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

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Re: [In response to TG3c Call for Proposals (IEEE P802.15-07-0586-02-003c)]

Abstract: [CoMPA proposal for IEEE 802.15 WPAN Millimeter Wave Alternative PHY]

Purpose: [To be considered in TG3C baseline document.]

CoMPA PHY proposal

(CoMPA: Consortium of millimeter-wave practical applications)

May 7, 2007

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Goal of CoMPA PHY

- Promote millimeter-wave systems commercialization and the standard which supports various applications and can be deployed immediately
- Promote a simple air-interface with low power-consumption for portable devices
- Promote a flexible standard to support multiple PHYs, each suitable for various applications

Contents

Summary of CoMPA PHY proposal

- **Channelization**
  - 2080MHz bandwidth/ch, 4ch/9GHz bandwidth
- **Mandatory Features: over 2Gbps@PHY-SAP**
  - Single Carrier (SC) modulation (QPSK) with Reed Solomon (RS) coding (with frequency domain equalizer (FDE) for NLOS environments)
- **Optional Features: over 3Gbps@PHY-SAP**
  - SC modulation (8PSK or TC8PSK) with RS coding or LDPC (with FDE for NLOS environments)
- **Three transmission modes are supported**
  - High rate transmission mode (HRT)
  - Medium rate transmission mode (MRT)
  - Low rate transmission mode (LRT)
- **Flexible standard to support multiple PHYs**
  - Support co-existence of multiple PHYs and interference avoidance among the PHY networks with different channel plans
- **CoMPA PHY proposal meets all system requirements**

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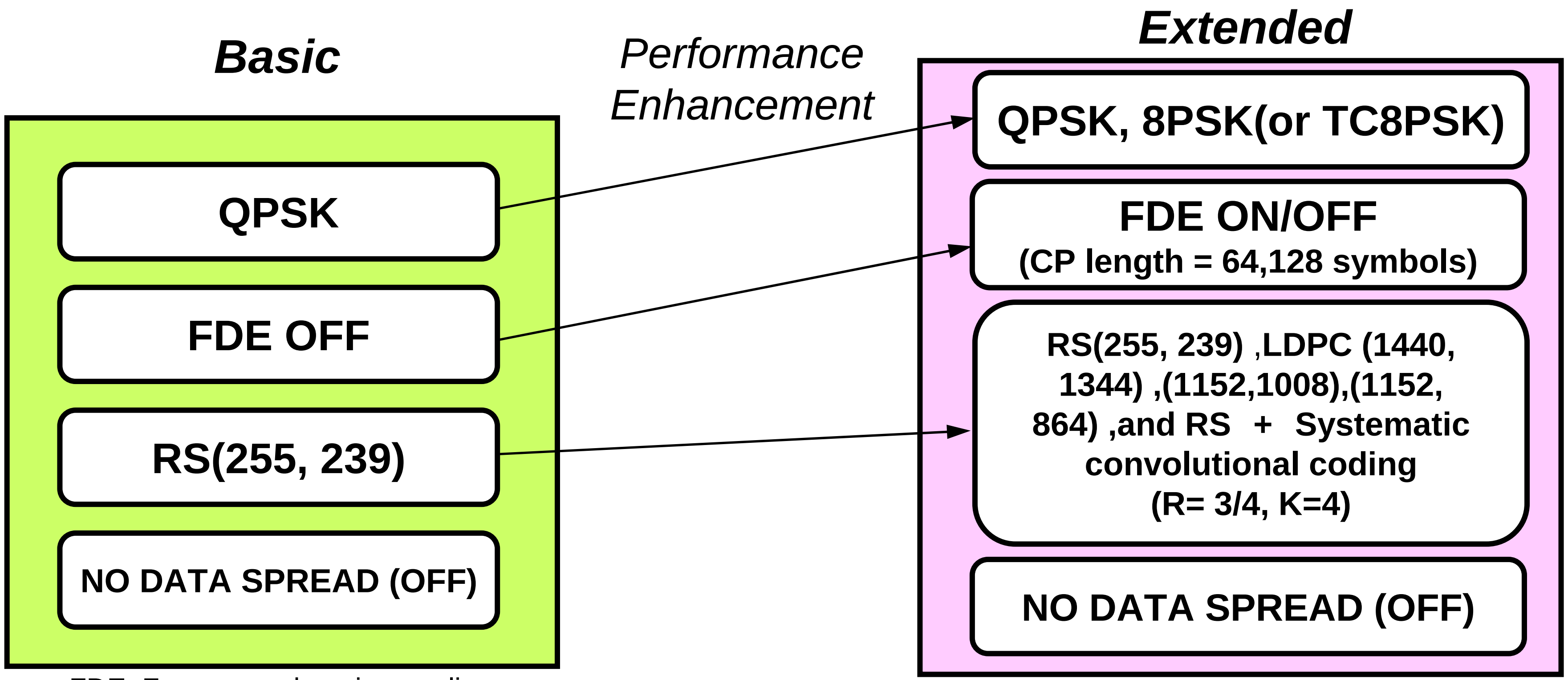
Overview of CoMPA PHY architecture

- High rate transmission mode (HRT) -


Basic

Performance Enhancement

Extended

QPSK

FDE OFF

RS(255, 239)

NO DATA SPREAD (OFF)

QPSK, 8PSK(or TC8PSK)

FDE ON/OFF
(CP length = 64,128 symbols)

RS(255, 239) ,LDPC (1440, 1344) ,(1152,1008),(1152, 864) ,and RS + Systematic convolutional coding (R= 3/4, K=4)

NO DATA SPREAD (OFF)

FDE: Frequency domain equalizer

Support over 2 Gbps PHY-SAP payload bit rate

Support over 2 Gbps PHY-SAP payload bit rate up to 4.679 Gbps and robustness against NLOS environments

CP: Cyclic Prefix

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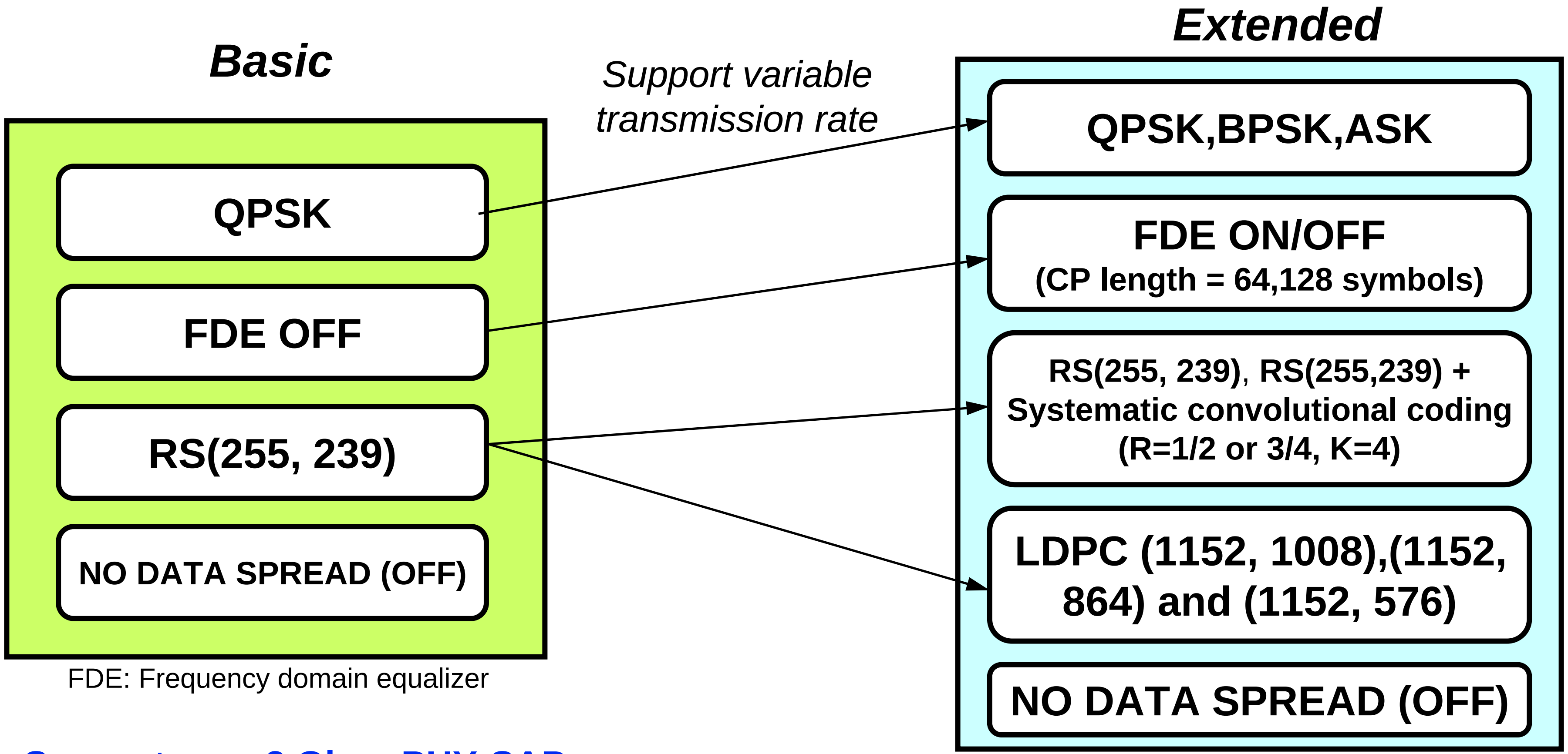
Overview of CoMPA PHY architecture

- Medium rate transmission mode (MRT) -



FDE: Frequency domain equalizer

Support over 2 Gbps PHY-SAP payload bit rate

Support from 100Mbps up to 2Gbps PHY-SAP payload bit rates

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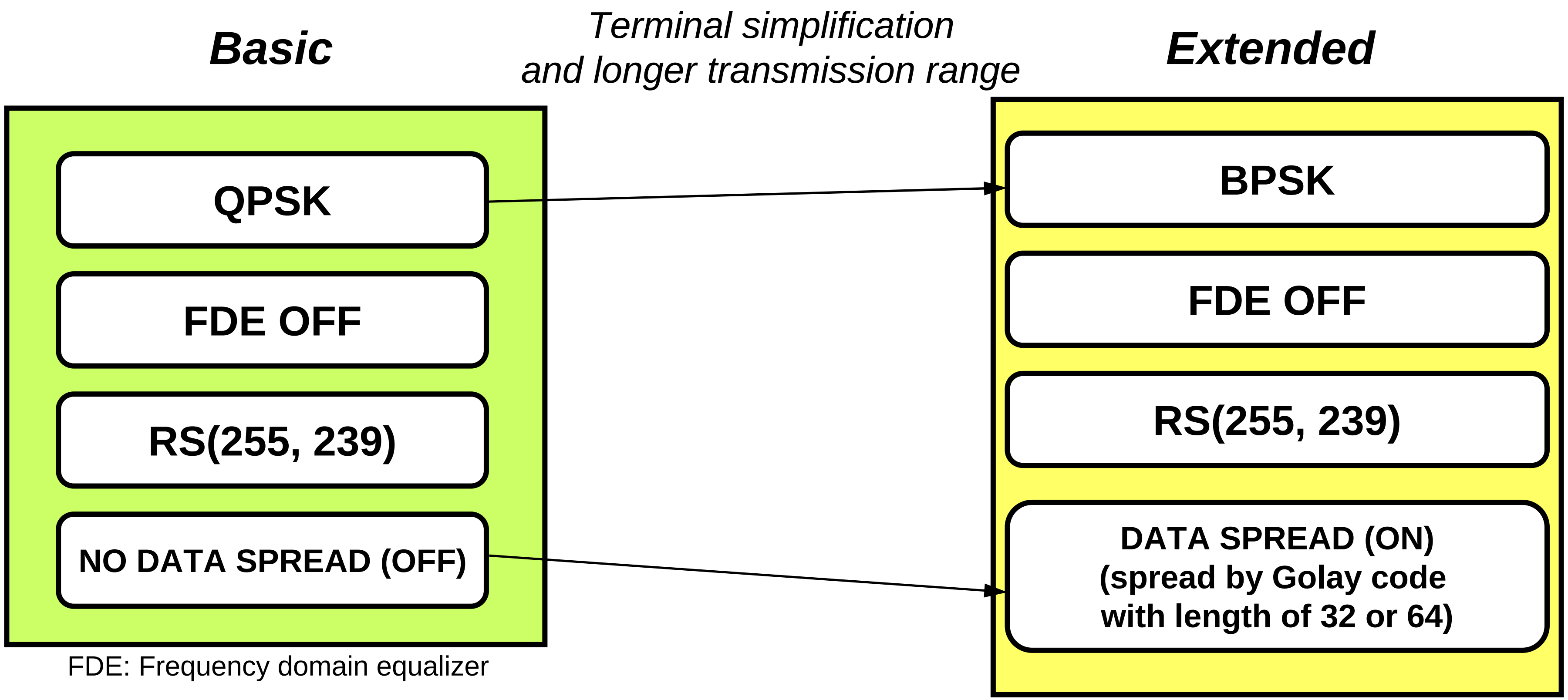
Overview of CoMPA PHY architecture
- Low rate transmission mode (LRT) -



Basic

Terminal simplification and longer transmission range

Extended

FDE: Frequency domain equalizer

Support over 2 Gbps PHY-SAP payload bit rate

Support less than 100 Mbps PHY-SAP payload bit rates and extended transmission range

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1. Channelization

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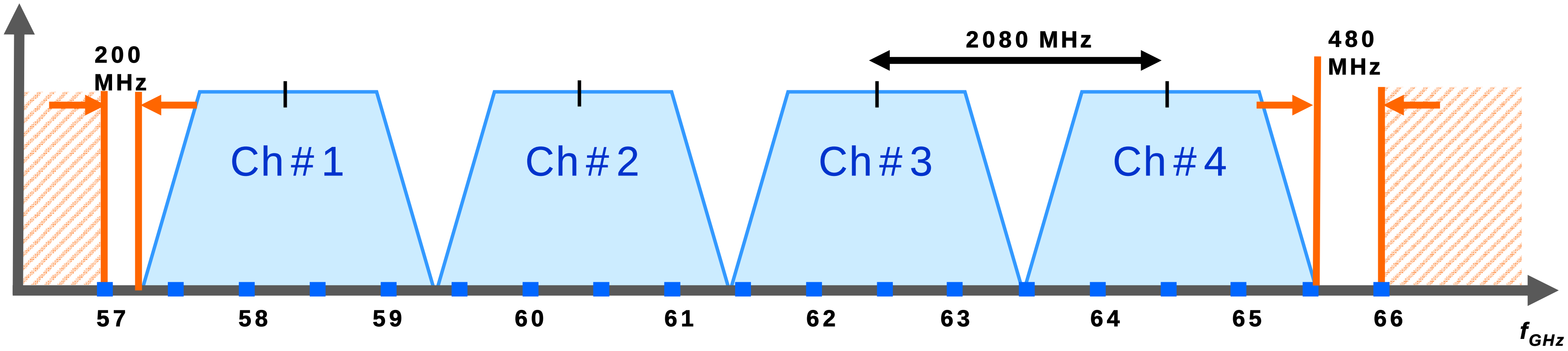
Channelization

Channel Number	Low Freq. (GHz)	Center Freq. (GHz)	High Freq. (GHz)	Nyquist BW (MHz)	Roll-Off Factor
1	57.200	58.240	59.280	1664	0.25
2	59.280	60.320	61.360	1664	0.25
3	61.360	62.400	63.440	1664	0.25
4	63.440	64.480	65.520	1664	0.25



- Balance upper and lower guard bands
- Support cell phone XTAL: 26 MHz
- Support higher frequency XTALs: 40 , 43.333, & 65 MHz
- Dual PLL
  - High frequency PLL that generates carrier frequencies
  - Low frequency PLL that generates the ADC/DAC & ASIC frequencies

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2. Modulation & coding

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Summary of modulation and coding

Basic Features :

- SC-PHY of QPSK with RS(255, 239) code for mandatory data-rate mode to support UM1 and UM5 scenarios with minimum hardware complexity

Extended Features:

- 8PSK modulation with RS(255, 239) or LDPC(1440, 1344) coding mode is available to achieve over 3 Gbps PHY-SAP payload bit rates
- FDE with 64 or 128 CP length is available to keep robustness against NLOS environments
- Other two modes
  - Medium rate transmission (MRT) mode
    - Additional modulation scheme: BPSK,ASK
    - Additional coding scheme:
      - ✓ Concatenation modes of systematic convolutional coding (R=1/2 or 3/4, K=4) and RS(255, 239)
      - ✓ LDPC(1152, 1008), (1152, 864) and (1152, 576)
  - Low rate transmission (LRT) mode
    - Based on BPSK with RS (255, 239)
    - Spreading of data payload by Golay code

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CoMPA PHY major parameters

Parameters	Specification
Channel separation	2080 MHz
Basic transmission scheme	Single Carrier (SC) transmission
Multiple access scheme	TDMA/CSMA
Symbol rate (Nyquist bandwidth)	1664 MHz
Root raised cosine filter	Roll-off factor =0.25
Modulation	Basic: QPSK (Gray-coded mapping) Extended: 8PSK (or TC8PSK), BPSK (Gray-coded mapping), ASK
Channel coding scheme	Basic: RS(255, 239) over GF(2^8) Extended: -LDPC(1440, 1344), (1152,1008), (1152, 864) and (1152, 576) -RS(255, 239) + Systematic convolutional coding (R=1/2 or 3/4, K=4)
CP (Cyclic prefix) length	Basic: 0 symbol, Extended: 64, 128 symbols
Number of symbols per block for FDE	512

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List of available data-rate mode

- High rate transmission (HRT) and Medium rate transmission (MRT) mode -

Mode	Modulation	FEC scheme	PHY-SAP payload bit rate [Gbps]		
			CP length = 0	CP length = 64	CP length = 128
1.1	BPSK	RS(255,239)	1.560	1.386	1.248
1.2.1		LDPC (1152, 864)	1.248	1.1093	0.9984
1.2.2		LDPC (1152, 576)	0.832	0.740	0.666
1.3		Outer: RS(255, 239) Inner: Systematic Convolutional (R=3/4, K=4)	1.170	1.040	0.936
1.4		Outer: RS(255, 239) Inner: Systematic Convolutional (R=1/2, K=4)	0.780	0.693	0.624
2.1	QPSK	RS(255, 239)	3.119	2.773	2.495
2.2.1		LDPC (1440, 1344)(*LDPC(1152,1008))	3.106(*2.912)	2.761(*2.588)	2.485(*2.330)
2.2.2		LDPC (1152, 864)	2.496	2.219	1.997
2.2.3		LDPC (1152, 576)	1.664	1.479	1.331
2.3		Outer: RS(255, 239) Inner: Systematic Convolutional (R=3/4, K=4)	2.339	2.080	1.872
2.4		Outer: RS(255, 239) Inner: Systematic Convolutional (R=1/2, K=4)	1.560	1.386	1.248
3.1	8 PSK	RS(255, 239)	4.679	4.159	3.743
3.2		LDPC (1440, 1344)	4.659	4.142	3.727

⬚ HRT

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List of available data-rate mode - Low rate transmission (LRT) mode -

- Low data-rate mode is available to increase scalability in data-rate and transmission range
- Low data-rate mode frame is spread by Golay code of length 64 or 32

Mode	Modulation	FEC scheme	PHY-SAP payload bit rate [Gbps]
4.1	BPSK	RS(255, 239) spread by Golay code of length 64	0.0487
4.2		RS(255, 239) spread by Golay code of length 32	0.0975

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Mandatory usage models and PHY candidates

Items	UM1				UM5			
Required MAC-SAP [Gbps]	1.78		3.65		1.5		2.25	
Channel model	1.3	2.3	1.3	2.3	3.1	9.1	3.1	9.1
Target BER or PER	BER = 10^{-6}				PER=0.08			
Transmission mode	Mode2.1		Mode3.1		Mode2.1			
Modulation	QPSK		8PSK		QPSK			
Channel coding	RS(255,239)							
CP length used with FFT 512	0	128	0	128	128	0	128	0
PHY-SAP payload bit rate [Gbps]	3.119	2.495	4.679	3.743	2.495	3.119	2.495	3.119

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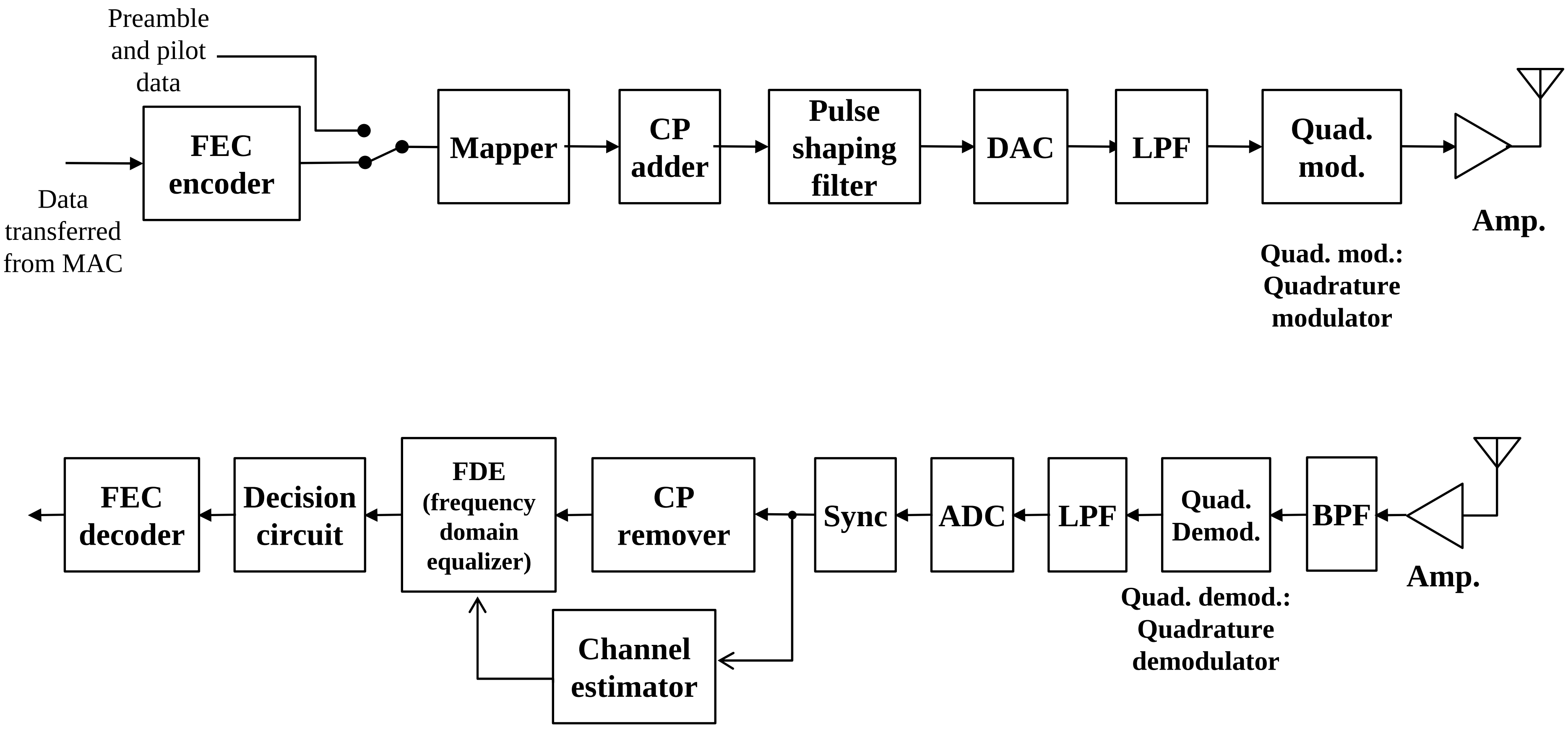
Basic block diagram of transmitter and receiver



Quad. mod.: Quadrature modulator

Quad. demod.: Quadrature demodulator

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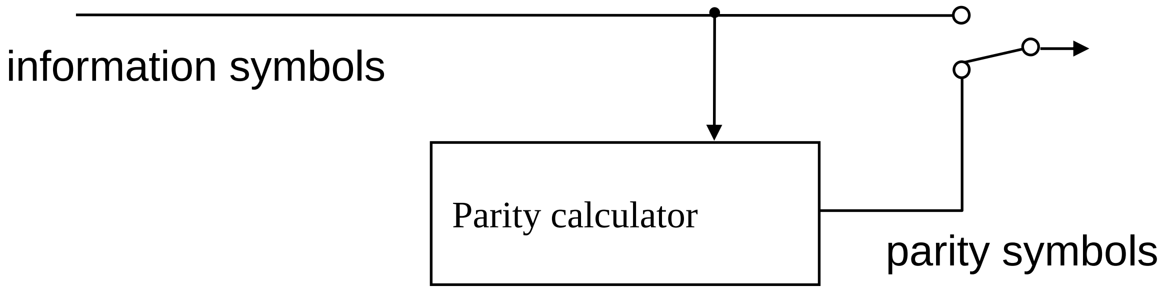
Architecture of RS (255, 239) encoder



Generator polynomial of the RS code is defined as,

$$g(x) = \prod_{i=0}^{15} (x - \alpha^i),$$

where α is a root of the primitive polynomial,

$$p(x) = x^8 + x^4 + x^3 + x^2 + 1.$$

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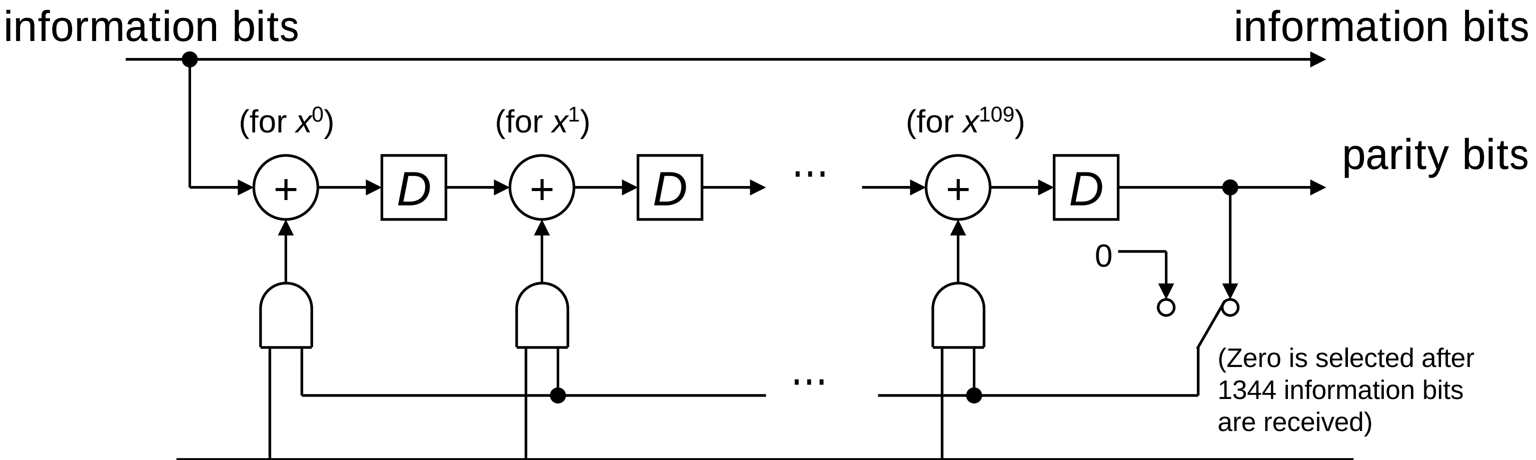
Architecture of LDPC(1440, 1344) encoder

The systematic quasi-cyclic (1440, 1344) LDPC code can be encoded by using 15 generator polynomials and a (96+15-1=) 110-stage shift register.



(Zero is selected after 1344 information bits are received)

Select $g_{(1439\text{ - }k)\text{mod}15}{*}x^{14\text{ - }\{(1439\text{ - }k)\text{mod}15\}}$ at time k, where k = 0 is defined as the time that the first 110 information bits are stored in the 110 shift registers.

15 generator polynomials in hexadecimal with the maximum order of 110th

g_0 = 02008A43C438280AD3220414CA2A

g_1 = 04002A09100310379125214082C6

g_2 = 0800000D28CCD0C1810880440132

g_3 = 10000D0C04900416612A24326480

g_4 = 2000020C28F089055000E41448A4

g_5 = 4000C00EC83E990842094444488C

g_6 = 0001C715CC84A50CF30800466488

g_7 = 00021D6C08806496E3284403E684

g_8 = 00044F0A2C76C4827000C003AE26

g_9 = 0008228098021139022FA0140069

g_{10} = 00104A04840E4D8A702200578618

g_{11} = 00206406B47A41CDC321844049AA

g_{12} = 0040CD0700BE4D87A31844017E24

g_{13} = 00801460E64A7198222BB21600A8

g_{14} = 0100C909A4C60C1F520AE010A62E

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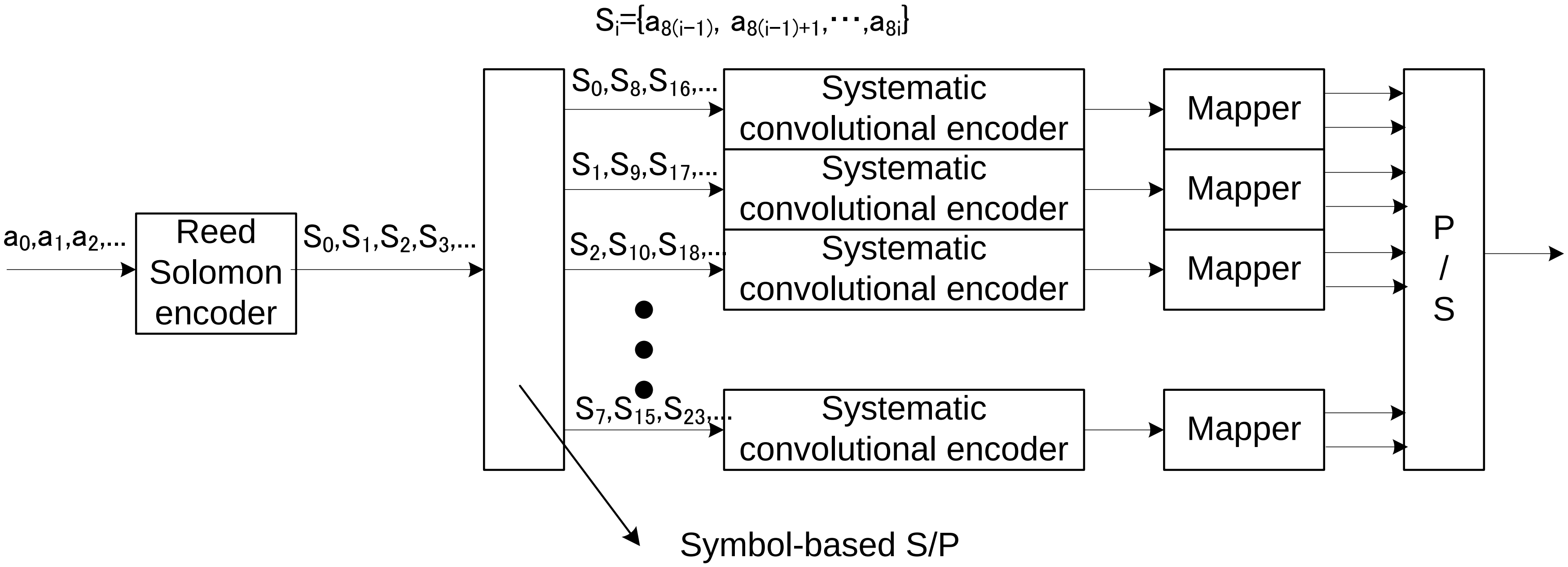
Architecture of concatenation of RS(255, 239) and systematic convolutional (R=1/2,3/4, K=4) encoder



$S_i=\{a_{8(i-1)}, a_{8(i-1)+1},\cdots,a_{8i}\}$

$a_0,a_1,a_2,\ldots$

Reed Solomon encoder

$S_0,S_1,S_2,S_3,\ldots$

$S_0,S_8,S_{16},\ldots$

$S_1,S_9,S_{17},\ldots$

$S_2,S_{10},S_{18},\ldots$

$S_7,S_{15},S_{23},\ldots$

Systematic convolutional encoder

Systematic convolutional encoder

Systematic convolutional encoder

Systematic convolutional encoder

Mapper

Mapper

Mapper

Mapper

P / S

Symbol-based S/P

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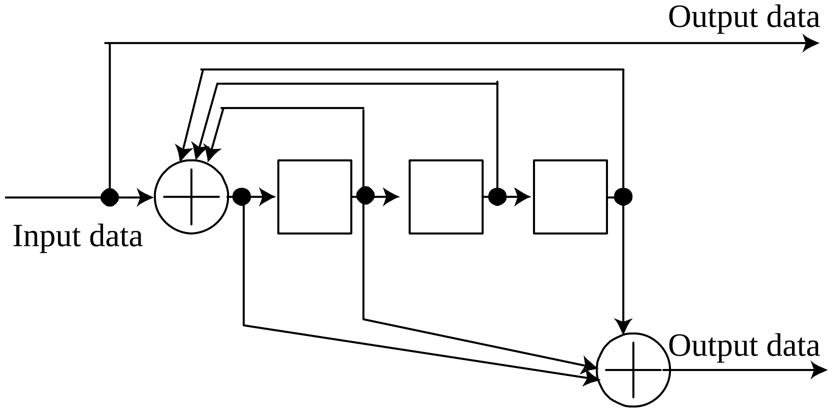
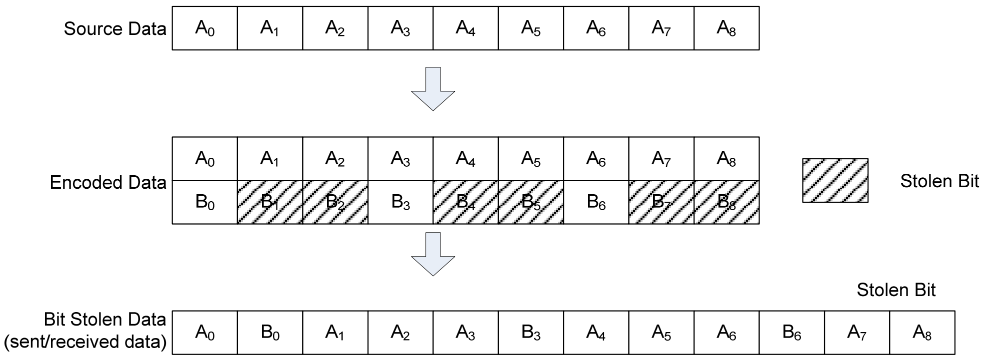
Architecture of systematic convolutional encoder (R=1/2 or 3/4, K=4)

- Generator polynomials: g0 = 17_{oct} and g1 = 15_{oct}



- Puncturing to generate coding rate R=3/4



Source Data

A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8

Encoded Data

A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
B_0	▨ B_1	▨ B_2	B_3	▨ B_4	▨ B_5	B_6	▨ B_7	▨ B_8

▨ Stolen Bit

Stolen Bit

Bit Stolen Data (sent/received data)

A_0	B_0	A_1	A_2	A_3	B_3	A_4	A_5	A_6	B_6	A_7	A_8

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3. PHY frame format

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Summary of frame format

- Two types of frames
  - Frame for HRT (High Rate Transmission) and MRT (Medium Rate Transmission) modes
    - Only preamble is spread by Golay code of length 128 bits
  - Frame for LRT (Low Rate Transmission) mode: Longer transmission range
    - Preamble is spread by Golay code of length 128
    - Header and payload are spread by Golay code of length 64 or 32
- Start frame delimiter (SFD) is included in the preamble
  - Used for common mode identification
  - Consist of information data spread by Golay code
- A new cyclic-redundancy-check code of $1A12B_{hex}$ for Header Check Sequence (HCS) is proposed

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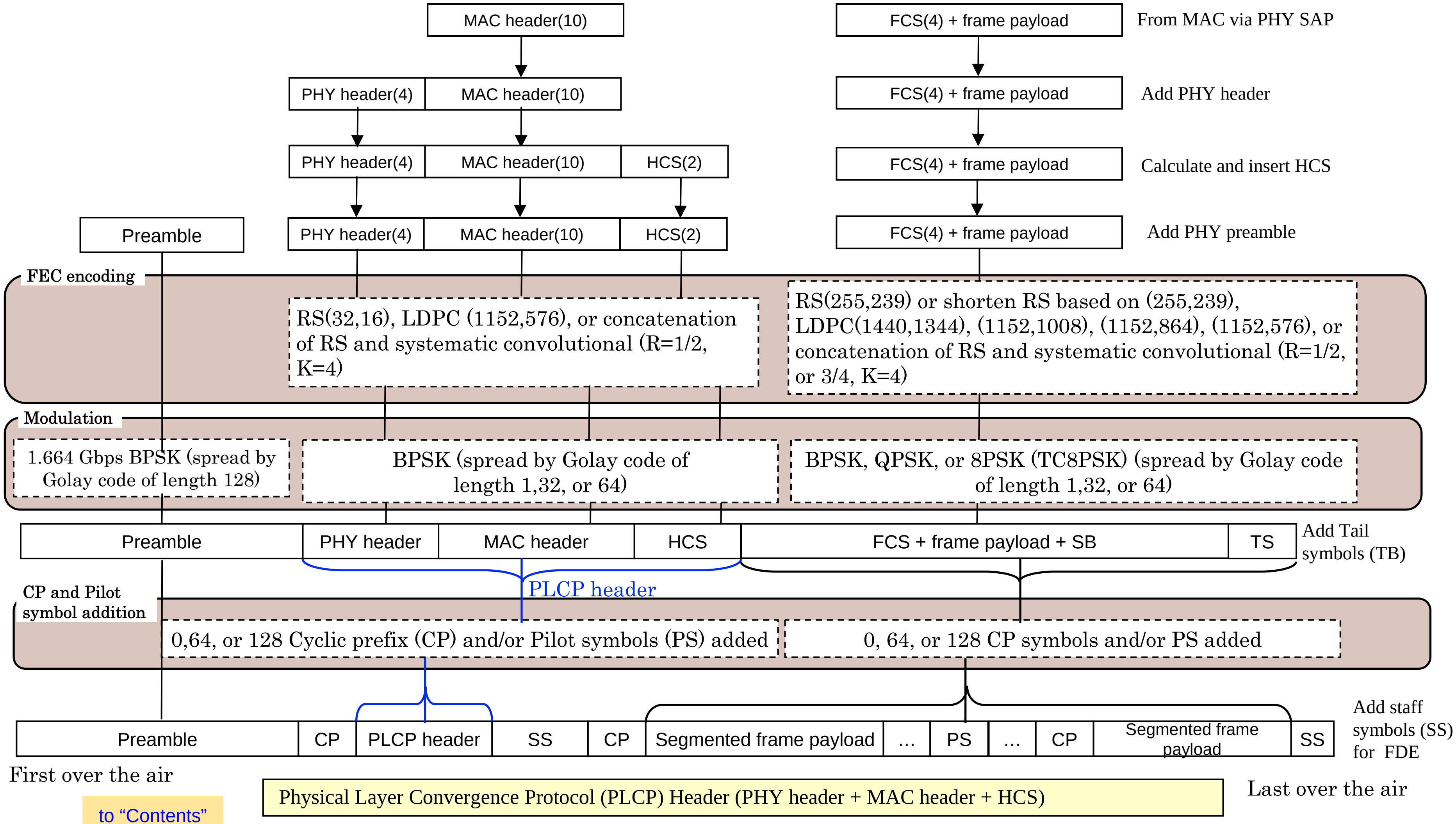
PHY frame formatting



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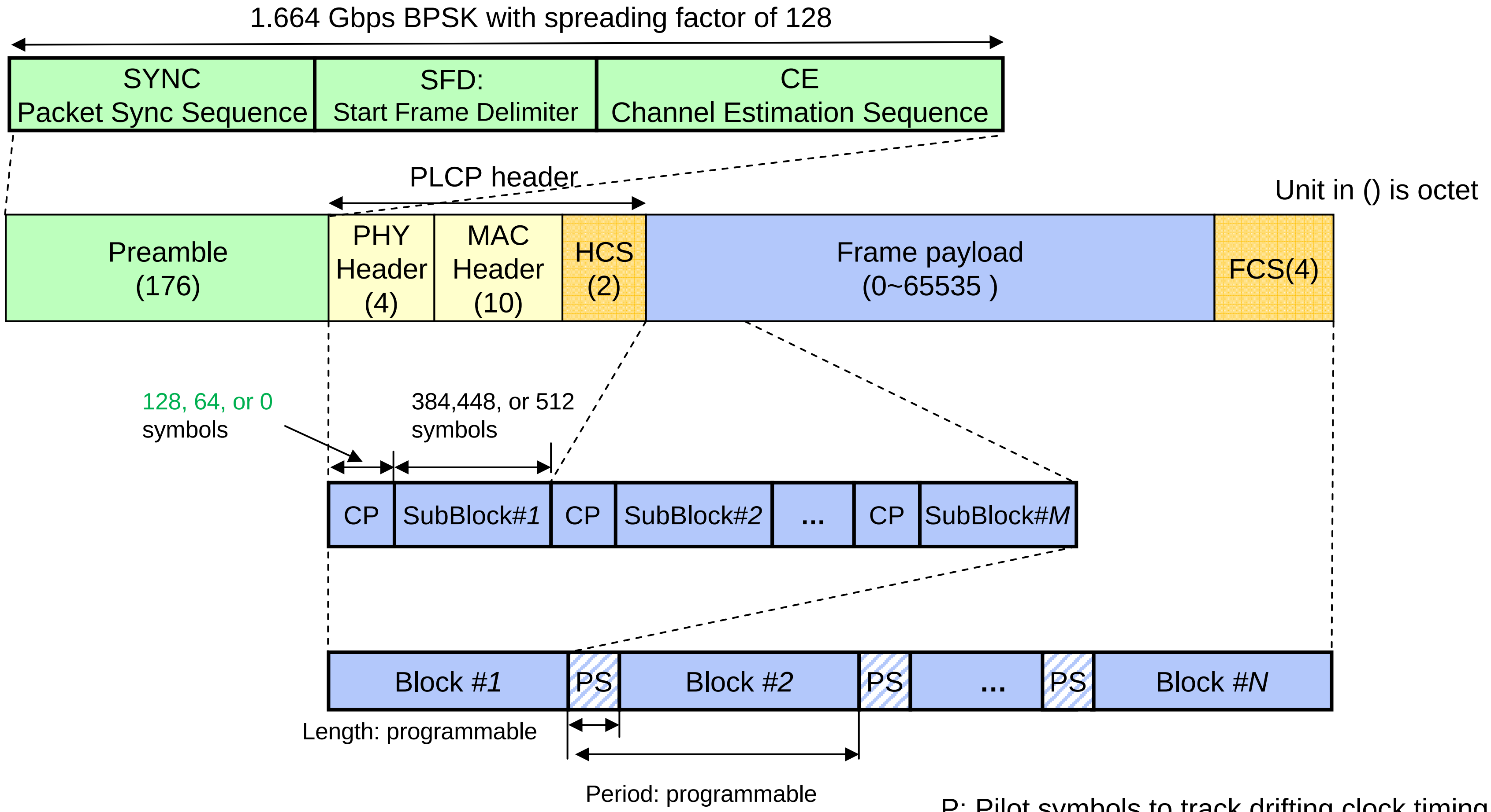
Detailed frame format before FEC



P: Pilot symbols to track drifting clock timing

CP: Cyclic Prefix

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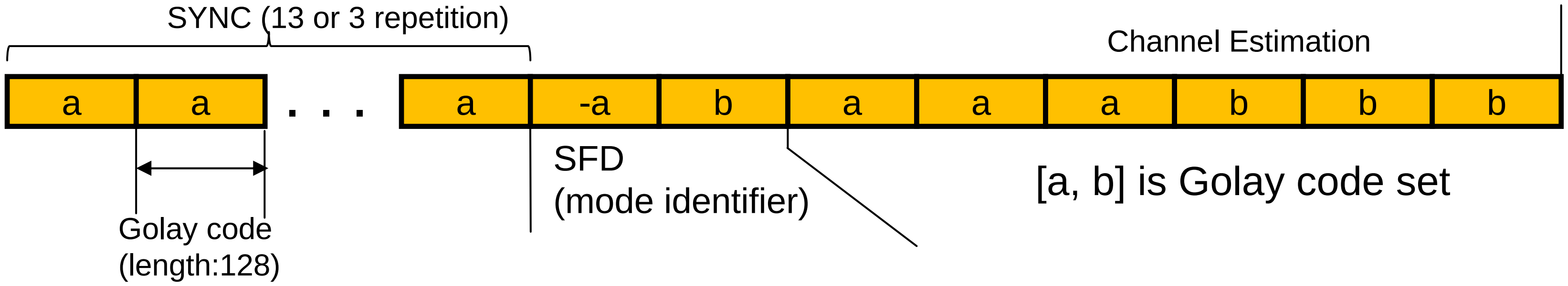
Preamble format



SFD
(mode identifier)

[a, b] is Golay code set

mode	Symbol rate	SYNC	SFD	CE	Total length	
	[Gsps]	Length of Sequence L_{sfd} [symbols]	Length of Sequence L_{sfd} [symbols]	Length of Sequence L_{sfd} [symbols]	symbols	nsec
HRT/MRT mode	1.664	3	2	6	1408	846.2
LRT mode	1.664	13	2	6	2688	1615.4

- Golay code of length 128 is used in all data-rate transmission frames
- In low-rate transmission modes, PLCP header and payload are spread by Golay code of length 64 or 32
  - -48.7 Mbps data rate and 18 dB processing gain with code length of 64 bits
  - -97.5 Mbps data rate and 15 dB processing gain with code length of 32 bits

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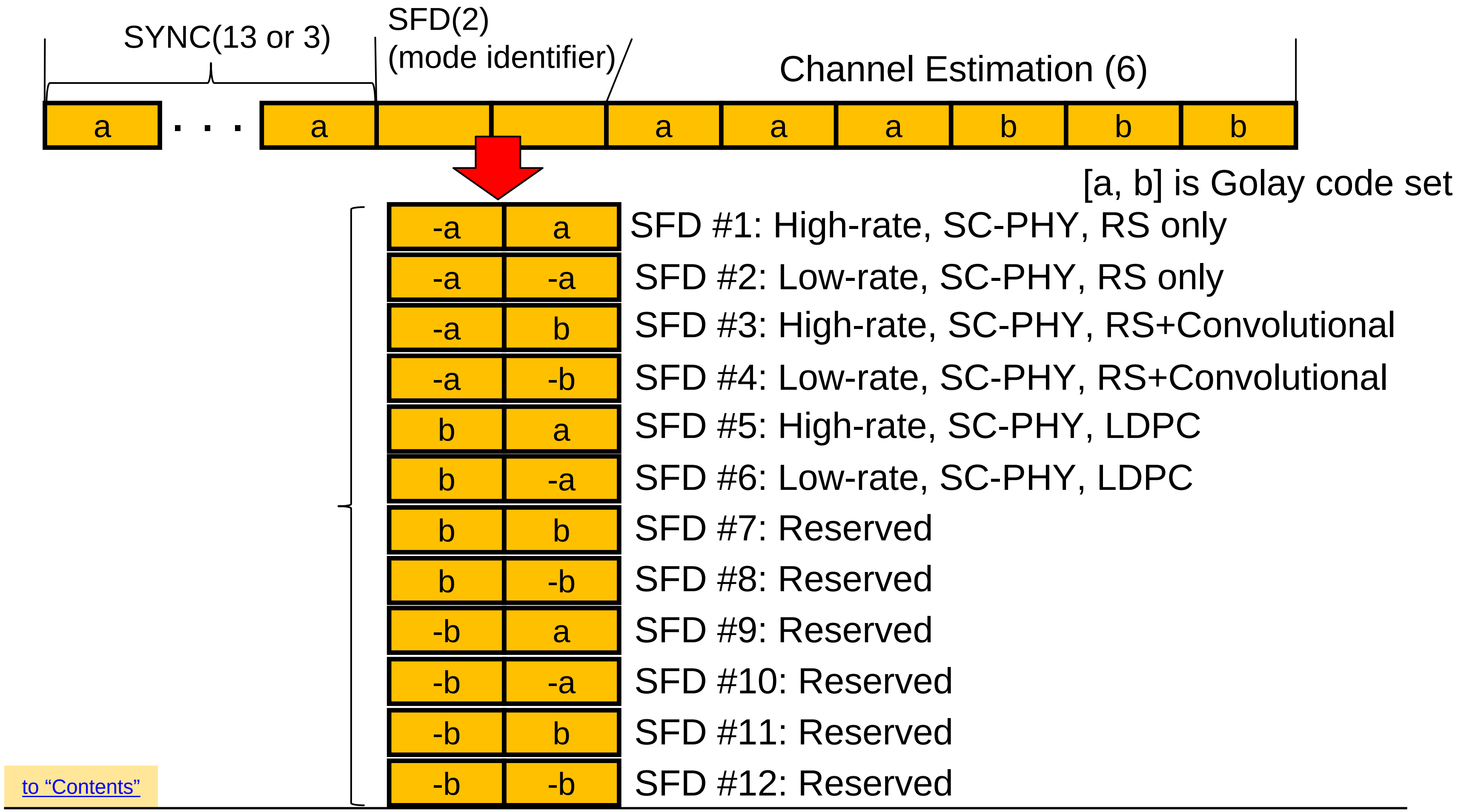
Preamble format example

SFD field is used to notify the PHY mode in Beacon frame as well as to set the start point of frame



SYNC(13 or 3)

SFD(2)
(mode identifier)

Channel Estimation (6)

[a, b] is Golay code set

-a	a	SFD #1: High-rate, SC-PHY, RS only
-a	-a	SFD #2: Low-rate, SC-PHY, RS only
-a	b	SFD #3: High-rate, SC-PHY, RS+Convolutional
-a	-b	SFD #4: Low-rate, SC-PHY, RS+Convolutional
b	a	SFD #5: High-rate, SC-PHY, LDPC
b	-a	SFD #6: Low-rate, SC-PHY, LDPC
b	b	SFD #7: Reserved
b	-b	SFD #8: Reserved
-b	a	SFD #9: Reserved
-b	-a	SFD #10: Reserved
-b	b	SFD #11: Reserved
-b	-b	SFD #12: Reserved

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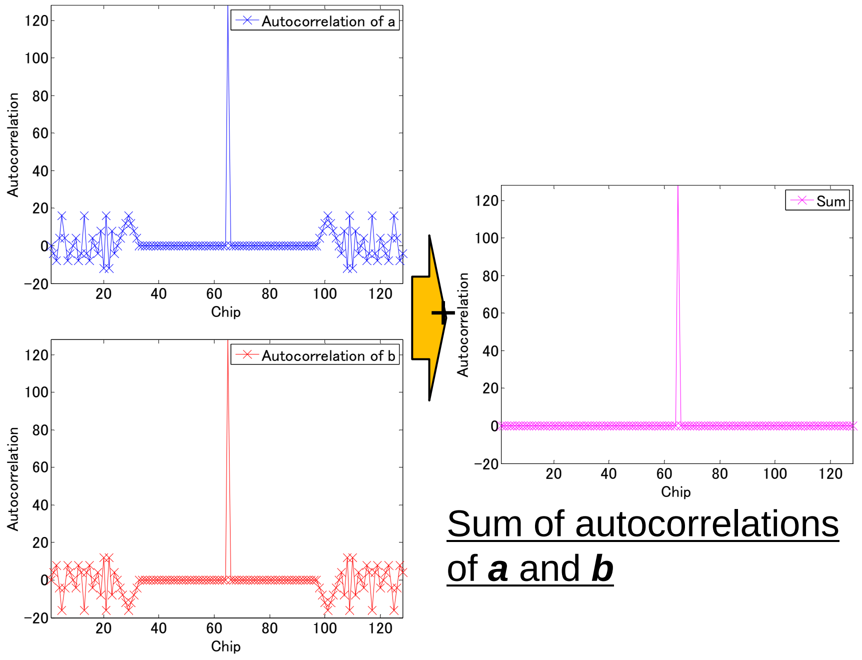
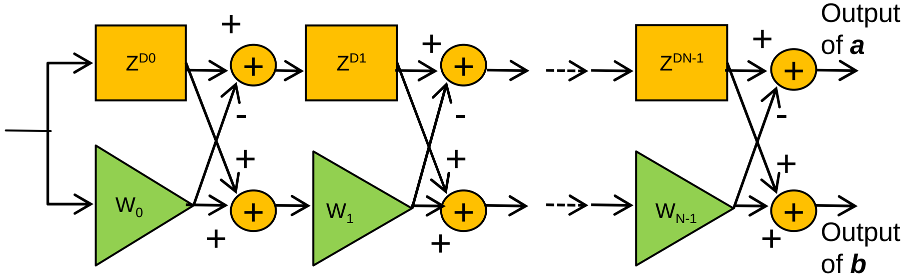
Features of Golay codes

- Golay codes consist of a pair of binary sequences ***a*** and ***b*** with length of 2^N chips, where N is a positive integer
- Autocorrelation of ***a*** and that of ***b*** can be calculated by a very simple matched filter with N delay elements, N inverters and $2N$ adders
- Sum of the autocorrelations results in unique main peak without side-lobe
- Golay codes can carry 2-bit (4-state) information by using +***a***, -***a***, +***b***, and –***b***



Sum of autocorrelations of ***a*** and ***b***



Configuration of matched filter for Golay codes

128 length Golay code:

- D = [64 32 8 2 16 1 4]
- W = [1 1 1 1 1 1 1]

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Golay code of length 128

a

$a_0\ a_1\ a_2\ a_3\ a_4\ a_5\ a_6\ a_7\ \dots\ a_{124}\ a_{125}\ a_{126}\ a_{127}$

Element of Golay code ***a***	Value	Element of Golay code ***a***	Value	Element of Golay code ***a***	Value	Element of Golay code ***a***	Value
a_{0}	1	a_{32}	1	a_{64}	1	a_{96}	-1
a_{1}	1	a_{33}	1	a_{65}	1	a_{97}	-1
a_{2}	1	a_{34}	1	a_{66}	1	a_{98}	-1
a_{3}	1	a_{35}	1	a_{67}	1	a_{99}	-1
a_{4}	1	a_{36}	1	a_{68}	1	a_{100}	-1
a_{5}	-1	a_{37}	-1	a_{69}	-1	a_{101}	1
a_{6}	1	a_{38}	1	a_{70}	1	a_{102}	-1
a_{7}	-1	a_{39}	-1	a_{71}	-1	a_{103}	1
a_{8}	1	a_{40}	-1	a_{72}	1	a_{104}	1
a_{9}	1	a_{41}	-1	a_{73}	1	a_{105}	1
a_{10}	-1	a_{42}	1	a_{74}	-1	a_{106}	-1
a_{11}	-1	a_{43}	1	a_{75}	-1	a_{107}	-1
a_{12}	1	a_{44}	-1	a_{76}	1	a_{108}	1
a_{13}	-1	a_{45}	1	a_{77}	-1	a_{109}	-1
a_{14}	-1	a_{46}	1	a_{78}	-1	a_{110}	-1
a_{15}	1	a_{47}	-1	a_{79}	1	a_{111}	1
a_{16}	1	a_{48}	1	a_{80}	1	a_{112}	-1
a_{17}	-1	a_{49}	-1	a_{81}	-1	a_{113}	1
a_{18}	-1	a_{50}	-1	a_{82}	-1	a_{114}	1
a_{19}	1	a_{51}	1	a_{83}	1	a_{115}	-1
a_{20}	1	a_{52}	1	a_{84}	1	a_{116}	-1
a_{21}	1	a_{53}	1	a_{85}	1	a_{117}	-1
a_{22}	-1	a_{54}	-1	a_{86}	-1	a_{118}	1
a_{23}	-1	a_{55}	-1	a_{87}	-1	a_{119}	1
a_{24}	1	a_{56}	-1	a_{88}	1	a_{120}	1
a_{25}	-1	a_{57}	1	a_{89}	-1	a_{121}	-1
a_{26}	1	a_{58}	-1	a_{90}	1	a_{122}	1
a_{27}	-1	a_{59}	1	a_{91}	-1	a_{123}	-1
a_{28}	1	a_{60}	-1	a_{92}	1	a_{124}	1
a_{29}	1	a_{61}	-1	a_{93}	1	a_{125}	1
a_{30}	1	a_{62}	-1	a_{94}	1	a_{126}	1
a_{31}	1	a_{63}	-1	a_{95}	1	a_{127}	1

b

$b_0\ b_1\ b_2\ b_3\ b_4\ b_5\ b_6\ b_7\ \dots\ b_{124}\ b_{125}\ b_{126}\ b_{127}$

Element of Golay code ***b***	Value	Element of Golay code ***b***	Value	Element of Golay code ***b***	Value	Element of Golay code ***b***	Value
b_{0}	1	b_{32}	1	b_{64}	1	b_{96}	-1
b_{1}	1	b_{33}	1	b_{65}	1	b_{97}	-1
b_{2}	1	b_{34}	1	b_{66}	1	b_{98}	-1
b_{3}	1	b_{35}	1	b_{67}	1	b_{99}	-1
b_{4}	-1	b_{36}	-1	b_{68}	-1	b_{100}	1
b_{5}	1	b_{37}	1	b_{69}	1	b_{101}	-1
b_{6}	-1	b_{38}	-1	b_{70}	-1	b_{102}	1
b_{7}	1	b_{39}	1	b_{71}	1	b_{103}	-1
b_{8}	1	b_{40}	-1	b_{72}	1	b_{104}	1
b_{9}	1	b_{41}	-1	b_{73}	1	b_{105}	1
b_{10}	-1	b_{42}	1	b_{74}	-1	b_{106}	-1
b_{11}	-1	b_{43}	1	b_{75}	-1	b_{107}	-1
b_{12}	-1	b_{44}	1	b_{76}	-1	b_{108}	-1
b_{13}	1	b_{45}	-1	b_{77}	1	b_{109}	1
b_{14}	1	b_{46}	-1	b_{78}	1	b_{110}	1
b_{15}	-1	b_{47}	1	b_{79}	-1	b_{111}	-1
b_{16}	1	b_{48}	1	b_{80}	1	b_{112}	-1
b_{17}	-1	b_{49}	-1	b_{81}	-1	b_{113}	1
b_{18}	-1	b_{50}	-1	b_{82}	-1	b_{114}	1
b_{19}	1	b_{51}	1	b_{83}	1	b_{115}	-1
b_{20}	-1	b_{52}	-1	b_{84}	-1	b_{116}	1
b_{21}	-1	b_{53}	-1	b_{85}	-1	b_{117}	1
b_{22}	1	b_{54}	1	b_{86}	1	b_{118}	-1
b_{23}	1	b_{55}	1	b_{87}	1	b_{119}	-1
b_{24}	1	b_{56}	-1	b_{88}	1	b_{120}	1
b_{25}	-1	b_{57}	1	b_{89}	-1	b_{121}	-1
b_{26}	1	b_{58}	-1	b_{90}	1	b_{122}	1
b_{27}	-1	b_{59}	1	b_{91}	-1	b_{123}	-1
b_{28}	-1	b_{60}	1	b_{92}	-1	b_{124}	-1
b_{29}	-1	b_{61}	1	b_{93}	-1	b_{125}	-1
b_{30}	-1	b_{62}	1	b_{94}	-1	b_{126}	-1
b_{31}	-1	b_{63}	1	b_{95}	-1	b_{127}	-1

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Basic configuration to generate FEC encoded PLCP header for RS, LDPC encoded payload

PHY Header

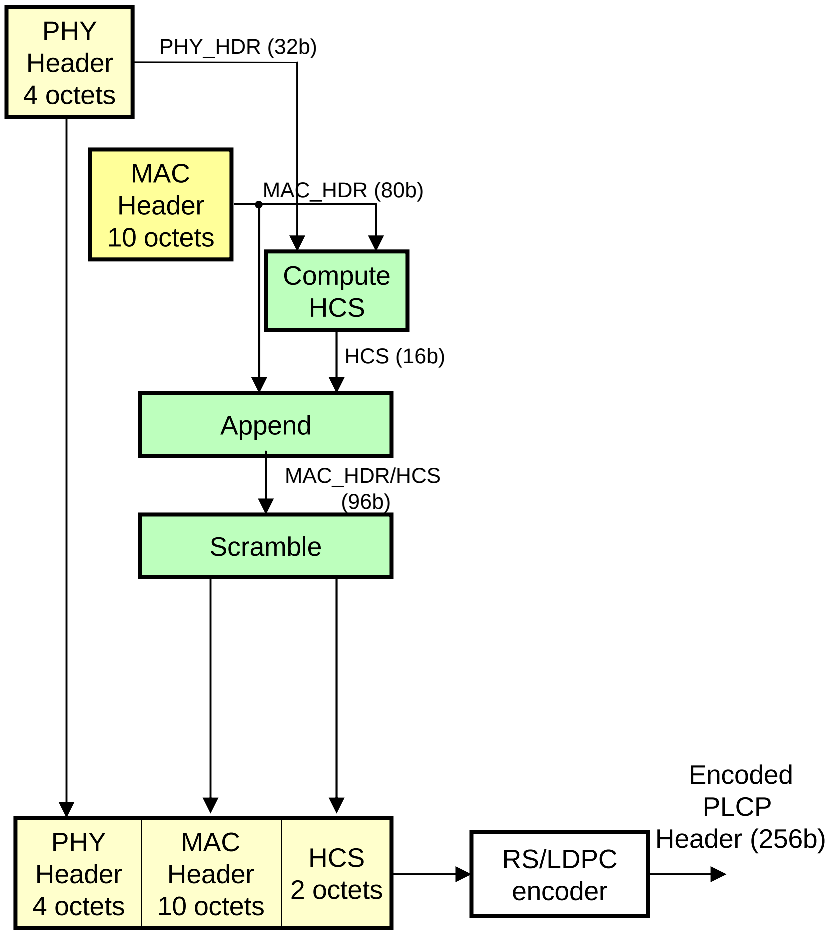
0~65535 byte

R E S	RATE (5 bits)	LENGTH (16 bits)	CP LEN	SCR 2b	R E S	BURST MODE
R 0:2	R1…R5 3:7	LSB to MSB 8:23	CL 24:25	S1:S2 26:27	R 28:30	BM 31

BM	Next Packet Status
1	Next packet is not part of burst
0	Next packet is part of burst

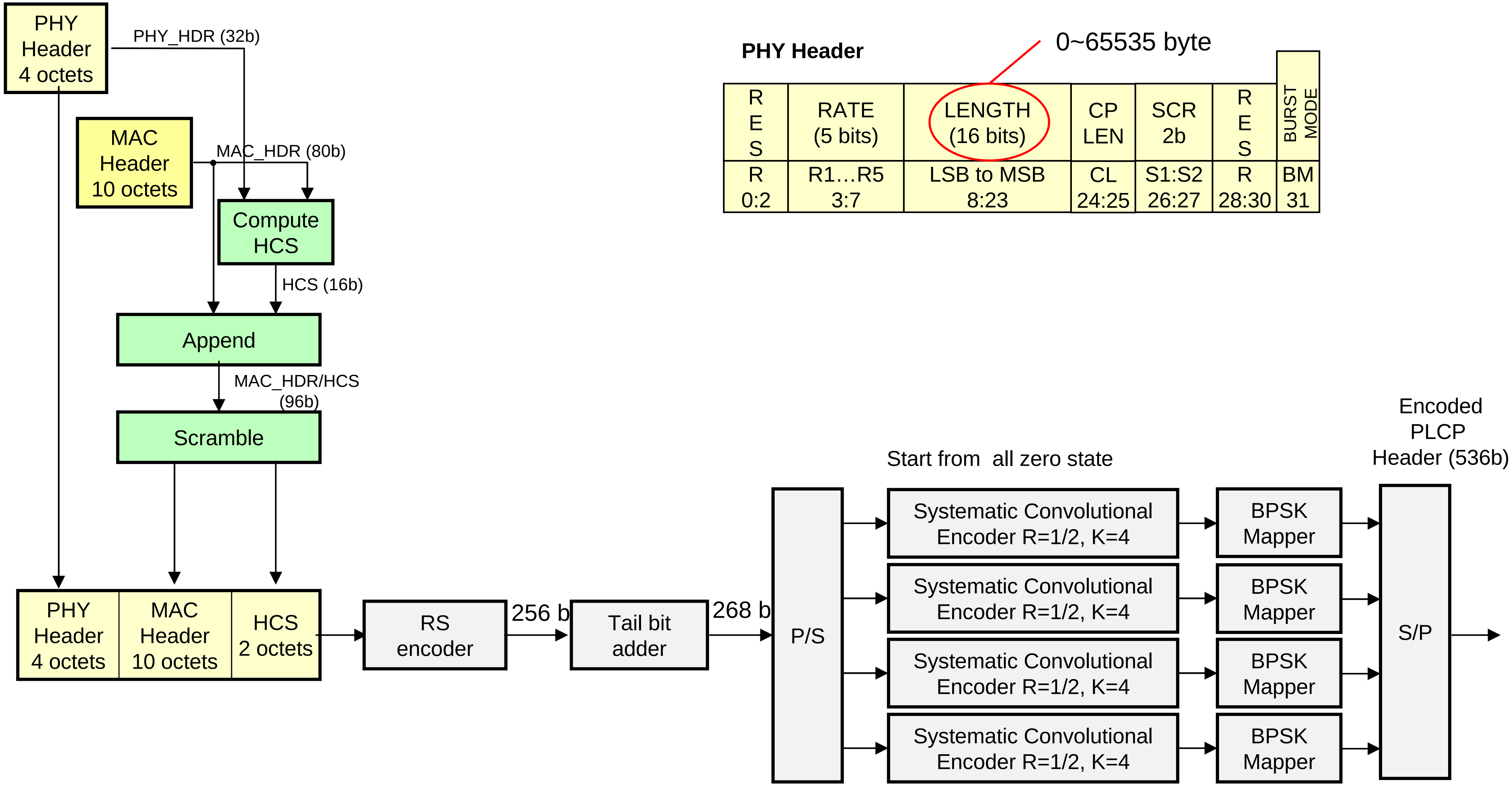
CL	Next Packet CP length
00	0
01	TBD
10	64
11	128

Data Rate Mode	R1-R5
1.1	00000
1.2.1	00001
1.2.2	00010
1.3	00011
1.4	00100
2.1	00101
2.2.1	00110
2.2.2	00111
2.2.3	01000
2.3	01001
2.4	01010
3.1	01011
3.2	01100
4.1	01101
4.2	01110



to “Contents”

Basic configuration to generate FEC encoded PLCP header for concatenation of RS, and systematic convolutional coding encoded payload



PHY Header

RES	RATE (5 bits)	LENGTH (16 bits)	CP LEN	SCR 2b	RES	BURST MODE
R 0:2	R1…R5 3:7	LSB to MSB 8:23	CL 24:25	S1:S2 26:27	R 28:30	BM 31

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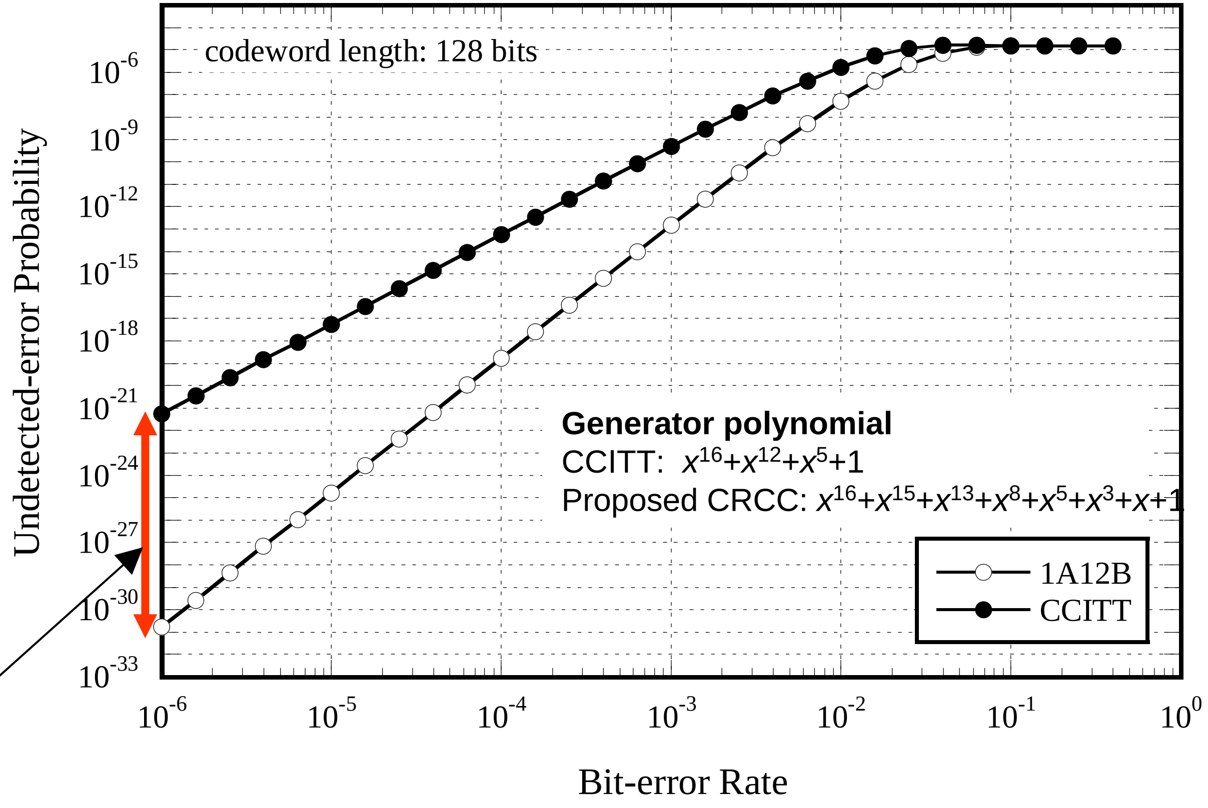
A Cyclic-redundancy-check code (1A12B) proposed for HCS



Generator polynomial

CCITT: $x^{16}+x^{12}+x^5+1$

Proposed CRCC: $x^{16}+x^{15}+x^{13}+x^8+x^5+x^3+x+1$

Excellent performance improvement for low bit error rate

Undetected-error probabilities as a function of bit-error rate for a codeword length of 128 bits

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4. MAC protocol

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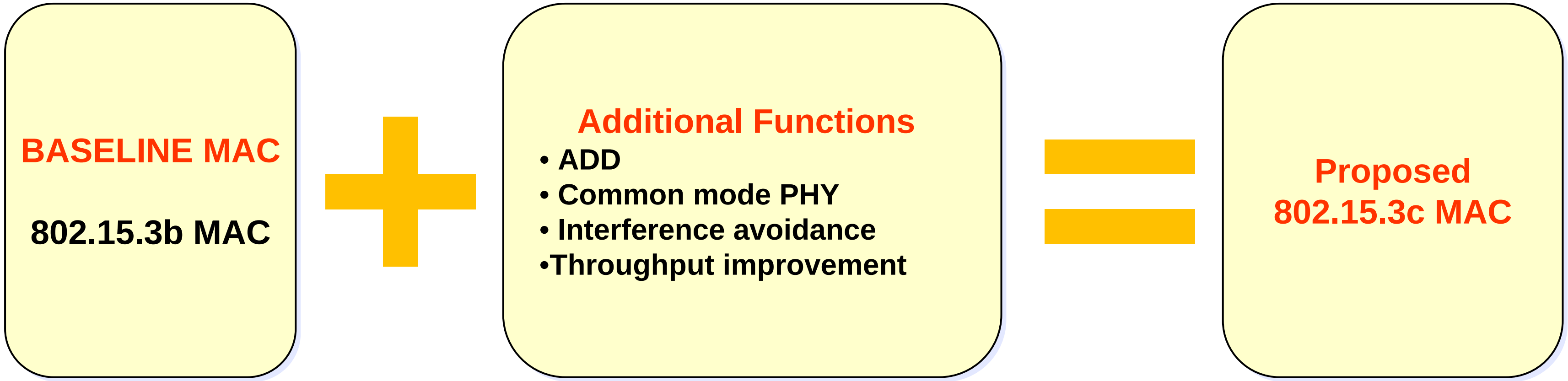
Summary of MAC protocol supplement

- Baseline MAC
  - 802.15.3b
- Additional MAC functions
  - Automatic device discovery (ADD)
  - Supporting common mode PHY(*)
  - Interference avoidance
  - Throughput improvement



BASELINE MAC

802.15.3b MAC

Additional Functions

- **ADD**
- **Common mode PHY**
- **Interference avoidance**
- **Throughput improvement**

Proposed 802.15.3c MAC

(*) See Sec. 5

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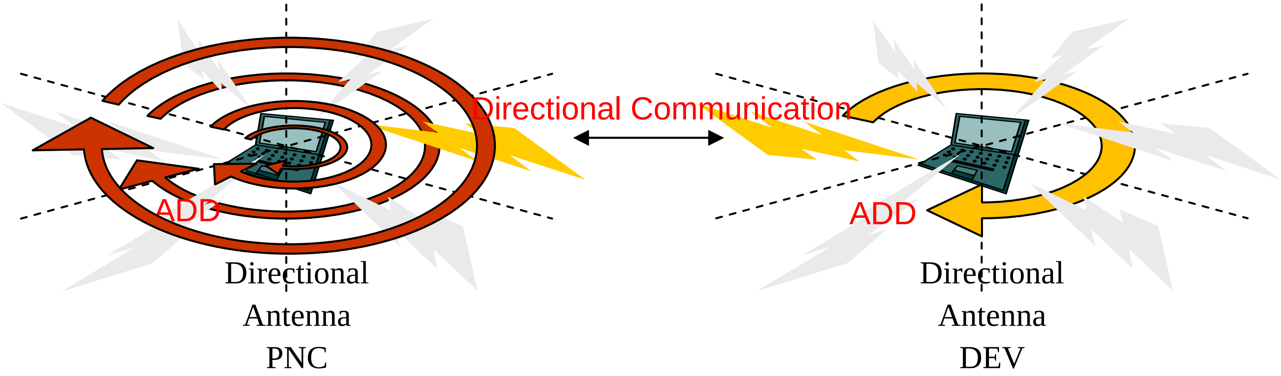
ADD for directional antenna device is required on TG3c alternate PHY

- The considered Automatic Device Discovery has following features
  - Device discovery process is carried out by using directional antenna and employing ‘sequential beaconing and scanning procedure’ in all directions
  - Fast-rotating beaconing PNC, and slow-rotating scanning DEV are assumed considering DEV burden reduction
  - ADD routine is periodically activated even after DEV association, which enables a new DEV association and recovery from failed matching of antenna directivity



(Automatic device discovery for directional antenna devices)

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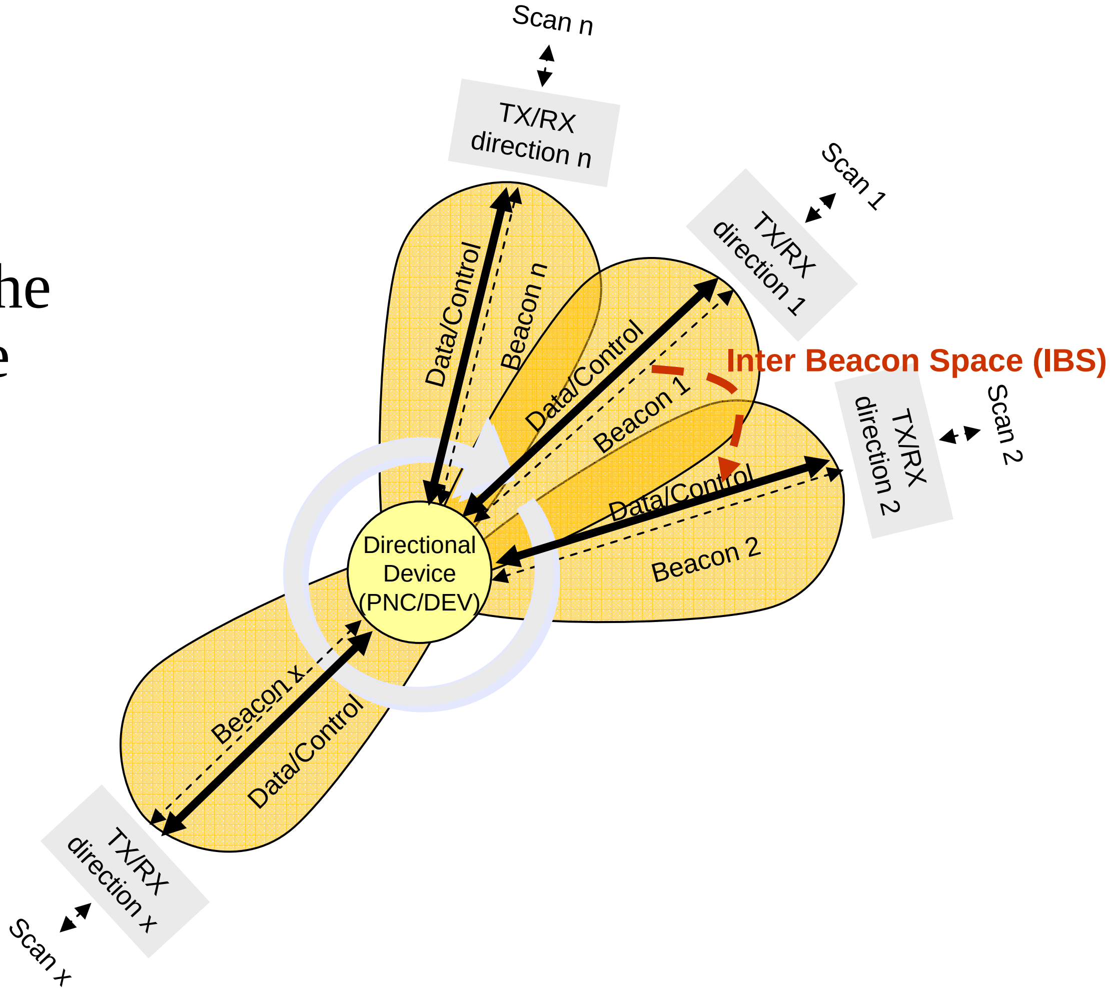
How directional antenna devices work ?

- *n* TX/RX directions are supported
- Inter Beacon Space (IBS)
  - time from the end of the previous beacon frame to the start of the next beacon frame



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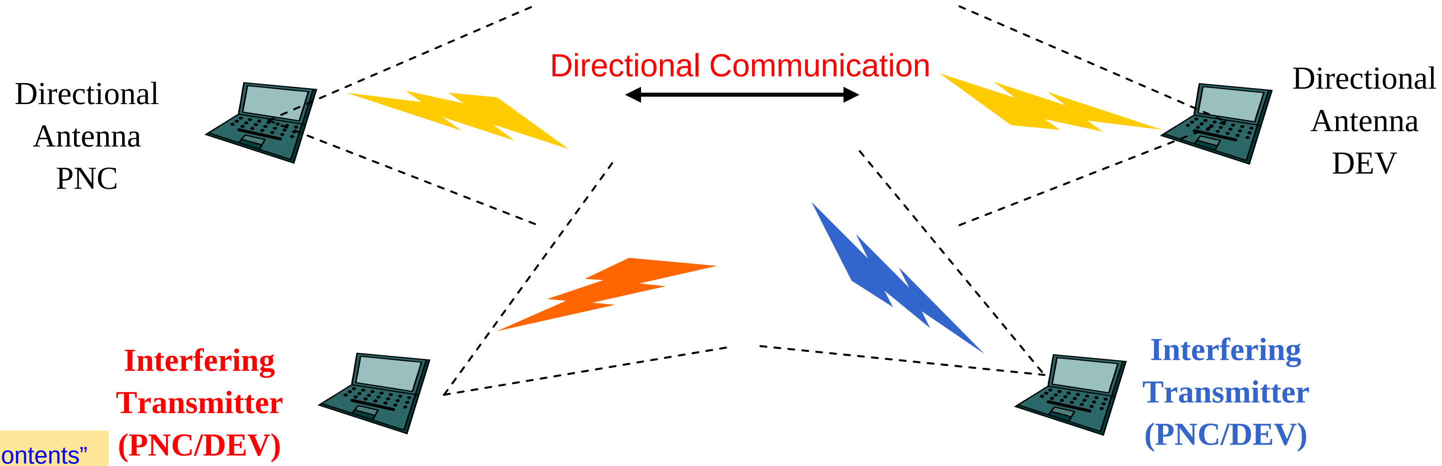
Interference avoidance

- New DEV or PNC may interfere with existing directional communications. Connection Admission Control (CAC) is necessary to avoid interference
- A new Information Element (IE) should be re-assigned for some specific DEVs not to associate with the existing PNC



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Throughput improvement

- To achieve higher throughput and improve MAC efficiency, frame aggregation or frame extension is necessary in TG3c alternate PHY
- The extension of the length of 12 bit to 16 bit is proposed to realize frame aggregation or frame size extension for higher throughput efficiency
- Reasons
  - The conventional 802.15 MAC protocols were not enough to achieve high throughput due to limited frame size (defined by up to 12 bit, 2048 byte)

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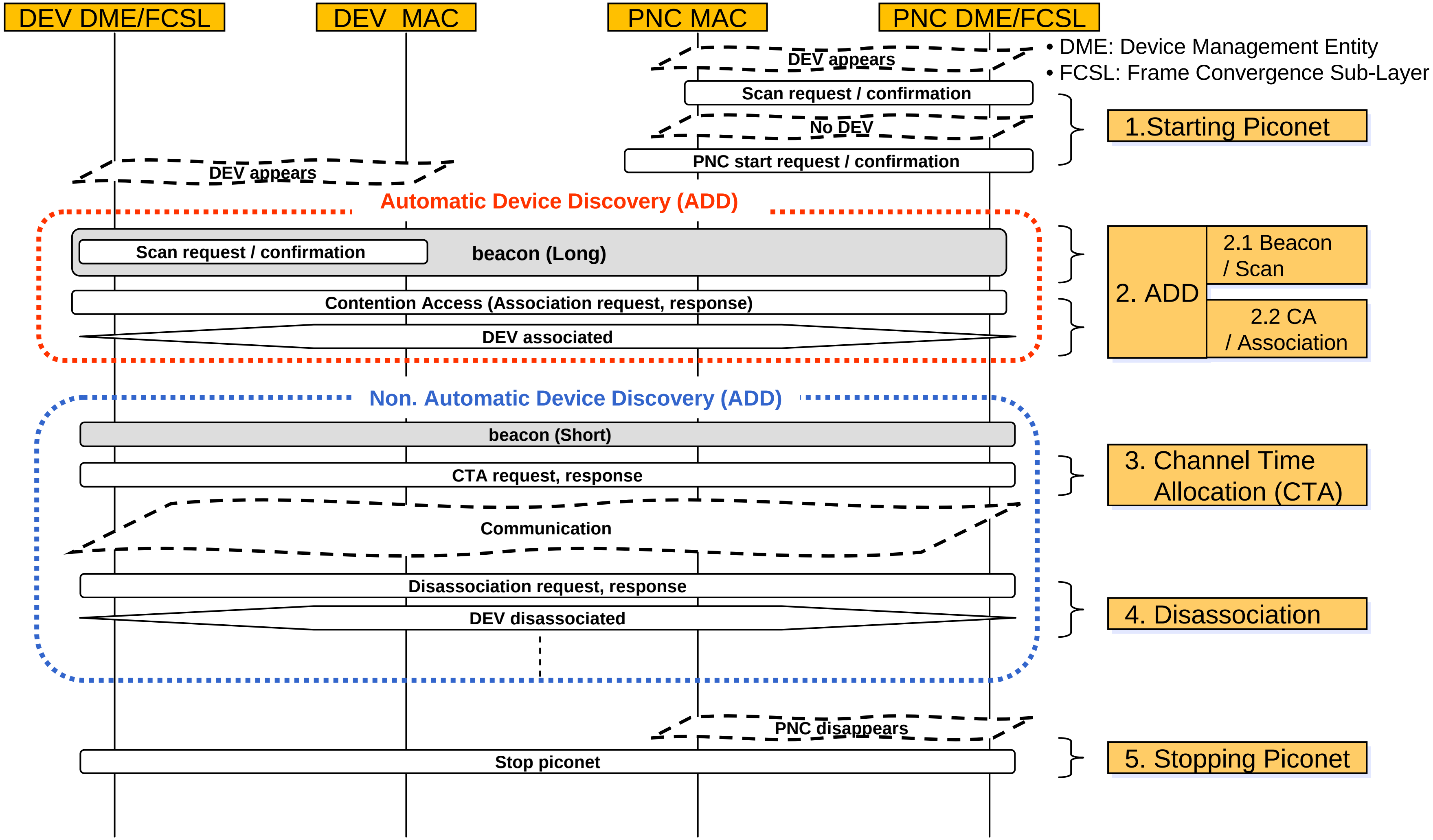
Basic Operation Flow



- DME: Device Management Entity
- FCSL: Frame Convergence Sub-Layer

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Basic Operation

1. Starting piconet

- DEV searches an active piconet using passive scanning for a period of time
- If no desired/connectable piconets are found and DEV is capable of PNC operation, it starts a piconet using an unoccupied channel

2. Automatic device discovery (ADD)

- When PNC initiates a piconet, automatic device discovery starts
- ADD interval
  - Automatic device discovery procedure is periodically performed to allow DEVs to join the piconet (ADD interval)

2.1 Beacon/Scan

- PNC transmits beacon frames to all TX/RX directions
- DEVs detect the beacon frames by scanning in all directions

2.2 Contention Access (CA)/Association

- When unassociated DEV receives a beacon frame, DEV's association process starts

3. Channel time allocation (CTA)

- When DEV wants to send a stream, DEV requests desired channel time to PNC
- PNC allocates the reserved time for the stream, and directional communication starts

4. Disassociation

- When DEV or PNC wants to drop out from a piconet or ATP (association time period) expires, disassociation process starts

5. Stopping piconet

- When PNC drops out, piconet is stopped.

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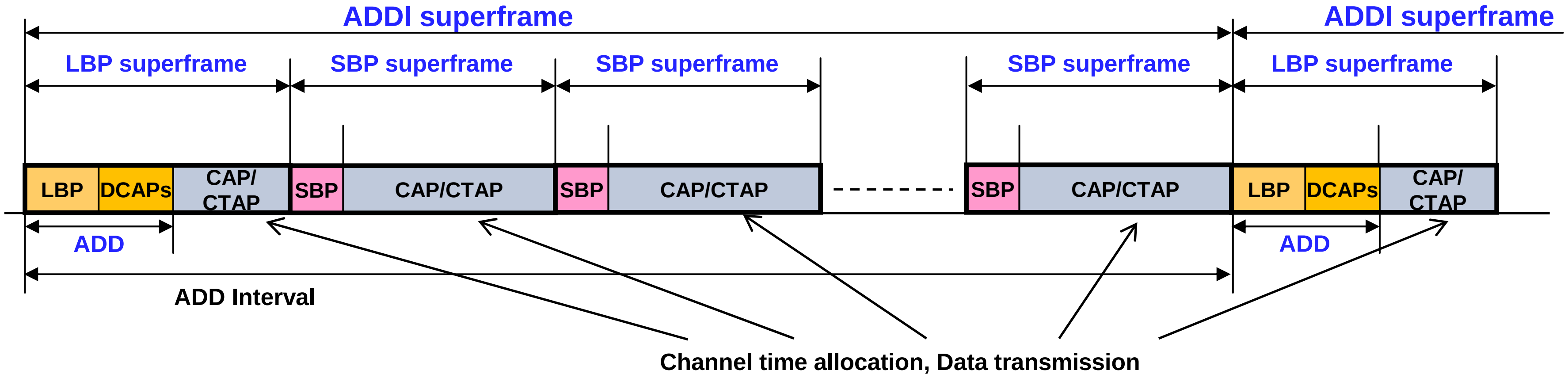
Three Superframes are defined and employed

- Three superframes are defined
  - ADDI (ADD interval) superframe
    - For ADD interval
    - Consists of one LBP superframe and several SBP superframes
  - LBP (Long Beacon Period) superframe
    - For performing ADD
    - For channel time allocation period– LBP+CAP (or MCTA)
    - For data transmission period– CTAP (or CAP)
  - SBP (Short Beacon Period) superframe
    - For non-LBP superframe
    - For channel time allocation period– SBP+CAP (or MCTA)
    - For data transmission period– CTAP (or CAP)



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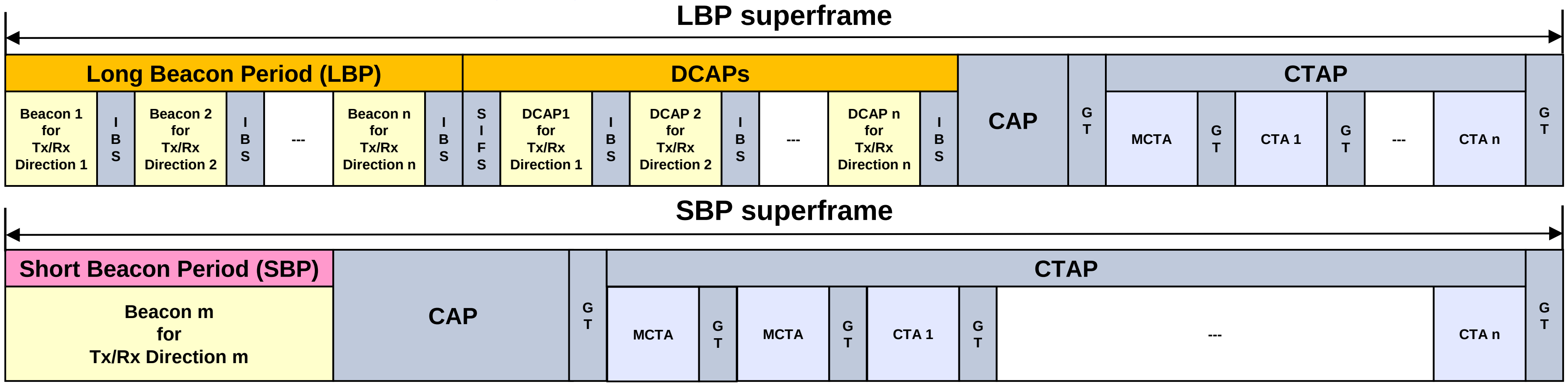
LBP and SBP Superframes

- LBP superframe employs following periods. A DEV detects a beacon from a PNC in its LBP and tries to associate in the directed DCAP, thereby achieves ADDs.
    1. **Long Beacon Period (LBP):** includes several beacon frames that are transmitted sequentially to different directions. LBP is used for automatic device discovery of directional antenna devices as well as SBP usage.
    2. **Directional CAP (DCAPs):** Each of DCAPs is assigned to one of the PNC’s TX/RX directions
    3. **Contention Access Period (CAP):** that is used for automatic device discovery and especially for transmitting command and data frames using contention based access (CSMA/CA) method. CAP can allocate several directional CAPs (DCAPs) for ADD association in case of LBP superframe.
    4. **Channel Time Allocation Period (CTAP):** that consists of channel time allocations (CTAs) and/or management CTAs (MCTAs). Command and data frames are transmitted in CTAs

- SBP superframes employ following periods.
    1. **Short Beacon Period (SBP):** that is used for piconet synchronization and automatic device discovery by transmitting beacon frames from PNC instead of LBP. Two kinds of beacon periods are used as well as for LBP
    2. **Contention Access Period (CAP)**
    3. **Channel Time Allocation Period (CTAP)**



- CAP : Contention Access Period
- DCAP : Directional CAP
- CTAP: Channel Time Allocation Period
- MCTA : Management CTA
- GT : Guard Time
- IBS : Inter Beacon Period
- SIFS : Small Inter Frame Space

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5. Common mode

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Common mode summary

- Common mode offers Easy Expandability: From Single Carrier to OFDM (or other Single Carriers) and vice versa
- CoMPA basically promotes Single Carrier air interface which best fits to short range LOS communications
- Various WPAN applications, however, may require different air interfaces and market will decide the best air-interface for each
- Common mode proposed by CoMPA is to bridge different air interfaces for different applications offering multiple air interfaces fitting best to applications

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Common Mode Proposed for Huge Expandability

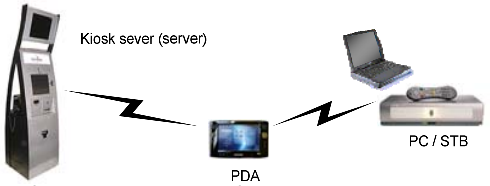
- **Common mode to bridge multiple PHY for various applications - from portable to high end by detecting available PHY through common mode**
- **Single Carrier for Portable applications (UM5) - low power and low cost applications and OFDM for high end applications**

I. With the same channel plan: **Huge expandability**

: OWN MODE and EXPANDED MODE from other parties – no need to give up emerging market

i. SC but different modulation and/or FEC – different bit rates

: “common mode” will give the opportunity to expand SC air interfaces EASILY if there is market



ii. OFDM

: “common mode” will give the opportunity to expand air interfaces to SC from OFDM EASILY if there is market

II. With different channel plans

Power detection for interference avoidance

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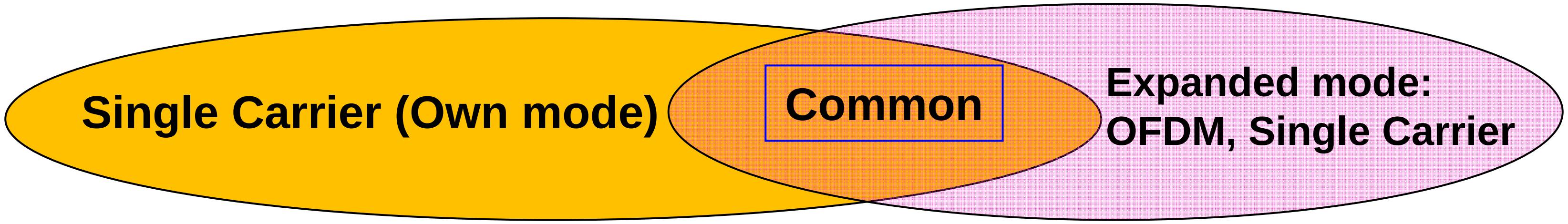
Easy Expandability: From Single Carrier to OFDM and vice versa

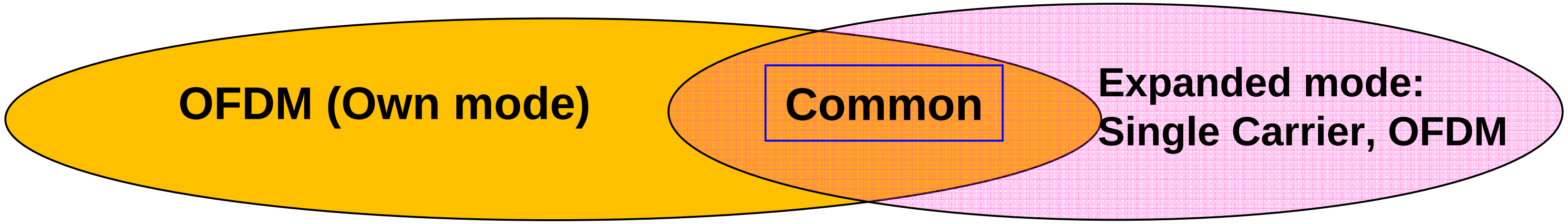


Single Carrier (Own mode)

Common

Expanded mode:
OFDM, Single Carrier

Expansion from Single Carrier to OFDM or Single Carrier



OFDM (Own mode)

Common

Expanded mode:
Single Carrier, OFDM

Expansion from OFDM to Single Carrier or OFDM

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6. Items to be reported for PHY

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6.1: Mean 90% PER and BER link success probability versus E_b/N_0 for each data rate mode (1st item to be reported for PHY)

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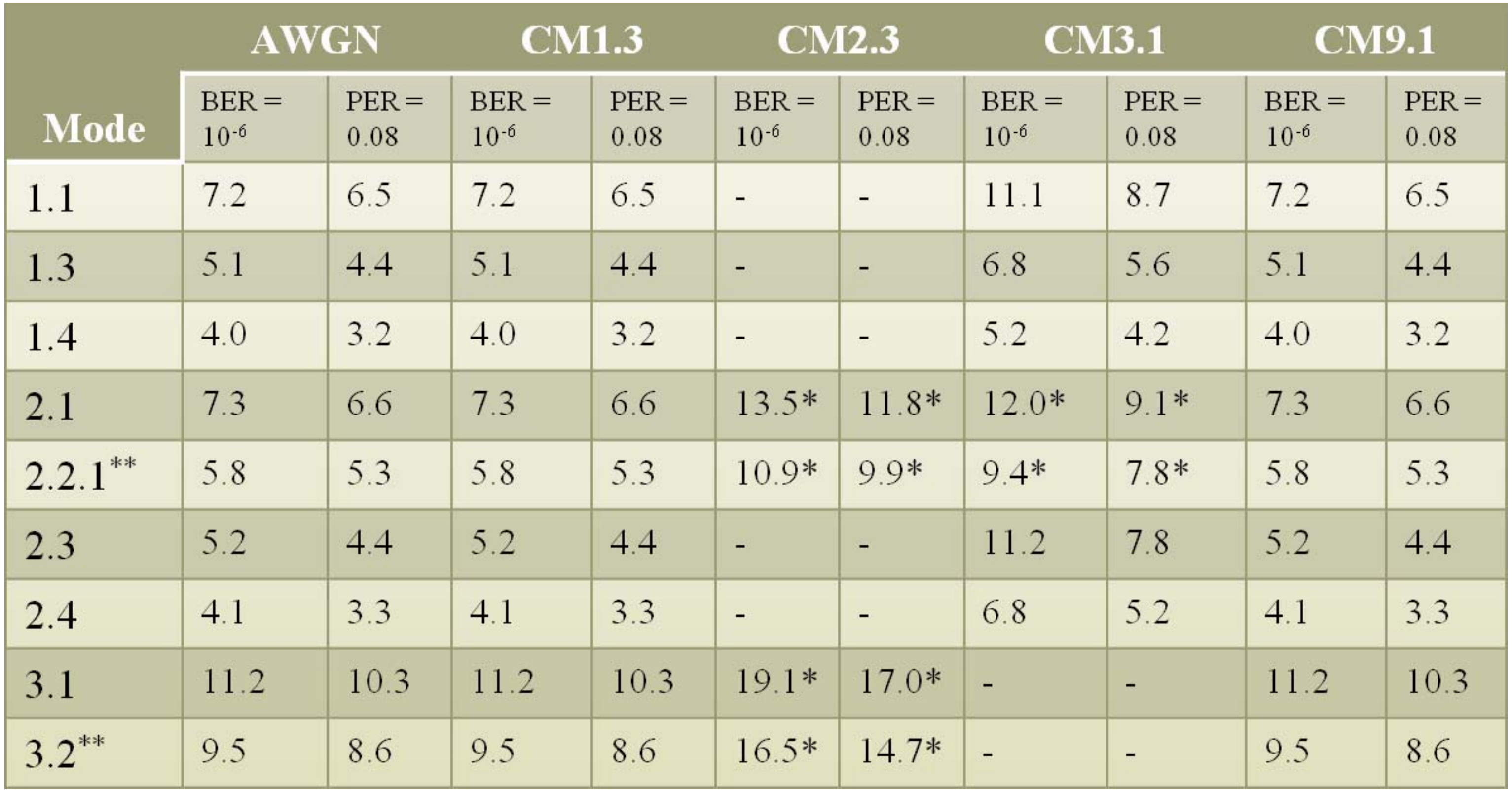
Summary of required Eb/No for each data-rate mode to obtain BER of 10^{-6} or PER of 0.08



Mode	AWGN		CM1.3		CM2.3		CM3.1		CM9.1	
	BER = 10^{-6}	PER = 0.08	BER = 10^{-6}	PER = 0.08	BER = 10^{-6}	PER = 0.08	BER = 10^{-6}	PER = 0.08	BER = 10^{-6}	PER = 0.08
1.1	7.2	6.5	7.2	6.5	-	-	11.1	8.7	7.2	6.5
1.3	5.1	4.4	5.1	4.4	-	-	6.8	5.6	5.1	4.4
1.4	4.0	3.2	4.0	3.2	-	-	5.2	4.2	4.0	3.2
2.1	7.3	6.6	7.3	6.6	13.5*	11.8*	12.0*	9.1*	7.3	6.6
2.2.1**	5.8	5.3	5.8	5.3	10.9*	9.9*	9.4*	7.8*	5.8	5.3
2.3	5.2	4.4	5.2	4.4	-	-	11.2	7.8	5.2	4.4
2.4	4.1	3.3	4.1	3.3	-	-	6.8	5.2	4.1	3.3
3.1	11.2	10.3	11.2	10.3	19.1*	17.0*	-	-	11.2	10.3
3.2**	9.5	8.6	9.5	8.6	16.5*	14.7*	-	-	9.5	8.6

Unit is dB

- ■Both effects of PA non-linearity and Phase-noise are considered
- ■* FDE with CP=128 is used
- ■** Number of iterations for an LDPC decoder is 16

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Summary of Simulation parameters

Parameters	Value
Symbol rate	1664 Msymbol/s
Root raised cosine filter	Roll-off factor = 0.25
Channel model	15-07-0648/r00
Antenna model	Tx and Rx antennas of 30 deg with reference side lobe model with antenna gain of 15.91 dBi (15-06-0474/r00)
Number of channel realizations	100
Power amplifier (PA) model	SiGe BiCMOS model with Output back off (OBO)= 3 dB (15-06-0477/r01)
Phase noise (PN) model	Pole frequency f_p =1 MHz, Zero frequency f_z= 100 MHz, PSD(0)=-93 dBc/Hz@1MHz (15-06-0477/r01)
Payload size	2052 byte (Data payload:2048 byte + FCS:4byte)
Frame and timing synchronization:	Perfect
Others	Sum of the whole received signals is the signal power to set E_b in each channel realization Number of iterations for an LDPC decoder: 16

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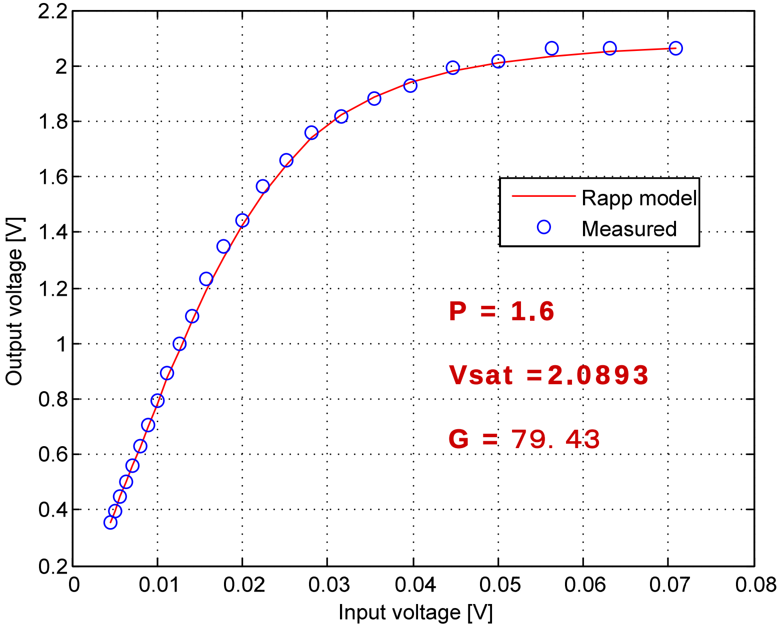
Power amplifier（PA) model

AM/AM distortion model

$$F_{AM-AM}(V_{out}) = \frac{GV_{in}}{\left(1+\left(\frac{GV_{in}}{V_{sat}}\right)^{2p}\right)^{\frac{1}{2p}}}$$



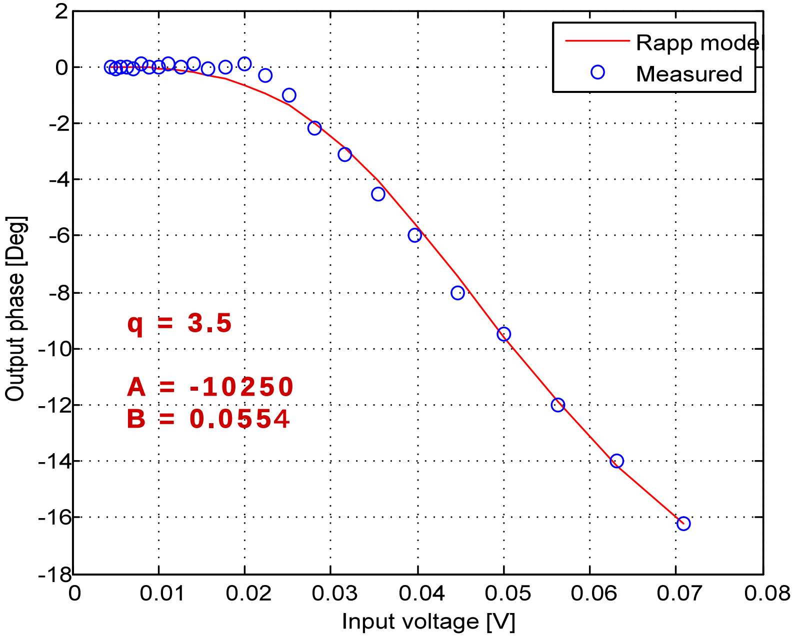
P = 1.6

Vsat =2.0893

G = 79. 43

AM/PM distortion model

$$F_{AM-PM}(\theta) = \frac{Ax^{q}}{\left(1+\left(\frac{x}{B}\right)^{q}\right)}$$



q = 3.5

A = -10250

B = 0.0554

Parameters were obtained by fitting to a Measured BiCMOS PA characteristics

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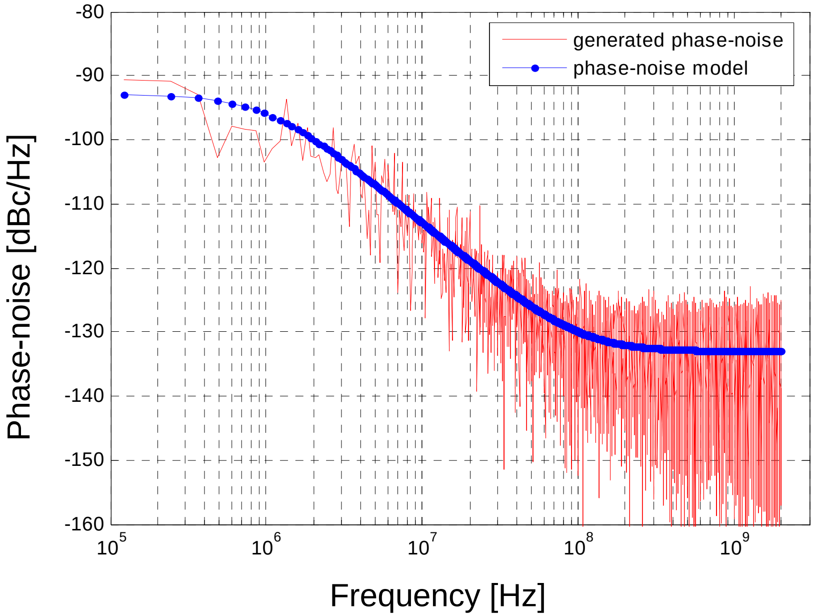
Phase noise (PN) model used



$$PSD(f) = PSD(0)\frac{[1+(f/f_z)^2]}{[1+(f/f_p)^2]}$$

PSD(0) = -93dBc/Hz@1MHz

Pole frequency f_p = 1MHz

Zero frequency f_z = 100MHz

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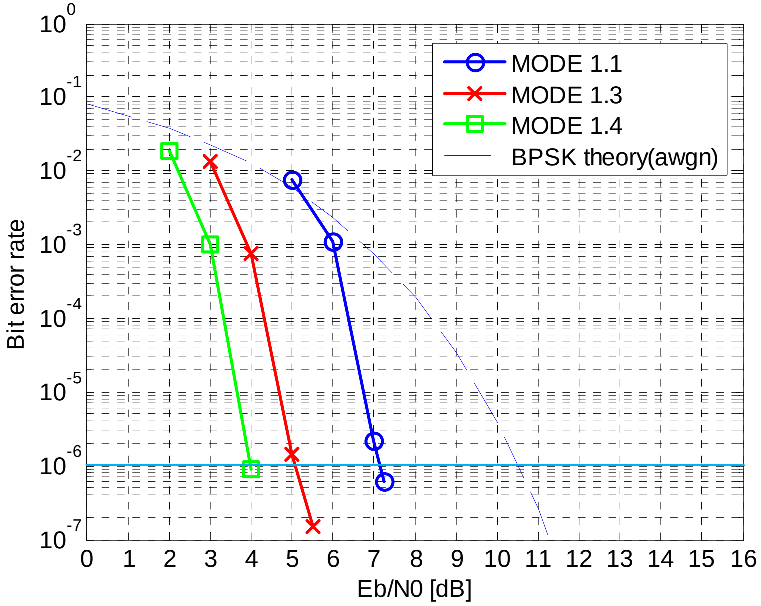
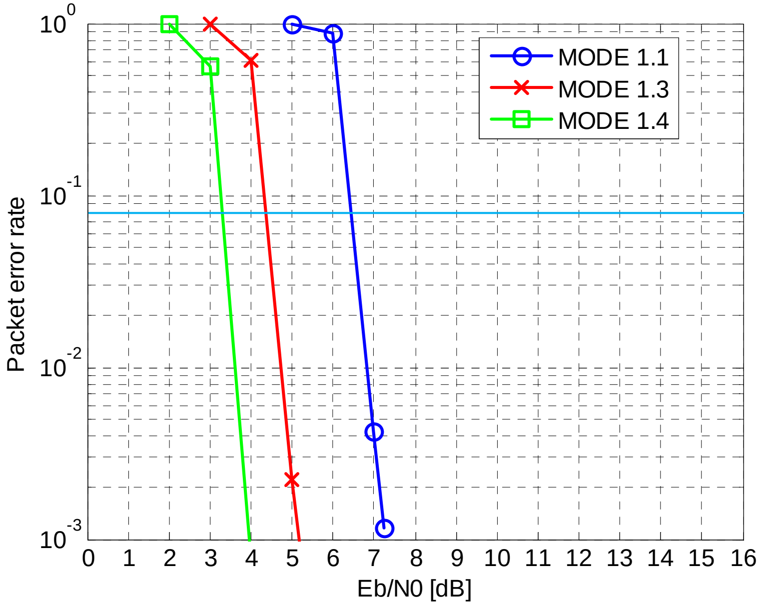
AWGN BPSK (w PA, w PN)

BER



PER



BER=10^{-6}

Mode 1.1: Required E_b/N_o=7.2 [dB]

Mode 1.3: Required E_b/N_o=5.1 [dB]

Mode 1.4: Required E_b/N_o=4.0 [dB]

PER=0.08

Mode 1.1: Required E_b/N_o=6.5 [dB]

Mode 1.3: Required E_b/N_o=4.4 [dB]

Mode 1.4: Required E_b/N_o=3.2 [dB]

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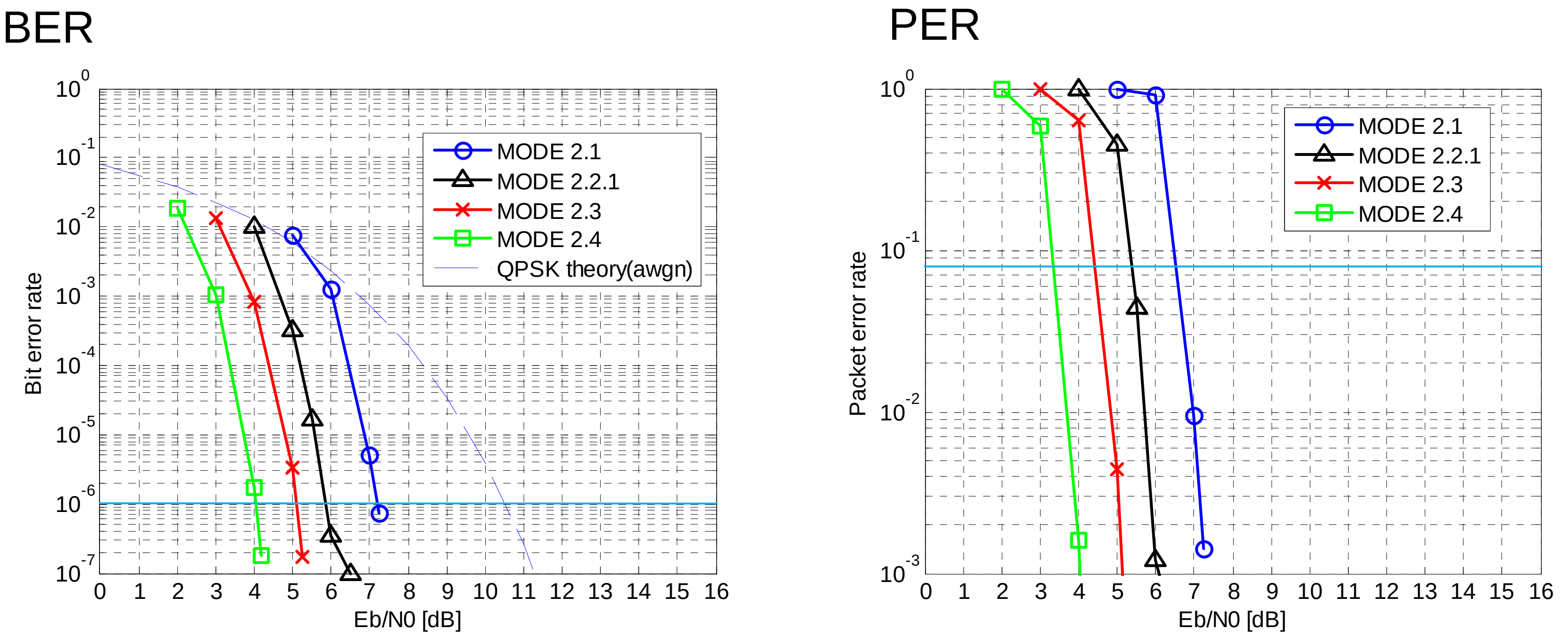
AWGN QPSK (w PA, w PN)



BER=10^{-6}

Mode 2.1 : Required E_b/N_o=7.3 [dB]

Mode 2.2.1: Required E_b/N_o=5.8 [dB]

Mode 2.3 : Required E_b/N_o=5.2 [dB]

Mode 2.4 : Required E_b/N_o=4.1 [dB]

PER=0.08

Mode 2.1 : Required E_b/N_o=6.6 [dB]

Mode 2.2.1: Required E_b/N_o=5.3 [dB]

Mode 2.3 : Required E_b/N_o=4.4 [dB]

Mode 2.4 : Required E_b/N_o=3.3 [dB]

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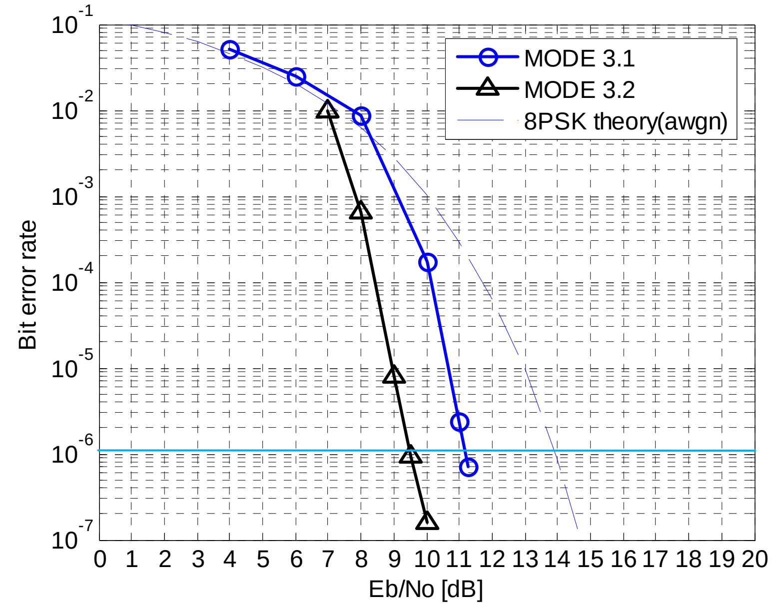
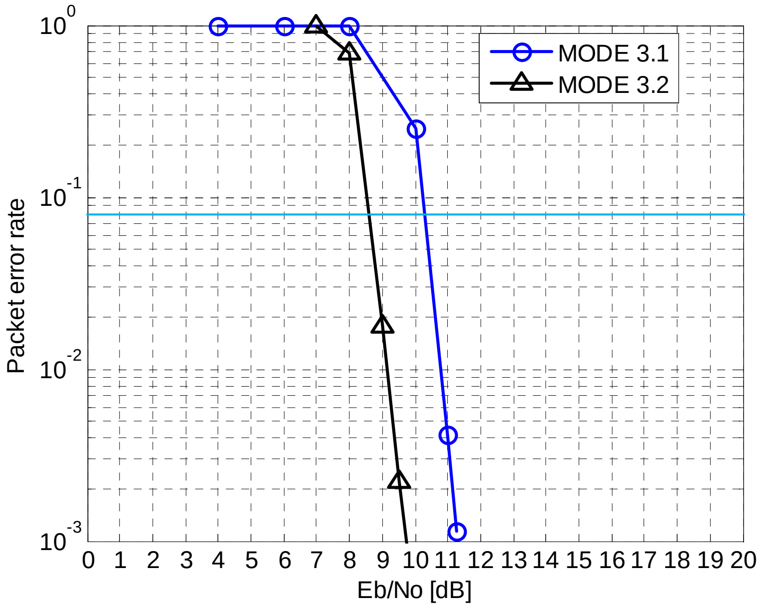
AWGN 8PSK (w PA, w PN)

BER



PER



BER=10^{-6}

Mode 3.1: Required E_b/N_o=11.2 [dB]

Mode 3.2: Required E_b/N_o=9.5 [dB]

PER=0.08

Mode 3.1: Required E_b/N_o=10.3 [dB]

Mode 3.2: Required E_b/N_o=8.6 [dB]

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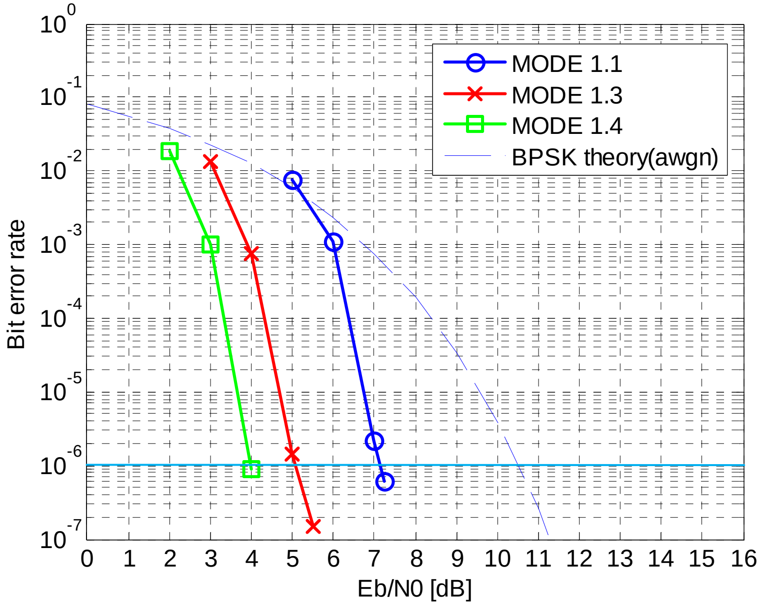
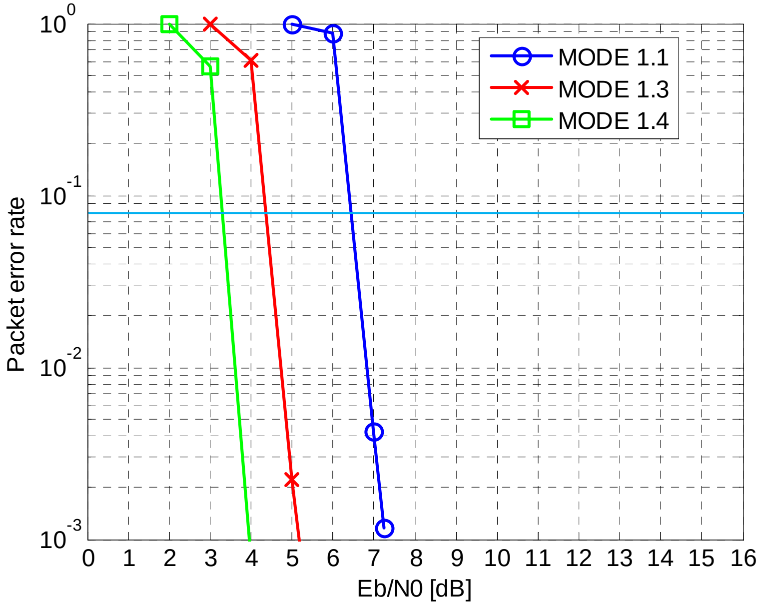
CM1.3 BPSK (w PA, w PN)

BER



PER



BER=10^{-6}

Mode 1.1: Required E_b/N_o=7.2 [dB]

Mode 1.3: Required E_b/N_o=5.1 [dB]

Mode 1.4: Required E_b/N_o=4.0 [dB]

PER=0.08

Mode 1.1: Required E_b/N_o=6.5 [dB]

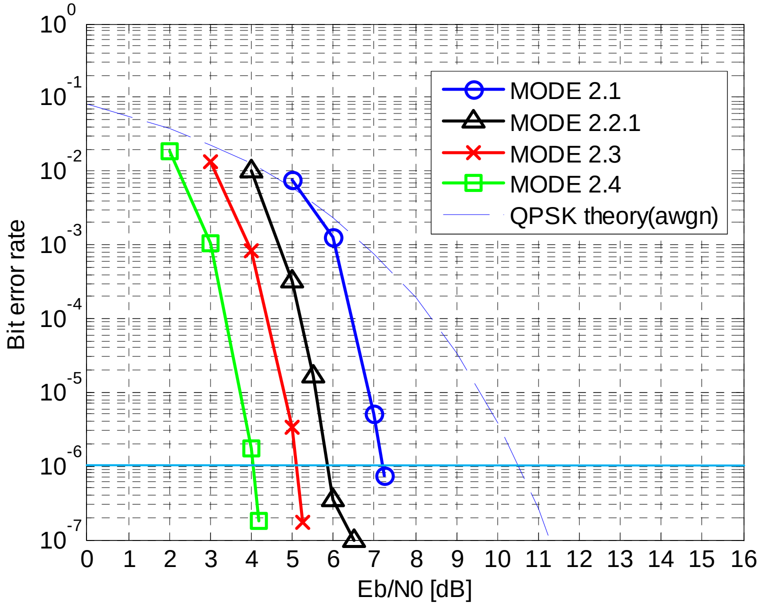
Mode 1.3: Required E_b/N_o=4.4 [dB]

Mode 1.4: Required E_b/N_o=3.2 [dB]

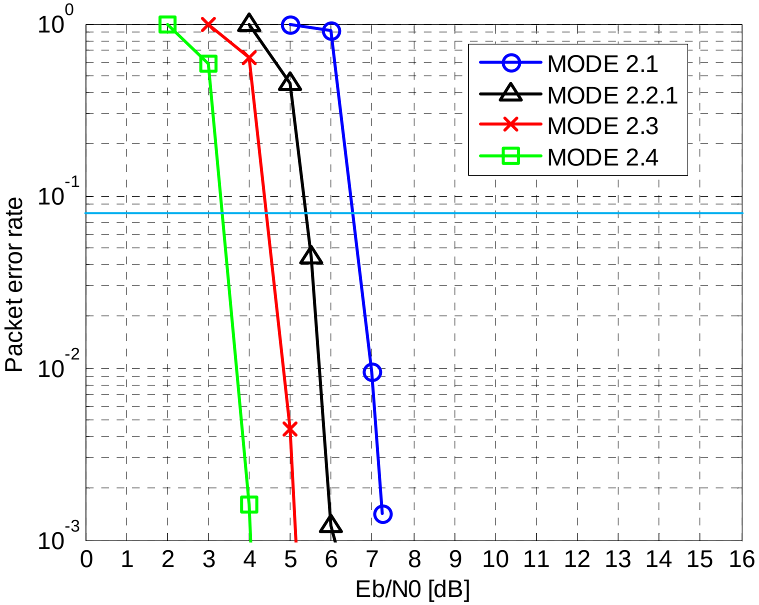
to “Contents”

CM1.3 QPSK (w PA, w PN)

BER



PER



BER=10^{-6}

Mode 2.1 : Required E_b/N_o=7.3 [dB]
Mode 2.2.1: Required E_b/N_o=5.8 [dB]
Mode 2.3 : Required E_b/N_o=5.2 [dB]
Mode 2.4 : Required E_b/N_o=4.1 [dB]

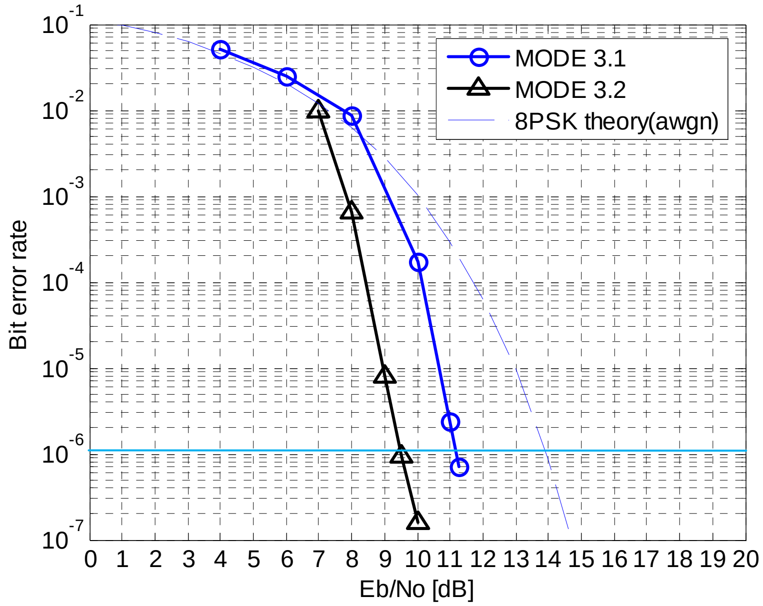
PER=0.08

Mode 2.1 : Required E_b/N_o=6.6 [dB]
Mode 2.2.1: Required E_b/N_o=5.3 [dB]
Mode 2.3 : Required E_b/N_o=4.4 [dB]
Mode 2.4 : Required E_b/N_o=3.3 [dB]

to “Contents”

CM1.3 8PSK (w PA, w PN)

BER



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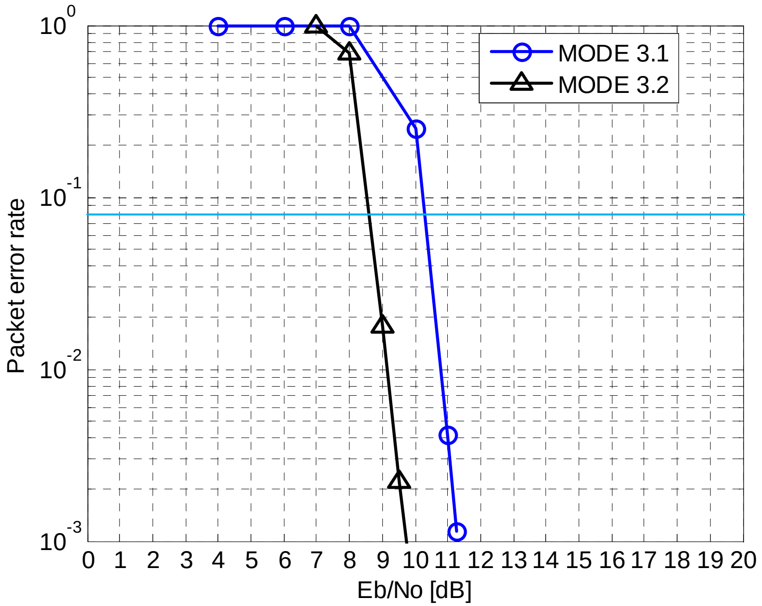


BER=10^{-6}

Mode 3.1: Required E_b/N_o=11.2 [dB]

Mode 3.2: Required E_b/N_o=9.5 [dB]

PER=0.08

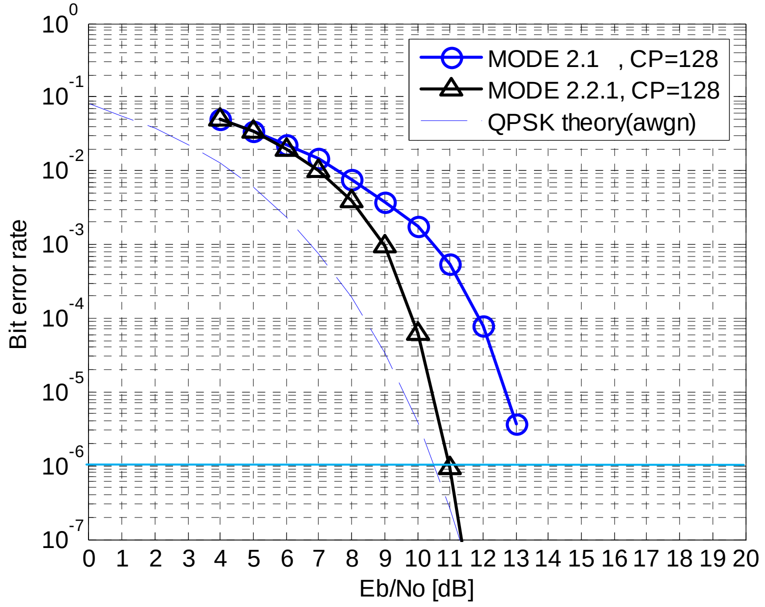
Mode 3.1: Required E_b/N_o=10.3 [dB]

Mode 3.2: Required E_b/N_o=8.6 [dB]

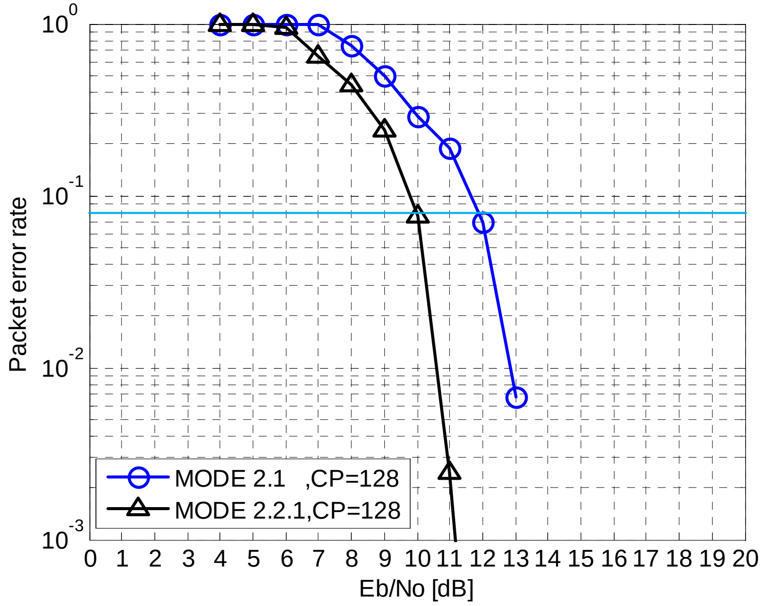
to “Contents”

CM2.3 QPSK (w PA, w PN, w FDE)

BER



PER



BER=10^{-6}

Mode 2.1 : Required E_b/N_o=13.5 [dB]

Mode 2.2.1: Required E_b/N_o=10.9 [dB]

PER=0.08

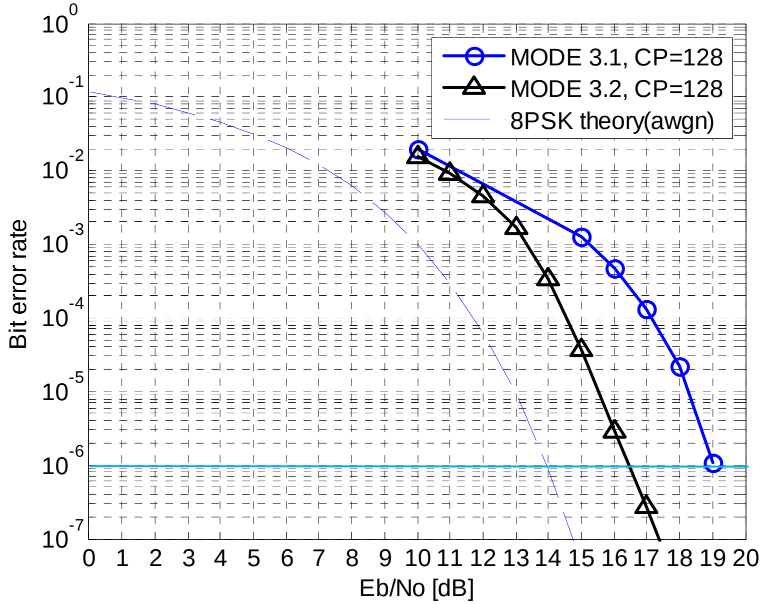
Mode 2.1 : Required E_b/N_o=11.8 [dB]

Mode 2.2.1: Required E_b/N_o=9.9 [dB]

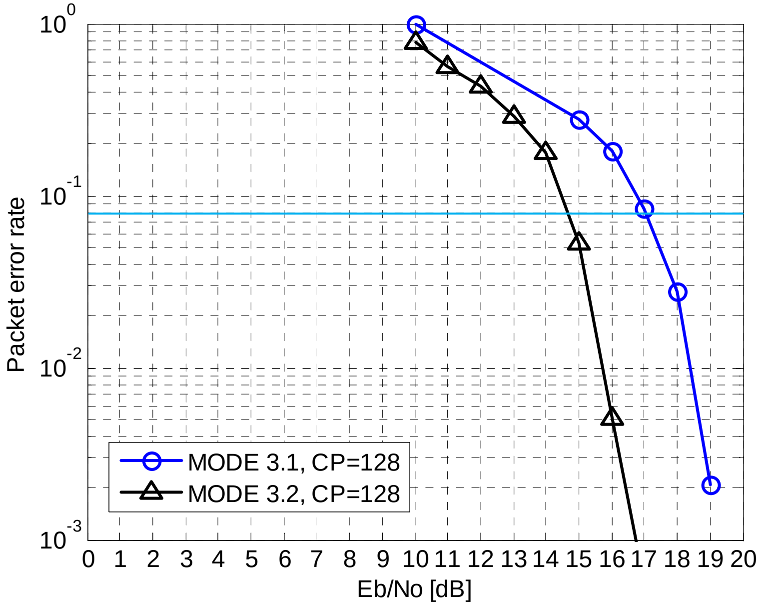
to “Contents”

CM2.3 8PSK (w PA, w PN, w FDE)

BER



PER



BER=10^{-6}

Mode 3.1: Required E_b/N_o = 19.1 [dB]

Mode 3.2: Required E_b/N_o = 16.5 [dB]

PER=0.08

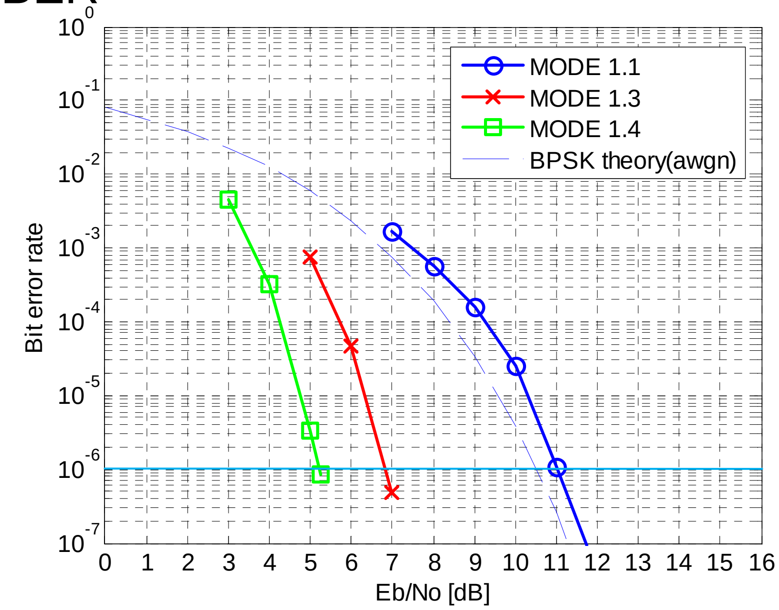
Mode 3.1: Required E_b/N_o= 17.0 [dB]

Mode 3.2: Required E_b/N_o= 14.7 [dB]

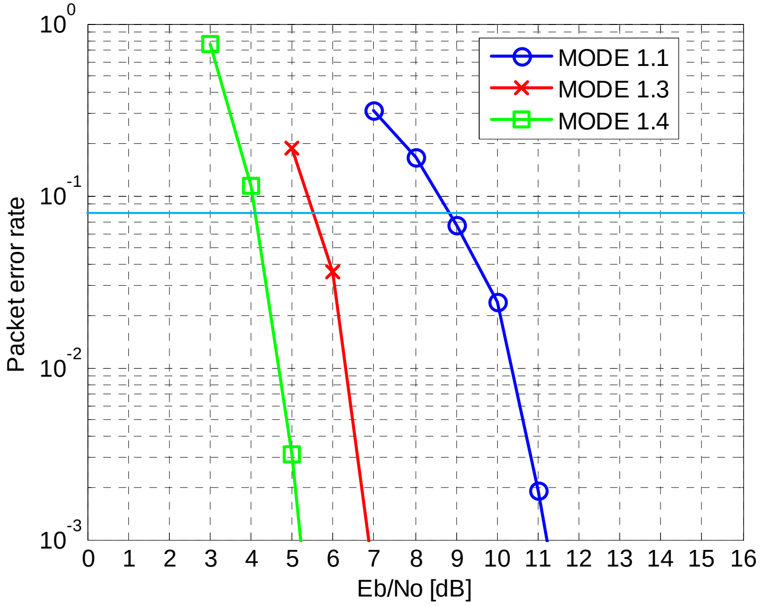
to “Contents”

CM3.1 BPSK (w PA, w PN, w/o FDE)

BER



PER



BER=10^{-6}

Mode 1.1: Required E_b/N_o=11.1 [dB]

Mode 1.3: Required E_b/N_o=6.8 [dB]

Mode 1.4: Required E_b/N_o=5.2 [dB]

PER=0.08

Mode 1.1: Required E_b/N_o=8.7 [dB]

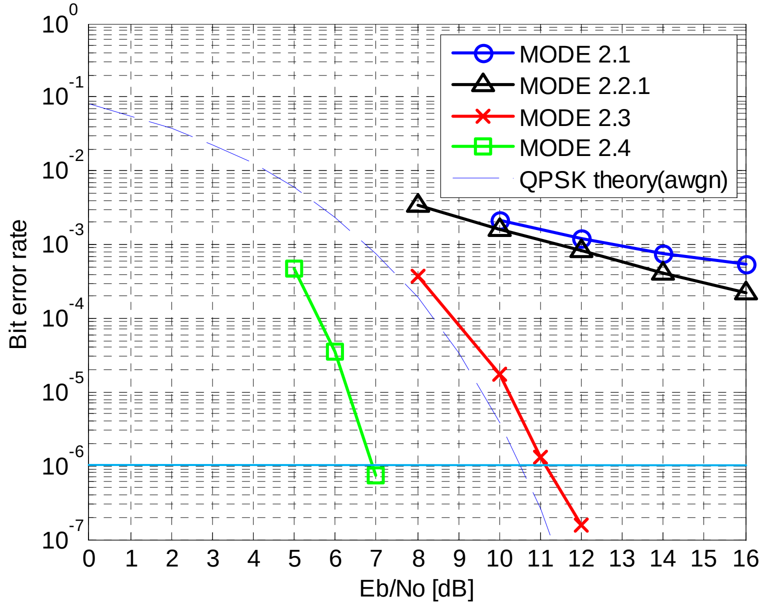
Mode 1.3: Required E_b/N_o=5.6 [dB]

Mode 1.4: Required E_b/N_o=4.2 [dB]

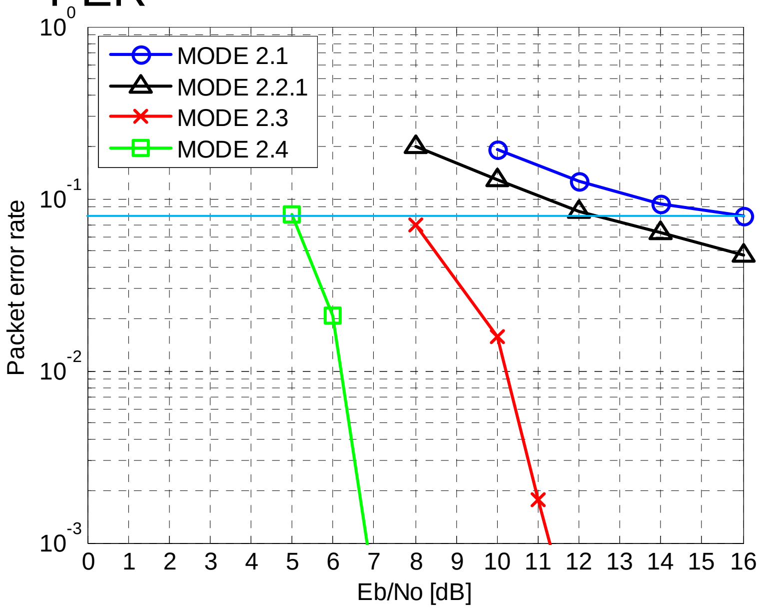
to “Contents”

CM3.1 QPSK (w PA, w PN,w/o FDE)

BER



PER



BER=10^{-6}

Mode 2.1: Out of required performance

Mode 2.2.1: Out of required performance

Mode 2.3: Required E_b/N_o=11.2 [dB]

Mode 2.4: Required E_b/N_o=6.8 [dB]

PER=0.08

Mode 2.1: Required E_b/N_o=16.0 [dB]

Mode 2.2.1: Required E_b/N_o=12.5 [dB]

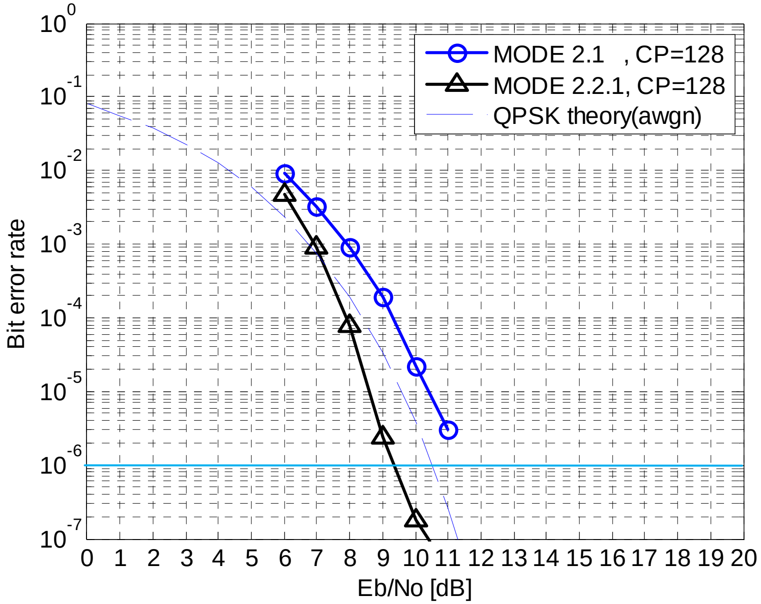
Mode 2.3: Required E_b/N_o=7.8 [dB]

Mode 2.4: Required E_b/N_o=5.2 [dB]

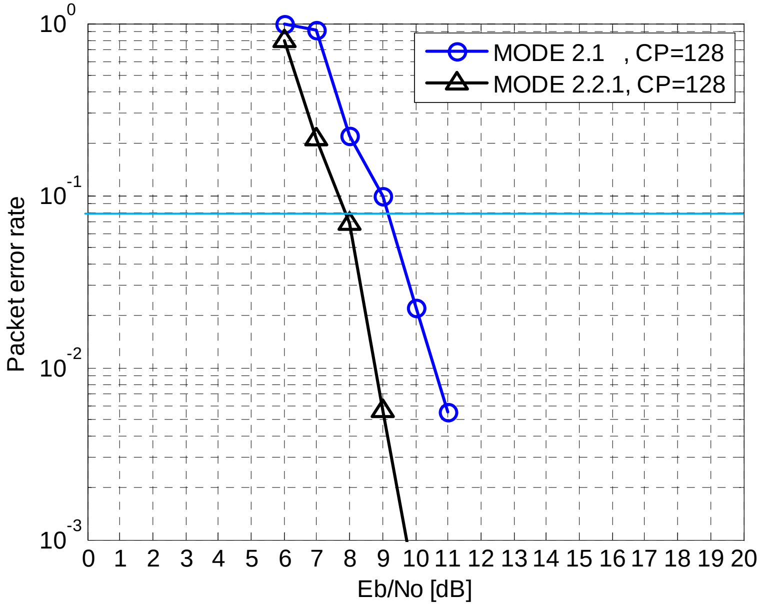
to “Contents”

CM3.1 QPSK (w PA, w PN, w FDE)

BER



PER



BER=10^{-6}

Mode 2.1 : Required E_b/N_o=12.0 [dB]

Mode 2.2.1: Required E_b/N_o=9.4 [dB]

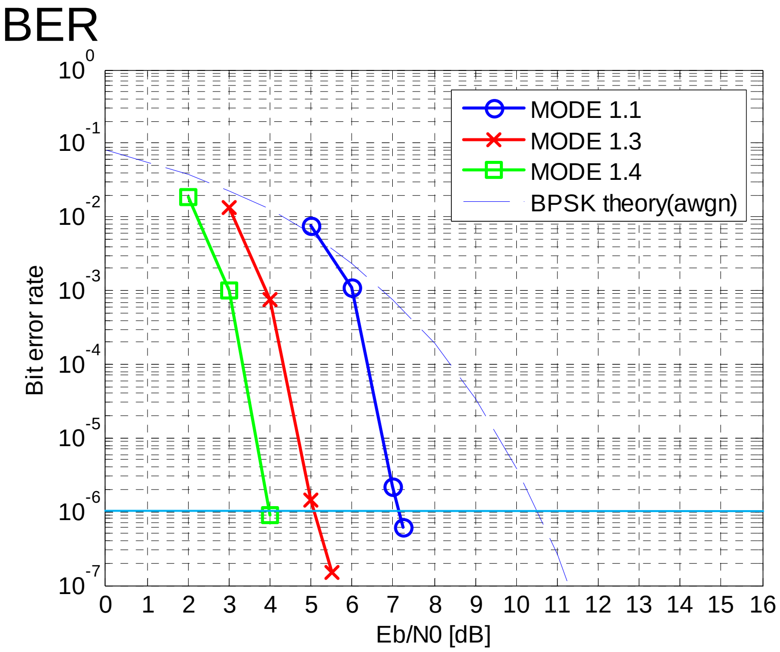
PER=0.08

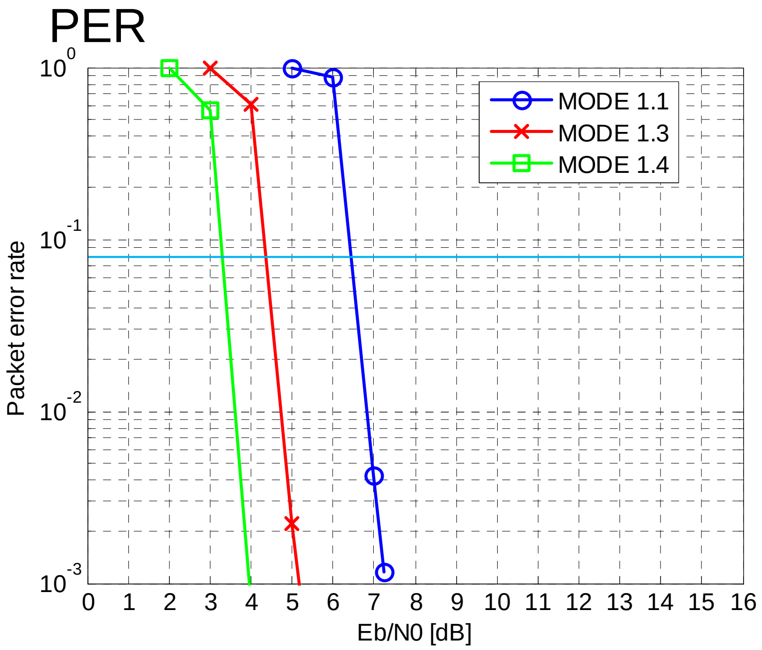
Mode 2.1 : Required E_b/N_o=9.1 [dB]

Mode 2.2.1: Required E_b/N_o=7.8 [dB]

to “Contents”

CM9.1 BPSK (w PA, w PN)





BER=10^{-6}

Mode 1.1: Required E_b/N_o=7.2 [dB]

Mode 1.3: Required E_b/N_o=5.1 [dB]

Mode 1.4: Required E_b/N_o=4.0 [dB]

PER=0.08

Mode 1.1: Required E_b/N_o=6.5 [dB]

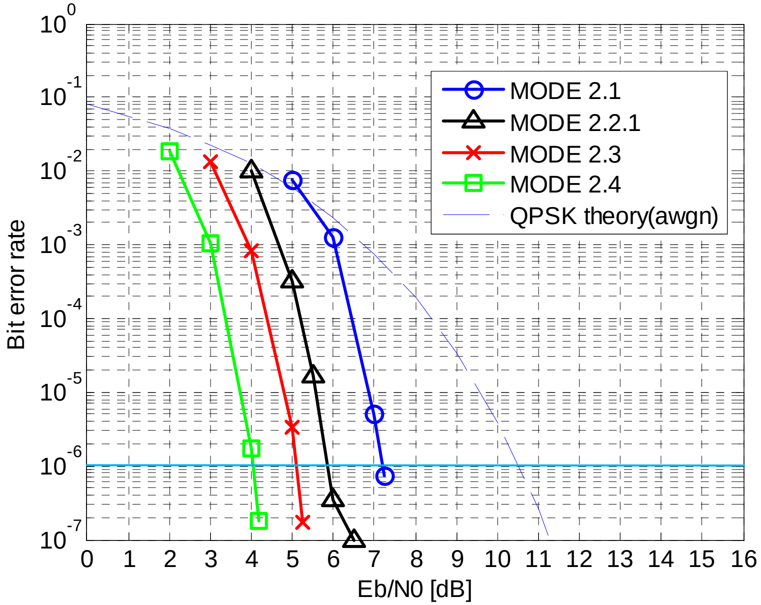
Mode 1.3: Required E_b/N_o=4.4 [dB]

Mode 1.4: Required E_b/N_o=3.2 [dB]

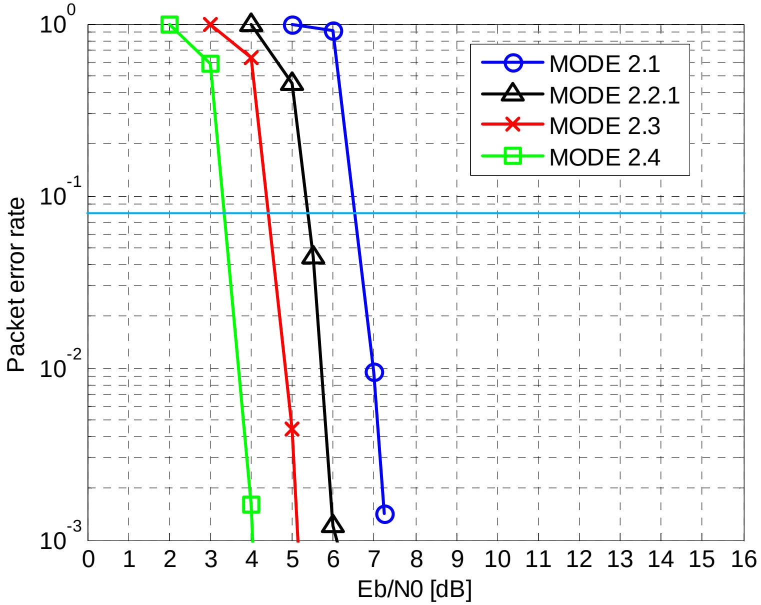
to “Contents”

CM9.1 QPSK (w PA, w PN)

BER



PER



BER=10^{-6}

Mode 2.1 : Required E_b/N_o=7.3 [dB]
Mode 2.2.1: Required E_b/N_o=5.8 [dB]
Mode 2.3 : Required E_b/N_o=5.2 [dB]
Mode 2.4 : Required E_b/N_o=4.1 [dB]

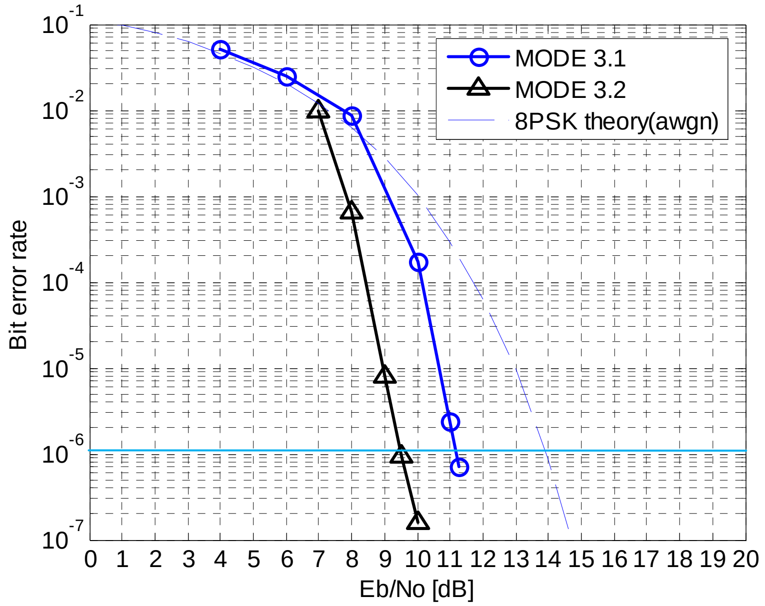
PER=0.08

Mode 2.1 : Required E_b/N_o=6.6 [dB]
Mode 2.2.1: Required E_b/N_o=5.3 [dB]
Mode 2.3 : Required E_b/N_o=4.4 [dB]
Mode 2.4 : Required E_b/N_o=3.3 [dB]

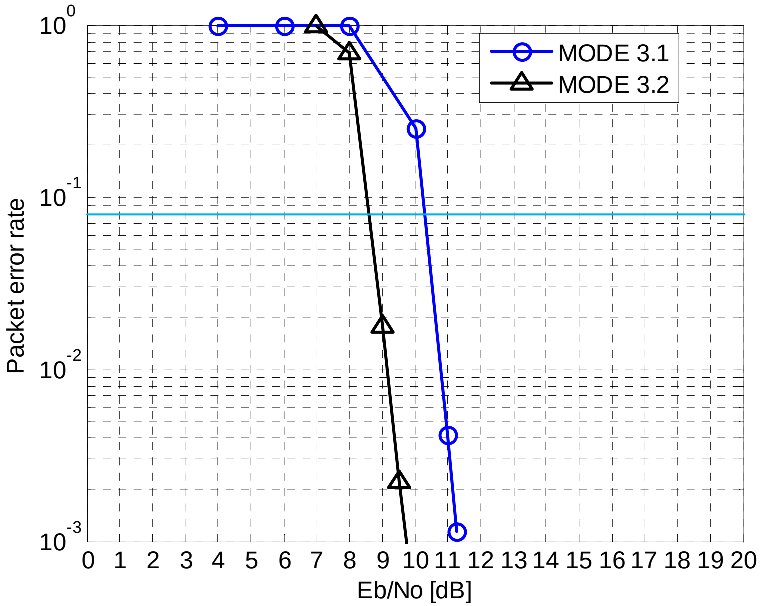
to “Contents”

CM9.1 8PSK (w PA, w PN)

BER



PER



BER=10^{-6}

Mode 3.1 : Required E_b/N_o=11.2 [dB]

Mode 3.2 : Required E_b/N_o=9.5 [dB]

PER=0.08

Mode 3.1 : Required E_b/N_o=10.3 [dB]

Mode 3.2 : Required E_b/N_o=8.6 [dB]

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6.2. Mean 90% PER and BER link success distance for each data rate mode

(2nd item to be reported for PHY)

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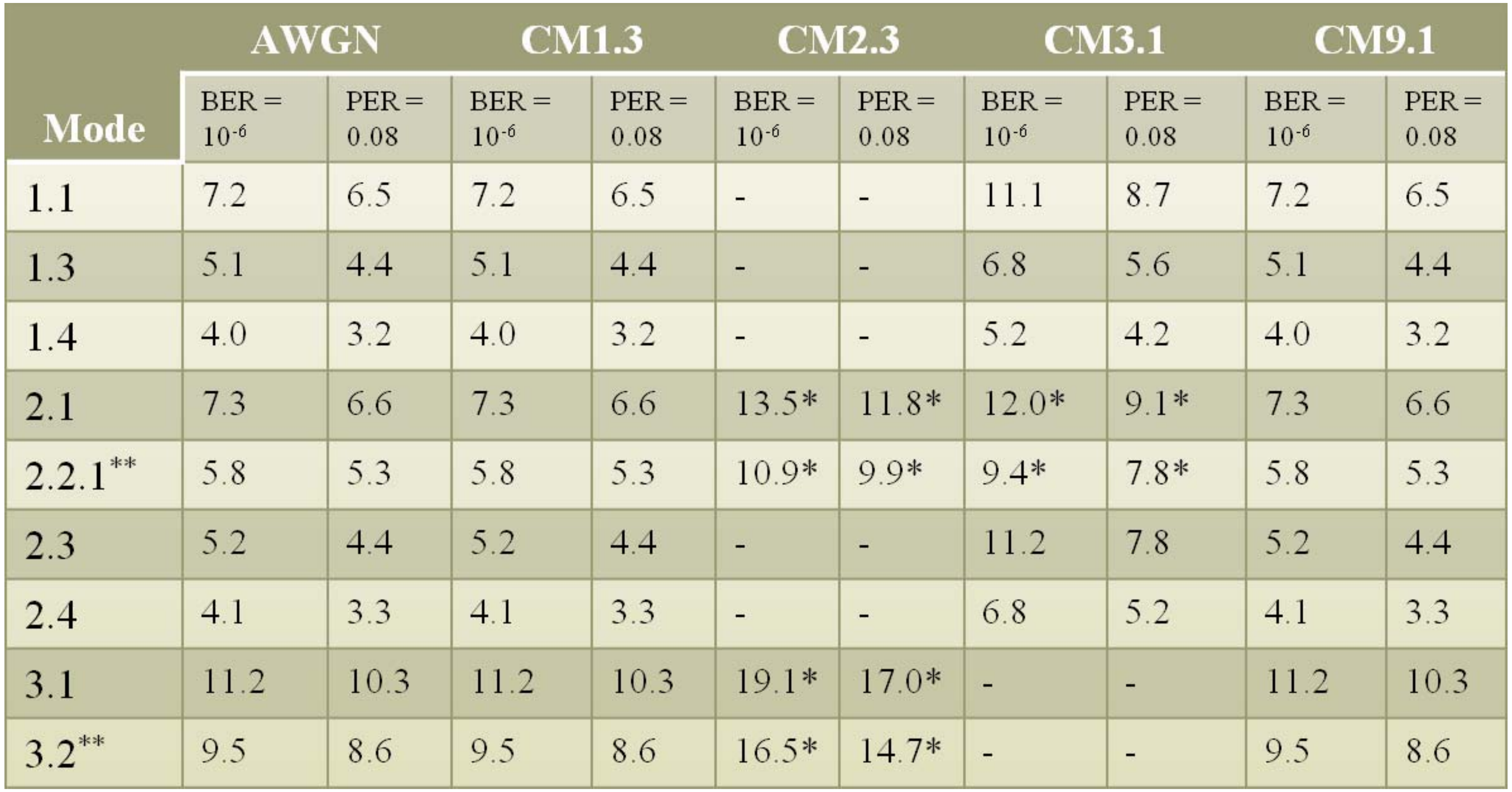
Summary of required E_b/N_o for each data-rate mode to obtain BER of 10^{-6} or PER of 0.08



Mode	AWGN		CM1.3		CM2.3		CM3.1		CM9.1	
	BER = 10^{-6}	PER = 0.08	BER = 10^{-6}	PER = 0.08	BER = 10^{-6}	PER = 0.08	BER = 10^{-6}	PER = 0.08	BER = 10^{-6}	PER = 0.08
1.1	7.2	6.5	7.2	6.5	-	-	11.1	8.7	7.2	6.5
1.3	5.1	4.4	5.1	4.4	-	-	6.8	5.6	5.1	4.4
1.4	4.0	3.2	4.0	3.2	-	-	5.2	4.2	4.0	3.2
2.1	7.3	6.6	7.3	6.6	13.5*	11.8*	12.0*	9.1*	7.3	6.6
2.2.1**	5.8	5.3	5.8	5.3	10.9*	9.9*	9.4*	7.8*	5.8	5.3
2.3	5.2	4.4	5.2	4.4	-	-	11.2	7.8	5.2	4.4
2.4	4.1	3.3	4.1	3.3	-	-	6.8	5.2	4.1	3.3
3.1	11.2	10.3	11.2	10.3	19.1*	17.0*	-	-	11.2	10.3
3.2**	9.5	8.6	9.5	8.6	16.5*	14.7*	-	-	9.5	8.6

Unit is dB

- ■Both effects of PA non-linearity and Phase-noise are considered
- ■* FDE with CP=128 is used
- ■** Number of iterations for an LDPC decoder is 16

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Summary of Link budget and maximum operating range

Items	UM1				UM5	
Required MAC-SAP [Gbps]	1.78		3.56		1.5 & 2.25	
Channel model	1.3	2.3	1.3	2.3	3.1	9.1
Target BER and PER	BER = 10^{-6}				PER=0.08	
Transmission mode	Mode2.1(HRT)		Mode3.1(HRT)		Mode2.1(HRT)	
Modulation	QPSK		8PSK		QPSK	
Channel coding	RS(255,239)					
CP length used with FFT 512	0	128	0	128	128	0
PHY-SAP payload bit rate	3.119	2.495	4.679	3.743	2.495	3.119
MAC-SAP rate [Gbps]	2.595(*)	2.136(*)	3.593(*)	3.560(*)	1.921(*)	2.321(*)
Required E_b/N_o [dB]	7.2	13.5	11.2	19.1	9.1	6.6
Maximum operating range [m]	**24.7**	**8.4**	**7.7**	**2.8**	**19.8**	**26.5**

(*) Refer Sections 7.1 and 7.2

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Link budget for each usage model

Usage model	AWGN	UM1				UM5		Unit
Required MAC-SAP	-	1.78		3.65		1.50 & 2.25		Gbps
Channel model	AWGN	CM1.3(LOS residential)	CM2.3(NLOS residential)	CM1.3(LOS residential)	CM2.3(NLOS residential)	CM3.1(LOS office)	CM9.1(Kiosk)	
Target BER or PER	-	BER=10^{-6}				PER=0.08		
Symbol rate	1.664							Gsymbol/s
Transmission mode to realize required MAC-SAP	2.1(HRT)	2.1(HRT)		3.1(HRT)		2.1(HRT)		
Modulation	QPSK	QPSK		8PSK		QPSK		
Channel coding sheme	RS(255, 239)							
Cyclic Prefix length against 512 code length for FDE	0	0	128	0	128	128	0	
PHY-SAP Payload Bit Rate (R_b)	3.119	3.119	2.495	4.679	3.743	2.495	3.119	Gbps
Average Tx power (P_T)	10	10	10	10	10	10	10	dBm
Tx antenna gain (G_T)	15	15	15	15	15	15	15	dBi
Center frequency (f_c)	60							GHz
Path loss at 1 meter ($PL0$)	68							dB
Rx antenna gain (G_R)	15	15	15	15	15	15	15	dBi
Average noise power per bit (N=-174+10*log10(R_b))	-79.1	-79.1	-80.0	-77.3	-78.3	-79.1		dBm
Rx Noise Figure Referred to the Antenna Terminal (N_F)	10							dB
Average noise power per bit (P_N=N+N_F)	-69.1	-69.1	-70.0	-67.3	-68.3	-69.1		dBm
Required Eb/No (S) to achieve PER=0.08	-	-	-	-	-	* 9.1	6.6	
Required Eb/No (S) to achieve BER=10^{-6}	7.2	7.2	* 13.5	11.2	* 19.1	-	-	dB
Shadowing link margin ($M_{shadowing}$)	1	1	5	1	5	1	1	dB
Implementation Loss (I)	5							dB
Receiver sensitivity ($Pth = S + P_N + M_{sahowing} + I$)	-55.9	-55.9	-46.5	-50.1	-39.2	-54.0	-56.5	dBm
Tolerable path loss ($PL = P_T + G_T + G_R - P_N - S - M_{shadowing} - I - PL0$)	27.9	27.9	18.5	22.1	11.2	26.0	28.5	dB
Link margin for reference distance (1 m for UM5, 5 m for UM1)	**-**	**13.9**	**1.0**	**8.1**	**-6.3**	**26.0**	**28.5**	**dB**
Maximum operating range ($d = 10^{PL/10n}$) where n is path loss exponent	**24.7**	**24.7**	**5.5**	**12.7**	**2.8**	**19.8**	**26.5**	**m**

(*) FDE is used

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n (path loss exponent) is assumed to be 2 for LOS and 2.5 for NLOS following “Selection criteria”

6.3: Miss detection and false alarm performance of the synchronization versus SNR

(3rd item to be reported for PHY)

- Reference BER performance
  - For high-rate transmission (HRT) mode: Mode1.4 (BPSK, RS(255,239)+CC(R=1/2))
  - For low-rate transmission (LRT) mode: Mode4.1 (BPSK, RS(255,239), 64 spreading)

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Summary for synchronization performance

- The target probabilities of miss detection and false alarm are set at 10^{-8} against BER threshold of 10^{-6}
- The proposed preambles achieve the target probabilities in all modes and channels

List of miss detection and false alarm probabilities and SNR margin

		AWGN		CM1.3		CM2.3		CM3.1		CM9.1	
		Probability @ required SNR	SNR margin @ 10^{-6}	Probability @ required SNR	SNR margin @ 10^{-6}	Probability @ required SNR	SNR margin @ 10^{-6}	Probability @ required SNR	SNR margin @ 10^{-6}	Probability @ required SNR	SNR margin @ 10^{-6}
HRT/ MRT mode	P_m	$< 10^{-8}$	7.5 dB	$< 10^{-8}$	7 dB	$< 10^{-8}$	2.7 dB	$< 10^{-8}$	5 dB	$< 10^{-8}$	7.5 dB
	P_f	$< 10^{-8}$	9.5 dB	$< 10^{-8}$	8.5 dB	$< 10^{-8}$	8 dB	$< 10^{-8}$	7.5 dB	$< 10^{-8}$	9.5 dB
LRT mode	P_m	$< 10^{-8}$	7 dB	$< 10^{-8}$	6.5 dB	$< 10^{-8}$	1.5 dB	$< 10^{-8}$	7 dB	$< 10^{-8}$	7 dB
	P_f	$< 10^{-8}$	3.5 dB	$< 10^{-8}$	2.5 dB	$< 10^{-8}$	3 dB	$< 10^{-8}$	4.5 dB	$< 10^{-8}$	3.5 dB

* P_m = Miss detection probability, P_f = False alarm probability
HRT: High rate transmission, LRT: Low rate transmission

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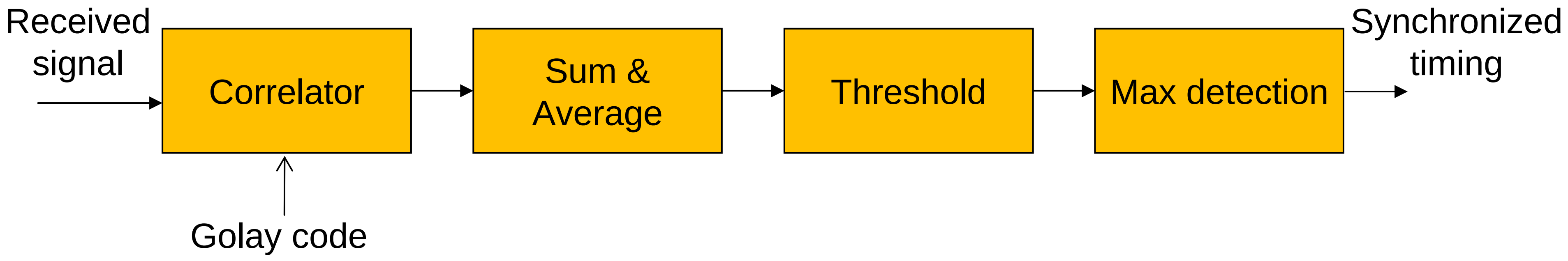
Synchronization process

Block diagram of synchronization part


Received signal

Correlator

Sum & Average

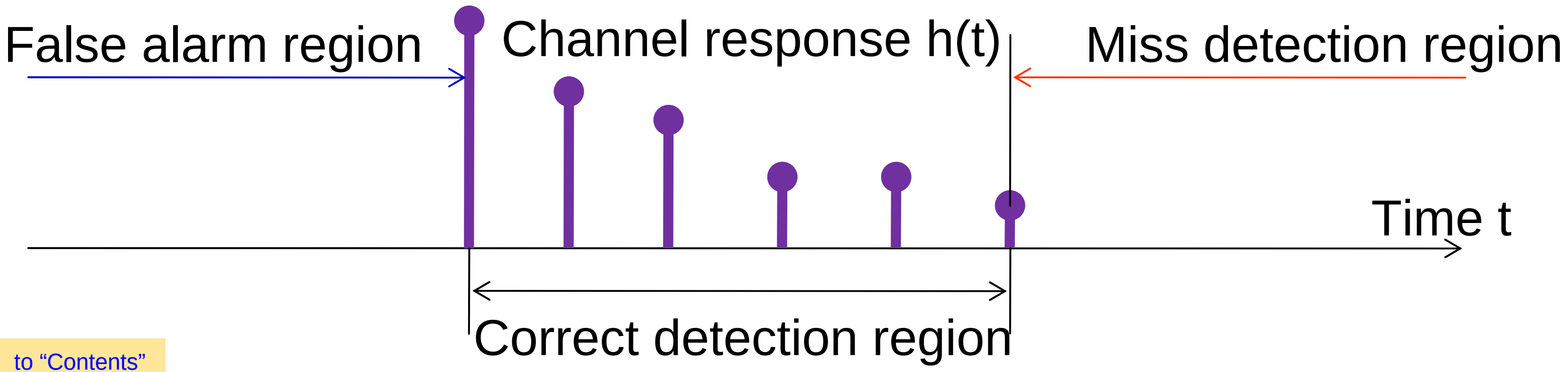
Threshold

Max detection

Synchronized timing

Golay code

Definition of miss detection and false alarm


False alarm region

Channel response h(t)

Miss detection region

Time t

Correct detection region

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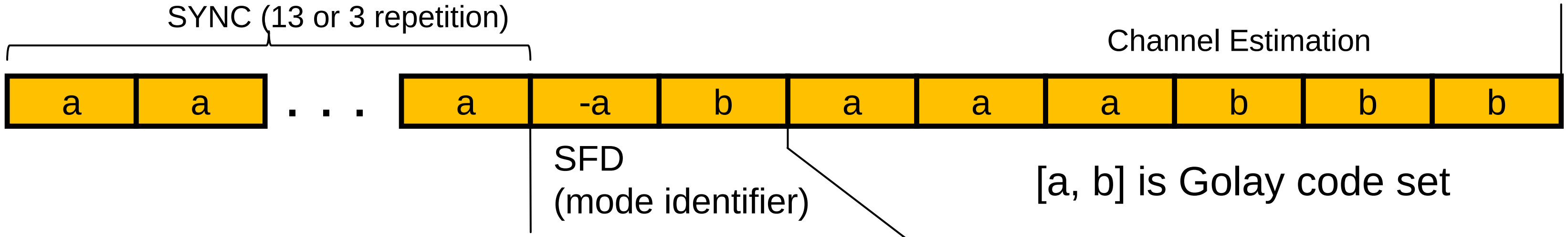
Parameters for preamble



SYNC (13 or 3 repetition)

Channel Estimation

SFD
(mode identifier)

[a, b] is Golay code set

Mode	Symbol rate [Gsps]	SYNC		SFD		CE		Total length	
		Code length L_s [symbols]	# repetitions N_s	Code length L_{sfd} [symbols]	# repetitions N_{sfd}	Code length L_{ce} [symbols]	# repetitions N_{ce}	symbols	nsec
HRT/MRT mode	1.664	128	3	128	2	128	6	1408	846.2
LRT mode	1.664	128	13	128	2	128	6	2688	1615.4

- 1 of 3 and 1 of 13 codes in SYNC are used for AGC and symbol timing recovery in high-rate and low-rate modes, respectively

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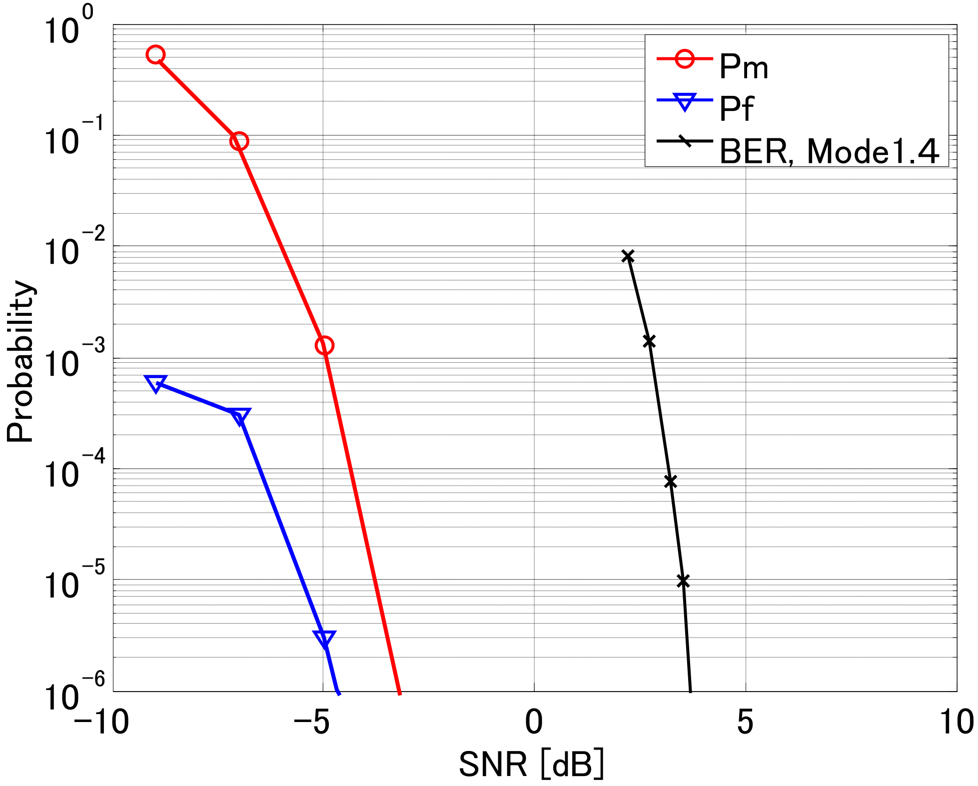
Synchronization performance of high-rate transmission mode in AWGN

- 7.5 dB of SNR margin for P_m against 10^{-6} of the reference BER
- 9.5 dB of SNR margin for P_f against 10^{-6} of the reference BER



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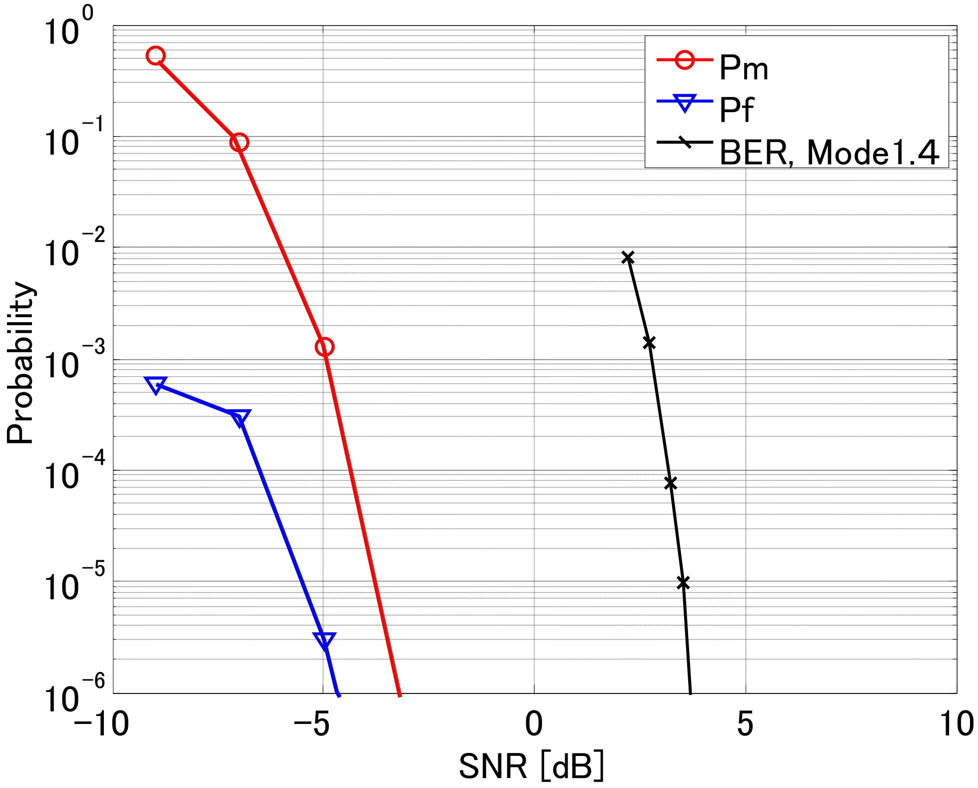
Synchronization performance of high-rate transmission mode in CM1.3

- 7.0 dB of SNR margin for P_m against 10^{-6} of the reference BER
- 8.5 dB of SNR margin for P_f against 10^{-6} of the reference BER



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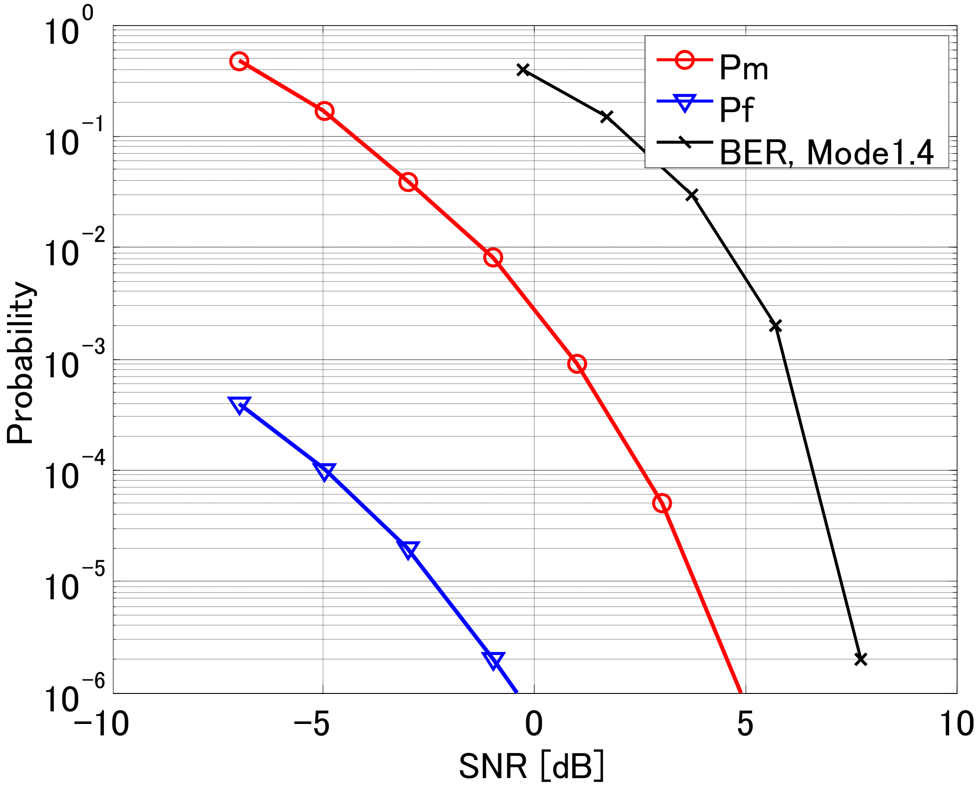
Synchronization performance of high-rate transmission mode in CM2.3

- 2.7 dB of SNR margin for P_m against 10^{-6} of the reference BER
- 8.0 dB of SNR margin for P_f against 10^{-6} of the reference BER



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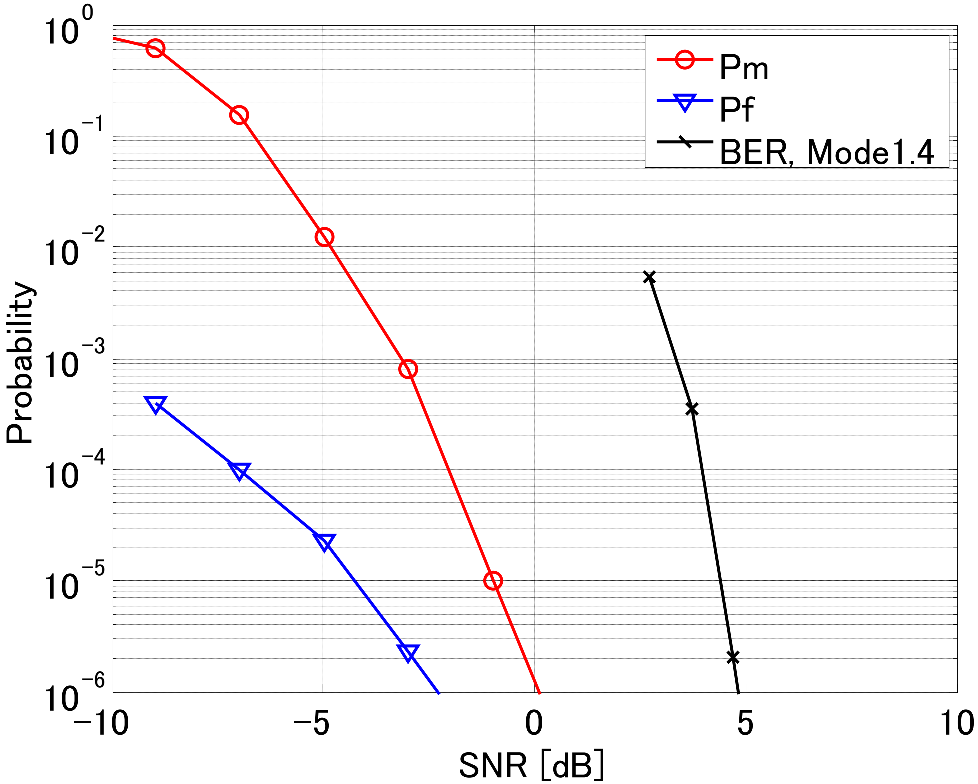
Synchronization performance of high-rate transmission mode in CM3.1

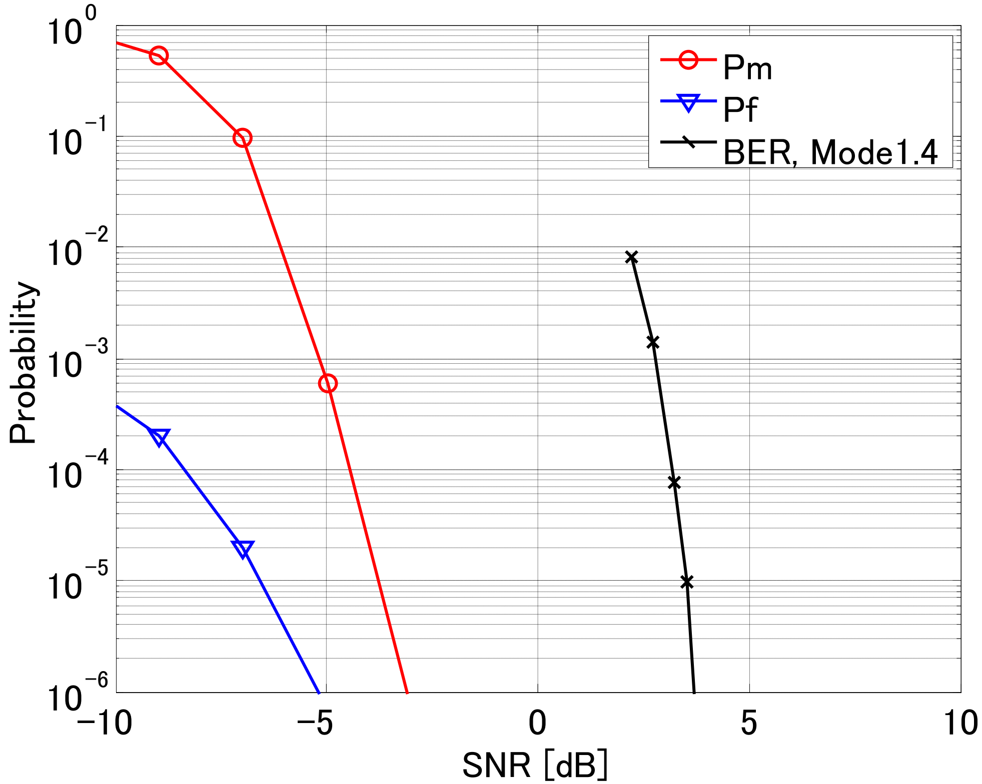
- 5.0 dB of SNR margin for P_m against 10^{-6} of the reference BER
- 7.5 dB of SNR margin for P_f against 10^{-6} of the reference BER



to “Contents”

Synchronization performance of high-rate transmission mode in CM9.1

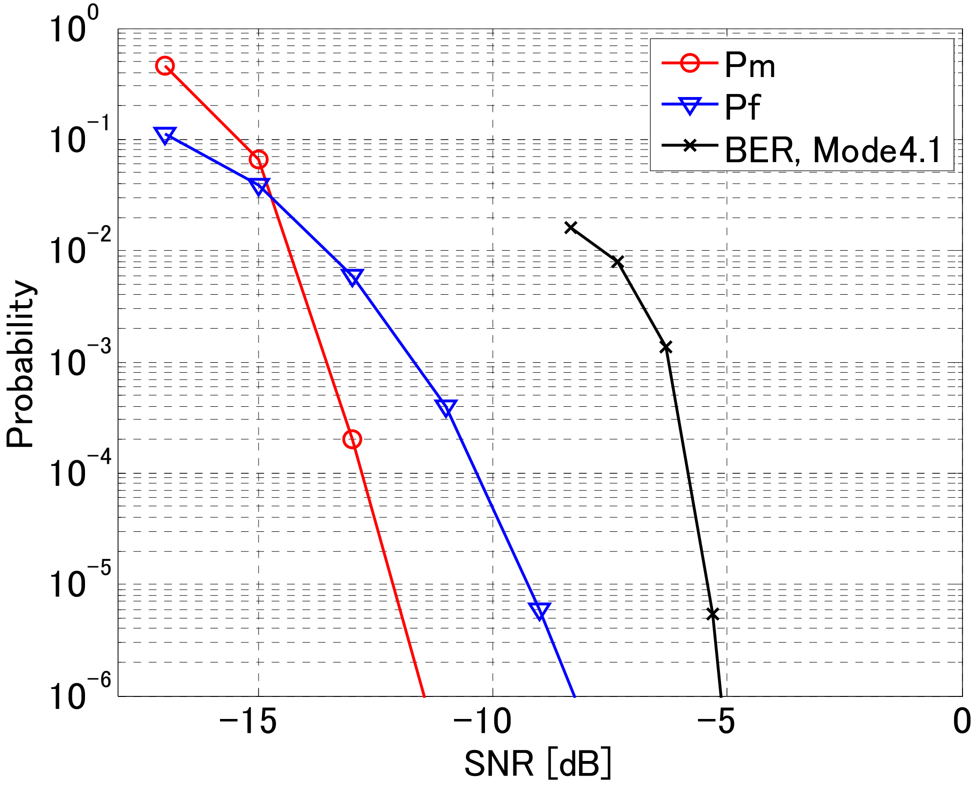
- 7.5 dB of SNR margin for P_m against 10^{-6} of the reference BER
- 9.5 dB of SNR margin for P_f against 10^{-6} of the reference BER



to “Contents”

Synchronization performance of low-rate transmission mode in AWGN

- 7.0 dB of SNR margin for P_m against 10^{-6} of the reference BER
- 3.5 dB of SNR margin for P_f against 10^{-6} of the reference BER



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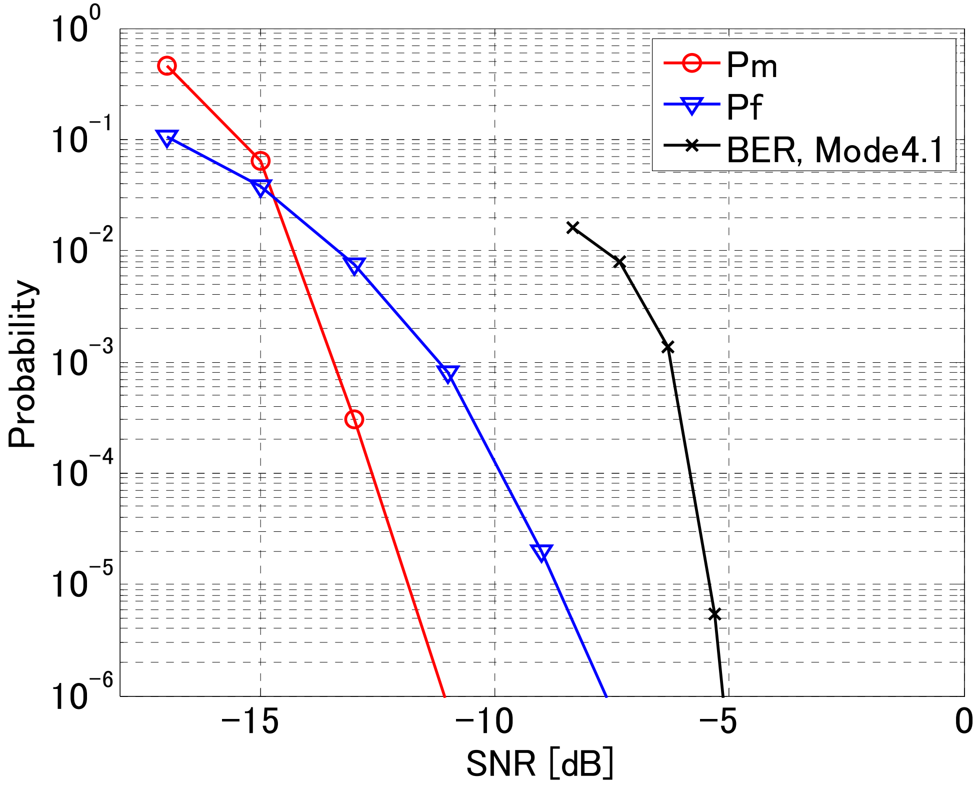
Synchronization performance of low-rate transmission mode in CM1.3

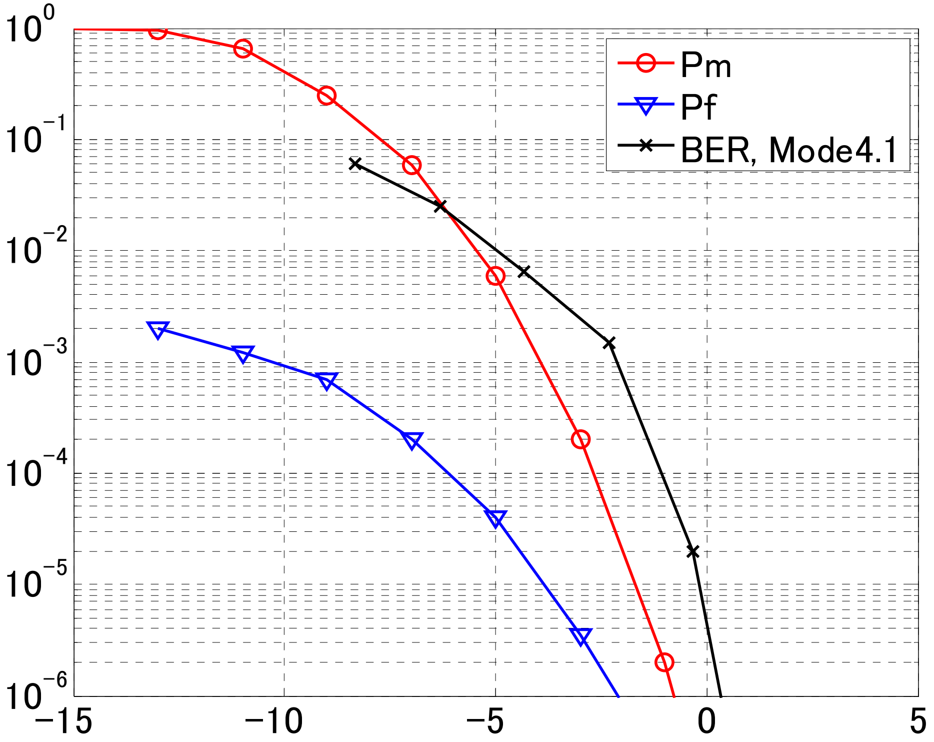
- 6.5 dB of SNR margin for P_m against 10^{-6} of the reference BER
- 2.5 dB of SNR margin for P_f against 10^{-6} of the reference BER



to "Contents"

Synchronization performance of low-rate transmission mode in CM2.3

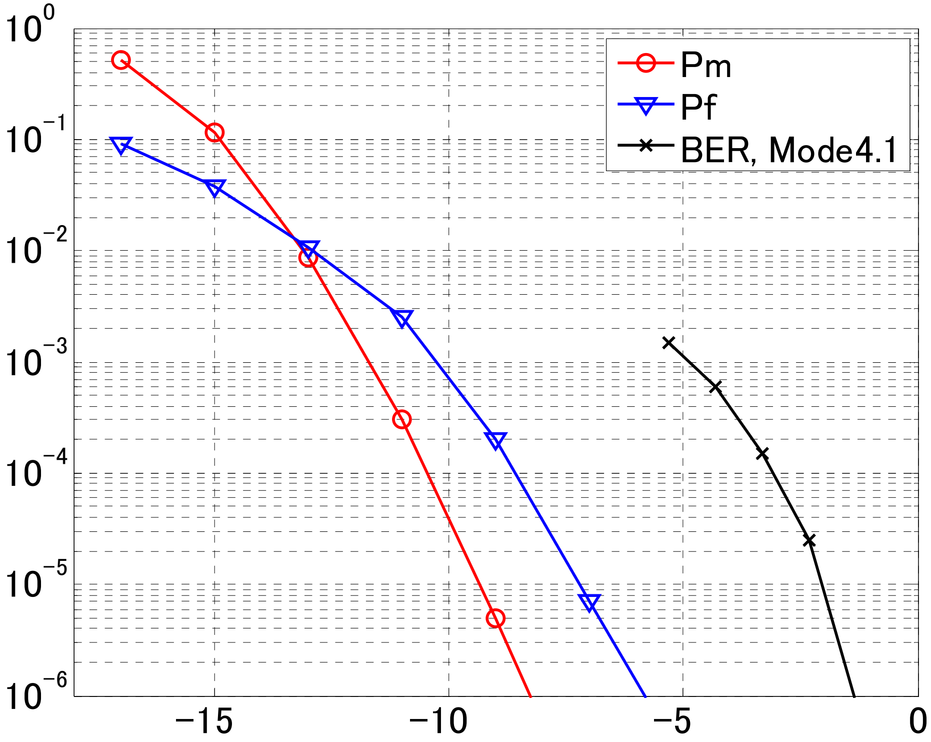
- 1.5 dB of SNR margin for P_m against 10^{-6} of the reference BER
- 3.0 dB of SNR margin for P_f against 10^{-6} of the reference BER



to “Contents”

Synchronization performance of low-rate transmission mode in CM3.1

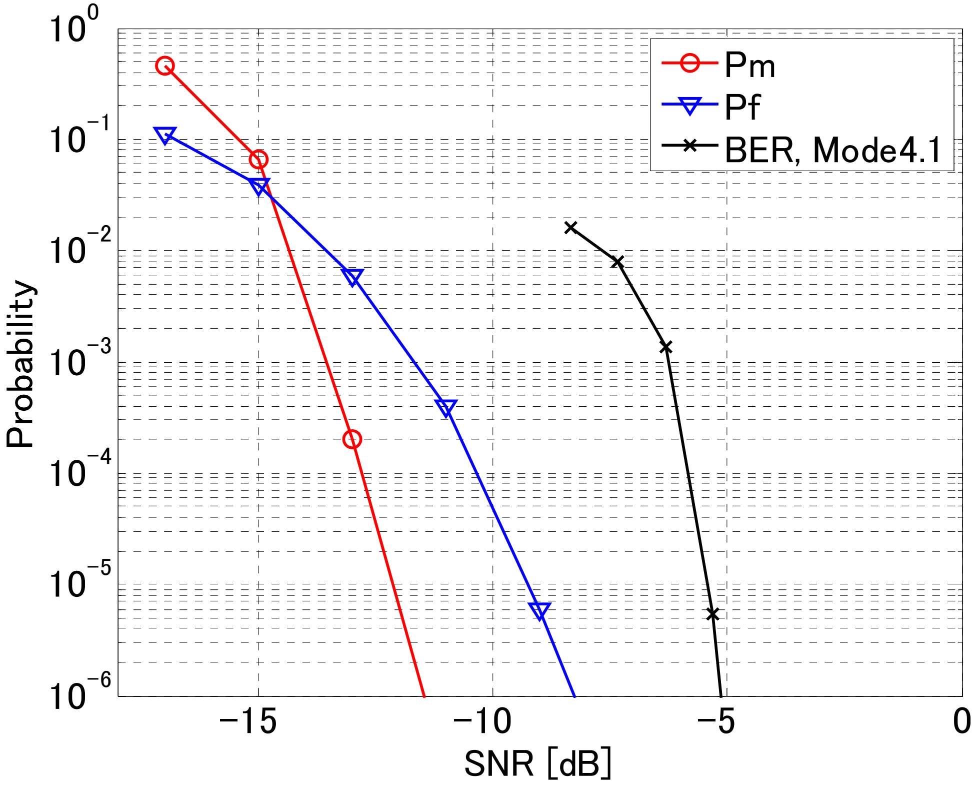
- 7.0 dB of SNR margin for P_m against 10^{-6} of the reference BER
- 4.5 dB of SNR margin for P_f against 10^{-6} of the reference BER



to "Contents"

Synchronization performance of low-rate transmission mode in CM9.1

- 7.0 dB of SNR margin for P_m against 10^{-6} of the reference BER
- 3.5 dB of SNR margin for P_f against 10^{-6} of the reference BER



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6.4: Packet structure parameters

(4th item to be reported for PHY)

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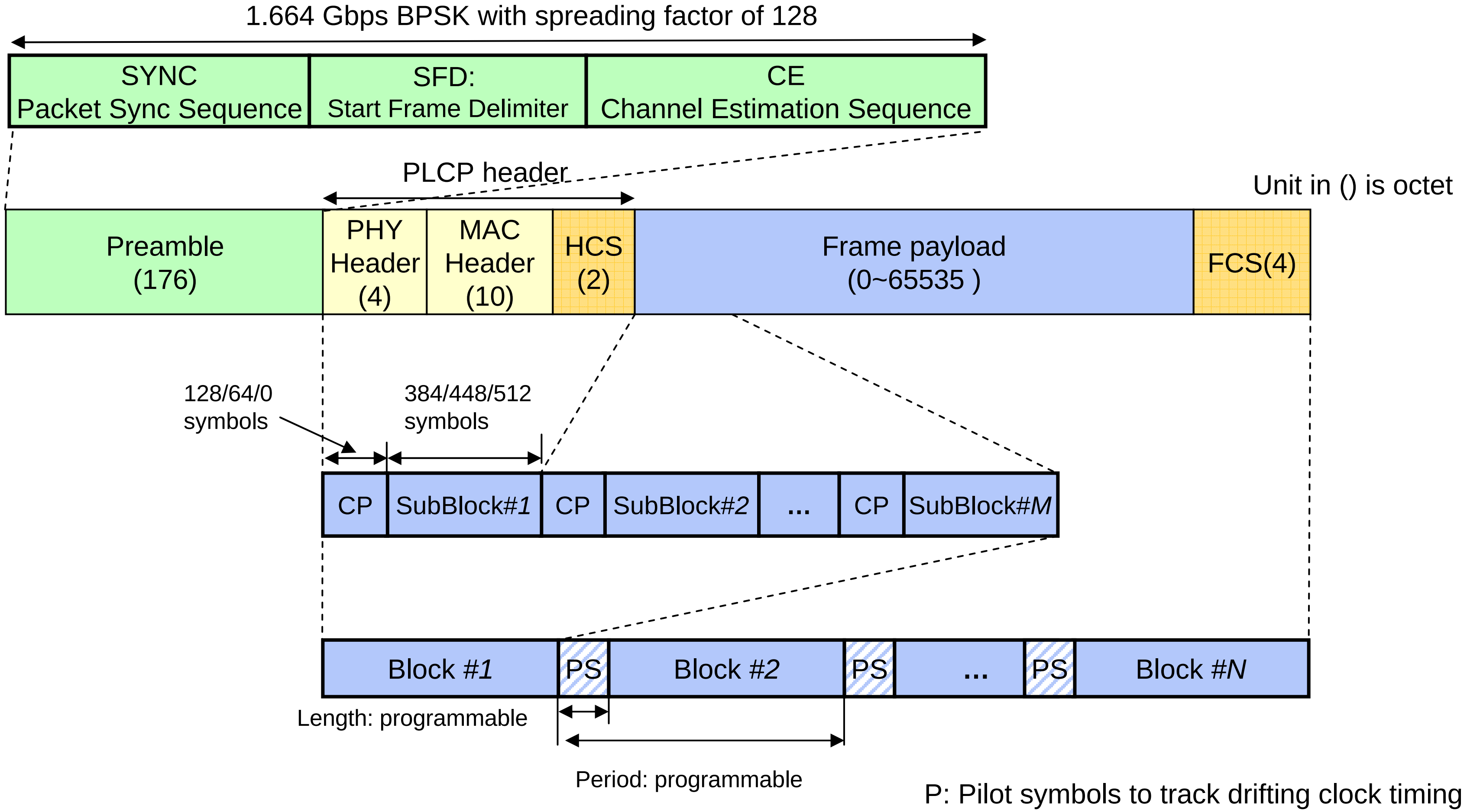
Detailed frame format (before FEC)



P: Pilot symbols to track drifting clock timing

CP: Cyclic Prefix

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Major frame format parameters

- Preamble
  - Described in slide 28
- Symbol rate
  - Described in slide 15
- Modulation
  - Described in slide 15~18
- FEC
  - Described in slide 15~18

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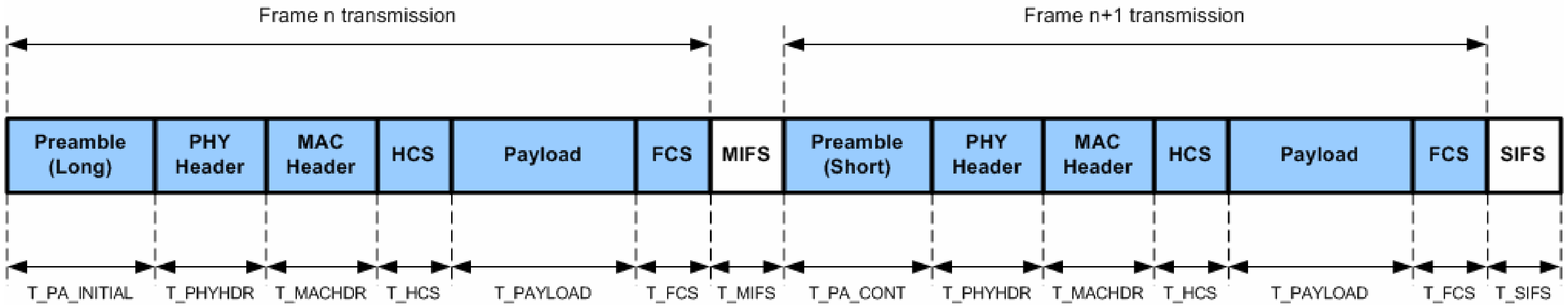
Packet structure parameters for data throughput comparison



- T_PA_INITIAL: Length of the initial (long) preamble
- T_PA_CONT: Length of the short preamble
- T_PHYHDR: Length of the PHY header
- T_MACHDR: Length of the MAC header
- T_HCS: Length of the header checksum
- T_PAYLOAD: Length of the payload
- T_FCS: Length of the frame checksum
- T_MIFS: Length of the Minimum Inter Frame Space (MIFS)
- T_SIFS: Length of the Short Inter Frame Space (SIFS)

Packet overhead is defined here as …

$$\frac{T_{\mathrm{PA\_INITIAL}} + T_{\mathrm{PHYHDR}} + T_{\mathrm{MACHDR}} + T_{\mathrm{FCS}} + T_{\mathrm{HCS}}}{T_{\mathrm{PA\_INITIAL}} + T_{\mathrm{PHYHDR}} + T_{\mathrm{MACHDR}} + T_{\mathrm{FCS}} + T_{\mathrm{HCS}} + T_{\mathrm{PAYLOAD}}}$$

Tail bits, staffing bits, pad symbols, and shorting of the last block for RS or LDPC are disregarded for this packet over head calculation. 2048 byte payload is used for this calculation.

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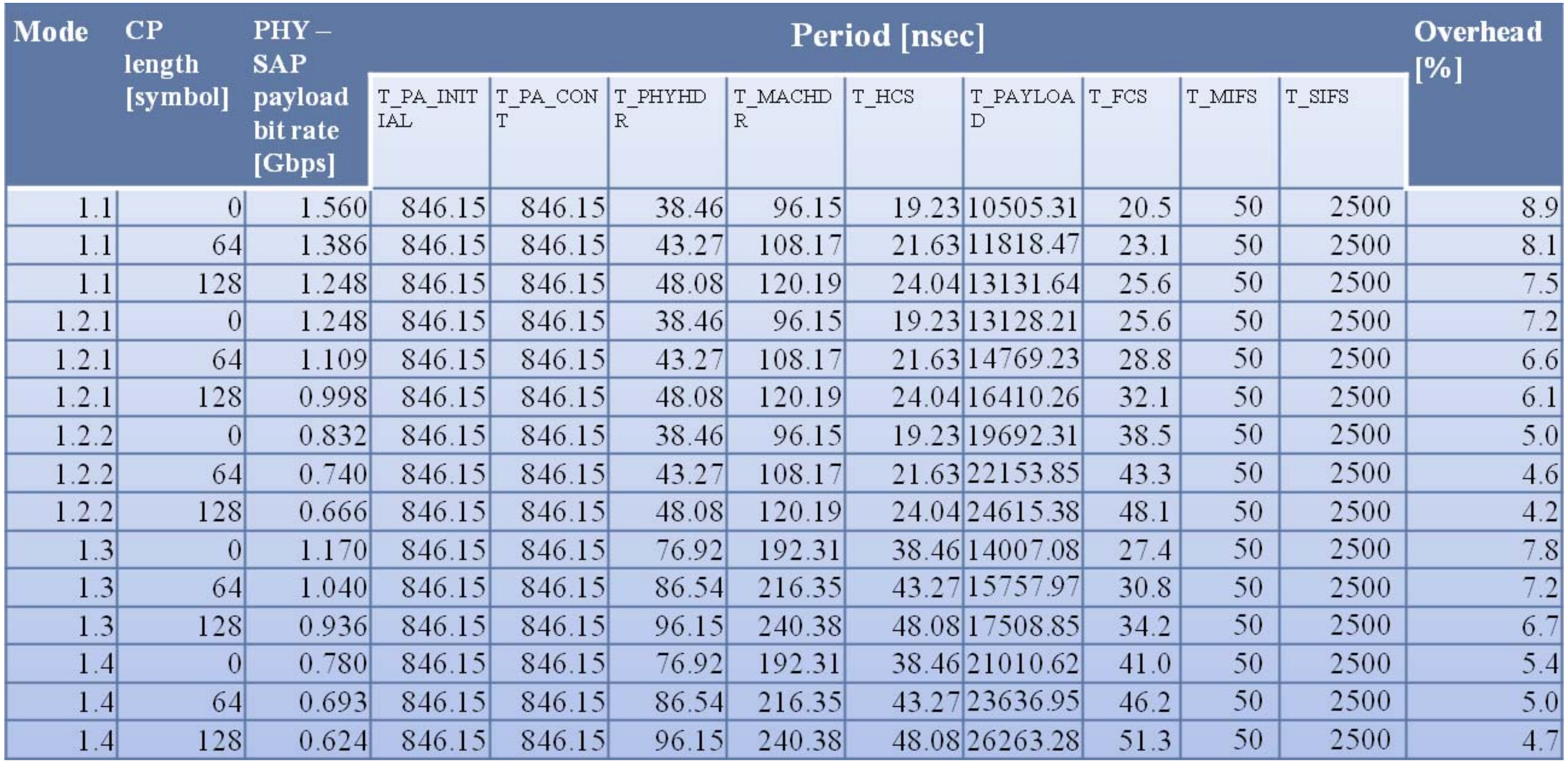
Packet overhead in each data-rate mode



Mode	CP length [symbol]	PHY – SAP payload bit rate [Gbps]	Period [nsec]									Overhead [%]
			T_PA_INITIAL	T_PA_CONT	T_PHYHDR	T_MACHDR	T_HCS	T_PAYLOAD	T_FCS	T_MIFS	T_SIFS	
1.1	0	1.560	846.15	846.15	38.46	96.15	19.23	10505.31	20.5	50	2500	8.9
1.1	64	1.386	846.15	846.15	43.27	108.17	21.63	11818.47	23.1	50	2500	8.1
1.1	128	1.248	846.15	846.15	48.08	120.19	24.04	13131.64	25.6	50	2500	7.5
1.2.1	0	1.248	846.15	846.15	38.46	96.15	19.23	13128.21	25.6	50	2500	7.2
1.2.1	64	1.109	846.15	846.15	43.27	108.17	21.63	14769.23	28.8	50	2500	6.6
1.2.1	128	0.998	846.15	846.15	48.08	120.19	24.04	16410.26	32.1	50	2500	6.1
1.2.2	0	0.832	846.15	846.15	38.46	96.15	19.23	19692.31	38.5	50	2500	5.0
1.2.2	64	0.740	846.15	846.15	43.27	108.17	21.63	22153.85	43.3	50	2500	4.6
1.2.2	128	0.666	846.15	846.15	48.08	120.19	24.04	24615.38	48.1	50	2500	4.2
1.3	0	1.170	846.15	846.15	76.92	192.31	38.46	14007.08	27.4	50	2500	7.8
1.3	64	1.040	846.15	846.15	86.54	216.35	43.27	15757.97	30.8	50	2500	7.2
1.3	128	0.936	846.15	846.15	96.15	240.38	48.08	17508.85	34.2	50	2500	6.7
1.4	0	0.780	846.15	846.15	76.92	192.31	38.46	21010.62	41.0	50	2500	5.4
1.4	64	0.693	846.15	846.15	86.54	216.35	43.27	23636.95	46.2	50	2500	5.0
1.4	128	0.624	846.15	846.15	96.15	240.38	48.08	26263.28	51.3	50	2500	4.7

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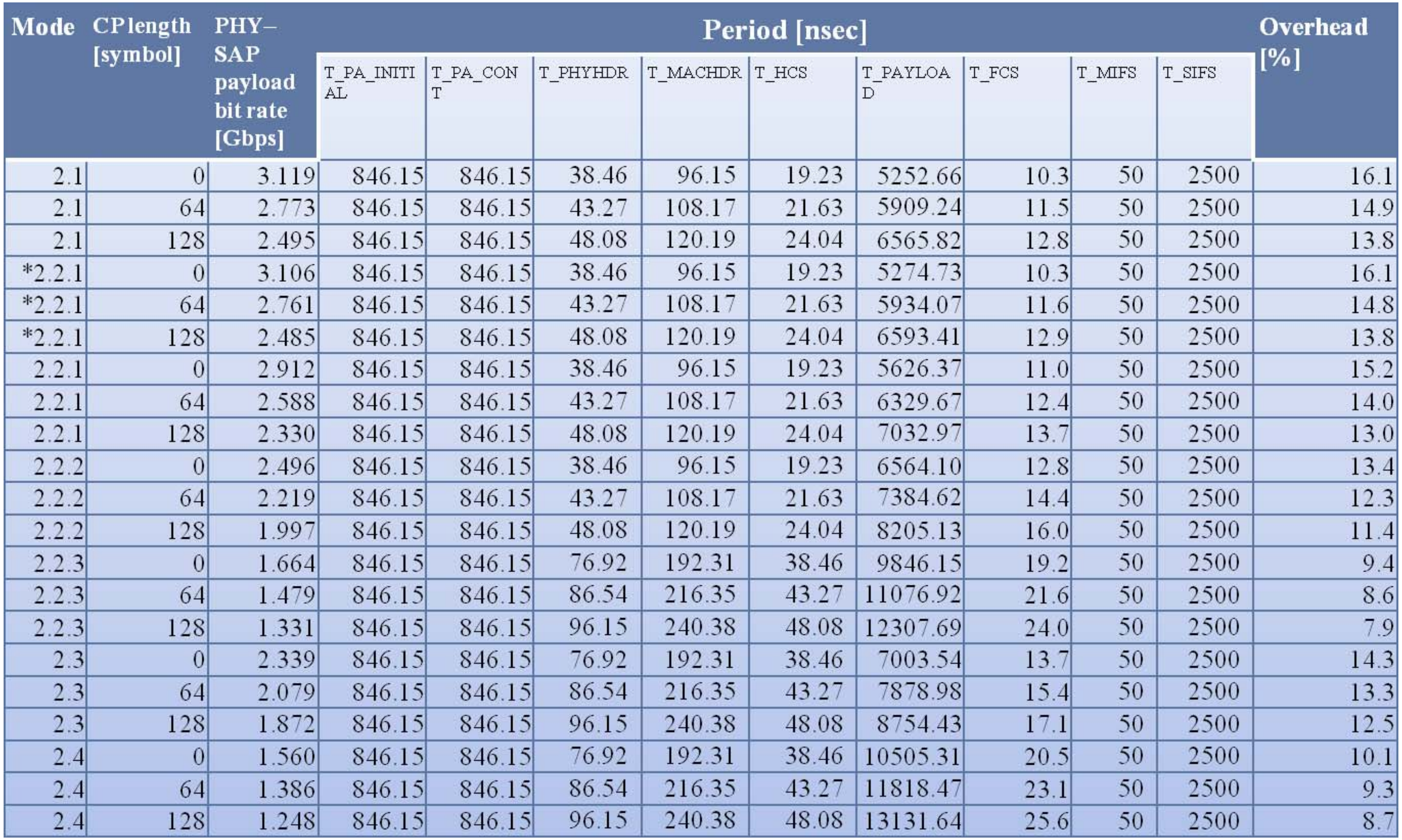
Packet overhead in each data-rate mode (Cont’)



Mode	CP length [symbol]	PHY–SAP payload bit rate [Gbps]	Period [nsec]									Overhead [%]
			T_PA_INITIAL	T_PA_CONT	T_PHYHDR	T_MACHDR	T_HCS	T_PAYLOAD	T_FCS	T_MIFS	T_SIFS	
2.1	0	3.119	846.15	846.15	38.46	96.15	19.23	5252.66	10.3	50	2500	16.1
2.1	64	2.773	846.15	846.15	43.27	108.17	21.63	5909.24	11.5	50	2500	14.9
2.1	128	2.495	846.15	846.15	48.08	120.19	24.04	6565.82	12.8	50	2500	13.8
*2.2.1	0	3.106	846.15	846.15	38.46	96.15	19.23	5274.73	10.3	50	2500	16.1
*2.2.1	64	2.761	846.15	846.15	43.27	108.17	21.63	5934.07	11.6	50	2500	14.8
*2.2.1	128	2.485	846.15	846.15	48.08	120.19	24.04	6593.41	12.9	50	2500	13.8
2.2.1	0	2.912	846.15	846.15	38.46	96.15	19.23	5626.37	11.0	50	2500	15.2
2.2.1	64	2.588	846.15	846.15	43.27	108.17	21.63	6329.67	12.4	50	2500	14.0
2.2.1	128	2.330	846.15	846.15	48.08	120.19	24.04	7032.97	13.7	50	2500	13.0
2.2.2	0	2.496	846.15	846.15	38.46	96.15	19.23	6564.10	12.8	50	2500	13.4
2.2.2	64	2.219	846.15	846.15	43.27	108.17	21.63	7384.62	14.4	50	2500	12.3
2.2.2	128	1.997	846.15	846.15	48.08	120.19	24.04	8205.13	16.0	50	2500	11.4
2.2.3	0	1.664	846.15	846.15	76.92	192.31	38.46	9846.15	19.2	50	2500	9.4
2.2.3	64	1.479	846.15	846.15	86.54	216.35	43.27	11076.92	21.6	50	2500	8.6
2.2.3	128	1.331	846.15	846.15	96.15	240.38	48.08	12307.69	24.0	50	2500	7.9
2.3	0	2.339	846.15	846.15	76.92	192.31	38.46	7003.54	13.7	50	2500	14.3
2.3	64	2.079	846.15	846.15	86.54	216.35	43.27	7878.98	15.4	50	2500	13.3
2.3	128	1.872	846.15	846.15	96.15	240.38	48.08	8754.43	17.1	50	2500	12.5
2.4	0	1.560	846.15	846.15	76.92	192.31	38.46	10505.31	20.5	50	2500	10.1
2.4	64	1.386	846.15	846.15	86.54	216.35	43.27	11818.47	23.1	50	2500	9.3
2.4	128	1.248	846.15	846.15	96.15	240.38	48.08	13131.64	25.6	50	2500	8.7

* For LDPC (1440,1344)

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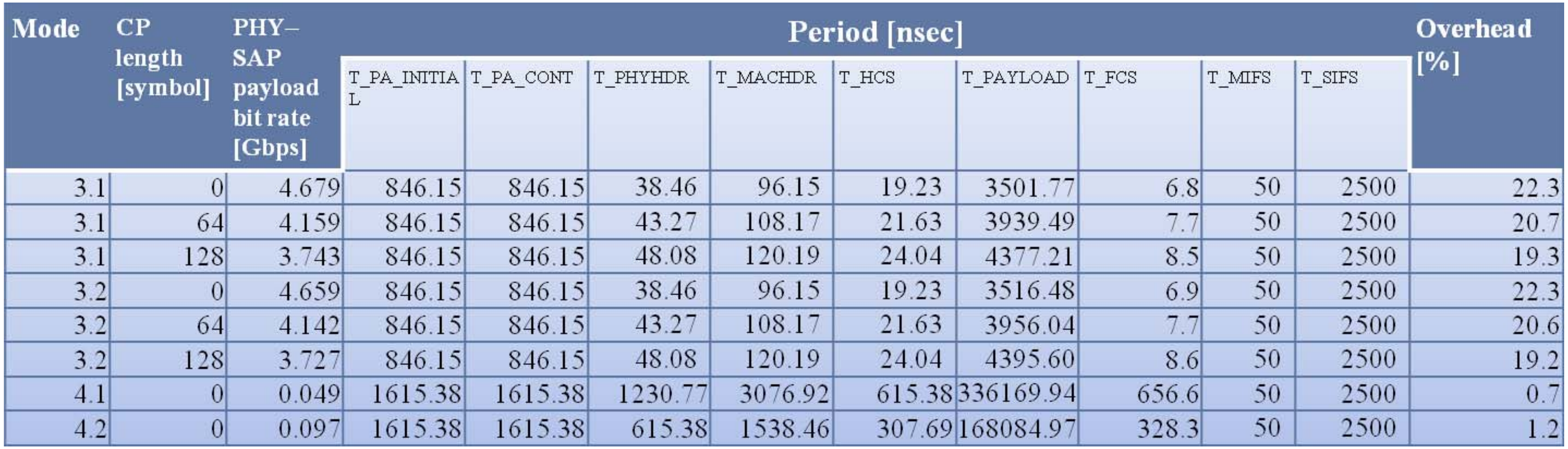
Packet overhead in each data-rate mode (Cont’)



Mode	CP length [symbol]	PHY–SAP payload bit rate [Gbps]	Period [nsec]									Overhead [%]
			T_PA_INITIAL	T_PA_CONT	T_PHYHDR	T_MACHDR	T_HCS	T_PAYLOAD	T_FCS	T_MIFS	T_SIFS	
3.1	0	4.679	846.15	846.15	38.46	96.15	19.23	3501.77	6.8	50	2500	22.3
3.1	64	4.159	846.15	846.15	43.27	108.17	21.63	3939.49	7.7	50	2500	20.7
3.1	128	3.743	846.15	846.15	48.08	120.19	24.04	4377.21	8.5	50	2500	19.3
3.2	0	4.659	846.15	846.15	38.46	96.15	19.23	3516.48	6.9	50	2500	22.3
3.2	64	4.142	846.15	846.15	43.27	108.17	21.63	3956.04	7.7	50	2500	20.6
3.2	128	3.727	846.15	846.15	48.08	120.19	24.04	4395.60	8.6	50	2500	19.2
4.1	0	0.049	1615.38	1615.38	1230.77	3076.92	615.38	336169.94	656.6	50	2500	0.7
4.2	0	0.097	1615.38	1615.38	615.38	1538.46	307.69	168084.97	328.3	50	2500	1.2

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7. Items to be reported for MAC

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Summary of items to be reported for MAC

- Assumptions
  - QPSK with RS(255, 239) transmission mode for both UM1 and UM5 fundamentally
  - No-Ack mode for UM1, but Dly-Ack mode for UM5
  - FDE (frequency domain equalization) with CP=128 for NLOS environments in UM1
  - 8PSK with RS(255, 239) transmission mode for higher data-rate demand in UM1

- **CoMPA proposal meets all system requirements**
  - Over 2.5 Gbps can be expected for LOS UM1 condition, and over 2.1 Gbps even if in NLOS UM1 condition
  - Over 3.56 Gbps can be expected for both LOS and NLOS UM5 conditions
  - Over 2.3 Gbps can be expected for UM5 condition

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MAC items to be reported

1. Throughput analysis for the UM1 scenario, including Character Error Rate (CER) analysis
2. Throughput analysis for the UM5 scenario
3. The ARQ method (if used) and packet aggregation parameters (if used)
4. Assumed durations of Inter-frame spaces
5. PHY mode assumed
6. Frame size
7. CAP duration
8. Preamble types used (if different)
9. Super frame size and guard interval duration

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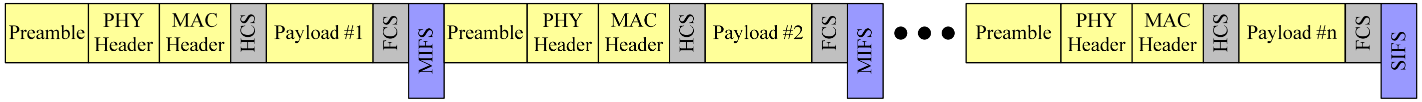
Definition of ‘data throughput’

- Data throughput definition in 05/493r27 (‘Selection criteria’) is used for throughput analysis for No-ACK and Dly-ACK cases

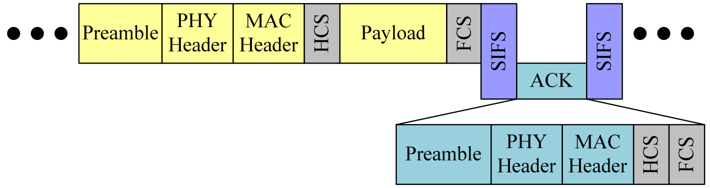
No-ACK

n: analyzed frame numbers, *m: size of Dly-ACK,*



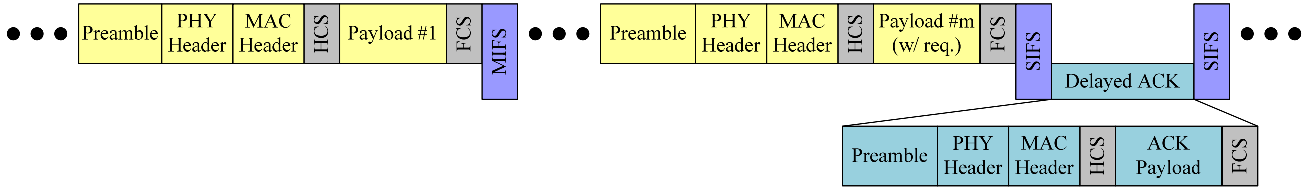
$$Data\_throughput\_No\_ACK = n \times Payload\_bits /$$
$$[n \times (T\_preamble + T\_MACHDR + T\_PHYHDR + T\_HCS + T\_Payload + T\_FCS) + (n-1) \times T\_MIFS + T\_SIFS]$$

Imm-ACK



$$Data\_throughput\_Dly\_ACK = Payload\_bits /$$
$$[T\_Payload + 2 \times (T\_preamble + T\_MACHDR + T\_PHYHDR + T\_HCS + T\_FCS) + 2 \times T\_SIFS]$$

Dly-ACK



$$Data\_throughput\_Dly\_ACK = (m \times Payload\_bits) /$$
$$[m \times (T\_preamble + T\_MACHDR + T\_PHYHDR + T\_HCS + T\_Payload + T\_FCS) + (m-1) \times T\_MIFS + 2 \times T\_SIFS + T\_Dly\_ACK]$$

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7.1: Throughput analysis for the UM1 scenario, including Character Error Rate (CER) analysis

- Throughput analysis for the UM1 scenario is shown in the table below

	Requirement	LOS	NLOS
UM1	1.78Gbps	Data Throughput =2.595Gbps (QPSK with RS (255,239))	Data Throughput =2.136Gbps (QPSK with RS (255,239) (CP=128))
	3.56Gbps	Data Throughput=3.593Gbps (8PSK with RS (255,239))	Data Throughput =3.560Gbps (8PSK with RS (255,239) (CP=128))

- Assumptions
  - No-ACK for data transmission
  - Imm-ACK for channel allocation
- Since CER according to PiER of 10^{-9} or BER of 10^{-10} causes very low FER, data throughput is calculated assuming no frame error

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7.2: Throughput analysis for the UM5 scenario

- Throughput analysis for the UM5 scenario is shown in the table below

	Requirement	LOS	NLOS
UM5	1.50Gbps	Data Throughput =2.321Gbps (*) (QPSK with RS (255,239))	
	2.25Gbps	Data Throughput =2.321Gbps(*) (QPSK with RS (255,239))	

(*) 1.921Gbps, if CP=128 is employed

- Assumptions
  - Dly-ACK for data transmission
  - Imm-ACK for channel allocation
  - Size of ‘Dly-ACK’ is 16 in the analysis
- For analysis simplification, ‘8% of FER’ is translated to 108% transmission instead of 100% transmission

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7.3: The ARQ method and packet aggregation parameters

- ARQ
  - Go-Back-N(N>=1) is assumed as the ARQ method
  - No-ACK is employed in UM1
  - Dly-ACK is employed in UM5
- Packet aggregation
  - Expanded payload up to 10k octet is used for throughput analysis by expanding 16bit-frame-length-field in PHY header (up to 65k octet is possible)
  - MSDU (MAC Service Data Unit) aggregation or MPDU (MAC Protocol Data Unit) aggregation is also available

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7.4: Assumed durations of inter frame space

- Following durations are assumed
  - SIFS: 2.5 μs
    - SIFS is the length of time that PHY to switch between transmit and receive
    - Determined by following signal processing durations with 100% margin for implementation
      - ✓ Equalization: 0.4μs
      - ✓ LDPC decoding: 0.85μs
  - MIFS: 0.05 μs
    - MIFS is the length of time required for PHY either between successive transmissions or successive reception

to “Contents”

7.5: PHY mode assumed

- Assumed PHY modes:

		LOS	NLOS
UM1	1.78Gbps	QPSK with RS (PHY-SAP TR=3.119Gbps)	QPSK with RS or LDPC +FDE (CP=128) (PHY-SAP TR=2.495Gbps)
	3.56Gbps	8PSK with RS (PHY-SAP TR=4.679Gbps)	8PSK with RS or LDPC +FDE (CP=128) (PHY-SAP TR=3.743Gbps)
UM5	1.50Gbps	QPSK with RS (PHY-SAP TR=3.119Gbps)	
	2.25Gbps	QPSK with RS (PHY-SAP TR=3.119Gbps)	

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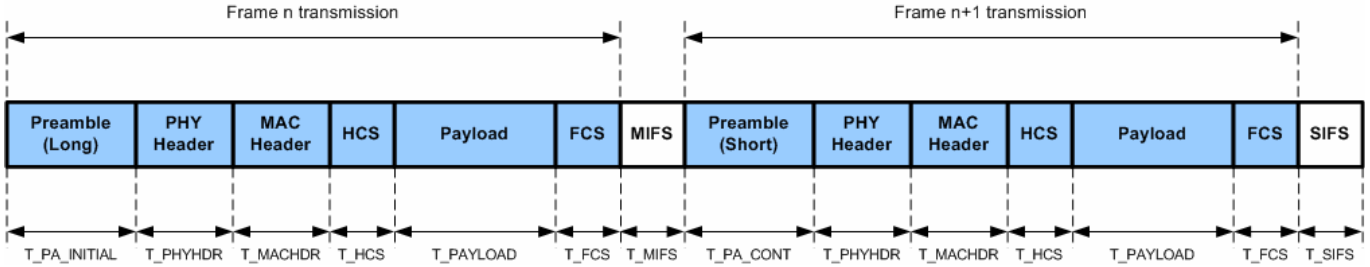
7.6: Frame size

- Assumed Frame size:



(05/493r27)

	Requirements	Transmission mode	T_PA_INITIAL/ T_PA_CONT(ns)	T_PHYHDR (ns)	T_MACHDR (ns)	T_HCS (ns)	T_PAYLOAD (ns)	T_FCS (ns)	Frame size (ns)
UM1	1.78Gbps, LOS	QPSK with RS (PHY-SAP TR=3.119Gbps)	846.15	38.46	96.15	19.23	5252.97	10.26	6263.22
	1.78Gbps, NLOS	QPSK with RS or LDPC +FDE (CP=128) (PHY-SAP TR=2.495Gbps)	846.15	48.05	120.12	24.02	6566.73	12.83	7617.9
	3.56Gbps, LOS	8PSK with RS (PHY-SAP TR=4.679Gbps)	846.15	38.46	96.15	19.23	3501.6	6.84	4508.43
	3.56Gbps, NLOS	8PSK with RS or LDPC +FDE (CP=128) (PHY-SAP TR=3.743Gbps)	846.15	48.05	120.12	24.02	21390.33	8.55	22428.67
UM5	1.50Gbps,LOS	QPSK with RS (PHY-SAP TR=3.119Gbps)	846.15	38.46	96.15	19.23	5252.97	10.26	6263.22
	2.25Gbps, LOS	QPSK with RS (PHY-SAP TR=3.119Gbps)	846.15	38.46	96.15	19.23	5252.97	10.26	6263.22

- In UM1-3.56Gbps-NLOS case, frame expansion 10008 octets payload is employed (If MSDU aggregation is used, 5frames aggregation for 10240octets needed for 3.564Gbps throughput)
- 2048 octets payload is employed for all others

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7.7: CAP duration

- A CAP duration of 300μs is assumed (for ADD frame, long CAP may be required)

7.8: Preamble types used (if different)

- The same preambles (as shown in slide 103) are used

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7.9: Superframe size and guard interval duration

- Superframe size -

- Two superframe lengths are defined
  - For beacon period and time slot assignment
    - 1- 20 ms
  - For Automatic Device Discovery
    - Multi-superframe

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7.9: Superframe size and guard interval duration

- Guard interval duration -

- Guard interval duration is proposed as following
  - GuardTime = 1μs

  Assumption:
  - GuardTime = (Beacon_missing_times*2+2) x MaxDrift

    = 1μs
    - MaxDrift = Clock accuracy (ppm) / 10^6 *Superframe length
      - MaxDrift = 5(ppm, assumed as 1-5) /10^6 * 20ms =100 ns
    - 4 is assumed for Beacon_missing_times

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8. Other items to be reported in “System requirements” and “Selection criteria” documents

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List of other Items

- Item 4.2.2: Interference and Susceptibility
- Item 4.2.3: Coexistence
- Item 4.3.1: Manufacturability
- Item 4.3.2: Time to Market
- Item 4.3.3: Regulatory impact
- Item 6.1: Size and form factor
- Item 6.7: Sensitivity
- Item 6.8: Power Management modes
- Item 6.9: Antenna practicality

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Item 4.2.2: Interference and Susceptibility

- DUR (Desired to undesired signal power ratio) of 9.3 dB is required against interference independently of symbol rates of in-band interferer

	Minimum tolerable DUR (Maximum P_I-P_d)	
Symbol rate of interferer	200 MHz	1200 MHz
Generic in-band modulated interferer	**9.3 (-9.3) dB**	**9.3 (-9.3) dB**
Out of band interference	Implementation dependent	

- Minimum tolerable DUR for PER of 8% was evaluated when the received desired signal power is 6 dB above the receiver sensitivity level
- Inverse of the tolerable DUR corresponds to the value of "P_I-P_d" defined in Selection criteria

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Item 4.2.3: Coexistence

Interferer (proposed PHY) parameter			
Tx power [dBm]	10	10	10
Tx ant gain [dBi]	15	15	15
Tx bandwidth [MHz]	2080	2080	2080
Victim parameter			
Victim bandwidth [MHz]	ARIB STD-T69	ARIB STD-T74	IEEE802.16
	1208	200	28
Victim Rx antenna gain [dBi]	ARIB STD-T69	ARIB STD-T74	IEEE802.16
	0	0	25
Victim Rx minimum sensitivity [dBm]	ARIB T69	ARIB T74	IEEE802.16
	-48	-64.8	-76
Separation distance and received interfering power			
The separation distance [m]	1.4	3.9	92
Received interference power [dBm]	-48.3	-65.0	-76.0

- The separation distance to be reported is the distance at which interfering average power is equal to the minimum sensitivity levels of victim devices

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Item 4.3.1: Manufacturability

- UM5 (Kiosk) devices can be implemented on CMOS
- Saturated power P_{sat} of Power amplifier can reach to 10 dBm approximately with 90nm CMOS technology

Reference:

T. Yao, et al.,"Algorithmic Design of CMOS LNAs and PAs for 60 GHz Radio", IEEE Solid-State Circuits, Vol. 42, No. 5, May 2007

- PSK modulation based Single Carrier (SC) transmission is one of appropriate choices for CMOS

- By integrating all the circuit blocks into CMOS, unnecessary interconnections can be eliminated, which results in less power consumption and lower cost

Low cost with CMOS

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CMOS RF Examples

- CMOS Receiver
  - *Razavi, "A 60GHz CMOS Receiver Front-End", IEEE J. Solid-State Circuits, Vol. 41, No.1, January 2006*
    - Voltage Gain 28 dB
    - Noise Figure 12.5 dB
    - 1-dB Compression Point -22.5 dBm
    - Power Dissipation 9 mW
    - Supply Voltage 1.2 V
    - Active Area 300um x 400um
    - Technology 0.13-um CMOS

- CMOS PA
  - *T. Yao, et al. "Algorithmic Design of CMOS LNAs and PAs for 60-GHz Radio", IEEE J. Solid-State Circuits, Vol.42, No.5 May 2007*
    - Frequency 60 GHz
    - Psat +9.3 dBm
    - Gain 5.2 dB
    - Current 26.5 mA (1.5 V)
    - Techinology 90 nm CMOS

- CMOS Prescaler
  - *C. Lee, et al, "44 GHz Dual-Modulus Devide-by-4/5 Prescaler in 90 nm CMOS Technology", IEEE CICC, 2006*
    - Frequency Range 38.7G ~ 44 GHz
    - Power Dissipation 45mW, (1.2V)

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Item 4.3.2: Time to Market

- 90nm/65nm CMOS process are available now
- Conventional packaging technology (eg. Flip-Chip) are ready to mass-produce

Item 4.3.3: Regulatory impact

- Our proposal can meet the US, JP, Canada, Korea regulations

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Item 6.1: Size and form factor

- Fully integrated RF front-end on commercialized CMOS processes have been demonstrated[*1]

[*1] S. Emami, C.Doan, A. Niknejad, and R. Brodersen, “A 60-GHz CMOS Front-End Receiver,” ISSCC’07, S10.2

Item 6.7: Sensitivity

- HRT mode (2.1:QPSK with RS(255, 239))
  - For 1.78 Gbps MAC-SAP throughput in UM1: < -54 dBm
  - For 1.5 Gbps MAC-SAP throughput in UM5: <-56 dBm

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Item 6.8: Power Management modes

- All 802.15.3b power management modes are supported

Item6.9: Antenna practicality

- Moderate gain antennas are very small
- 15 dBi Gain can be created with size of 35 mm square [*2]

[*2] H. Tanaka, T. Ohira, “Beam-steerable Planar Array Antennas Using Varactor Diodes for 60-GHz-band Applications,” 33rd European Microwave Conference, pp.1067-1070

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Summary of CoMPA PHY proposal

- **Channelization**
  - 2080MHz bandwidth/ch, 4ch/9GHz bandwidth
- **Mandatory Features: 2Gbps@PHY-SAP**
  - Single Carrier (SC) modulation (QPSK) with Reed Solomon (RS) coding (with frequency domain equalizer (FDE) for NLOS environments)
- **Optional Features: 3Gbps@PHY-SAP**
  - SC modulation (8PSK or TC8PSK) with RS coding or LDPC (with FDE for NLOS environments)
- **Three transmission modes are supported**
  - High rate transmission mode (HRT)
  - Medium rate transmission mode (MRT)
  - Low rate transmission mode (LRT)
- **Flexible standard to support multiple PHY**
  - Support co-existence of multiple PHYs and interference avoidance among the PHY networks with different channel plans
- **CoMPA PHY proposal meets all system requirements**

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