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

Submission Title: [Basic transmission characteristics of 802.15.4ad SUN OFDM LR payload and frequency hopping method between users]

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

Abstract: Show basic transmission characteristics of 802.15.4ad SUN OFDM LR payload and propose frequency hopping method between users. 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: Show basic transmission characteristics of 802.15.4ad SUN OFDM LR payload and propose frequency hopping method between users.

Basic transmission characteristics of 802.15.4ad SUN OFDM LR payload and frequency hopping method between users

March 13, 2025

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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
- However, the transmission characteristics of this system in an AWGN and multipath fading environment have not yet been evaluated
- In this contribution, we first show the basic transmission characteristics of the SUN OFDM LR3 proposed by authors

Proposed 802.15.4 SUN-OFDM LR (15−25−0035r0)

		Option LR1	Option LR2	Option LR3
Channel spacing		200 kHz		
Subcarrier spacing		31.25/3 kHz		
DFT size		16	16	16
Number of subcarriers used		14	14	14
Num. of data-subcarriers		12	6	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
	MCS 1		6.25	1.041
	MCS 2			2.083

Frame format SUN-OFDM LR (15−25−0035r0)

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

STF	LTF	PHR	PHY payload

4 OFDM symbols (480 us)

2.5 OFDM symbols (300 us)

120us/ OFDM symbol

OFDM LR3

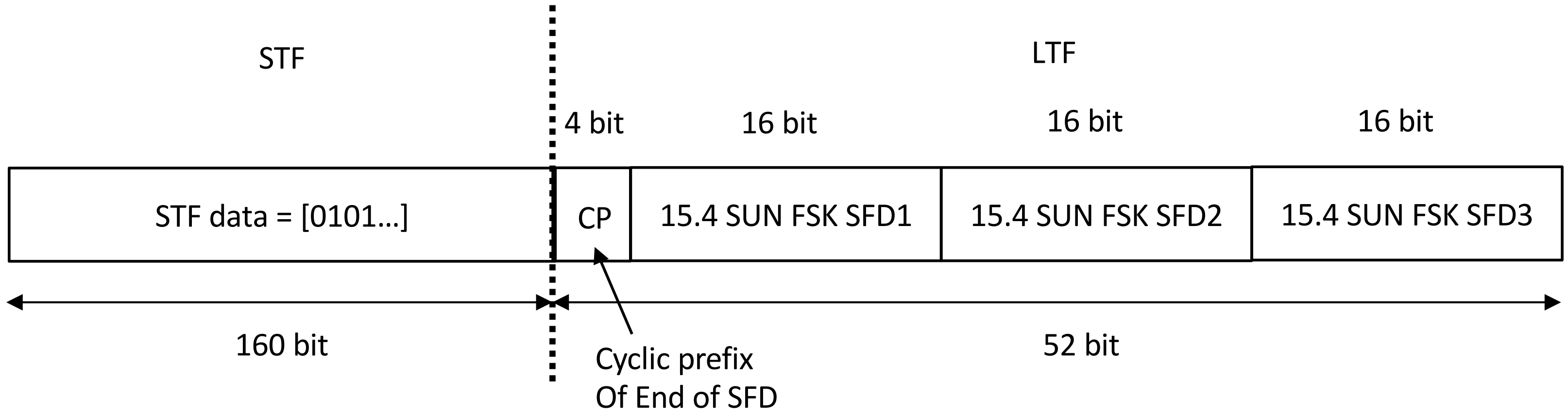
STF	LTF	PHR	PHY payload

160 bit

52 bit

120us/symbol= 8.33 ksymbol/s

Proposed SHR of SUN-OFDM LR3 (15−25−0035r0)



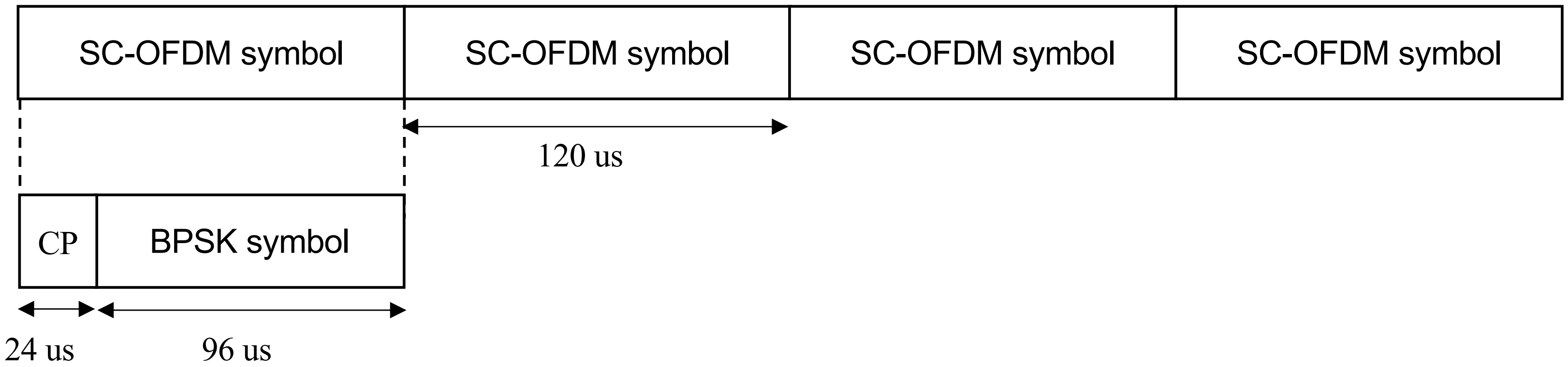
STF

- Preamble is 160 bits
- Repetitive data of 01 or other sequences are used in 15.4-2024 SUN FSK

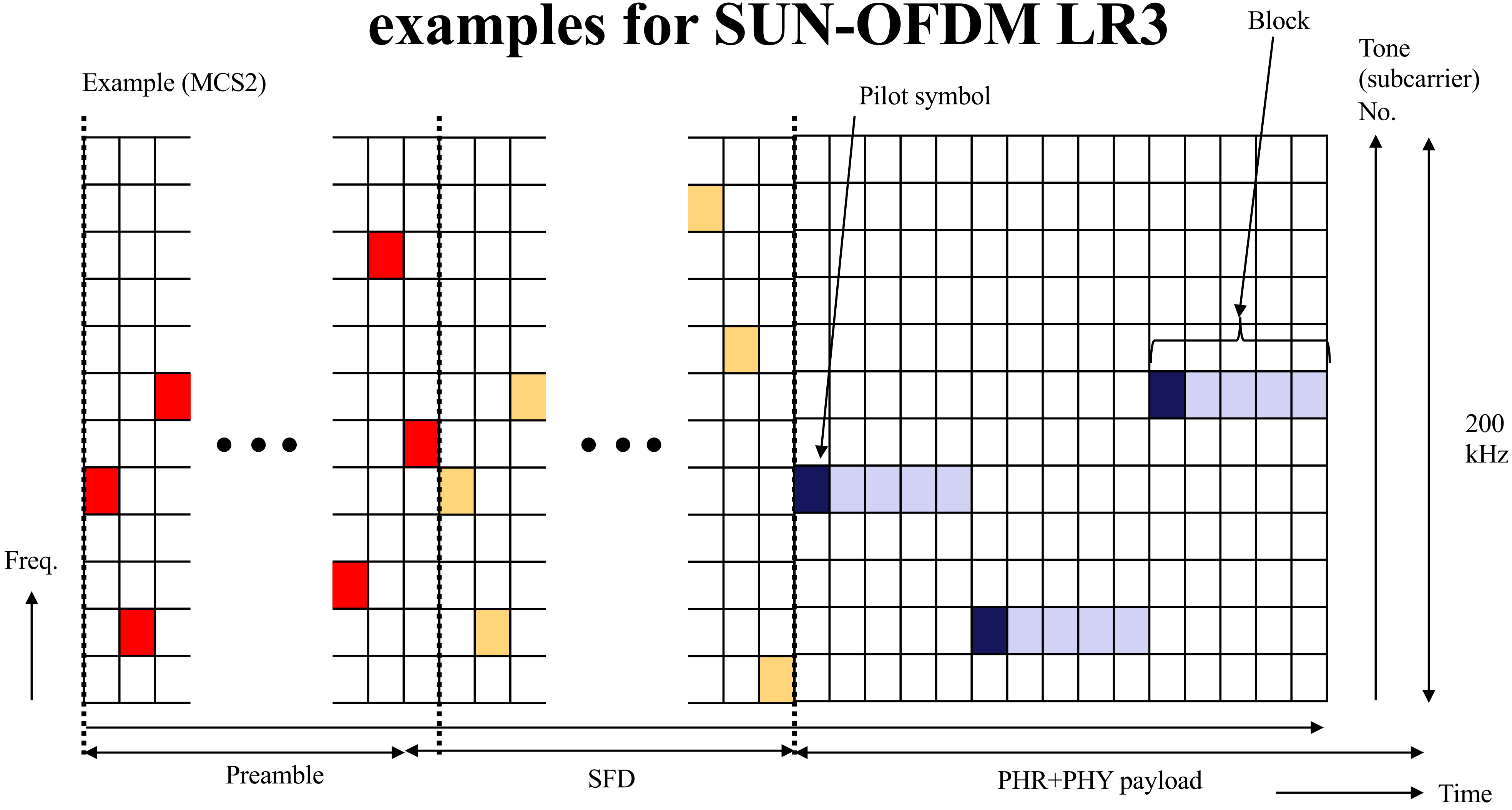
LTF

- SFD1, SFD2, and SFD3 are the same as those used in 15.4-2024 SUN FSK
- Basically, different ones are used, but some of them may be the same
- Each SFD has already been commercialized and its characteristics are well known
- The last 4 bits of the SFD are added as CP at the beginning

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



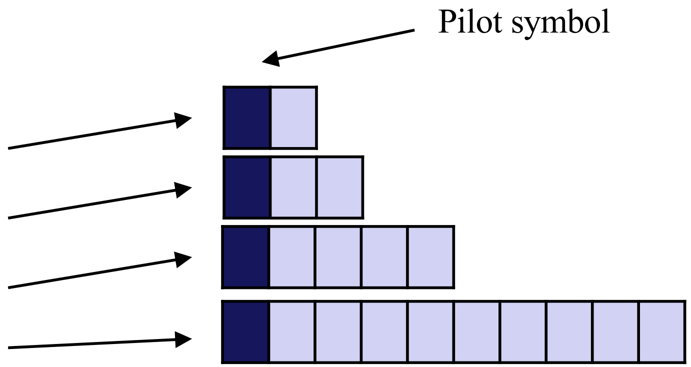
Frame construction and frequency hopping examples for SUN-OFDM LR3



- 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.

Simulation parameters

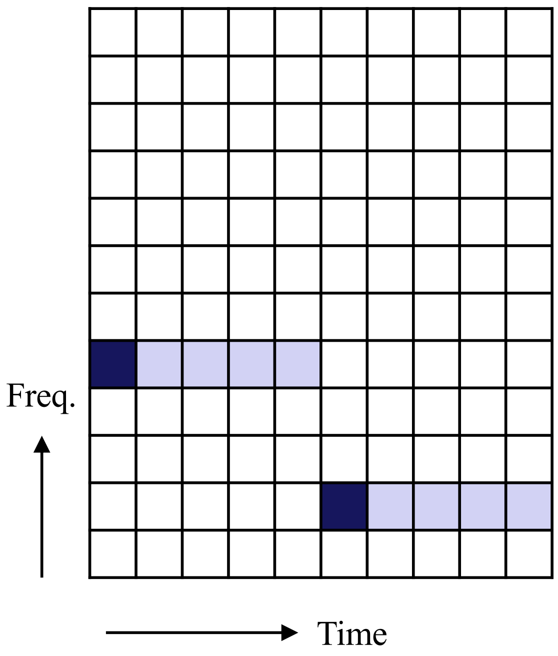
- Block structure
  - BL1: 1 Pilot symbol and 1 Data symbols
  - BL2: 1 Pilot symbol and 2 Data symbols
  - BL4: 1 Pilot symbol and 4 Data symbols
  - BL8: 1 Pilot symbol and 8 Data symbols



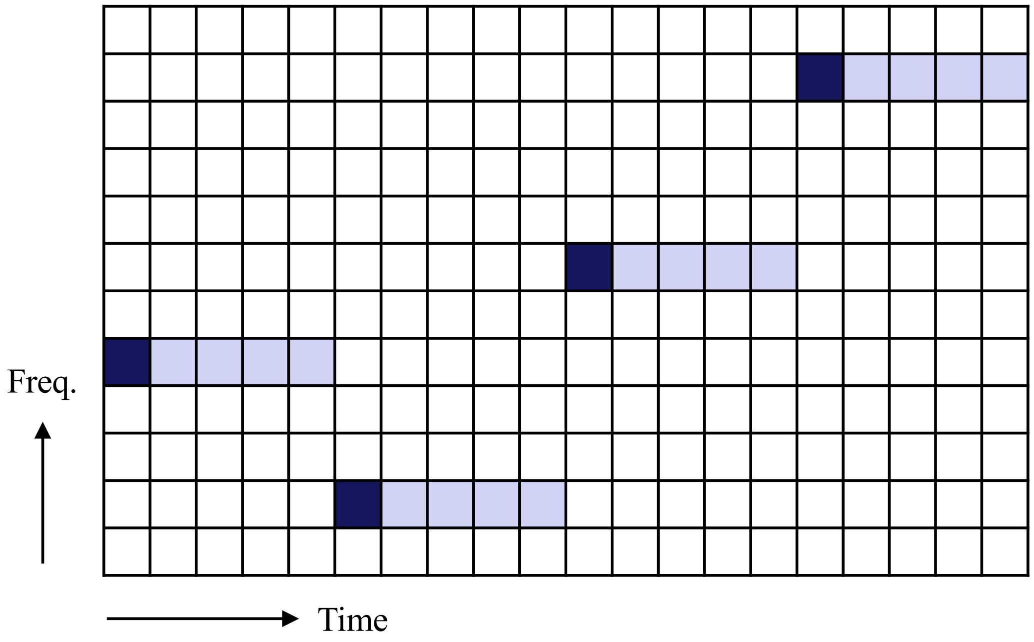
- Of the 14 subcarriers (Option 4), the subcarriers that each user selects as FH(Frequency Hopping)
  - Nsub 2: 2 subcarriers
  - Nsub 4: 4subcarriers
  - Nsub 8: 8 subcarriers
  - Nsub14: 14 subcarriers
- In this simulation, the subcarriers selected as FH are randomly selected from among 14 subcarriers.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



Simulation parameters (others)

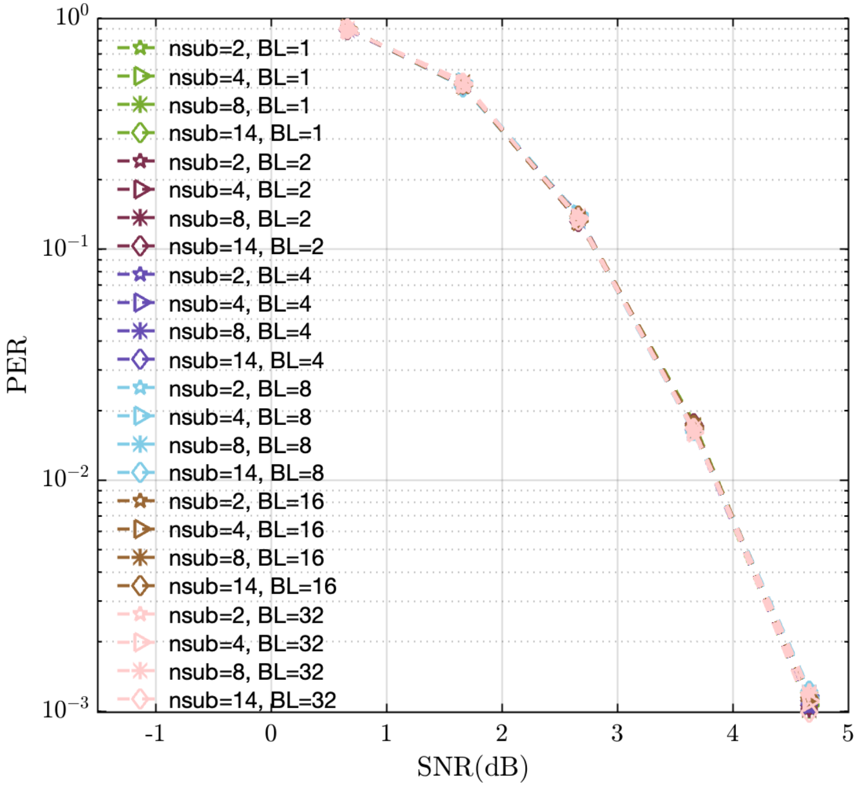
- Spreading: No spreading
- Channel model: GSM typical urban, IEEE 802.22 Profile A
- Doppler frequency: 0.6 Hz and 6 Hz
- Packet size: 20 byte
- Interleave size: Random
- Evaluation index: Packet Error Rate (PER)
- Padding bit: 2bit
- Tail bit: 6bit
- Gurad interval: 1/4

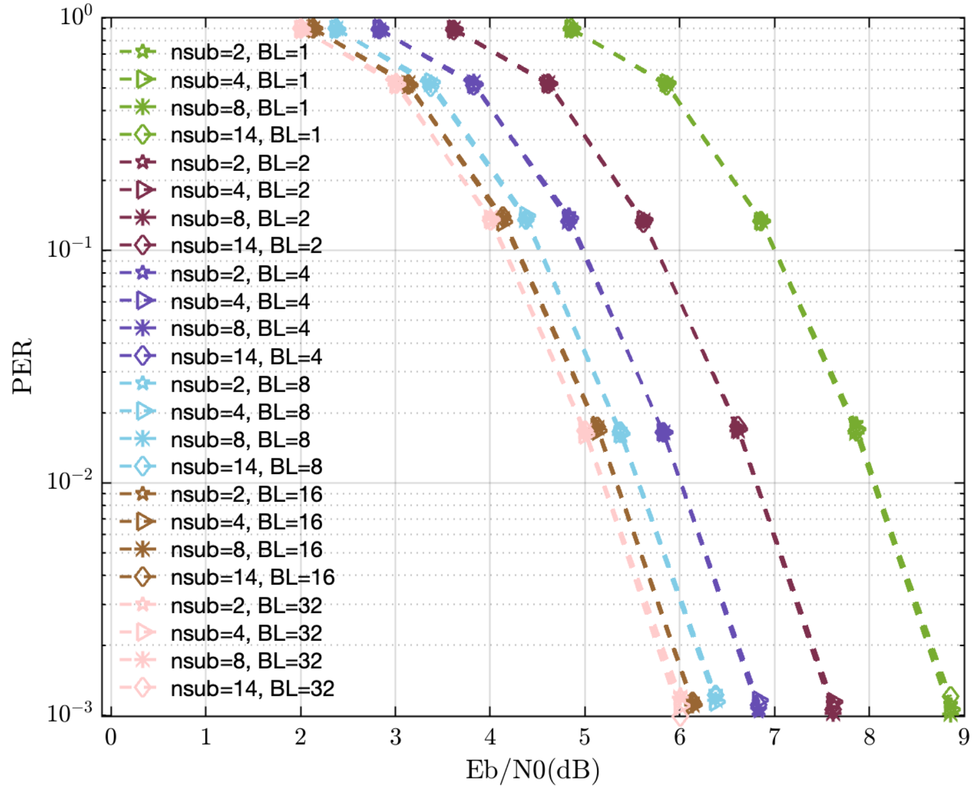
SNR and received signal power conversion

- 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

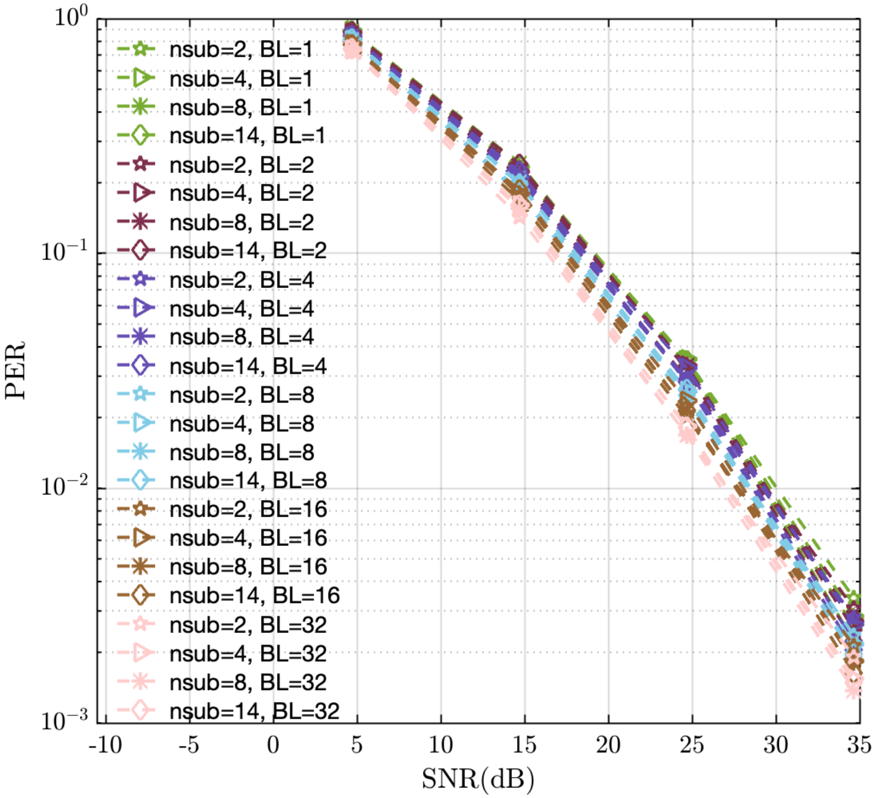
PER under AWGN

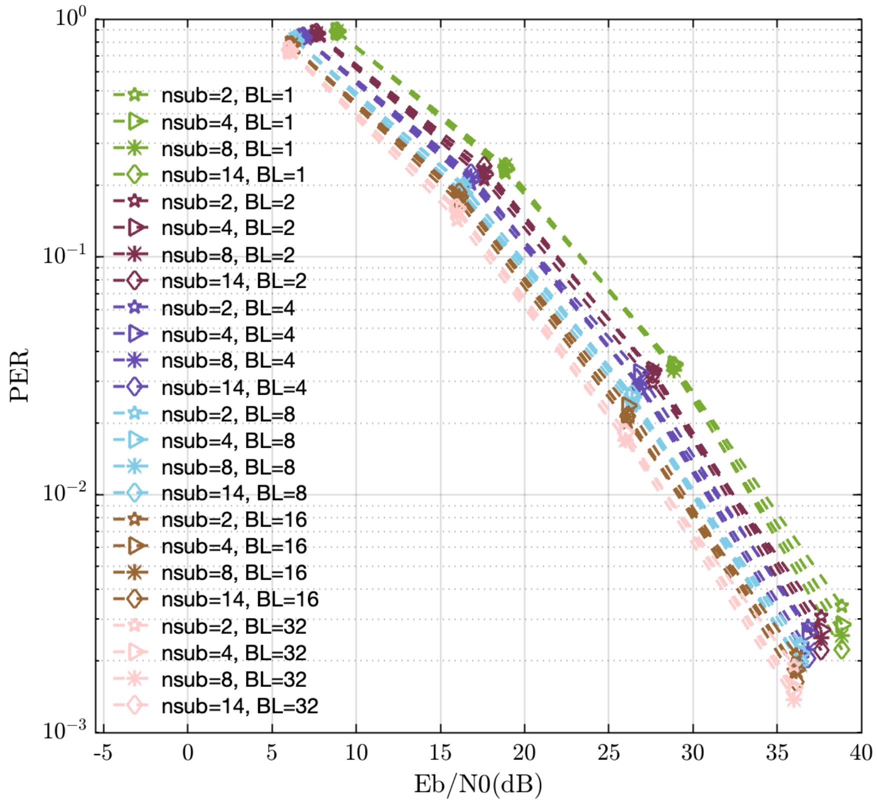




- The required SNR to achieve PER=10^{-2} is around 3.8dB (Received power: −130 dBm).
- As the BL becomes smaller, efficiency decreases and the required Eb/No increases.

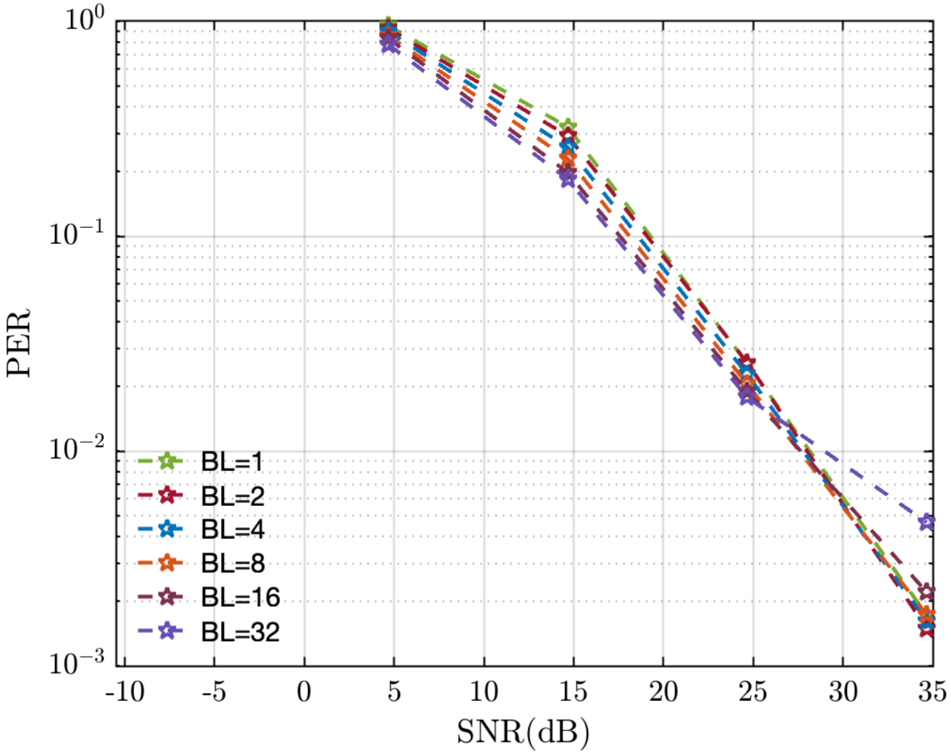
PER under GSM Typical Urban (fd=0.6Hz)

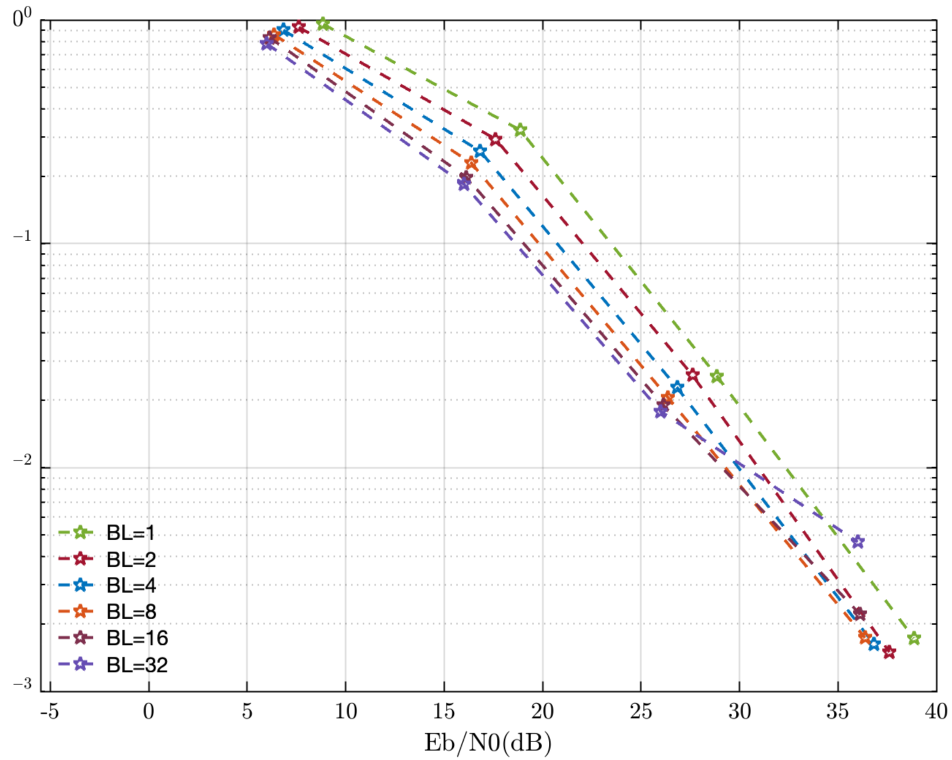




- The required SNR to achieve PER=10^{-2} is around 28 dB (Received power: −105.8dBm).
- Because pilot signals are inserted in each block, the shorter the BL, the longer the time it takes to transmit a single packet. As a result, it becomes more susceptible to fading.

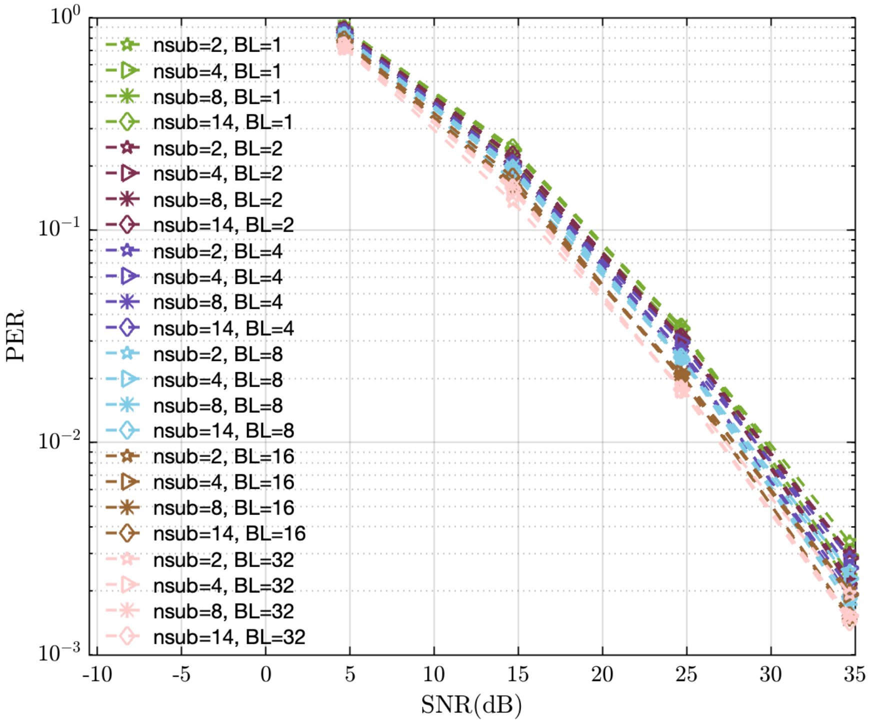
PER under GSM Typical Urban (fd=6Hz, Nsub=14)

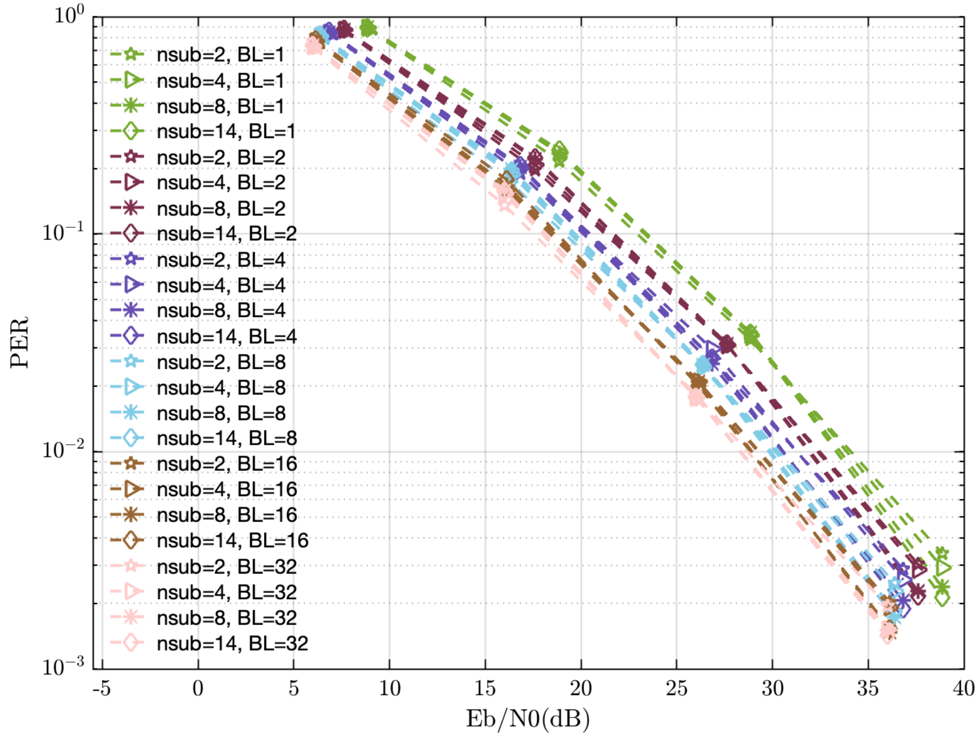




- The required SNR to achieve PER=10^{-2} is around 27.5 dB (Received power: −106.3 dBm).
- The longer the BL, the less influence the pilot signal estimation has on the entire BL and the worse the PER characteristics.
- BL should be 16 or below.

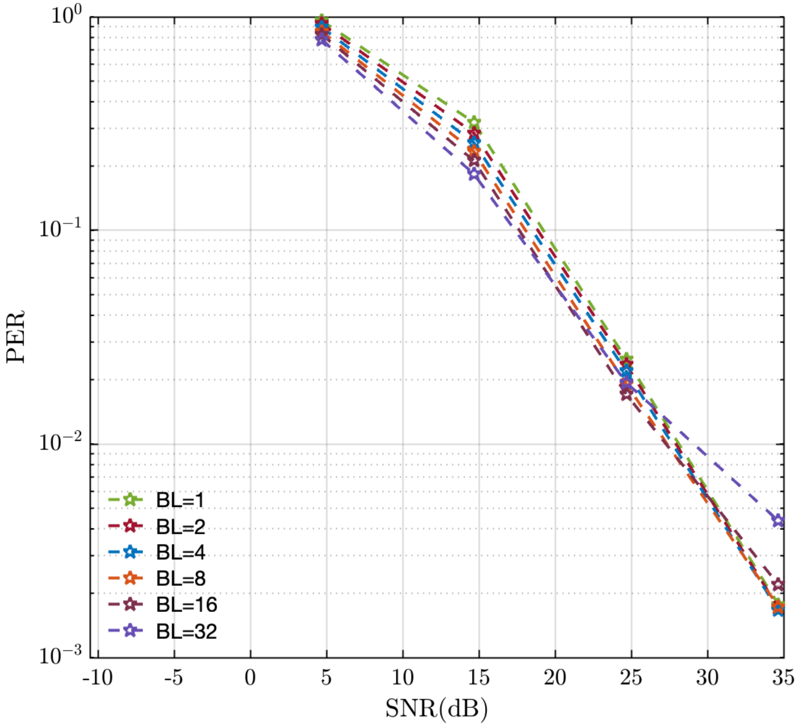
PER under IEEE 802.22 Profile A (fd=0.6Hz)

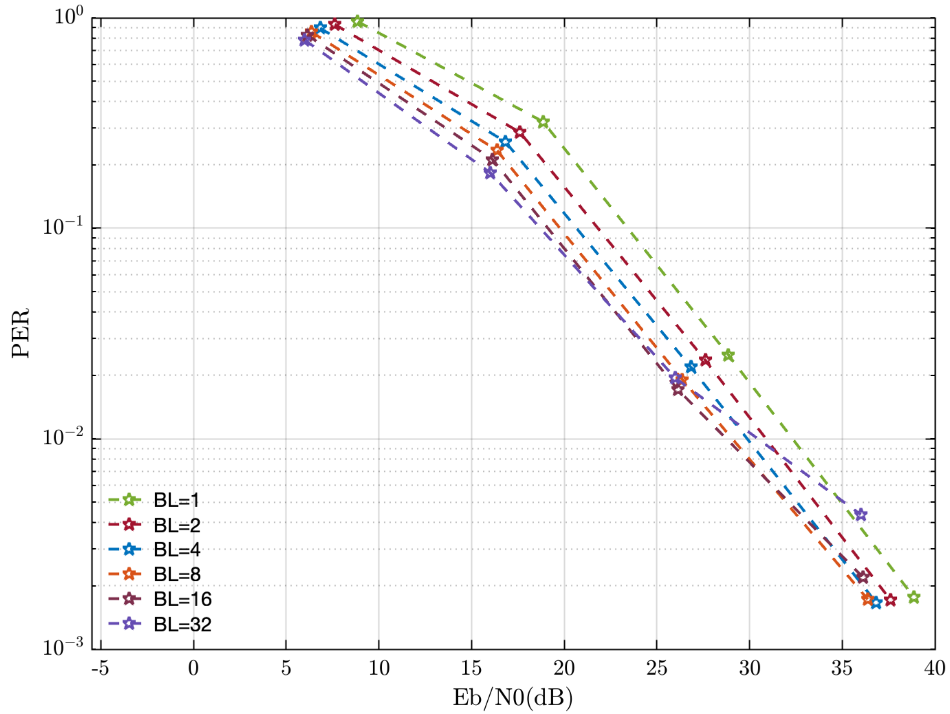




- The required SNR to achieve PER=10^{-2} is around 27.5 dB (Received power: −106.3 dBm).
- This channel model has strong frequency selectivity because it receives long delay waves.
- However, the guard interval is longer than the maximum delay time, so there is no significant impact on PER.
- The longer 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 27.5 dB (Received power: −106.3 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.

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 mapping scheme (Nsub=14)

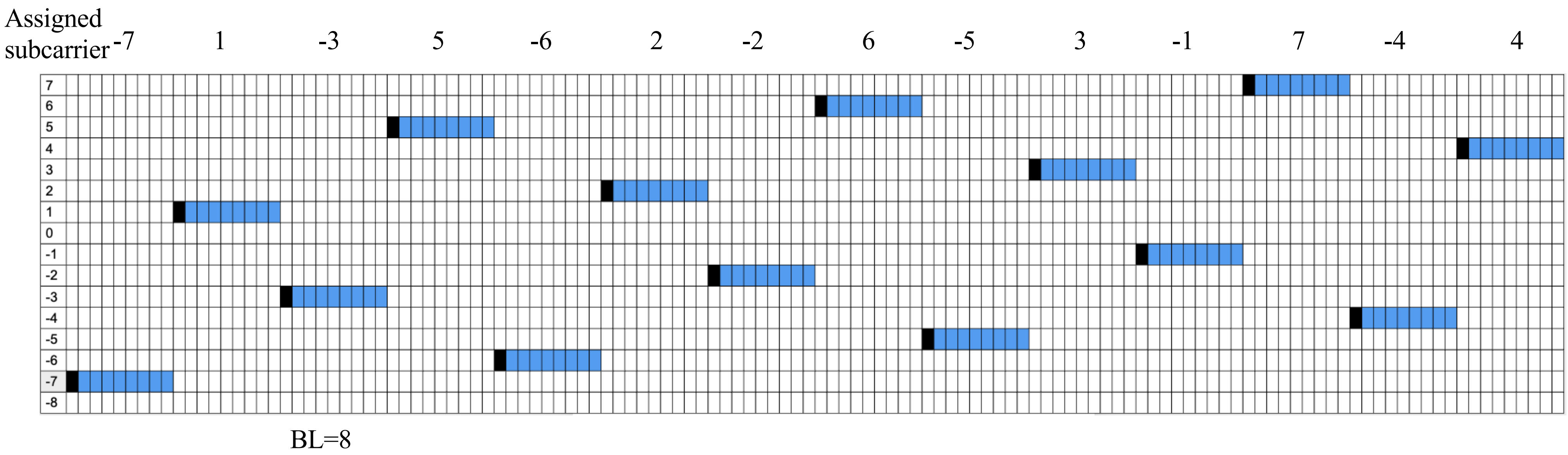
The tone(subcarrier) number assigned to each blocks: $-\frac{N_{FFT}}{2}, -\frac{N_{FFT}}{2}+1, \ldots, \frac{N_{FFT}}{2}-1 \quad (i = 1,2,3, \ldots)$

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

Inactive subcarriers are excluded.

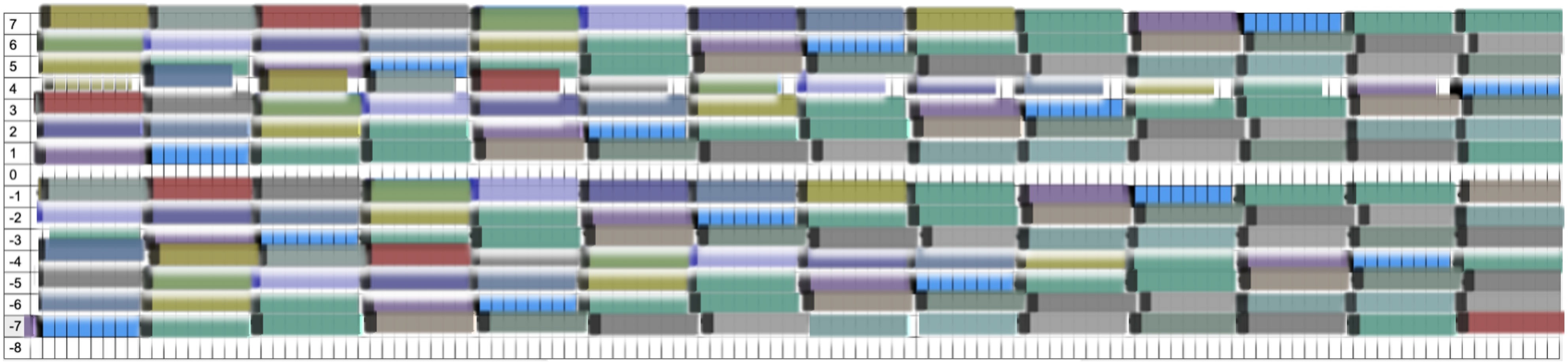
In the case of Option4 (N_{FFT}=16), the subcarriers selected in the i-th block are as follows.

$n_{sub,i}$=-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, …



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

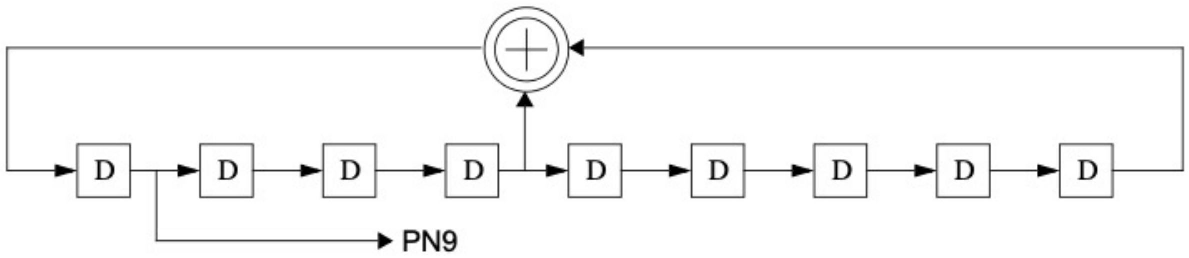


Figure 16-2—Schematic of the PN generator

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

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,….)

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

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

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

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}

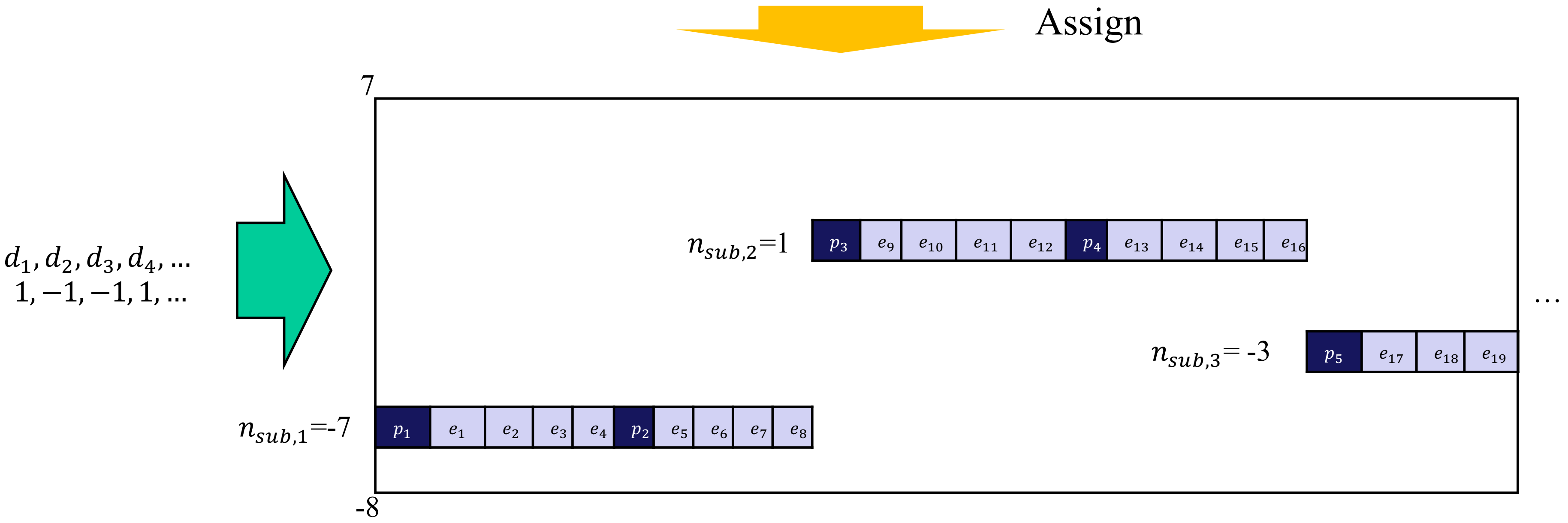
Example of data spreading (Option=4, SF=2)

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

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

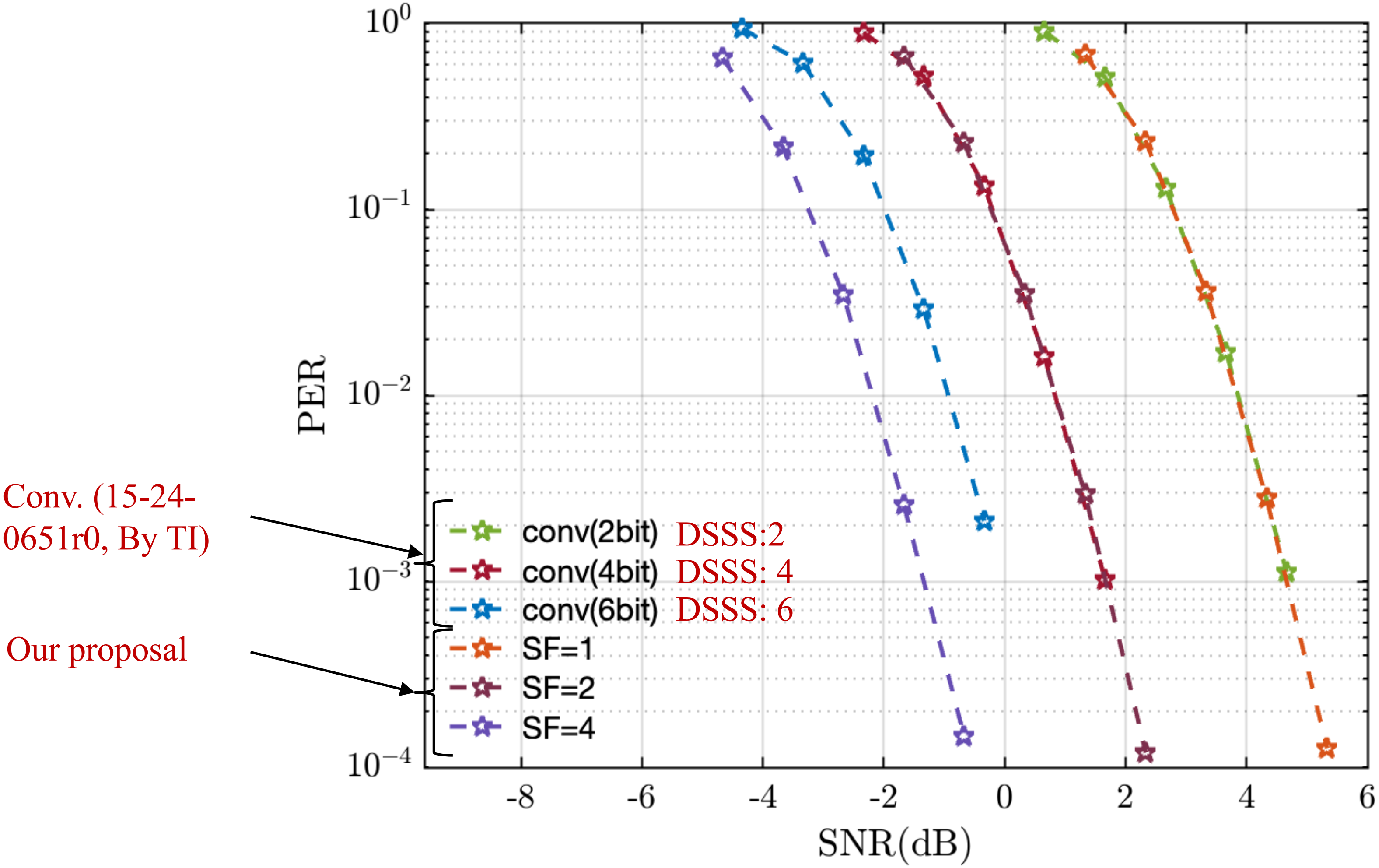
Subcarrier $n_{sub,i}$=-7,1,-3,…



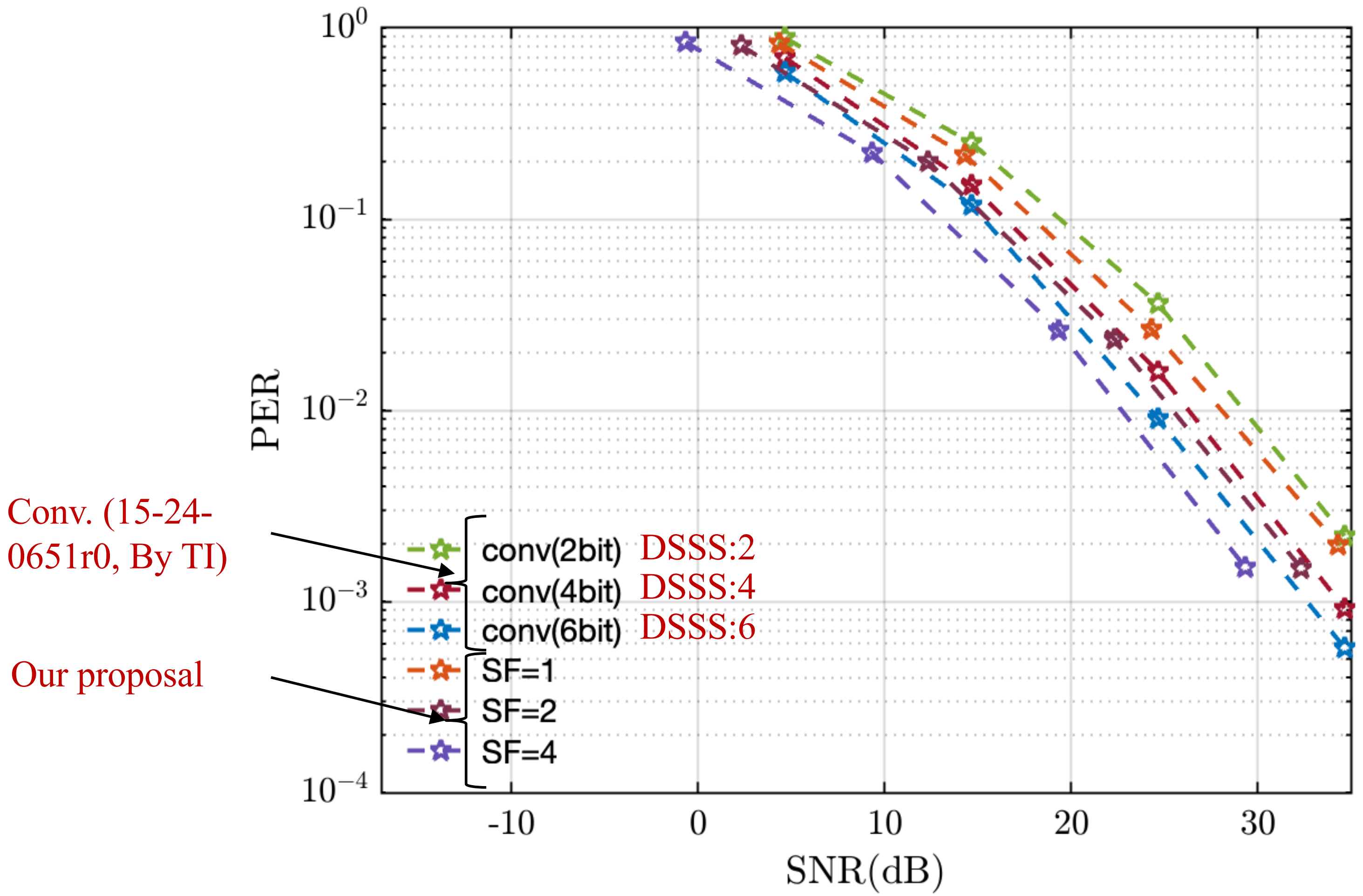
Simulation parameters (others)

- Spreading factor: 1, 2, 4 (Our proposal) and 2, 4, 6 as Conv. (15-24-0651r0, By TI)
- Channel model: GSM typical urban, IEEE 802.22 Profile A
- Doppler frequency: 0.6 Hz
- Packet size: 20 byte
- Interleave size: Random
- Evaluation index: Packet Error Rate (PER)
- Padding bit: 2bit
- Tailbit: 6bit
- Gurad interval: 1/4

PER under AWGN (fd=0.6Hz, Nsub=14, BL=8)



PER under GSM Typical Urban (fd=0.6Hz, Nsub=14, BL=8)



PER under IEEE 802.22 Profile A (fd=0.6Hz, Nsub=14, BL=8)