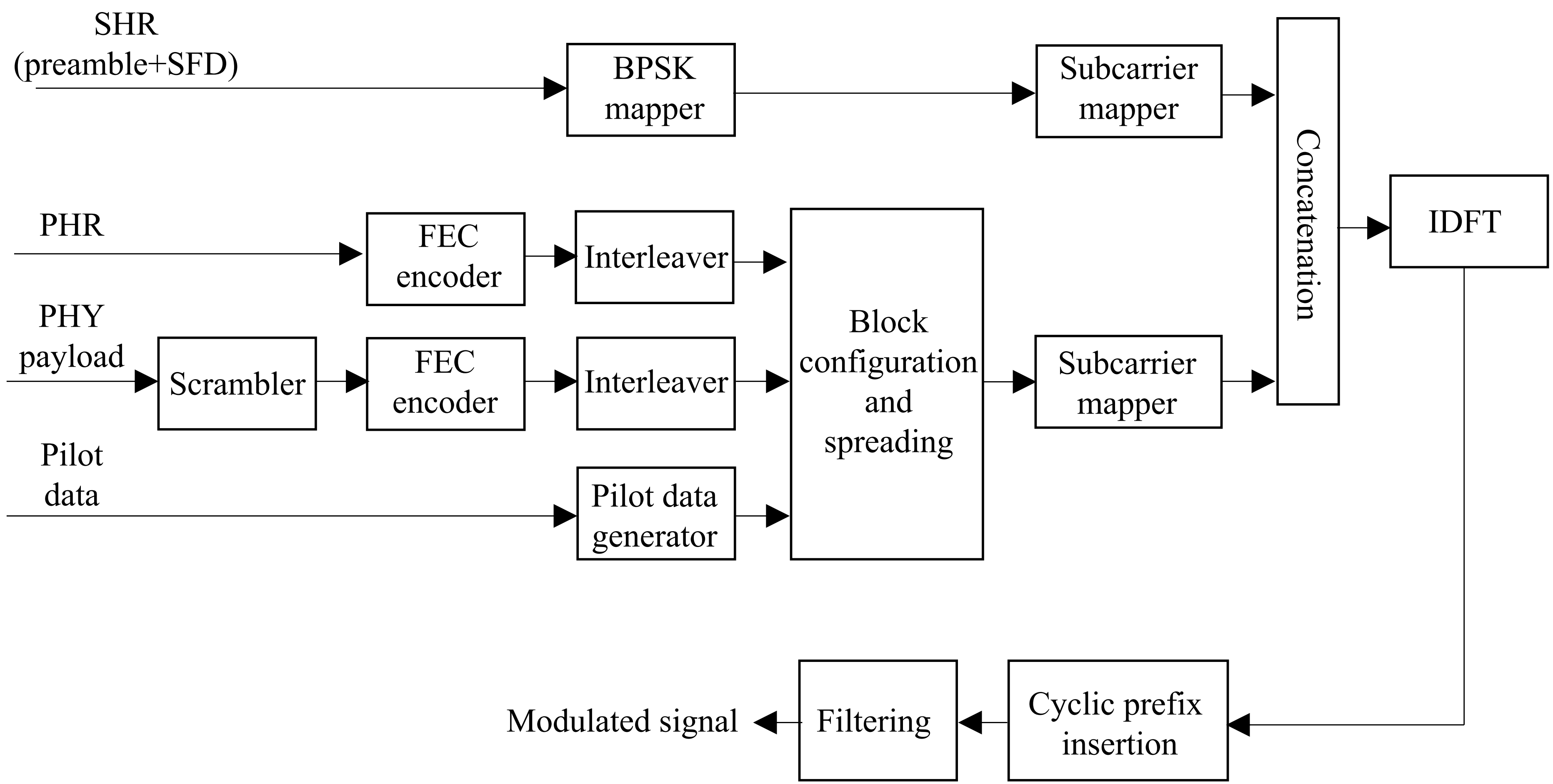
120 us/symbol= 8.33 ksymbol/s

15-25/0247r0

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



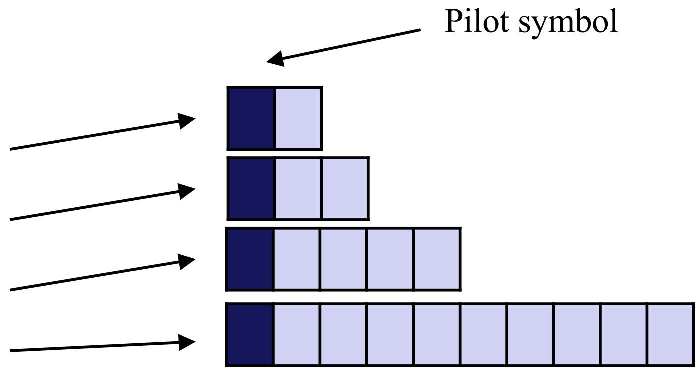
Reference modulator diagram



PHR, PHY payload, and Pilot data only
or
SHR, PHR, PHY payload, and Pilot data

Simulation parameters

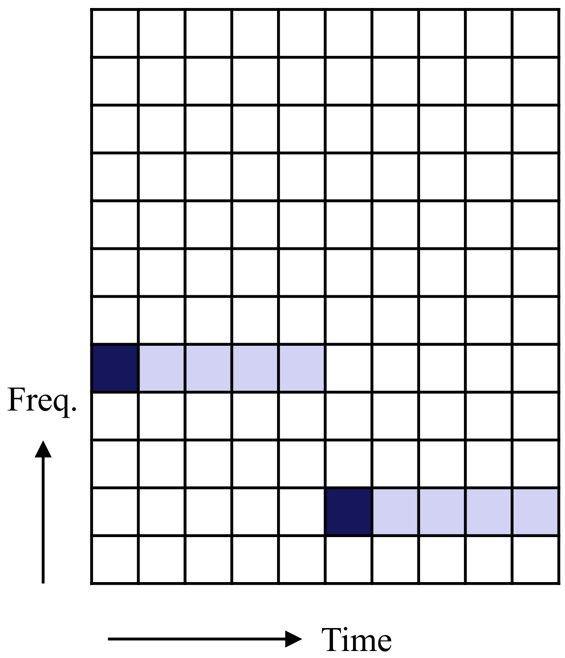
- Block structure
  - BL1: 1 Pilot symbol and 1 Data symbols
  - BL2: 1 Pilot symbol and 2 Data symbols
  - BL4: 1 Pilot symbol and 4 Data symbols
  - BL8: 1 Pilot symbol and 8 Data symbols



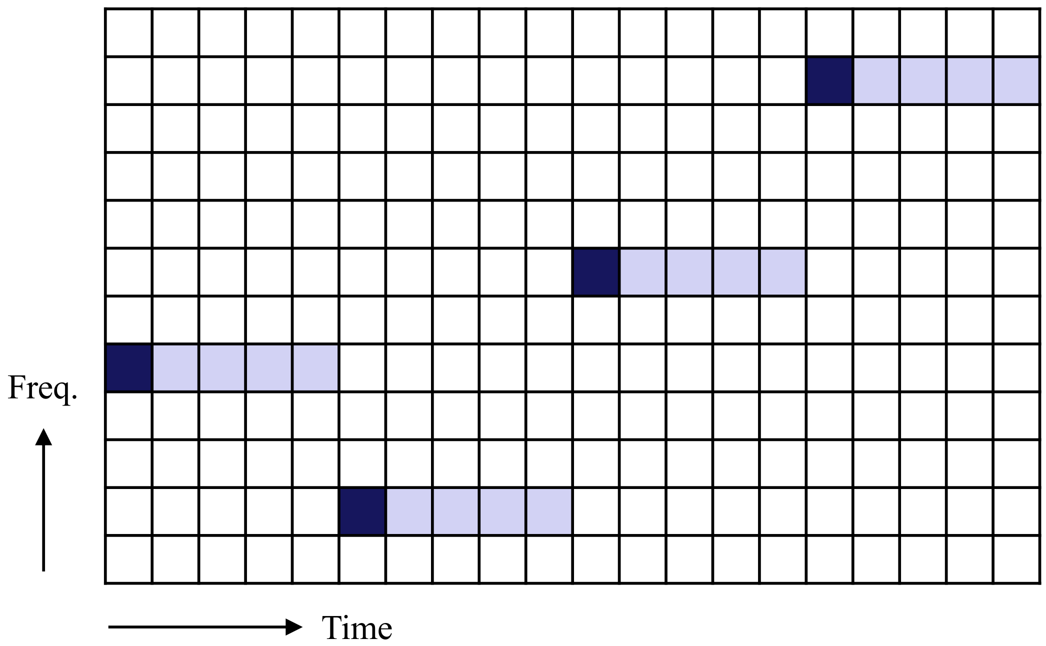
- Of the 14 subcarriers (Option 4), the subcarriers that each user selects as FH(Frequency Hopping)
  - Nsub 2: 2 subcarriers
  - Nsub 4: 4subcarriers
  - Nsub 8: 8 subcarriers
  - Nsub14: 14 subcarriers
- In this simulation, the subcarriers selected as FH are randomly selected from among 14 subcarriers.
- 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



PER under AWGN and multipath fading environments

Simulation parameters (others)

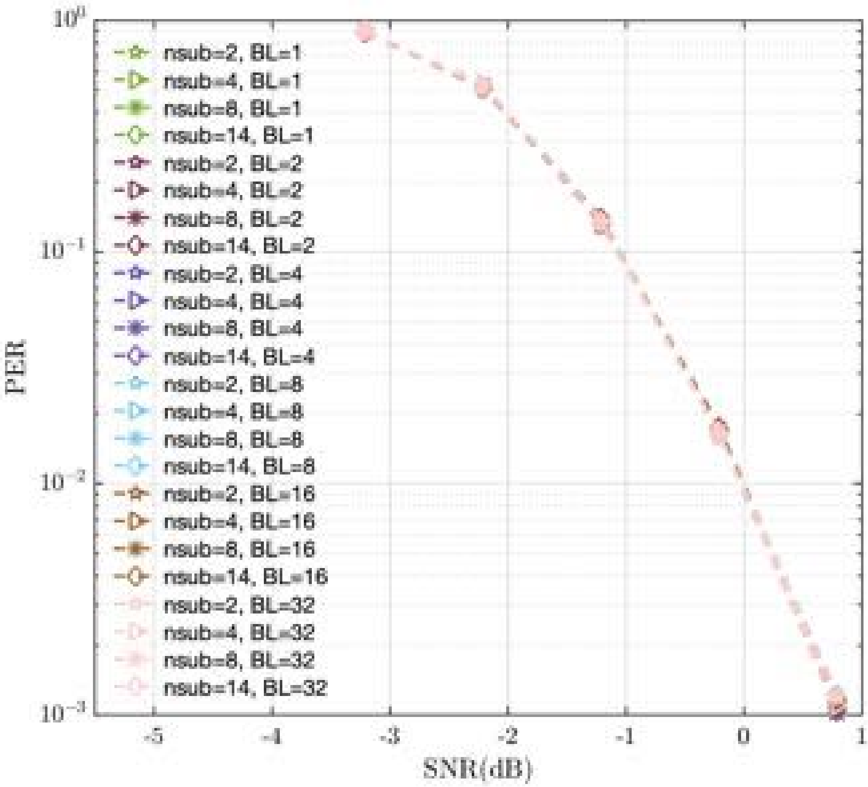
- Spreading: with spreading and no spreading (SF=1,2,4)
- Packet size: 20 byte
- Interleave size: Random
- Evaluation index: Packet Error Rate (PER)
- Padding bit: 2bit
- Tail bit: 6bit
- Gurad interval: 1/4

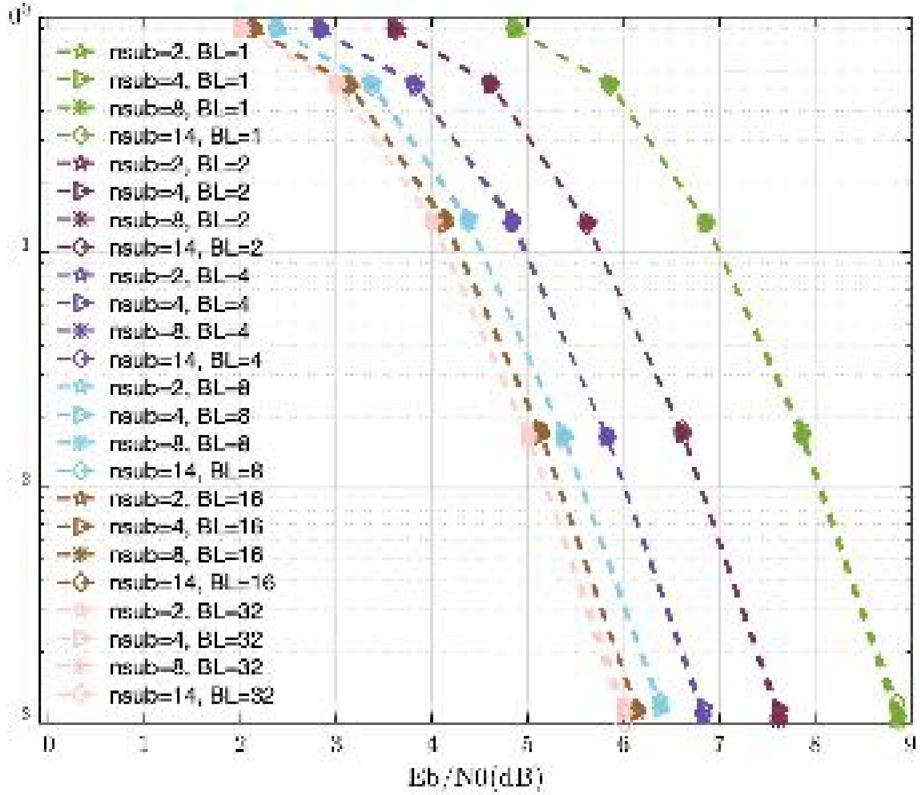
SNR and received signal power conversion

- In the case of Noise Figure (NF) =0dB and bandwidth =31.25/3 kHz, noise power should be -133.8 dB

SNR(dB)	Received power (dBm)
-10	-143.8 dBm
-5	-138.8 dBm
0	-133.8 dBm
5	-128.8 dBm
10	-123.3 dBm

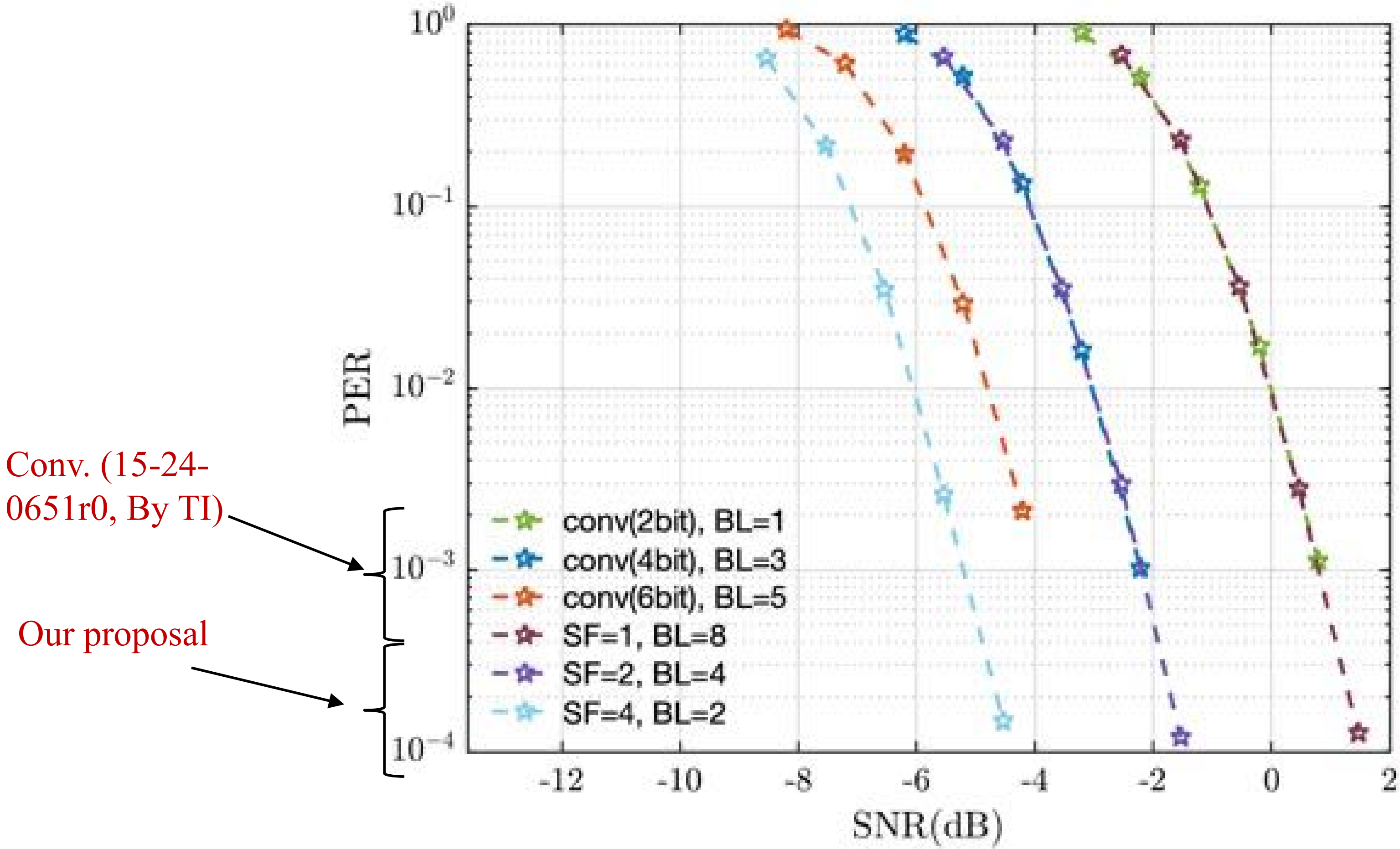
PER under AWGN





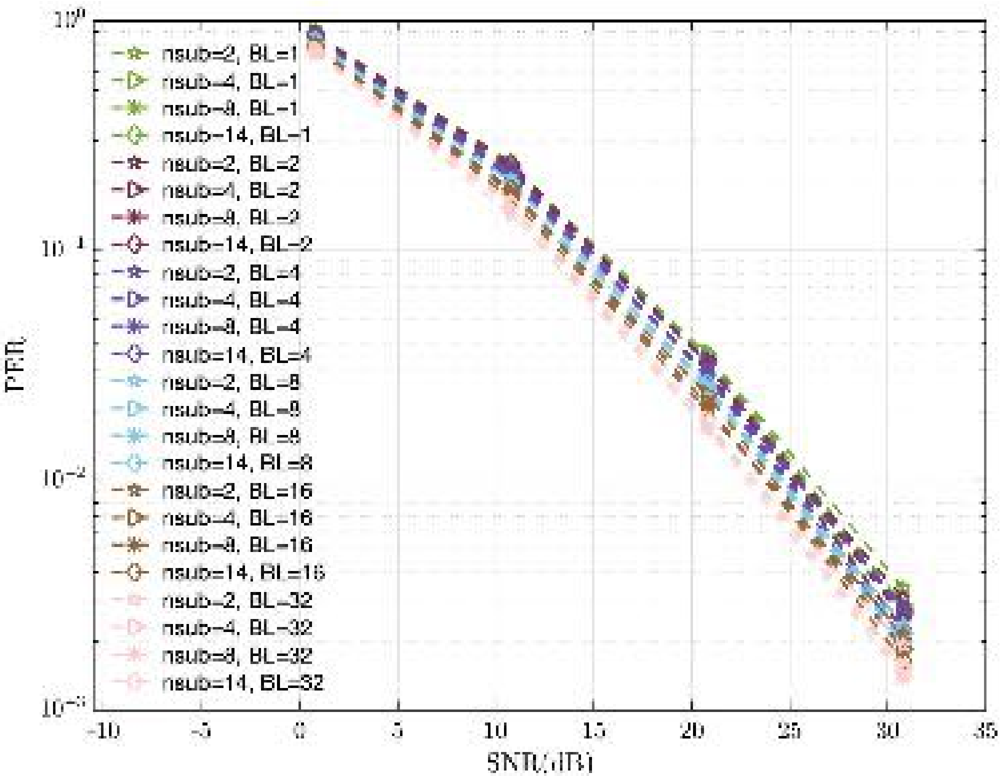
- The required SNR to achieve PER=10^{-2} is around 0 dB (Received power: −133.8 dBm).
- As the BL becomes smaller, efficiency decreases and the required Eb/No increases.

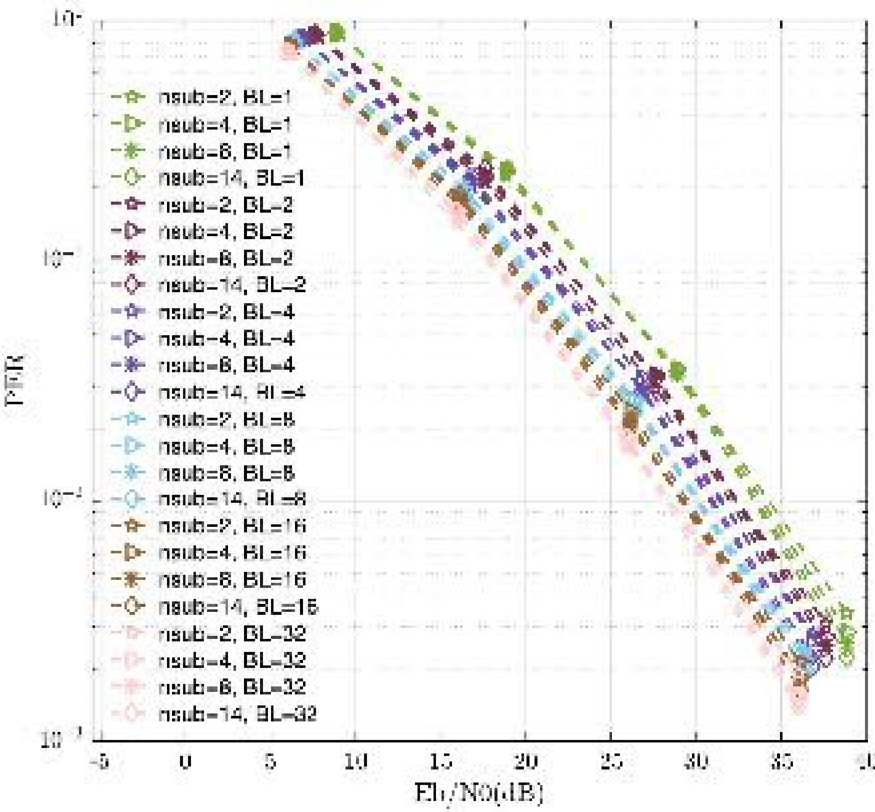
PER under AWGN



- The required SNR to achieve PER=10^{-2} is around 1-6 dB (SF=4, Received power: −139.8 dBm).

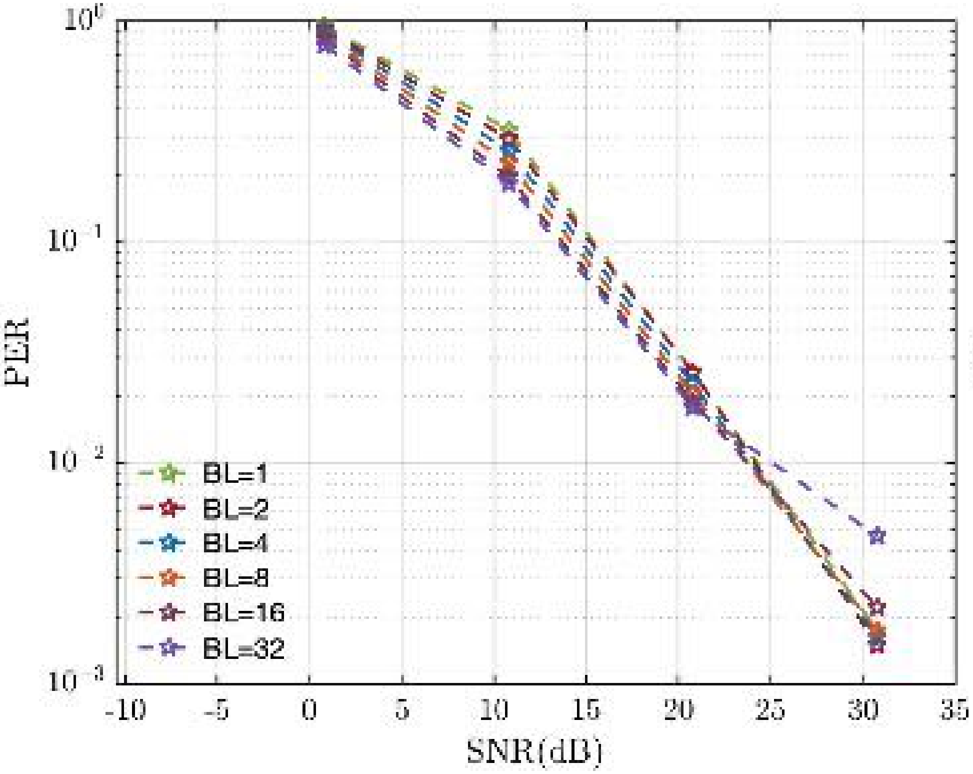
PER under GSM Typical Urban (fd=0.6Hz)

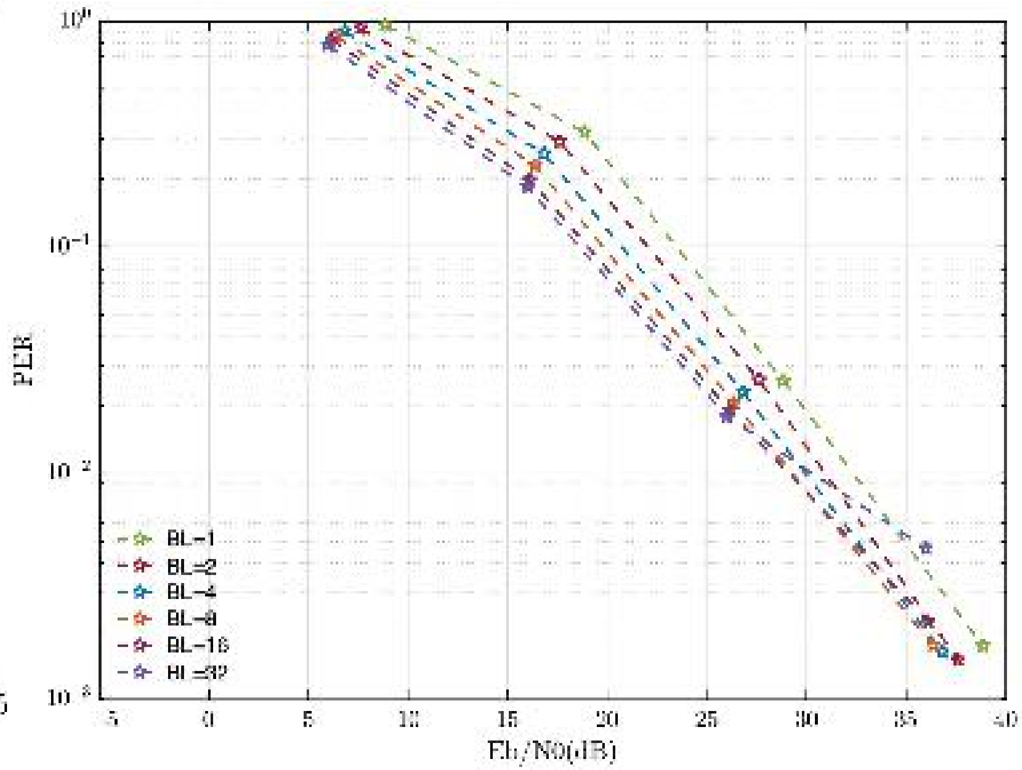




- The required SNR to achieve PER=10^{-2} is around 25 dB (Received power: −108.8dBm).
- Because pilot signals are inserted in each block, the shorter the BL, the longer the time it takes to transmit a single packet. As a result, it becomes more susceptible to fading.

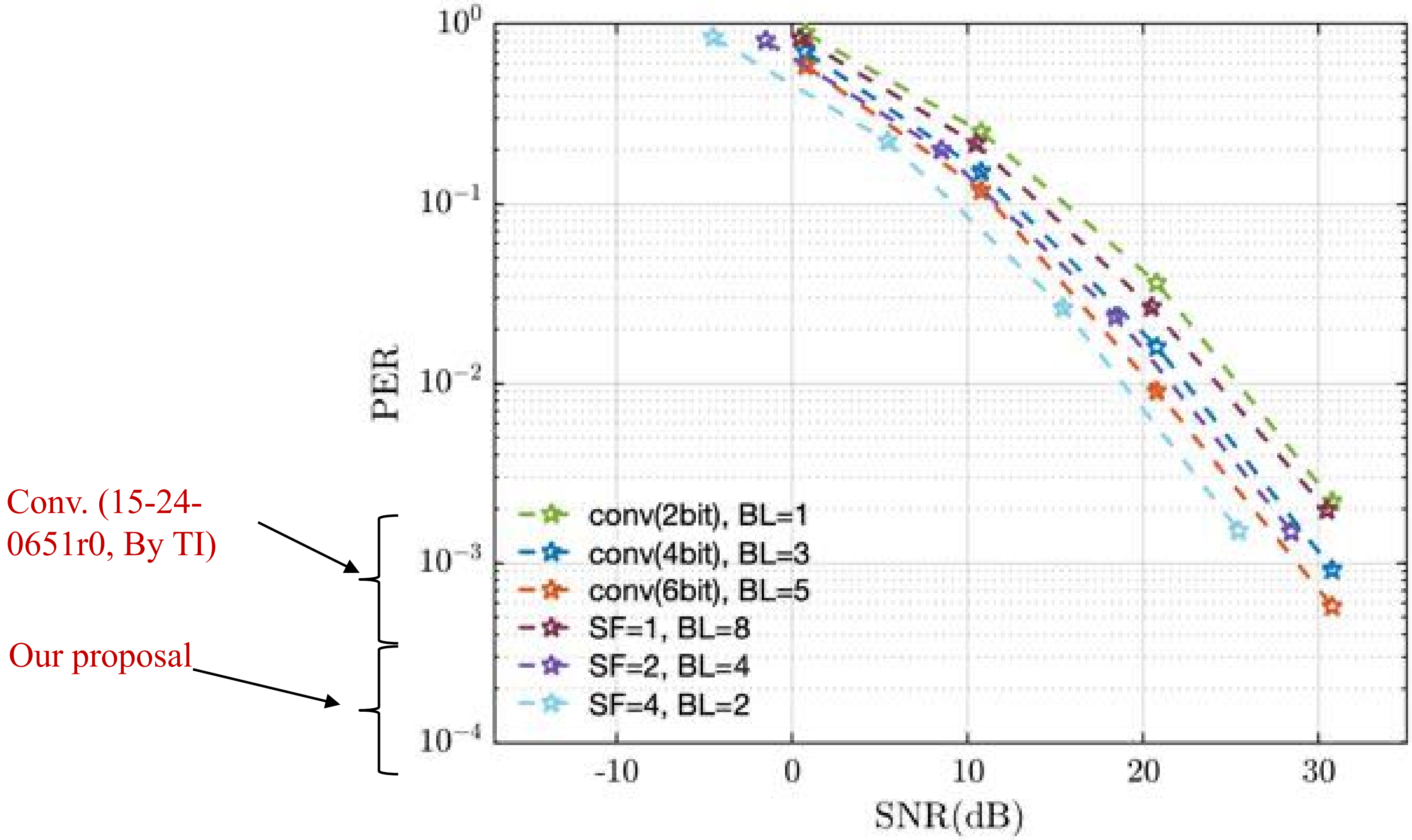
PER under GSM Typical Urban (fd=6Hz, Nsub=14)





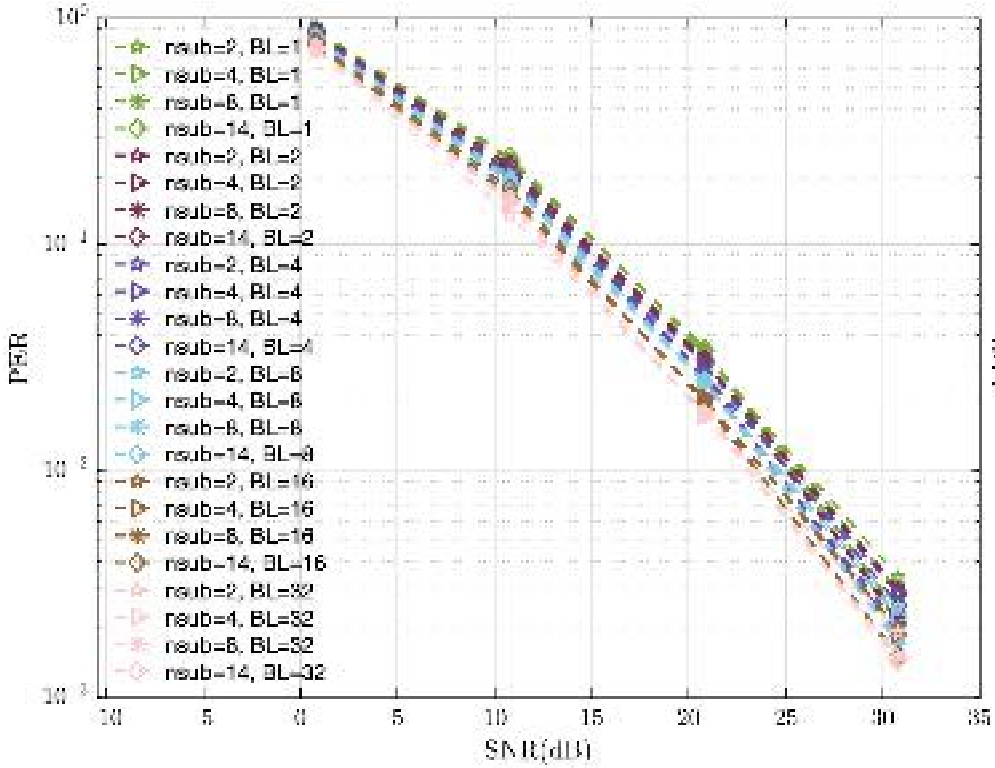
- The required SNR to achieve PER=10^{-2} is around 24.5 dB (Received power: −109.3 dBm).
- The longer the BL, the less influence the pilot signal estimation has on the entire BL and the worse the PER characteristics.
- BL should be 16 or below.

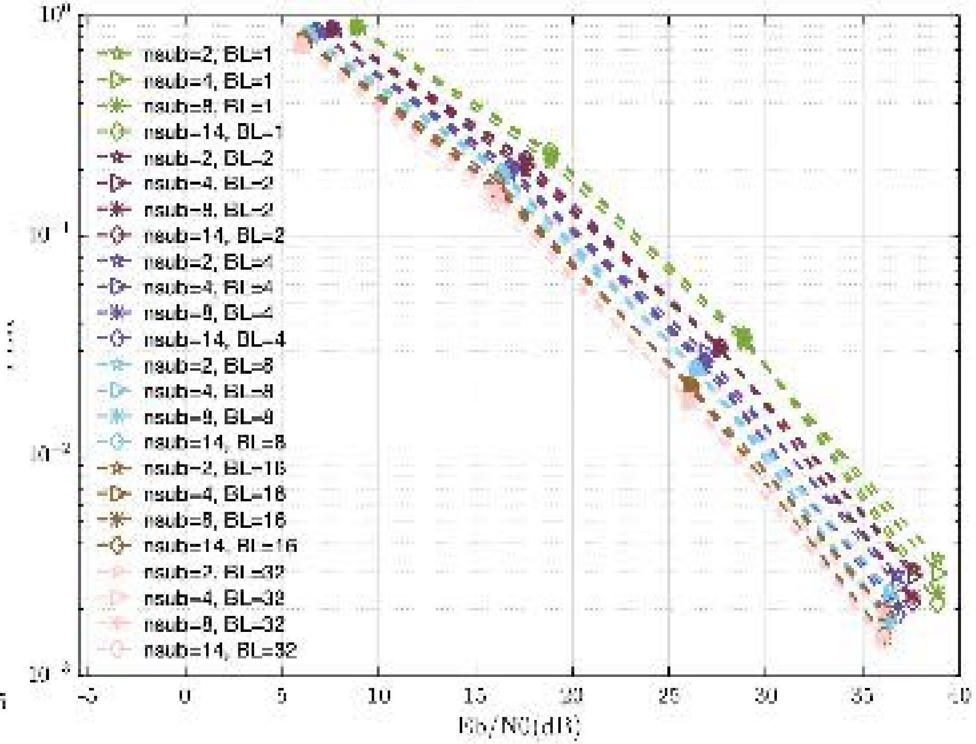
PER under GSM Typical Urban (fd=0.6Hz)



- The required SNR to achieve PER=10^{-2} is around 18 dB (SF=4, Received power: −115.8 dBm).

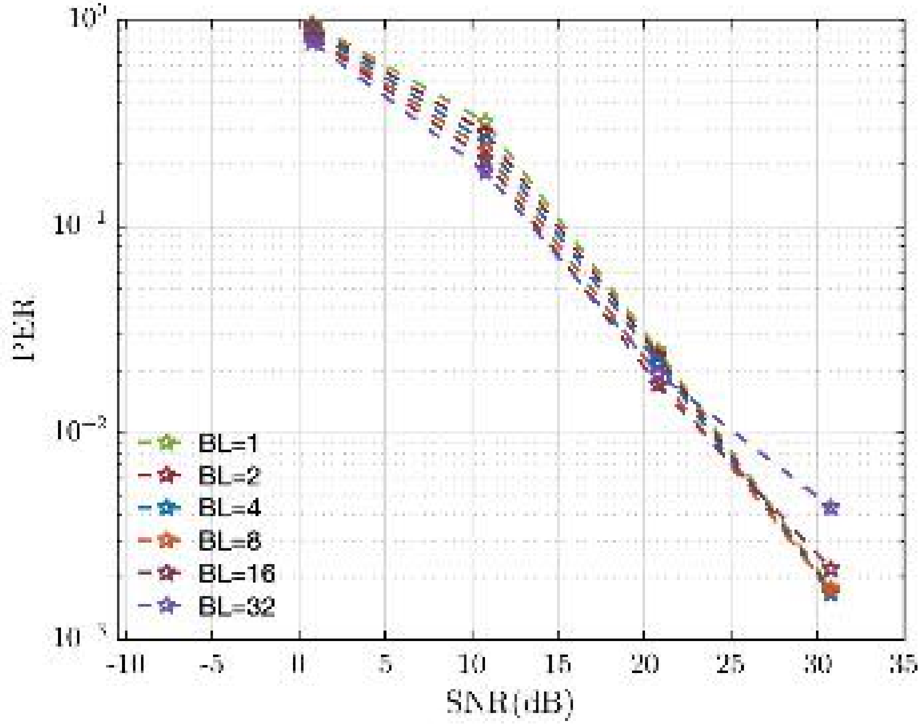
PER under IEEE 802.22 Profile A (fd=0.6Hz)

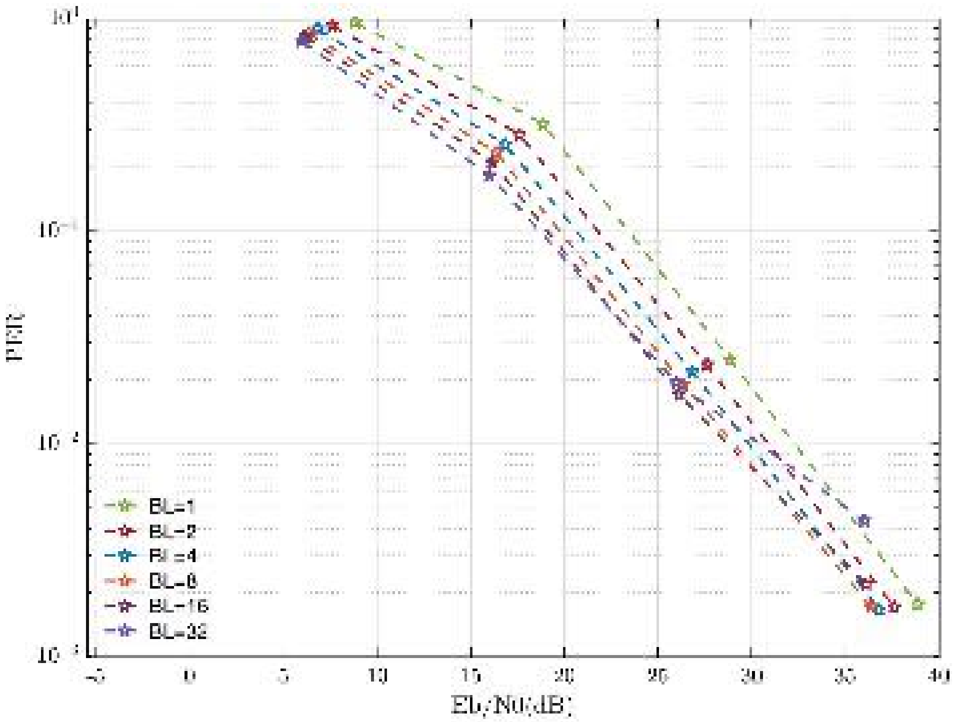




- The required SNR to achieve PER=10^{-2} is around 24.5 dB (Received power: −109.3 dBm).
- This channel model has strong frequency selectivity because it receives long delay waves.
- However, the guard interval is longer than the maximum delay time, so there is no significant impact on PER.
- The longer the BL, the less influence the pilot signal estimation has on the entire BL and the worse the PER characteristics.

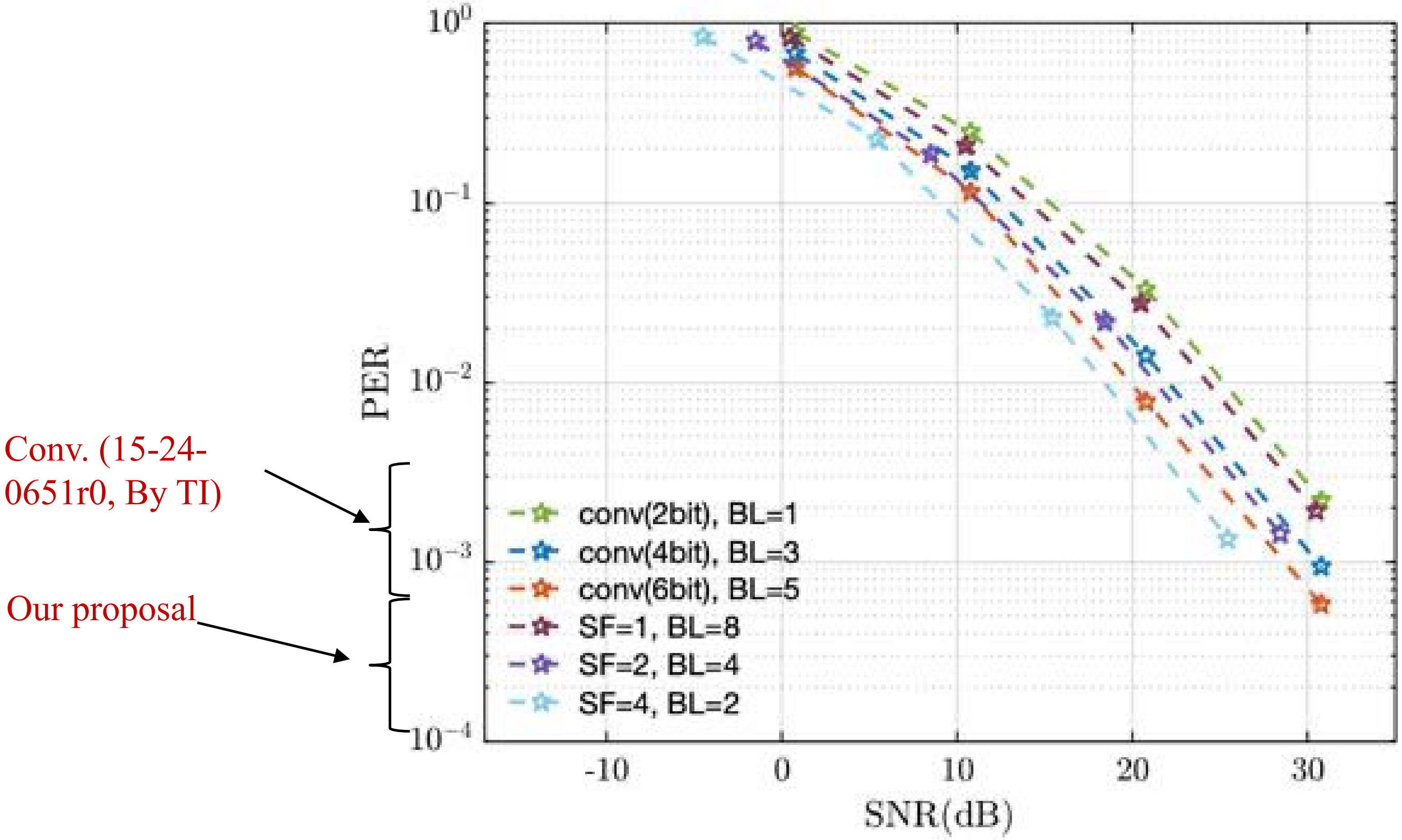
PER under IEEE 802.22 Profile A (fd=6Hz, Nsub=14)





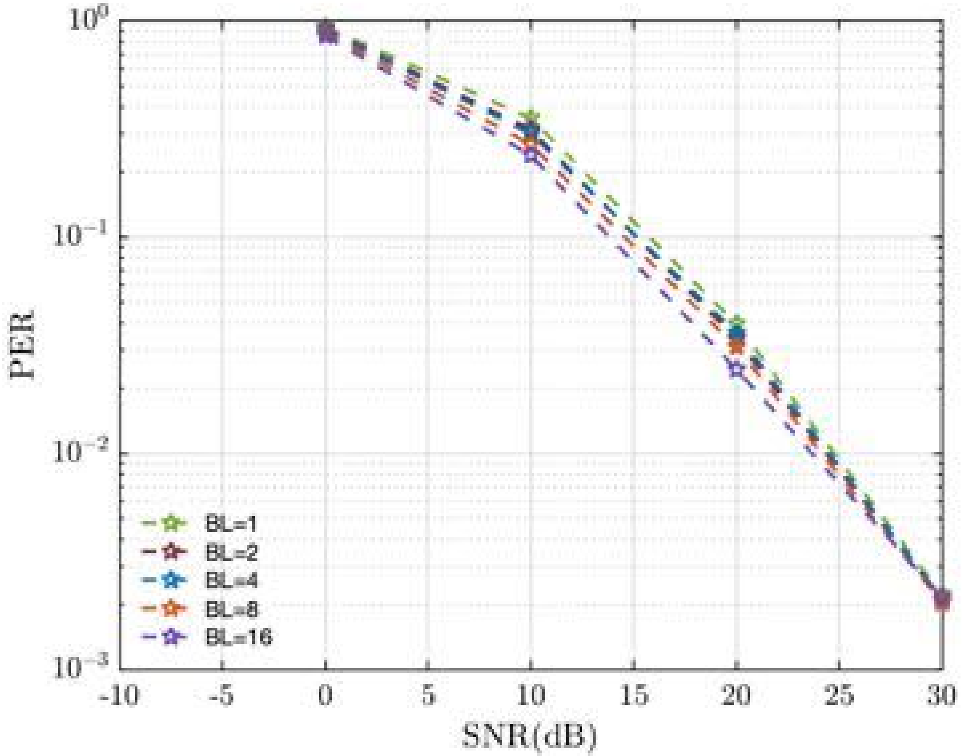
- The required SNR to achieve PER=10^{-2} is around 24.5 dB (Received power: −109.3 dBm).
- This channel model has strong frequency selectivity because it receives long delay waves.
- The longer the BL, the less influence the pilot signal estimation has on the entire BL and the worse the PER characteristics.
- BL should be 16 or below.

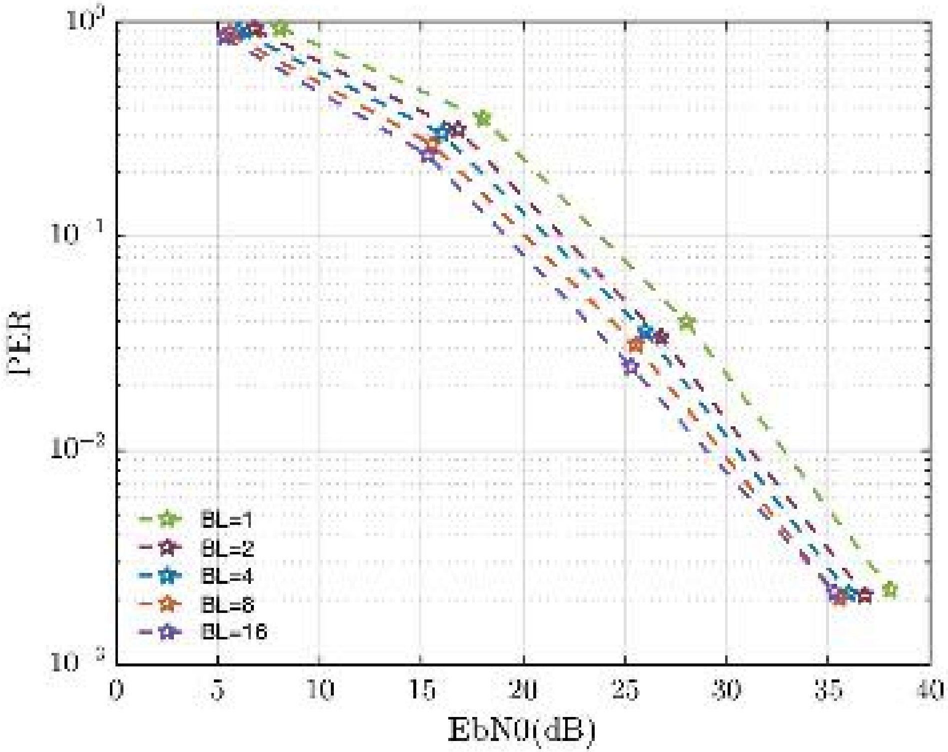
PER under IEEE 802.22 Profile A (fd=0.6Hz)



- The required SNR to achieve PER=10^{-2} is around 18 dB (SF=4, Received power: −115.8 dBm).

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



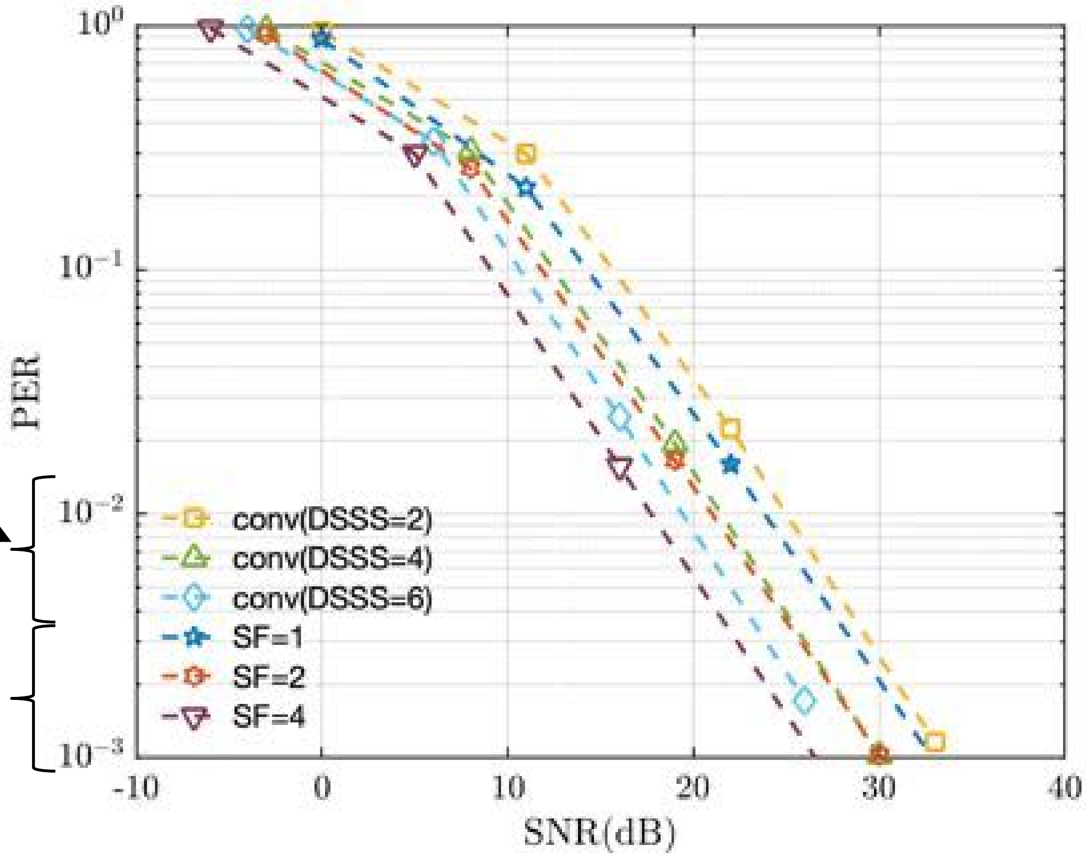


- The required SNR to achieve PER=10^{-2} is around 23 dB (Received power: −110.8 dBm).

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

Conv. (15-24-0651r0, By TI)

Our proposal



- The required SNR to achieve PER=10^{-2} is around 17.5 dB (SF=4, Received power: −116.3 dBm).

Required SNR and power

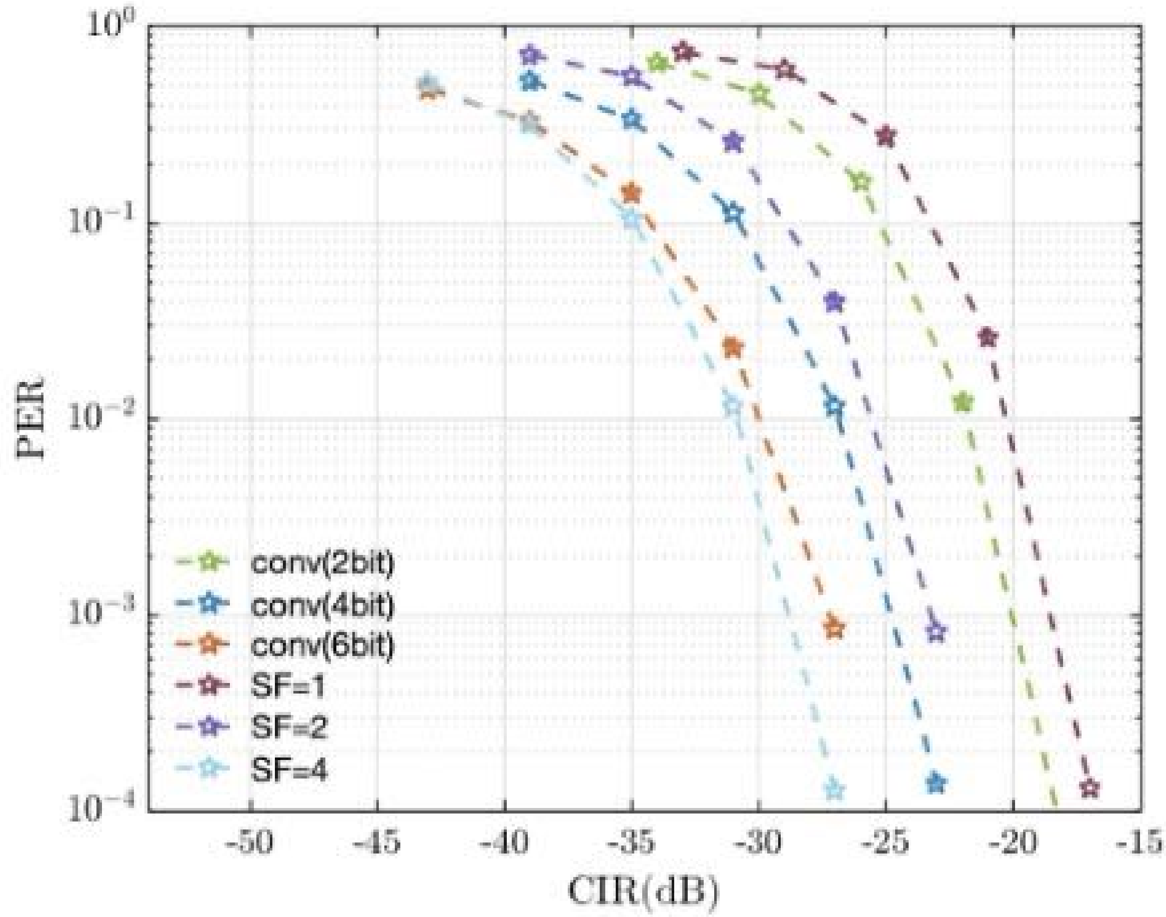
Channel model	Spreading factor	Expected Transmission rate (kbps)	Doppler frequency(Hz)	Required PER	Required SNR(dB)	Required power(dBm)
AWGN	1	4.166	N/A	10^{-2}	0	-133.8
	4	1.041	N/A	10^{-2}	-6	-139.8
COST 207 TU (GSM TU)	1	4.166	0.6	10^{-2}	25	-108.8
	1	4.166	6	10^{-2}	24.5	-109.3
	4	1.041	0.6	10^{-2}	18	-115.8
802.22 profile A	1	4.166	0.6	10^{-2}	24.5	-109.3
	1	4.166	6	10^{-2}	24.5	-109.3
	4	1.041	0.6	10^{-2}	18	-115.8
TDL-B	1	4.166	2.5	10^{-2}	23	-110.8
	4	1.041	2.5	10^{-2}	17.5	-116.3

PER under interference environments

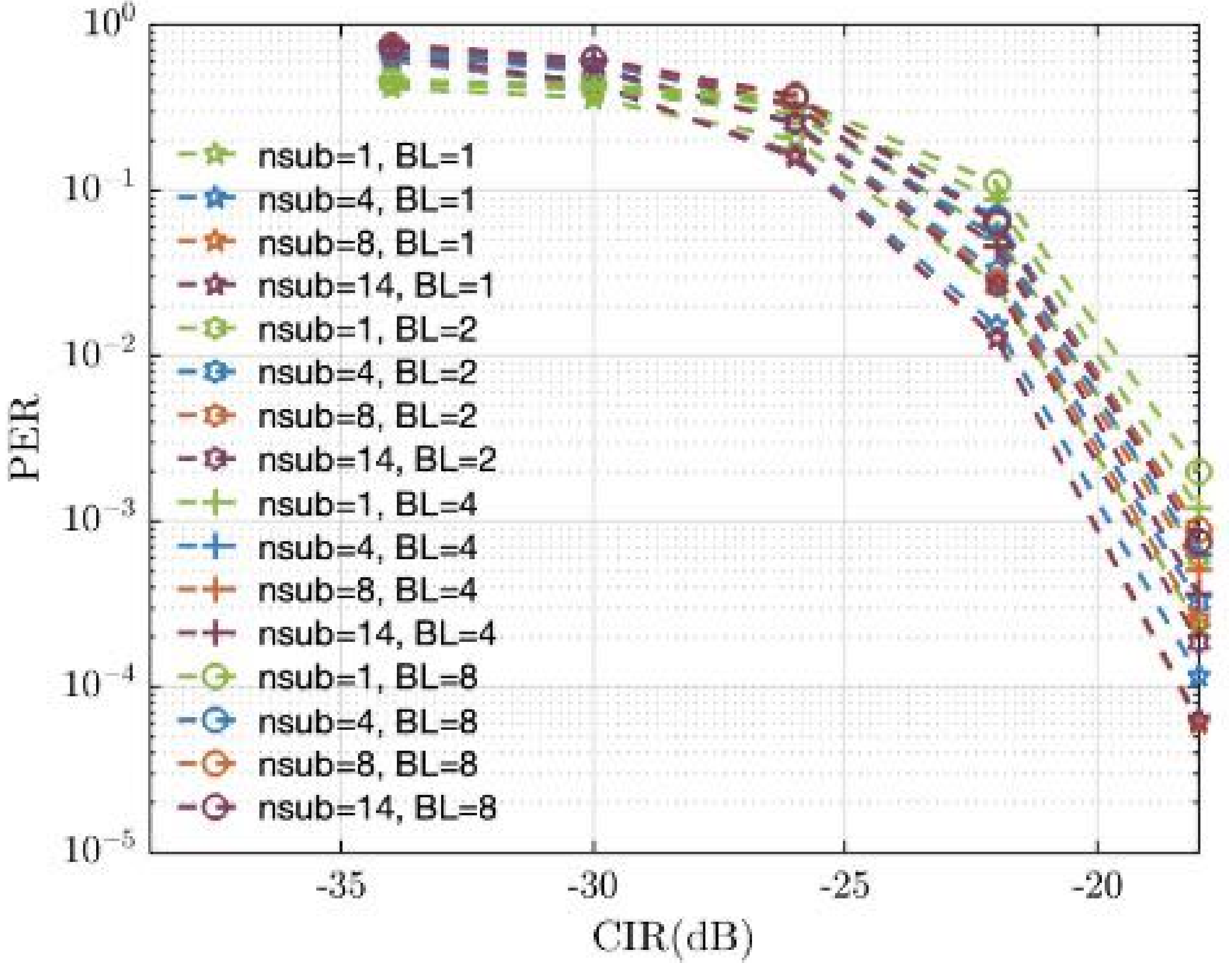
Simulation parameters (interference)

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

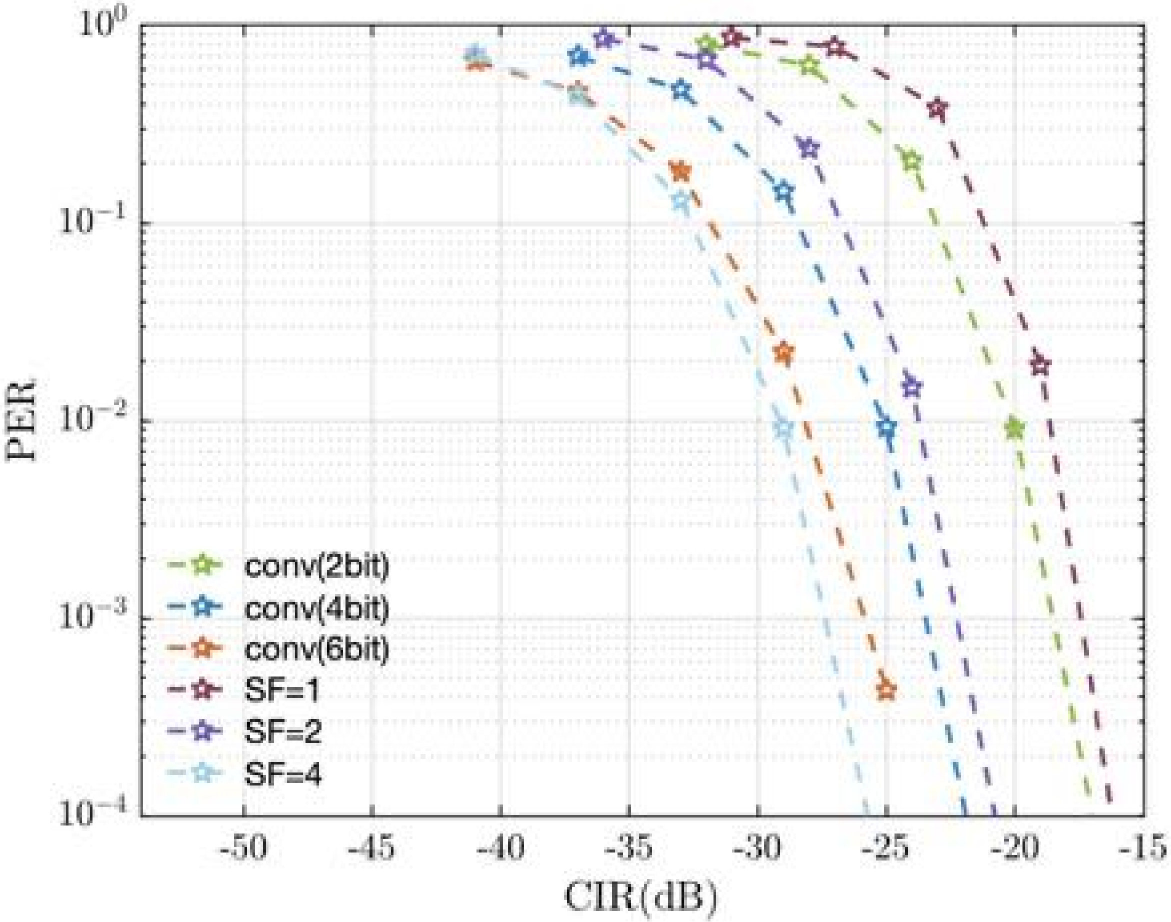
BW: 125 kHz, td: 5ms



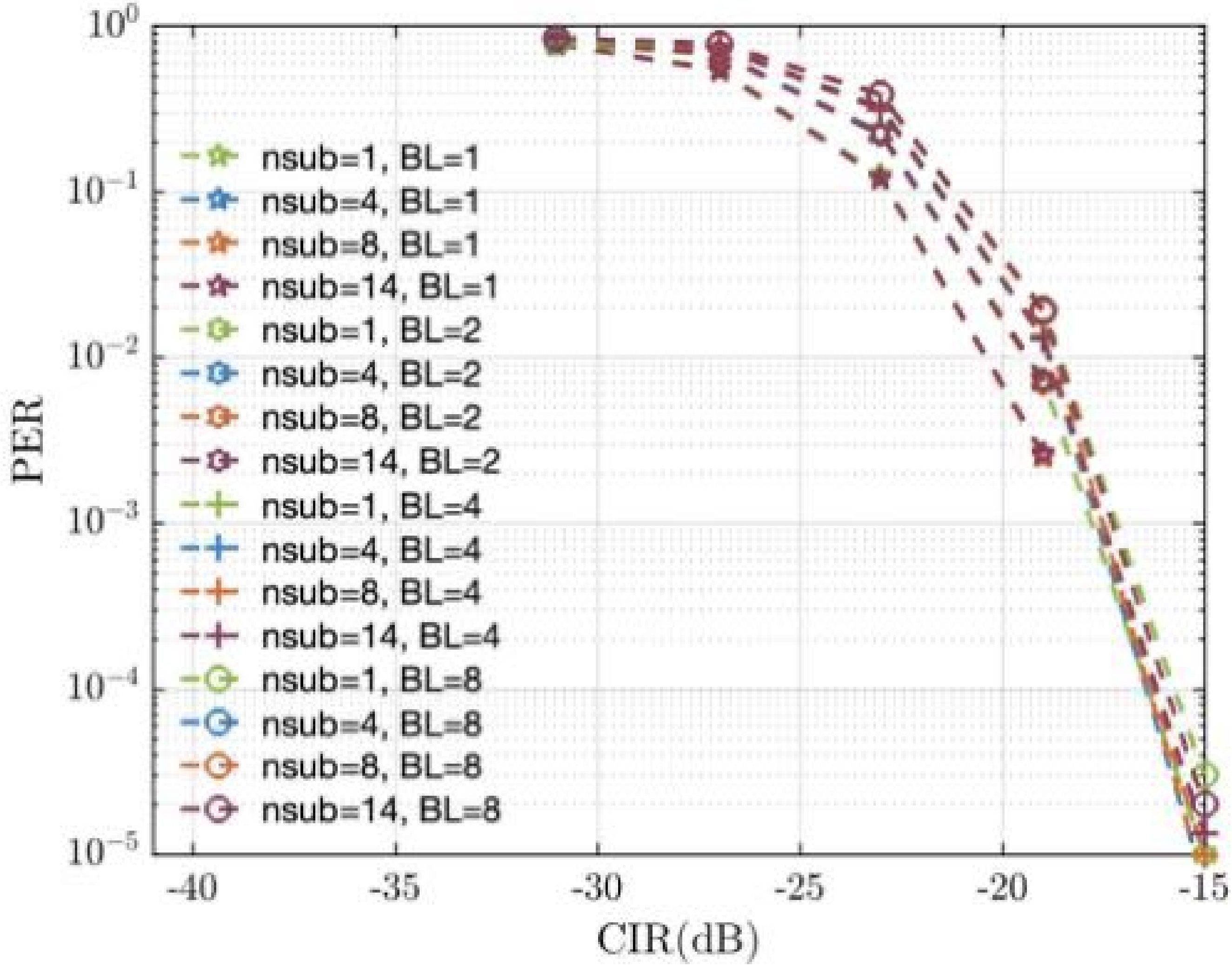
BW: 125 kHz, td: 5ms



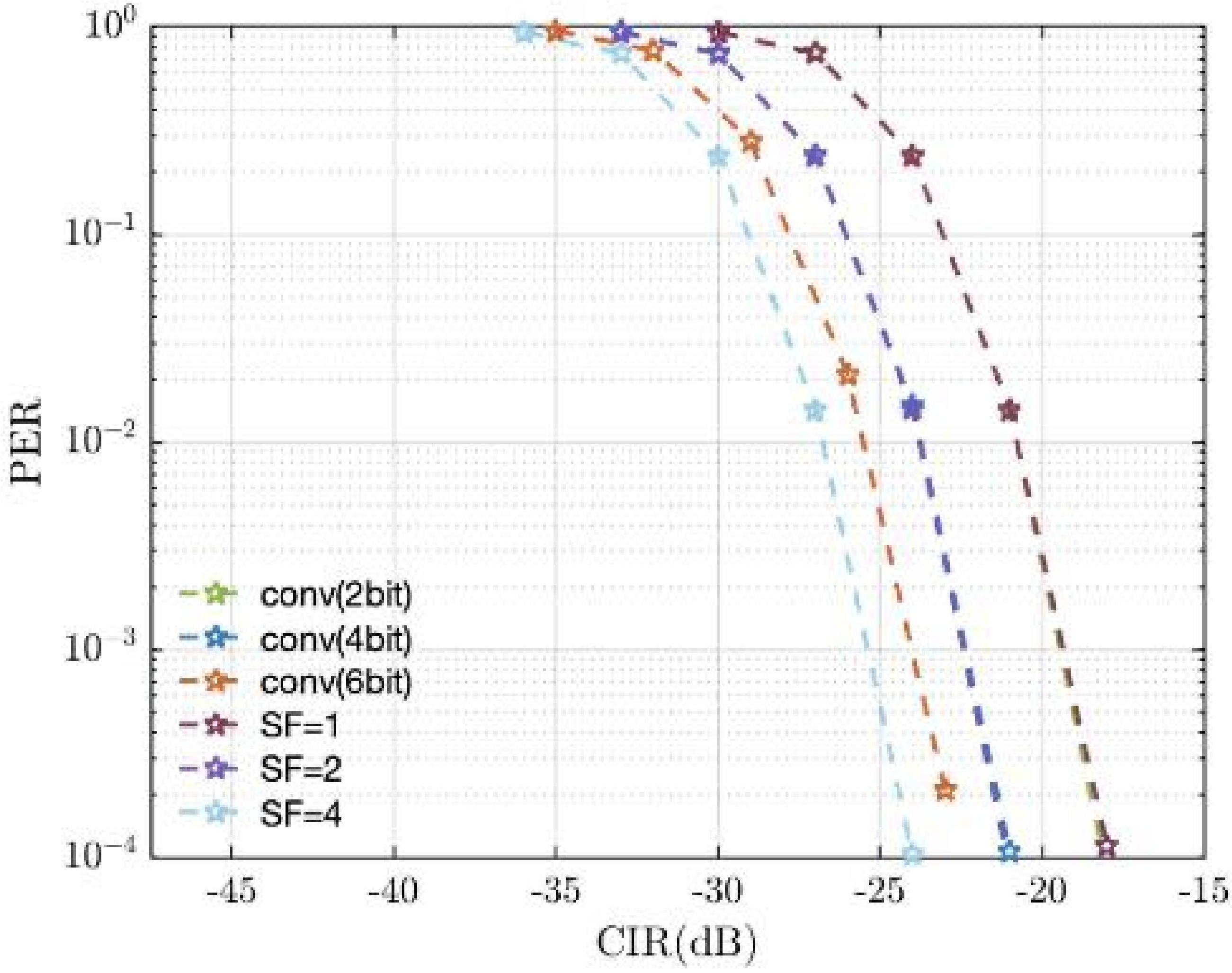
BW: 2000 kHz, td: 5ms



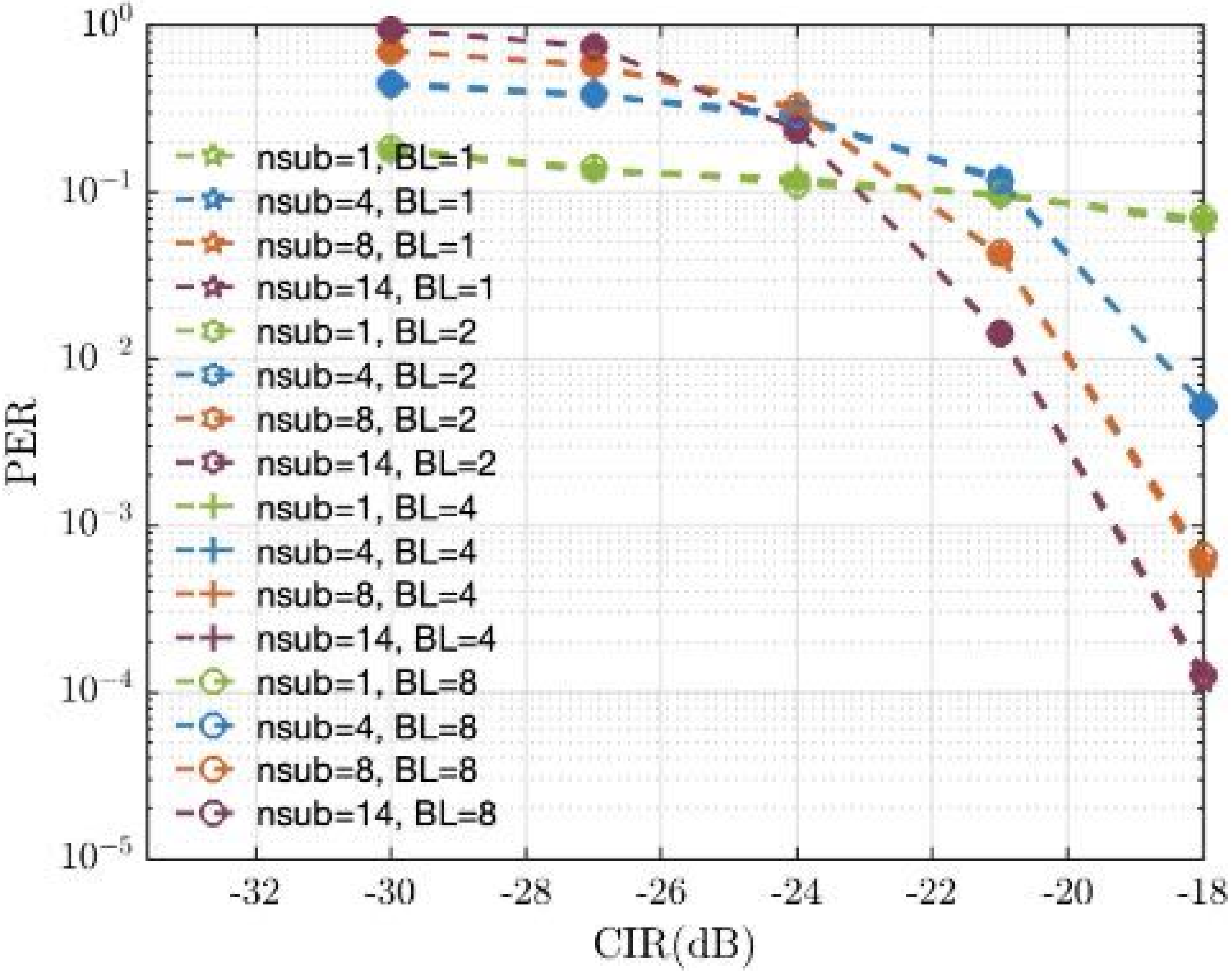
BW: 2000 kHz, td: 5ms



BW: 10 kHz, td: same as packet

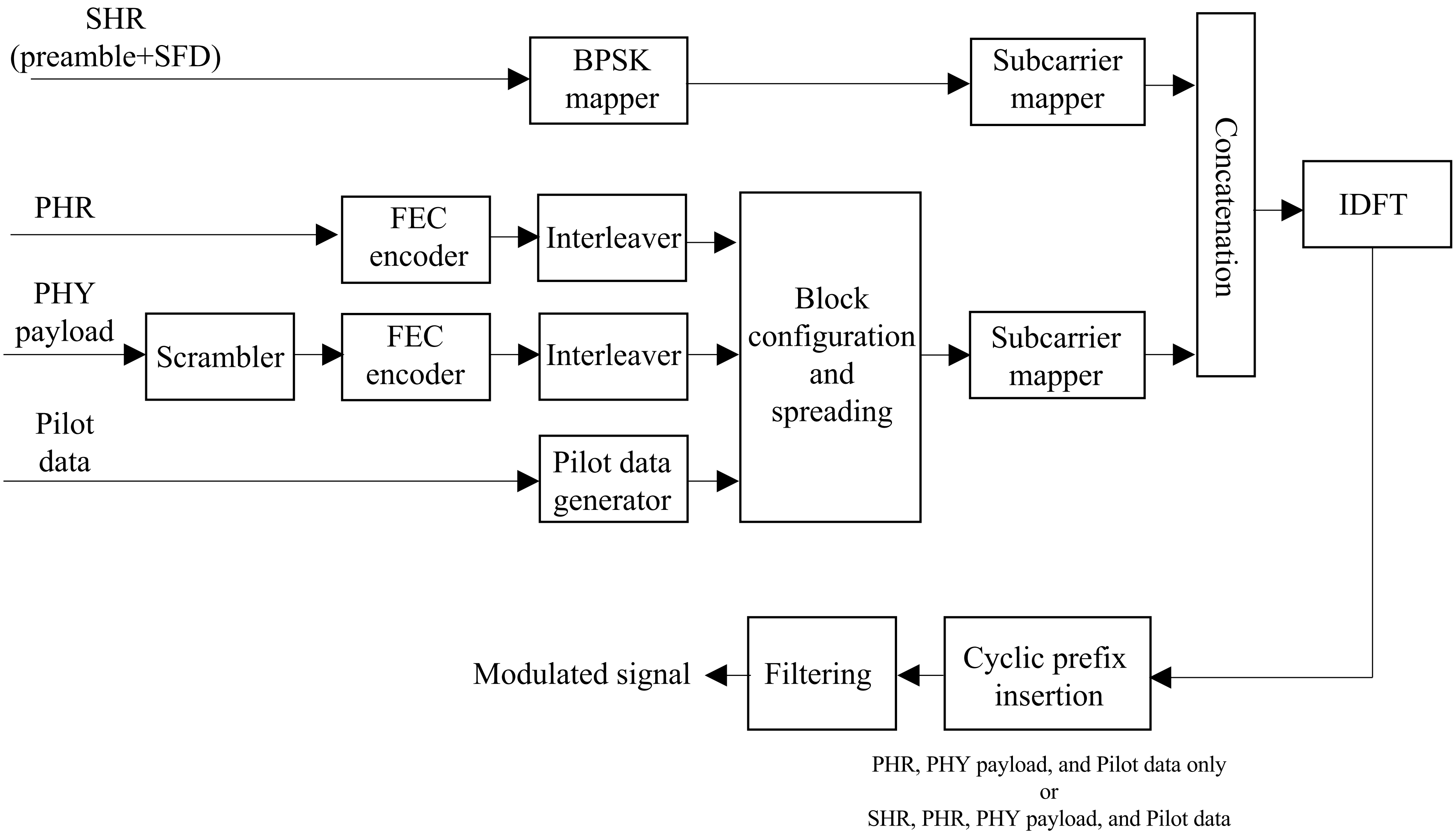


BW: 10 kHz, td: same as packet



Appendix
Configuration of proposed SUN OFDM LR3

Reference modulator diagram



Pilot Generator

Use the existing pilot generation method as is

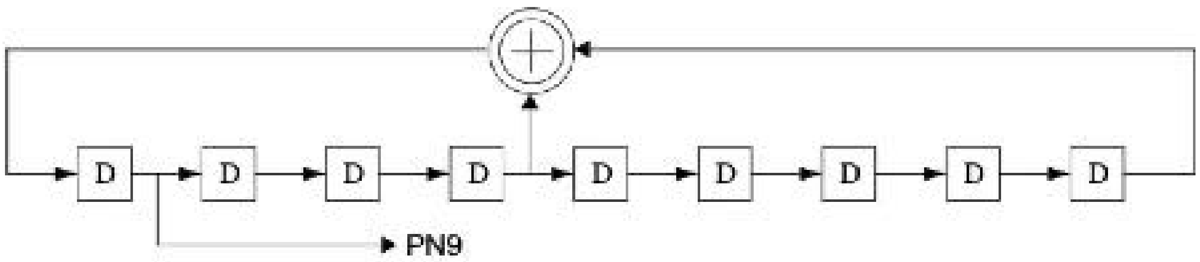


Figure 16-2—Schematic of the PN generator

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:

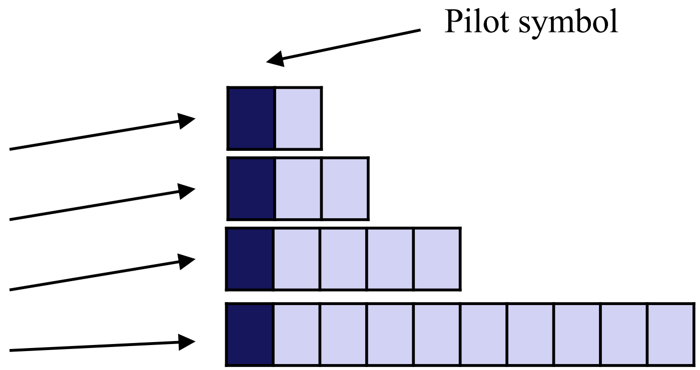
$$PN9_n = 0_0\ 0_1\ 0_2\ 0_3\ 1_4\ 1_5\ 1_6\ 1_7\ 0_8\ 1_9\ 1_{10}\ 1_{11}\ 0_{12}\ 0_{13}\ 0_{14}\ 0_{15}\ 1_{16}\ 0_{17}\ 1_{18}\ 1_{19}\ 0_{20}\ 0_{21}\ 1_{22}\ 1_{23}\ 0_{24}\ 1_{25}\ 1_{26}\ 0_{27}\ 1_{28}\ 1_{29}$$

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

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

Block configuration and hopping

- Block structure
  - BL1: 1 Pilot symbol and 1 Data symbols
  - BL2: 1 Pilot symbol and 2 Data symbols
  - BL4: 1 Pilot symbol and 4 Data symbols
  - BL8: 1 Pilot symbol and 8 Data symbols



- 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.

Spreading scheme (Payload)

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

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

Spreading scheme (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

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

$$e_{2k} = d_k$$

$d_k, d_{k+1}, d_{k+2}, d_{k+3}$ ⇒

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} ⇒

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 ⇒

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}

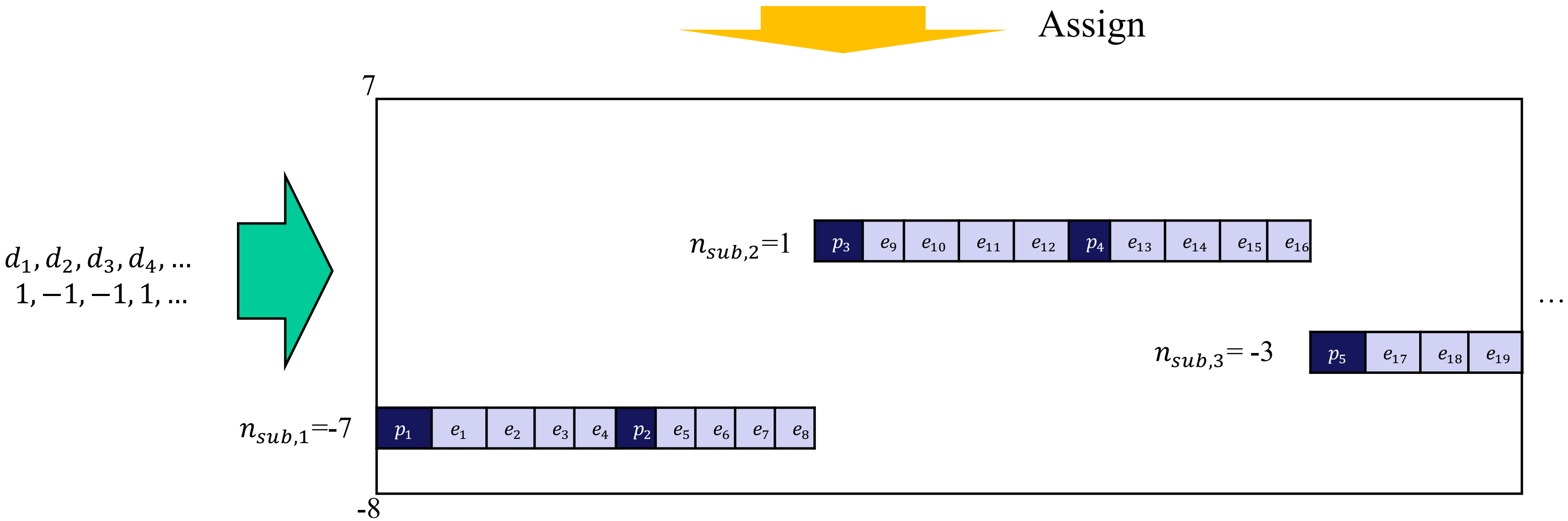
Example of data spreading (Option=4, SF=2)

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

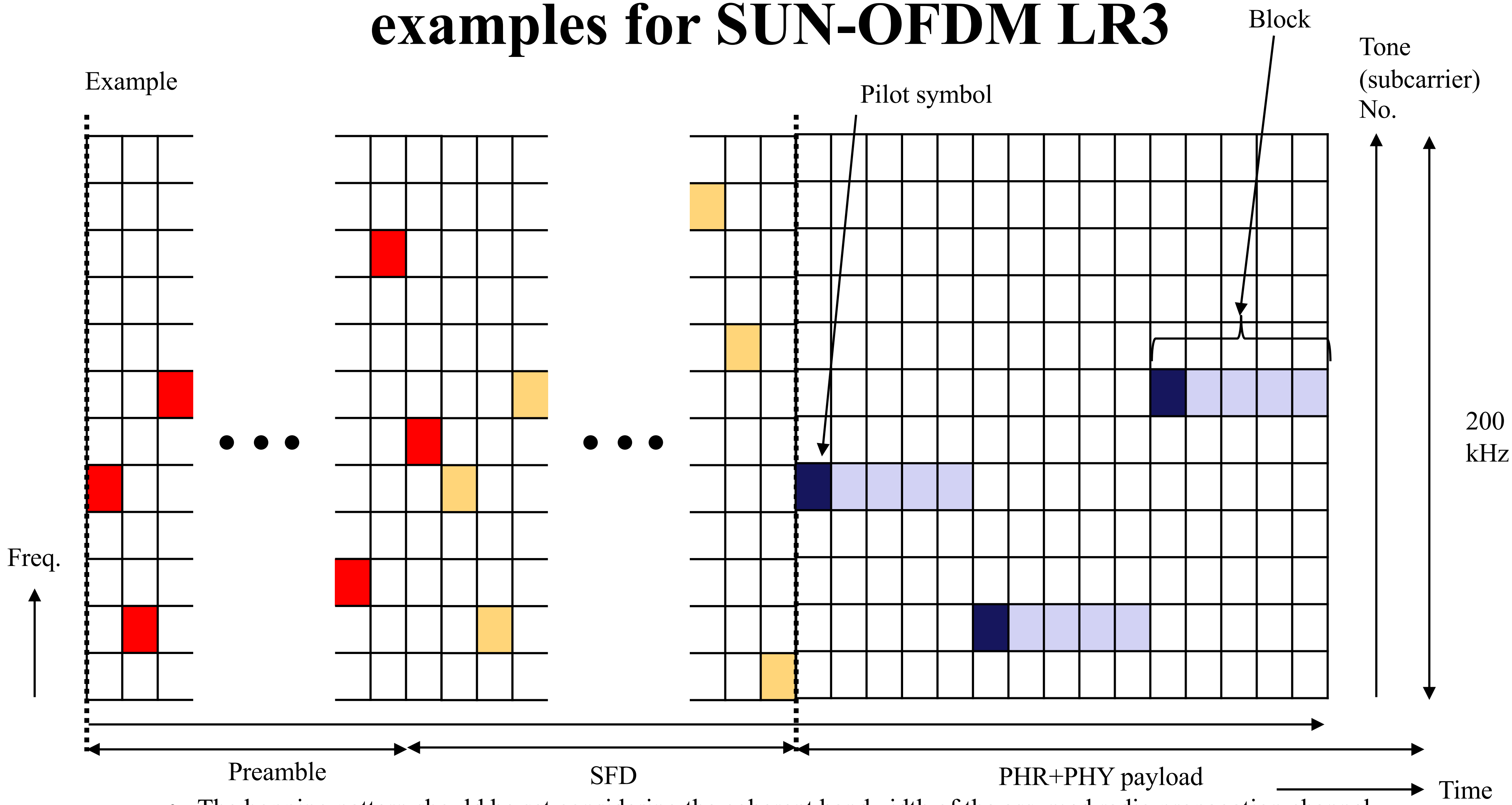
Spreading $e_1, e_2,\ e_3, e_4,\ e_5, e_6,\ e_7, e_8, \ldots = 1j, 1,\ \ 1j, -1,\ -1j, -1,\ -1j, 1, \ldots$ $\left\{ \begin{array}{l} e_{2k-1} = d_k \exp\left(j\frac{2\pi(2\times mod(k, N_{Data\ Tones}/2)-1)}{4}\right) \\ e_{2k} = d_k \end{array} \right\}$

Pilot $p_1, p_2, p_3, p_4, p_5, p_6, \ldots = -1, -1, -1, -1, 1, 1, \ldots$ $\{\ PN9_N\ \}$

Subcarrier $n_{sub,i}$=-7,1,-3,…



Frame construction and frequency hopping examples for SUN-OFDM LR3



- The hopping pattern should be set considering the coherent bandwidth of the assumed radio propagation channel.
- If each symbol is spread, perform a hop for each symbol that is spread.
- SHR (Preamble + SFD) may be transmitted at a single frequency without hopping.

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)

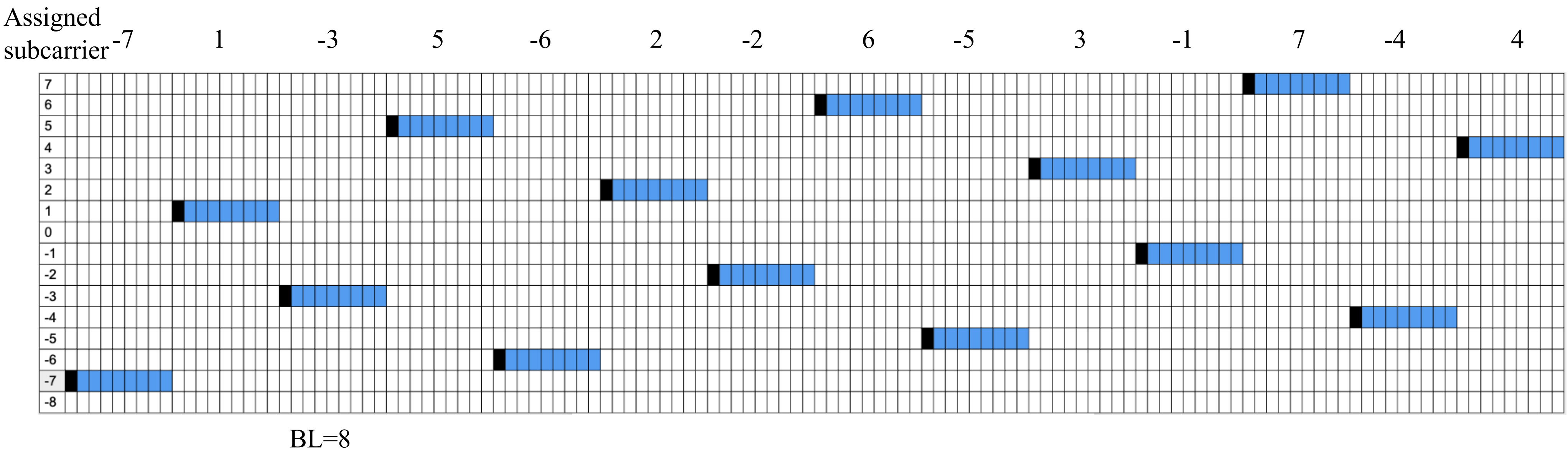
The tone(subcarrier) number assigned to each blocks: $-\frac{N_{FFT}}{2}, -\frac{N_{FFT}}{2}+1, \ldots, \frac{N_{FFT}}{2}-1 \quad (i = 1,2,3, \ldots)$

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

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.