

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

Submission Title: [Merged proposal: New PHY Layer and Enhancement of MAC for mmWave System Proposal]

Date Submitted: [November 13, 2007]

Source: [Hiroshi Harada⁽¹⁾, Ismail Lakkis⁽²⁾ (representative contributors), other contributors are listed in “Contributors” slides]

Company [National Institute of Information and Communications Technology (NICT), Tensorcom Inc., and other contributors are listed in “Contributors” slides]

Address¹[3-4 Hikari-no-oka, Yokosuka-shi, Kanagawa 239-0847, Japan]

Voice¹:[+81-46-847-5074] , FAX¹: [+81-46-847-5440]

Address²[10875, Rancho Bernardo Rd #108, San Diego, CA, USA]

Voice²:[858-231-9753], FAX²: [858-676-0300]

E-Mail:[harada@nict.go.jp, ilakkis@tensorcom.com (other contributors are listed in “Contributors” slides)]

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

Abstract: [Merged proposal of new PHY layer and enhancement of MAC for mmWave system proposal]

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

Notice: This document has been prepared to assist the IEEE P802.15. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein.

Release: The contributors acknowledge and accept that this contribution becomes the property of IEEE and may be made publicly available by P802.15.

Merged proposal:
New PHY Layer and Enhancement of
MAC for mmWave System Proposal

Nov 13, 2007

Contributors (1/4)

Name	Affiliation	E-mail
Hiroshi Harada	NICT	harada@nict.go.jp
Ismail Lakkis	Tensorcom Inc.	ilakkis@tensorcom.com
Yozo Shoji	NICT	shoji@nict.go.jp
Fumihide Kojima	NICT	f-kojima@nict.go.jp
Ryuhei Funada	NICT	funada@nict.go.jp
Ming Lei	NICT	minglei@nict.go.jp
Yoshinori Nishiguchi	NICT	nishiguchi@nict.go.jp
Ryota Kimura	NICT	r.kimura@nict.go.jp
Pyo Chang-Woo	NICT	cwpyo@nict.go.jp
Zhou Lan	NICT	lan@nict.go.jp
Chin-Sean Sum	NICT	sum@nict.go.jp
Tuncer Baykas	NICT	tuncerbaykas@nict.go.jp
Masahiro Umehira	NICT	umehira@mx.ibaraki.ac.jp
Shuzo Kato	NICT	shu.kato@nict.go.jp
Akio Iso	NICT	Akio.Iso@nict.go.jp
Hiroyo Ogawa	NICT	hogawa@nict.go.jp
Kenichi Kawasaki	Sony Corp.	Kenichi.Kawasaki@jp.sony.com
Makoto Noda	Sony Corp.	MakotoB.Noda@jp.sony.com
Hiroyuki Yamagishi	Sony Corp.	Hiroyuki.Yamagishi@jp.sony.com
Masashi Shinagawa	Sony Corp.	Masashi.Shinagawa@jp.sony.com
Keitarou Kondou	Sony Corp.	Keitarou.Kondou@jp.sony.com
Kazuaki Takahashi	Matsushita Electric Ind. Co., Ltd.	takahashi.kazu@jp.panasonic.com
Hiroyuki Nakase	Tohoku University	nakase@riec.tohoku.ac.jp
Ichihiko Toyoda	NTT Corp.	toyoda.ichihiko@lab.ntt.co.jp
Ichirou Ida	Fujitsu Limited	Ida.ichirou@jp.fujitsu.com
Yasuyuki Ooishi	Fujitsu Limited	yasu@labs.fujitsu.com

Contributors (2/4)

Name	Affiliation	E-mail
Tomohiro Seki	NTT Corp.	seki.tomohiro@lab.ntt.co.jp
Kaoru Yokoo	Fujitsu Limited	yokoo@labs.fujitsu.com
Taisuke Matsumoto	Matsushita Electric Ind. Co.,Ltd.	matsumoto.taisuke@jp.panasonic.com
Raymond Yu Zhan	Panasonic Singapore Laboratories	Raymond.Yuz@sg.panasonic.com
Michael Sim	Panasonic Singapore Laboratories	Michael.Simhc@sg.panasonic.com
Huang Lei	Panasonic Singapore Laboratories	Lei.Huang@sg.panasonic.com
Yukimasa Nagai	Mitsubishi Electric Corp.	Nagai.Yukimasa@ds.MitsubishiElectric.co.jp
Takahisa Yamauchi	Mitsubishi Electric Corp.	Yamauchi.Takahisa@cw.MitsubishiElectric.co.jp
Akinori Fujimura	Mitsubishi Electric Corp.	Fujimura.Akinori@dw.MitsubishiElectric.co.jp
Hideto Ikeda	Oki Electric Industry Co., Ltd.	ikeda637@oki.com
Tadahiko Maeda	Oki Electric Industry Co., Ltd.	maeda097@oki.com
Masamune Takeda	MASPRO DENKOH Corp.	takeda3026@maspro.co.jp
Hiroyoshi Konishi	MASPRO DENKOH Corp.	konishi2761@maspro.co.jp
Shoichi Kitazawa	ATR	kitazawa@atr.jp
Masazumi Ueba	ATR	ueba@atr.jp
Amane Miura	ATR	amane@atr.jp
Kenichi Maruhashi	NEC Corp.	k-maruhashi@bl.jp.nec.com
Yoshitsugu Fujita	KYOCERA Corp.	yoshitsugu.fujita.gt@kyocera.jp
Hiroshi Uchimura	KYOCERA Corp.	hiroshi.uchimura.hs@kyocera.jp
Makoto Ando	Tokyo Institute of Technology	mando@antenna.ee.titech.ac.jp
Jiro Hirokawa	Tokyo Institute of Technology	jiro@antenna.ee.titech.ac.jp
Junichi Takada	Tokyo Institute of Technology	takada@ide.titech.ac.jp
Takuichi Hirano	Tokyo Institute of Technology	hira@antenna.ee.titech.ac.jp
Yoshio Aoki	Eudyna Devices Inc	y.aoki@eudyna.com
Kazufumi Igarashi	Japan Radio Co., Ltd.	igarashi.kazufumi@jrc.co.jp
Tsukasa Yoneyama	EMMEX, INC.	yoneyama@tohtech.ac.jp
Yukihiro Shimakata	TAIYO YUDEN Co., LTD.	y-shima@jty.yuden.co.jp
Shoji Kuriki	RICOH COMPANY, LTD.	shoji.kuriki@nts.ricoh.co.jp
Toyoo Tanaka	Toyo System Engineering Co., Ltd.	toyoo_tanaka@u-tse.co.jp

Contributors (3/4)

Name	Affiliation	E-mail
Bruce Bosco	Motorola, Inc.	Bruce.A.Bosco@Motorola.com
Paul Gorday	Motorola, Inc.	Paul.Gorday@Motorola.com
Tian-Wei Huang	National Taiwan University	twhuang@cc.ee.ntu.edu.tw
Ching-Kuang Tzuang	National Taiwan University	cktzuang@cc.ee.ntu.edu.tw
Juinn-Horng Deng	CSIST Co.	jh.deng@nsa.hinet.net
Yu-Min Chuang	CSIST Co.	ymchuang@cml.hinet.net
André Bourdoux	IMEC	bourdoux@imec.be
Jimmy Nsenga	IMEC	nsengaj@imec.be
Wim Van Thillo	IMEC	vthillo@imec.be
Stefaan De Rore	IMEC	derore@imec.be
Pascal Pagani	France Telecom	pascal.pagani@orange-ftgroup.com
Isabelle Siaud	France Telecom	isabelle.siaud@orange-ftgroup.com
Wei Li	France Telecom	wei3.li@orange-ftgroup.com
Anne-Marie Ulmer-Moll	France Telecom	annemarie.ulmermoll@orange-ftgroup.com
Marie-Hélène Hamon	France Telecom	mhelene.hamon@orange-ftgroup.com
Maxim Piz	IHP	piz@ihp-microelectronics.com
Eckhard Grass	IHP	grass@ihp-microelectronics.com
Klaus Tittelbach	IHP	tittelbach@ihp-microelectronics.com
Frank Herzel	IHP	herzel@ihp-microelectronics.com
Alberto Valdes Garcia	IBM	avaldes@us.ibm.com
Troy Beukema	IBM	troyb@us.ibm.com
Yasunamo Katayama	IBM	yasunaok@jp.ibm.com
Brian Floyd	IBM	brianfl@us.ibm.com
Scott Reynolds	IBM	skreyn@us.ibm.com
Daiju Nakano	IBM	dnakano@jp.ibm.com
AbbieMathew	New LANs	amathew@newlans.com

Contributors (4/4)

Name	Affiliation	E-mail
Seongsoo Kim	Samsung Electronics Co., Ltd.	seongsoo1.kim@samsung.com
Edwin Kwon	Samsung Electronics Co., Ltd.	cy.kwon@samsung.com
Chiu Ngo	Samsung Electronics Co., Ltd.	chiu.ngo@samsung.com
Huaning Niu	Samsung Electronics Co., Ltd.	huaning.niu@samsung.com
Jisung Oh	Samsung Electronics Co., Ltd.	jisung0714.oh@samsung.com
Sandra Qin	Samsung Electronics Co., Ltd.	x.qin@samsung.com
Huai-Rong Shao	Samsung Electronics Co., Ltd.	hr.shao@samsung.com
Harkirat Singh	Samsung Electronics Co., Ltd.	har.singh@samsung.com
Pengfei Xia	Samsung Electronics Co., Ltd.	pengfei.xia@samsung.com
Su-Khiong Yong	Samsung Electronics Co., Ltd.	ysk@ieee.org
Dagnachew Birru	Philips	dagnachew.birru@philips.com
Richard Chen	Philips	richard.chen@philips.com
Chun-Ting Chou	Philips	chun-ting.chou@philips.com
Ciaran Connell	Decawave	ciaran.connell@decawave.com
Seungsik Eom	Korea University	drdja@korea.ac.kr
Brian Gaffney	Decawave	brian.gaffney@decawave.com
Jinkyong Kim	ETRI	jdkim@etri.re.kr
Yongsun Kim	ETRI	doori@etri.re.kr
Kyeongpyo Kim	ETRI	kpkim@etri.re.kr
Hyoungjin Kwon	ETRI	kwonjin@etri.re.kr
Young-Chai Ko	Korea University	koyc@korea.ac.kr
Joy Laskar	GEDC	joy.laskar@ece.gatech.edu
Wooyong Lee	ETRI	wylee@etri.re.kr
Michael Mc Laughlin	Decawave	michael@decawave.com
Stephane Pinel	GEDC	pinel@ece.gatech.edu
Alireza Seyedi	Philips	alireza.seyedi@philips.com
Hong Zhai	Philips	hong.zhai@philips.com
Arthur W. Astrin	Astrin Radio Artisty	art@astrinradio.com

Merged Proposal: New PHY Layer and Enhancement of MAC Layer for mmWave Systems Proposal By

COMPA and Partners:

NICT, Sony Corp., Matsushita Electric Ind. Co., Ltd., Tohoku University, NTT Corp., Fujitsu Limited, Panasonic Singapore Laboratories, Mitsubishi Electric Corp., Oki Electric Industry Co., Ltd., MASPRO DENKOH Corp., ATR, NEC Corp., KYOCERA Corp., Tokyo Institute of Technology, Eudyna Devices Inc., Japan Radio Co., Ltd., EMMEX, INC., TAIYO YUDEN Co., LTD., RICOH COMPANY, LTD., Toyo System Engineering Co., Ltd., Motorola, Inc., National Taiwan University, CSIST Co., IMEC, France Telecom, IHP, IBM, New LANs, Samsung Electronics Co., Ltd., Philips, Decawave, Korea University, ETRI, GEDC, Astrin Radio Artisty

Tensorcom and Partners:

Tensorcom, France Telecom, IHP, NICT, Samsung

Scope

This draft defines a new millimeter wave (mmWave) based alternative physical layer (PHY) for the existing 802.15.3 Wireless Personal Area Network (WPAN) Standard 802.15.3-2003 and Standard 802.15.3b-2005, and enhancements to Medium Access Control Layer (MAC) to enable operation in the mmWave, with multi-Gbps throughput.

The draft is composed of three parts: Common rate (CR) and Mandatory rate transmission, Single carrier (SC) transmission and OFDM transmission modes. The common rate is introduced to realize DAA (detection and avoidance) accurately and to protect interference vulnerable video transmissions from interference, and SC transmission modes are intended to cover various applications from low to high bit rate applications more suitable for power limited and in near LOS environments whereas OFDM transmission systems are more suitable for high bit rate transmissions over limited bandwidth and in non-LOS environments.

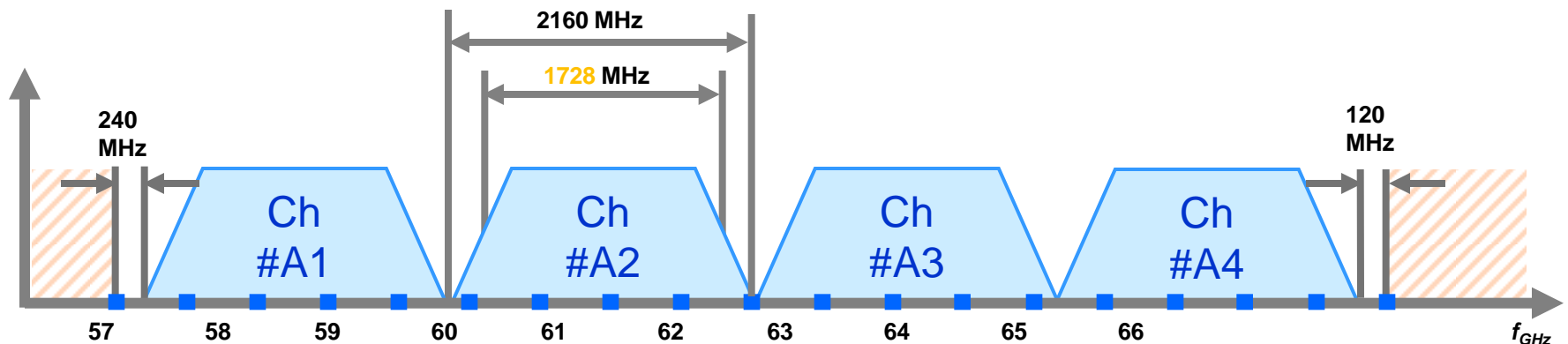
The proposed SC and OFDM transmission systems employ homogeneous frame format and parameters including the sampling clock frequency, preambles, cyclic prefix and so on which will allow vendors implement dual mode terminals in a very straight forward way and eventually lower product cost.

Conditions to Merge

1. The **same channel plan** to avoid interference efficiently – 3 (4) channels over 7 (9) GHz
2. The **Common rate** (50 Mbps single carrier) communication capability to avoid interference accurately - to ensure **interference free operation** through DEV-DEV communication which could be done by detection-and avoidance (DAA) with much lower accuracy
3. The **Mandatory rate** to meet
PAR: 1 Gbps or higher transmission
– **1.5 Gbps in Single carrier mode**

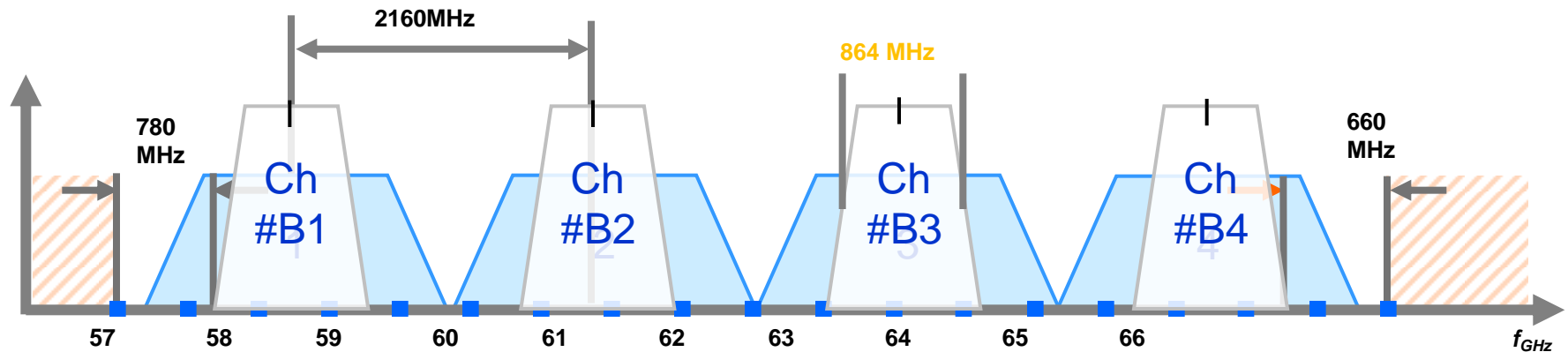
1. Same Channel plan: full-rate (2GHz)

Channel Number	Low Freq. (GHz)	Center Freq. (GHz)	High Freq. (GHz)	Nyquist BW (MHz)	Roll-Off Factor
A1	57.240	58.320	59.400	1728	0.25
A2	59.400	60.480	61.560	1728	0.25
A3	61.560	62.640	63.720	1728	0.25
A4	63.720	64.800	65.880	1728	0.25



1. Same Channel plan: Half-rate (1GHz)

Channel Number	Low Freq. (GHz)	Center Freq. (GHz)	High Freq. (GHz)	Nyquist BW (MHz)	Roll-Off Factor
B1	57.78	58.32	58.86	864	0.25
B2	59.94	60.48	61.02	864	0.25
B3	62.10	62.64	63.18	864	0.25
B4	64.26	64.80	65.34	864	0.25



2. Common rate (50 Mbps) communication

- Common rate:
 - **a base rate** single carrier (SC) transmission
 - **mandatory** for all devices except non-PNC capable OFDM or non-PNC capable OOK devices
 - **a bridge to realize coexistence and interoperability between SC and OFDM**, OOK and also functions
 - **the most robust performance** in all transmission modes,
 - a long transmission range **with “omni” * antennas in both LOS (AWGN) and NLOS channels without any equalization**
 - 10 m (TX and RX antenna gains are 4 dBi) in LOS (AWGN)
 - 10 m (TX and RX antenna gains are 4 dBi) in NLOS
 - **used for beaconing and signaling** for association / disassociation, beam forming, and channel probing
 - **employs p/2-BPSK and Reed Solomon (RS) (255, 239) and Golay code of 64 chips (equivalent spreading factor: 32)**,
 - can be **easily implemented**
 - extra protection designed for **preamble and header** of the Common mode to further increase its robustness for a “fallback mode”

2. PHY parameters for Common rate

Parameters	Specification		
Channel separation	2160 MHz		
Basic transmission scheme	Single Carrier (SC) transmission		
Multiple access scheme	TDMA/CSMA		
Chip rate	1728 MHz		
Root raised cosine filter	Roll-off factor =0.25		
Antenna	TX and RX antennas each with 4 dBi gain (8 dBi in total)		
	PHY Preamble	Frame Header	Payload
Modulation	$\pi/2$ BPSK/(G)MSK		
FEC scheme	N/A	RS(37, 21) (Shorten code of RS(255,239) (Coding rate = 0.57)	RS(255, 239) (Coding rate = 0.9373)
PHY Preamble	<p>Long preamble including SYNC and channel estimation (CE) sequences</p> <p>SYNC: 36 repetitions of Golay code of 128 chips</p> <p>CE sequence (CES): 4 repetitions of Golay code of 256 chips</p>	N/A	N/A
Code spreading	N/A	Golay code of 64 chips (equivalent SF: 32)	Golay code of 64 chips (equivalent SF: 32)
Information data (octets)	N/A	(PHY header :10 + MAC header: 10+ HCS:2). Total: 22	Payload: 0-65531 + FCS: 4
Information data rate (Mbps)	N/A	30.0	50.6
Operating range	10m in both LOS (AWGN) and NLOS (CM 2.3) channels		

2. Common rate (50 Mbps single carrier) communication capability required for all SC devices and PNC capable OFDM or OOK Devices

- All 802.15.3c compliant PNC capable devices shall support dependent piconets both as a parent PNC and as a dependent PNC. A DEV may start a dependent PNC as described in 8.2.5 and 8.2.6. enable communications with and among entities that do not support common rate
- A PNC capable OOK/OFDM device can become a member of an existing piconet. This PNC capable OOK/OFDM device can borrow a time slot in CTA and create a child piconet in which other non-PNC capable OOK/OFDM devices can enjoy OOK or OFDM piconet communications respectively.

3. Mandatory rate (single carrier) required for all SC devices and PNC capable devices only

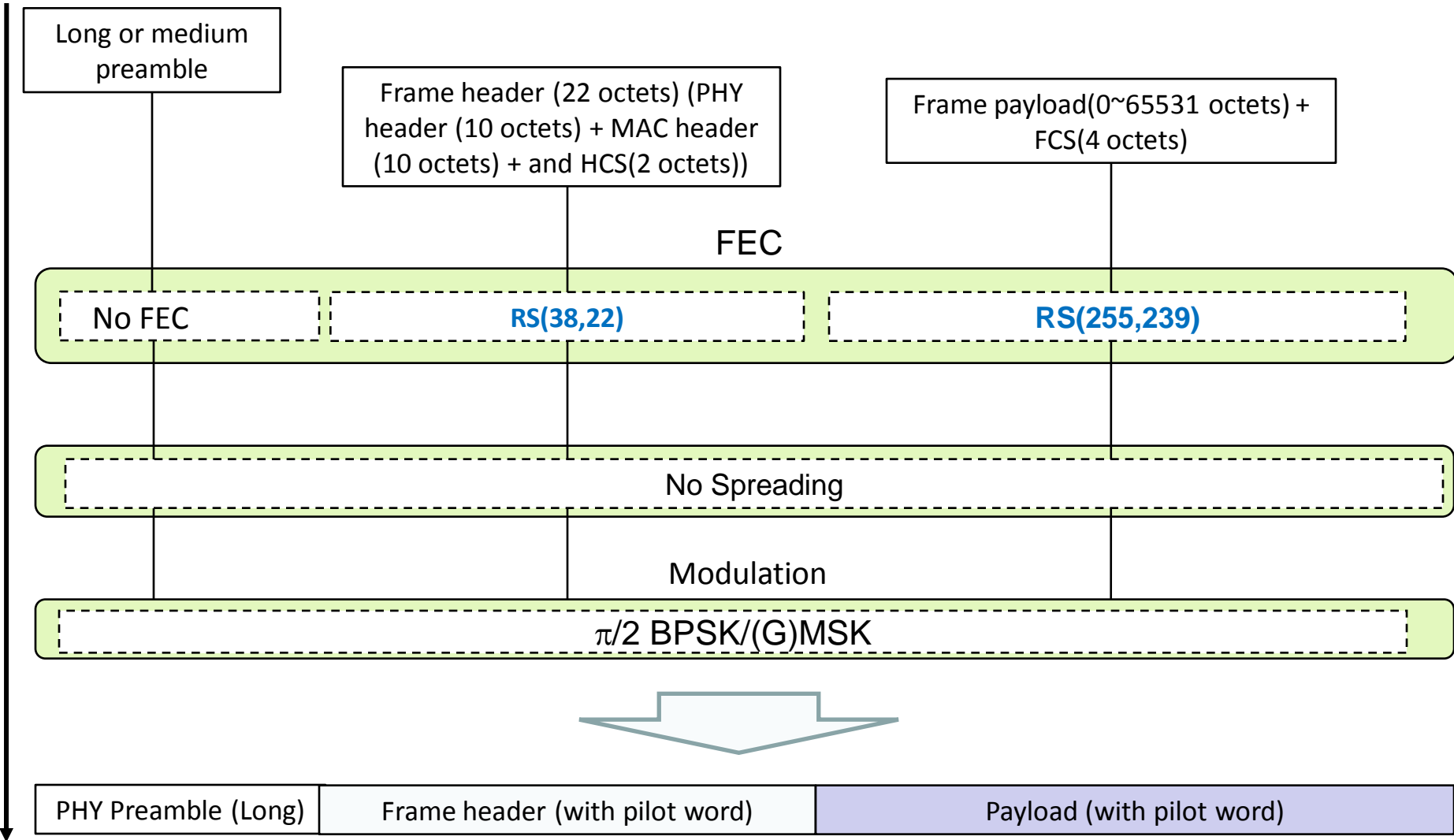
- To meet “PAR: 1 Gbps or higher transmission”
-1.5 Gbps (PHY-SAP)
- In Single carrier mode
- Transmission range: 5 m in LOS environments
- Based on Common rate transmission capability

3. Mandatory Rate Major Parameters

- Mandatory low rate (MLR) is a mandatory data transmission which shall be supported by all SC and PNC-capable devices.
- MLR is defined to fulfill the 1.5 Gbps data rate as required in PAR.

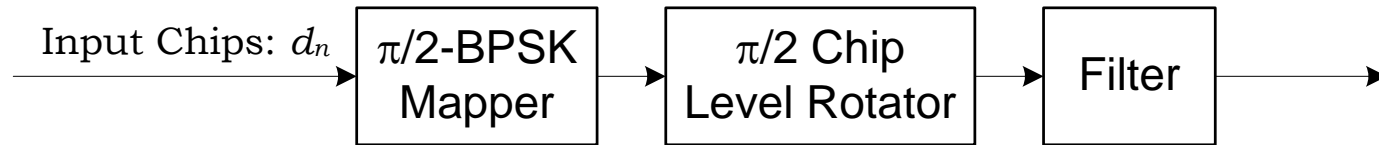
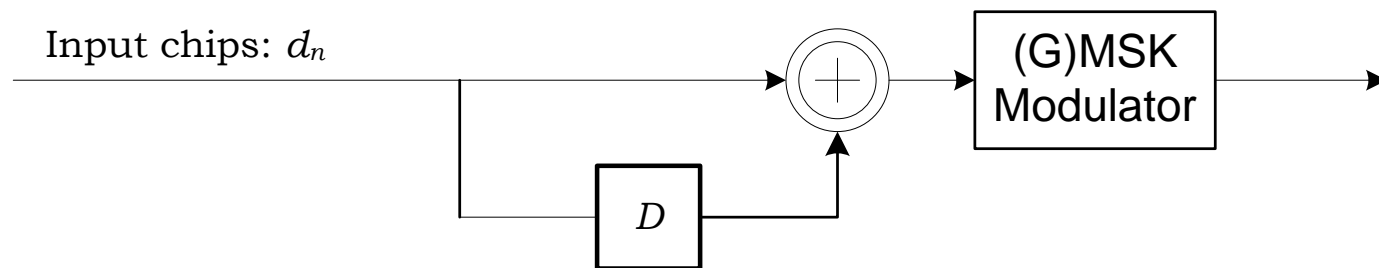
	PHY Preamble	Frame Header	Payload
Modulation	$\pi/2$ BPSK / (G)MSK		
FEC scheme	N/A	RS(38, 22) (Coding rate = 0.57)	RS(255, 239) (Coding rate = 0.9373)
PHY Preamble	<p>Long preamble: SYNC: 32 repetitions of Golay code of 128 chips Or Medium preamble SYNC: 16 repetitions of Golay code of 128 chips</p> <p>Both long and medium preamble also include: SFD: 4 Golay codes of 128 chips CES: 2 Golay codes of 256 chips with both cyclic prefix and postfix</p>	N/A	N/A
Code spreading	N/A		
Data burst length	N/A	64	<p>256 (mandatory) with pilot word length 0, 16 (default), 32 and 64</p> <p>512 (optional) with pilot word length 32, 64, 96 and 128</p>

3. Frame configuration



3. SC PHY mandatory parameters

Parameters	Specification	
	Common Rate (CR)	Mandatory Low Rate (MLR)
PHY-SAP data rate	50.2 Mbps	1506.6 Mbps
Channel separation	2160 MHz	
Chip rate	1728 MHz	
Modulation	$\pi/2$ BPSK	
Burst length	256 chips	
PHY preamble	Long preamble: 36 Golay codes of 128 chips for packet synchronization and 2 Golay codes of 256 chips with both cyclic prefix and post fix for channel estimation	
Header rate	31.3 Mbps	594.0 Mbps
Frame Header	FEC coding: RS(38,22)	
	Code spreading: 32	Code spreading: no spreading
	PWCP length: 0 chip	PWCP length: 64 chips
	Pilot CES length: 0 chip	
	Pilot CES period: Infinitely	
Frame payload	FEC coding : RS(255,239)	
	Code spreading: 32	Code spreading: No spreading
	PWCP length: 0	PWCP length: 16

a) $\pi/2$ -BPSK Modulator

b) Precoded (G)MSK Modulator

Figure S1 Examples of $\pi/2$ -BPSK realizations for CR and MLR
a) with $\pi/2$ -BPSK modulator, b) with Pre-coded (G)MSK modulator

Reed Solomon Encoder

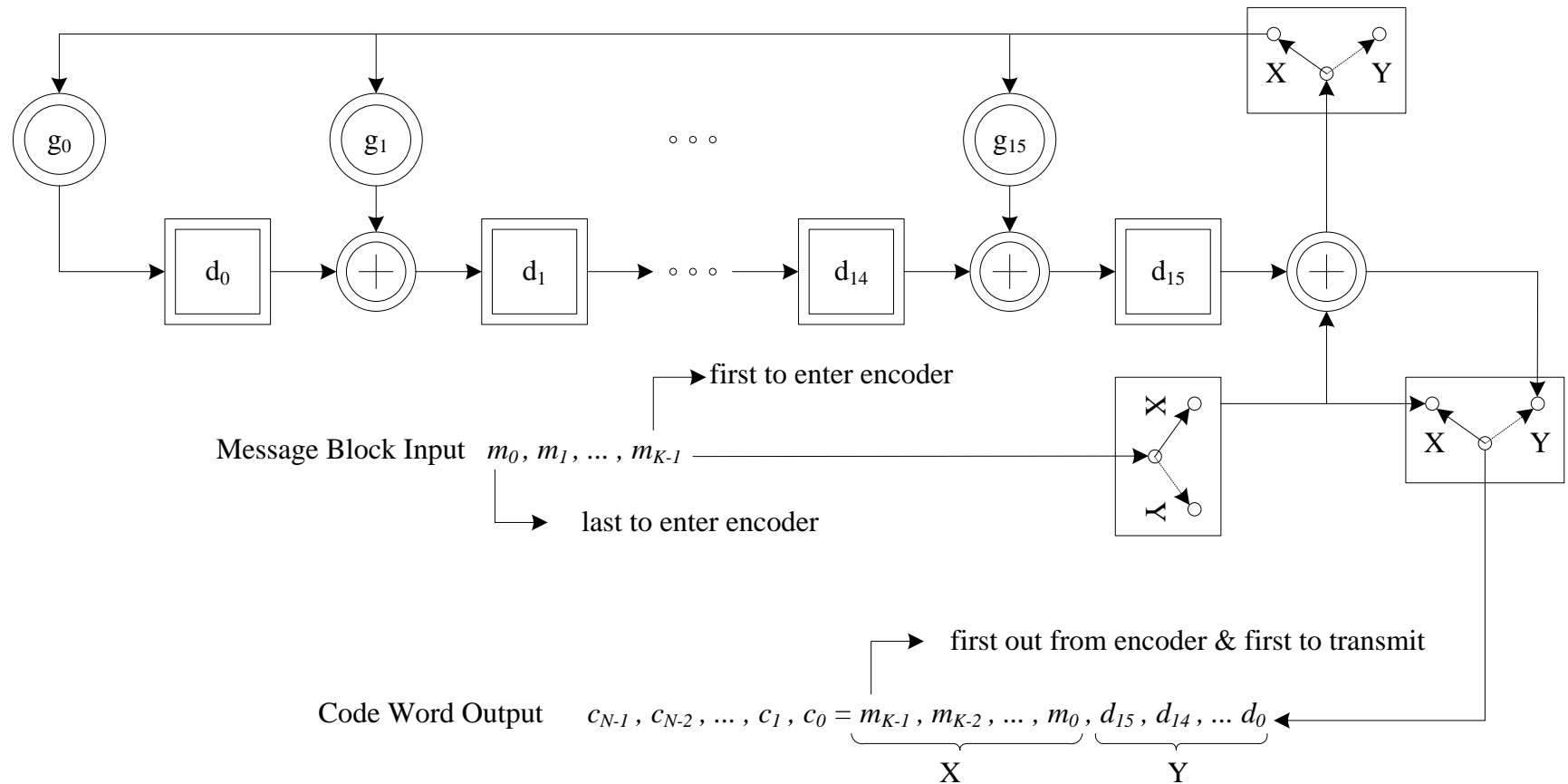


Figure S2 Reed Solomon encoder in GF(28).

Single Carrier (SC) Mode

Suitable for power limited and near line of sight communications with transmission speed ranging from low to high, for power efficient and low cost / portable device applications

1. Bit rates (PHY-SAP)
50 Mbps to 6Gbps, Various modulations and FEC together with FDE allows SC mode operation to realize from 1 Gbps class applications to several Gbps applications easier with proper header and preamble protection
2. Operation environments
Suitable for LOS and NLOS with FDE (Frequency domain equalizer)
3. Transmission range
10 m coverage by common mode in both LOS and NLOS environments, Higher bit rates with narrower coverage for personal area network
4. Applications:
SC allows low number of bit A/D converter implementation of receivers while a couple of Gbps are easily achievable resulting in very low power and high speed applications mandatory for portable terminal applications
5. MAC
Required MAC modifications are minimal to handle “strong directivity of millimeter wave” and a straight forward implementation is feasible

SC Mandatory Mode and Parameter Summary

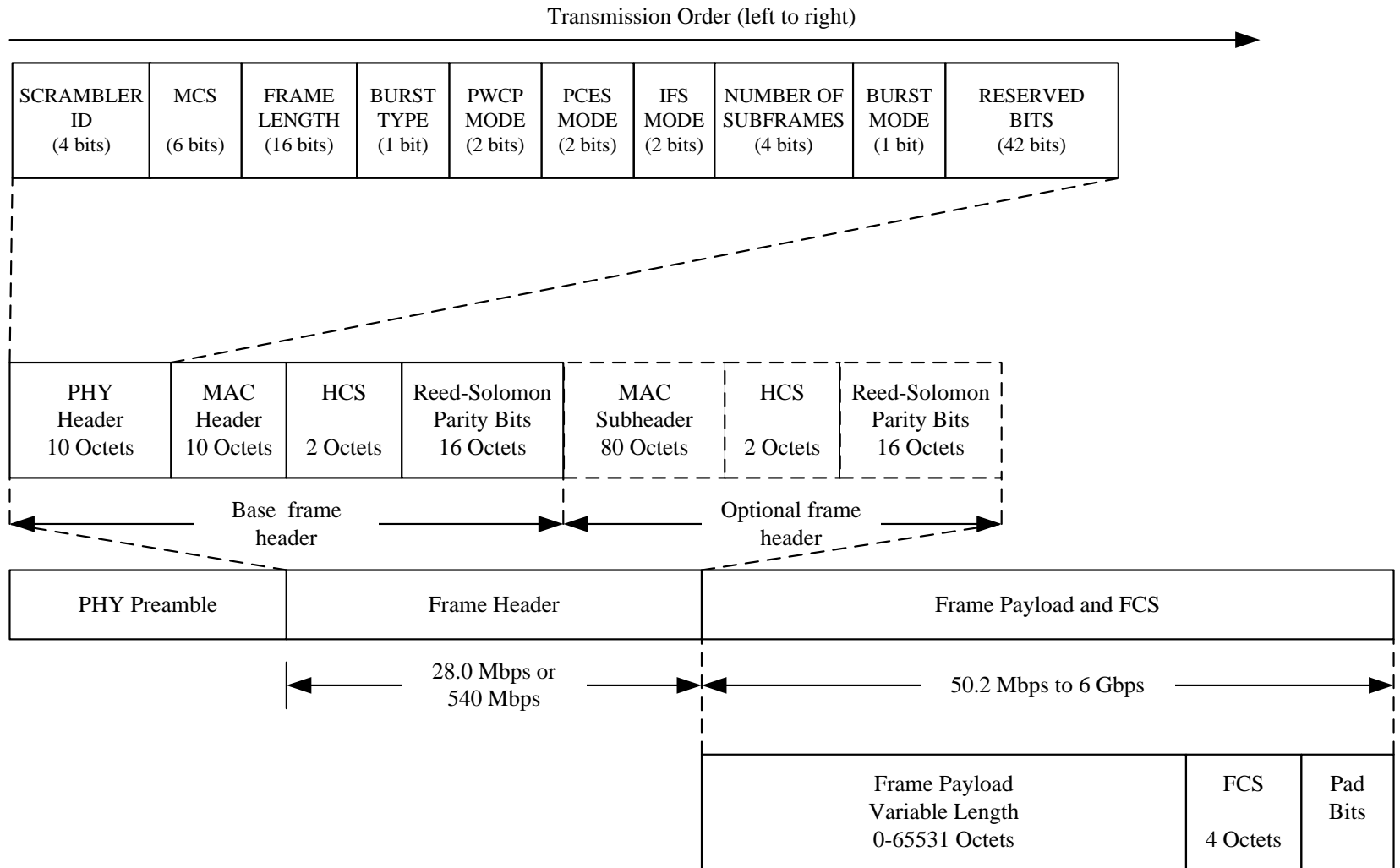
1. Mandatory modes: $\pi/2$ -BPSK/(G)MSK,
 - 50 Mbps for signaling (CR)
 - 1.5 Gbps for data transmission (MLR)
2. Mandatory FEC: Reed Solomon,
3. Optional modulation: $\pi/2$ -QPSK, $\pi/2$ -8 PSK, $\pi/2$ -16 QAM, TCM, $\pi/2$ -NSQAM, $\pi/2$ -Star8 QAM, DRB (Dual rail bipolar), OOK,
4. Optional FECs: LDPC, Convolutional coding
5. Optional frame aggregation, UEP, Beam forming

SC mode (CR, MLR, MR)

MCS Class	MCS Identifier	Data Rate (Mbps)	Symbol /Chip Rate (Mcps)	Modulation Scheme	Spreading factor	FEC Type	FEC Rate	Pilot Word Length (Symbols /chips)	Burst Length (Symbols /chips)
CR	CR (LR1)	50.2	1728	$\pi/2$ -BPSK/(G)MSK	32	RS(255,239)	0.937	0	256
MLR	MLR(LR13)	1506.6	1728	$\pi/2$ -BPSK/(G)MSK	1	RS(255,239)	0.937	16	256
LR	LR1 (CR)	50.2	1728	$\pi/2$ -BPSK/(G)MSK	32	RS(255,239)	0.937	0	256
	LR2	188.3	1728	$\pi/2$ -BPSK/(G)MSK	8	RS(255,239)	0.937	16	256
	LR3	376.6	1728	$\pi/2$ -BPSK/(G)MSK	4	RS(255,239)	0.937	16	256
	LR4	401.9	1728	$\pi/2$ -BPSK/(G)MSK	2	LDPC(576,288)	0.500	16	256
	LR5	401.9	1728	$\pi/2$ -BPSK/(G)MSK	2	CC(R=1/2,K=5)	0.500	16	256
	LR6	602.8	1728	$\pi/2$ -BPSK/(G)MSK	2	LDPC(576,432)	0.750	16	256
	LR7	703.3	1728	$\pi/2$ -BPSK/(G)MSK	2	LDPC(576,504)	0.875	16	256
	LR8	753.3	1728	$\pi/2$ -BPSK/(G)MSK	2	RS(255,239)	0.937	16	256
	LR9	803.7	1728	$\pi/2$ -BPSK/(G)MSK	1	LDPC(576,288)	0.500	16	256
	LR10	1071.6	1728	$\pi/2$ -BPSK/(G)MSK	1	CC(R=2/3,K=5)	0.667	16	256
	LR11	1205.6	1728	$\pi/2$ -BPSK/(G)MSK	1	LDPC(576,432)	0.750	16	256
	LR12	1406.5	1728	$\pi/2$ -BPSK/(G)MSK	1	LDPC(576,504)	0.875	16	256
	LR13 (MLR)	1506.6	1728	$\pi/2$ -BPSK/(G)MSK	1	RS(255,239)	0.937	16	256
	LR14	1506.6	1728	Dual Rail Bipolar	2	RS(255,239)	0.937	16	256
	LR15	1607.4	1728	$\pi/2$ -QPSK	1	LDPC(576,288)	0.500	16	256
	LR16	376.6	864	$\pi/2$ -BPSK/(G)MSK	2	RS(255,239)	0.937	16	256
	LR17	1506.6	864	$\pi/2$ -QPSK	1	RS(255,239)	0.937	16	256
MR	MR1	2143.3	1728	$\pi/2$ -QPSK	1	CC(R=2/3,K=5)	0.667	16	256
	MR2	2411.2	1728	$\pi/2$ -QPSK	1	LDPC(576,432)	0.750	16	256
	MR3	2806.6	1728	$\pi/2$ -star 8QAM	1	CC(R=2/3,K=4) & RS(63,55)	0.582	16	256
	MR4	2813.0	1728	$\pi/2$ -QPSK	1	LDPC(576,504)	0.875	16	256

SC mode (HR,SC-OOK)

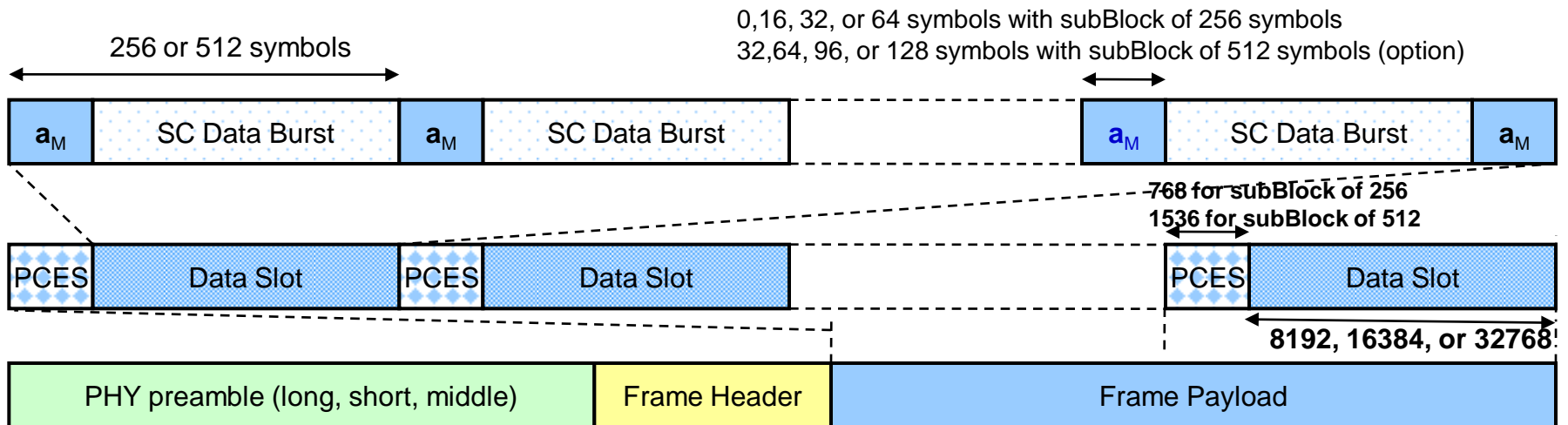
MCS Class	MCS Identifier	Data Rate (Mbps)	Symbol /Chip Rate (Mcps)	Modulation Scheme	Spreading factor	FEC Type	FEC Rate	Pilot Word Length (Symbols /chips)	Burst Length (Symbols /chips)
HR	HR1	3000.6	1728	$\pi/2$ -QPSK	1	LDPC(1440,1344)	0.933	16	256
	HR2	3013.2	1728	$\pi/2$ -QPSK	1	RS(255,239)	0.937	16	256
	HR3	3013.2	1728	Dual Rail Bipolar	1	RS(255,239)	0.937	16	256
	HR4	3214.9	1728	$\pi/2$ -NS8QAM	1	TCM(R=1/2,K=5)	0.667	16	256
	HR5	3214.9	1728	Dual Rail Bipolar	1	Uncoded	1.000	16	256
	HR6	3616.7	1728	$\pi/2$ -8PSK	1	LDPC(576,432)	0.750	16	256
	HR7	4210.0	1728	$\pi/2$ -star 8QAM	1	RS(63,55)	0.873	16	256
	HR8	4219.5	1728	$\pi/2$ -8PSK	1	LDPC(576,504)	0.875	16	256
	HR9	4500.8	1728	$\pi/2$ -8PSK	1	LDPC(1440,1344)	0.933	16	256
	HR10	4519.7	1728	$\pi/2$ -8PSK	1	RS(255,239)	0.937	16	256
	HR11	4519.7	1728	$\pi/2$ -NS8QAM	1	RS(255,239)	0.937	16	256
	HR12	4822.3	1728	$\pi/2$ -16QAM	1	TCM(R=2/3,K=5)	0.750	16	256
	HR13	4822.3	1728	$\pi/2$ -16QAM	1	LDPC(576,432)	0.750	16	256
	HR14	5626.0	1728	$\pi/2$ -16QAM	1	LDPC(576,504)	0.875	16	256
	HR15	6026.3	1728	$\pi/2$ -16QAM	1	RS(255,239)	0.937	16	256
SC- OOK	SCOOK1	50.2	1728	OOK	32	RS(255,239)	0.937	0	256
	SCOOK2	376.6	1728	OOK	4	RS(255,239)	0.937	16	256
	SCOOK3	753.3	1728	OOK	2	RS(255,239)	0.937	16	256
	SCOOK4	1506.6	1728	OOK	1	RS(255,239)	0.937	16	256



Packet Structure

Frame format

- Frame header and frame payload are independently segmented into subBlocks, with Golay code-based **cyclic prefix pilot symbols (CPPS)** and/or **pilot channel estimation sequence (PCES)** inserted in between subBlocks
 - SubBlock size: **256 symbols as mandatory, or 512 symbols as option** (including data symbols and pilot symbols)
 - CPPS length: 16, 0, 32, or 64 symbols with subBlock of 256 symbols
: 32, 64, 96, or 128 symbols with subBlock of 512 symbols (option)
 - Sequence for CPPS
 - Golay code a in all of the lengths (96 symbols is the combination of a_{32} and a_{64})
 - Role of CPPS
 - (a) Timing tracking, (b) Compensation for clock drift, and (c) Compensation for frequency offset error that resides after fine AFC and that caused by phase noise in LOS environment
 - Cyclic prefix (CP) for frequency domain equalizer (FDE) (Optional CP design is available as option)
 - PCES length : **768 for subBlock of 256, 1536 for subBlock of 512 (symbol)**
 - PCES period : **8192, 16384, or 32768 (symbol)**
 - Role of PCES
 - (a) Timing tracking, (b) Compensation for clock drift, and (c) Compensation for frequency offset error that resides after fine AFC and that caused by phase noise in LOS environment

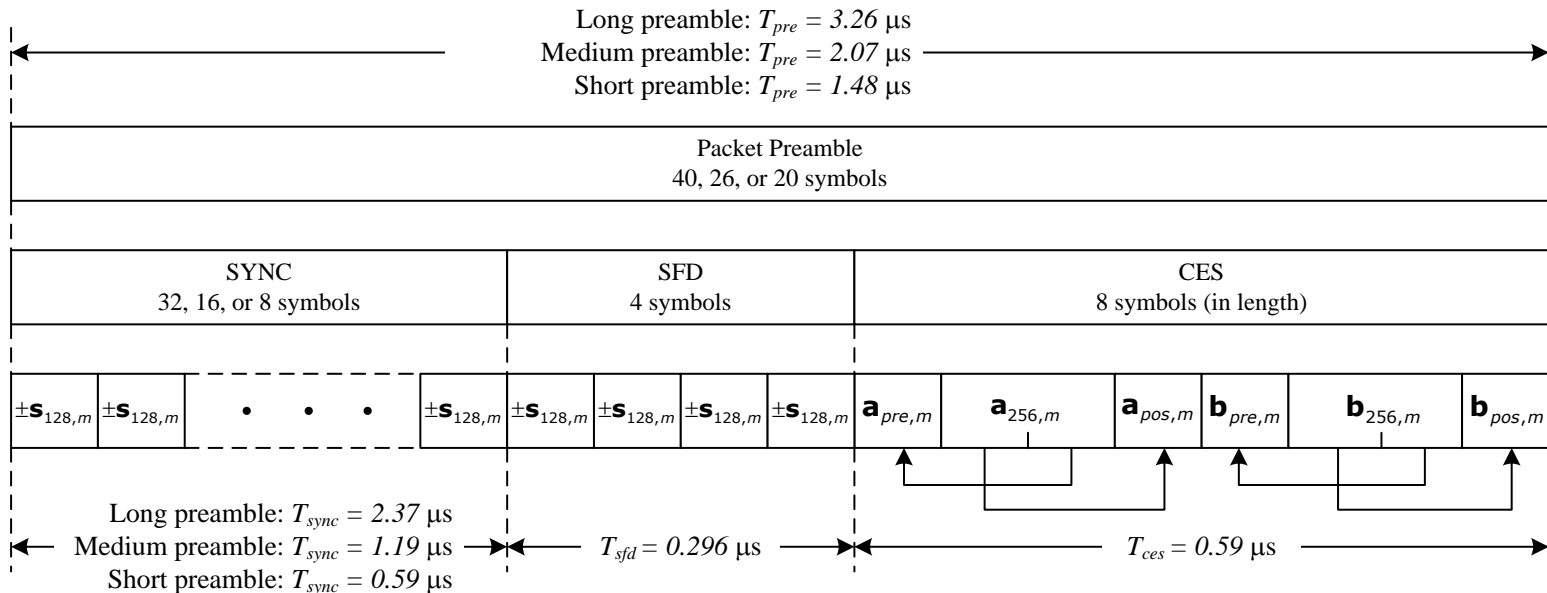


PHY header

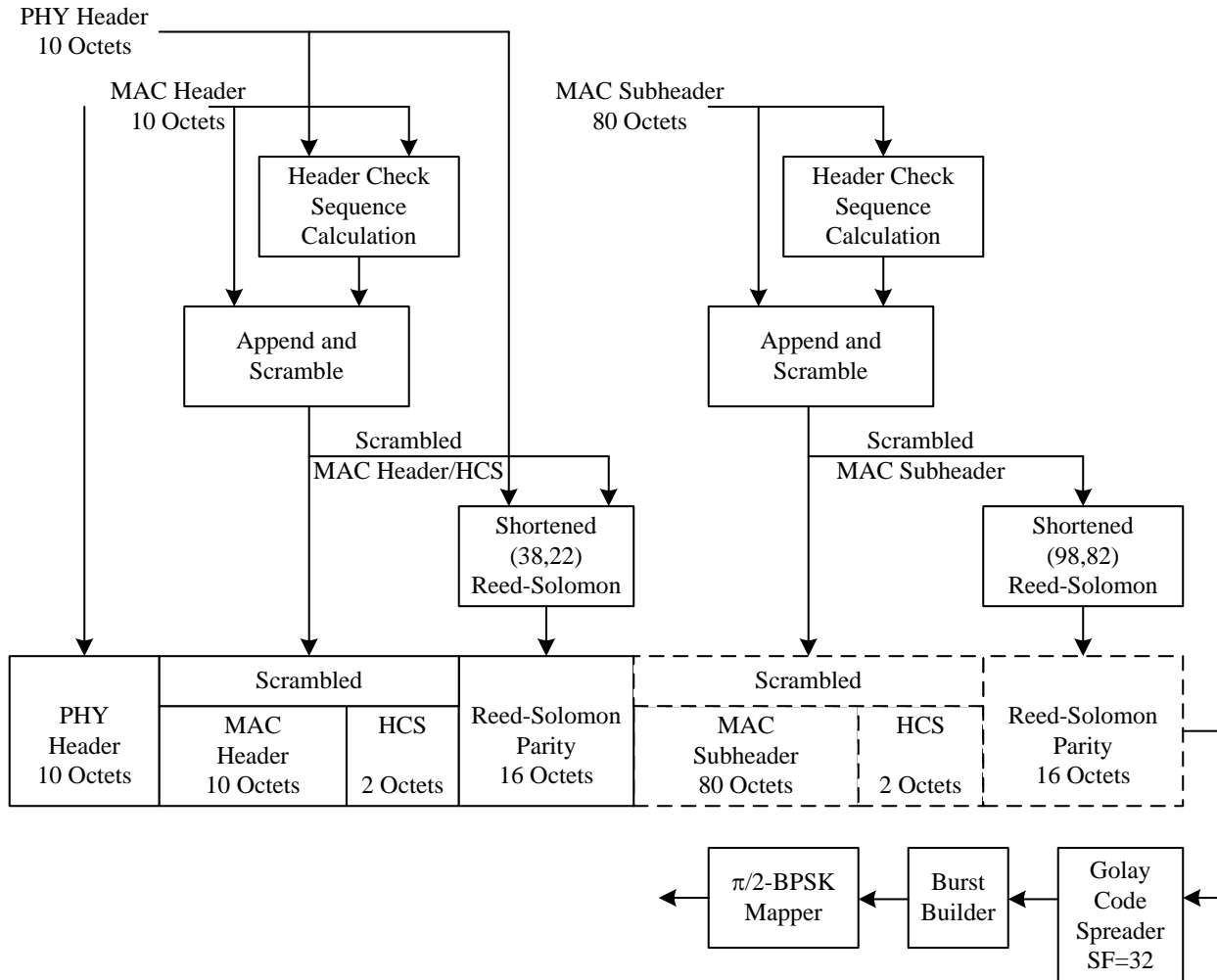
		Definition
SCRAMBLER ID	4	Set the bits according to the scrambler seed identifier value.
MCS	6	Indicate modulation and coding scheme (MCS) used in the frame payload
FRAME LENGTH	16	Indicate the number of octets in the frame payload (which excludes the FCS) that the MAC is currently requesting the PHY to transmit
BURST TYPE	1	Indicate the type of burst used in the current packet (PW-Burst is mandatory, and CP-Burst is optional)
PWCP TYPE	2	Set the length of the Pilot Word (PW) or Cyclic Prefix (CP). These bits shall be interpreted according to the burst length in use.
PCES TYPE	2	Indicate the exact Pilot CES period when the Pilot CES symbols are present
IFS TYPE	2	Specify the IFS value to be used in the next packet
NUM. of SUBFRAMES	4	Indicate the number of subframes
BURST MODE	1	Indicate the burst length
RESERVED BIT	40	Reserved bits for future use

Preamble structure

- Three types of preambles: **long**, **medium**, and **short** preambles, for each transmission mode
- The preambles can be selected according to the information included in PHY header
- The preambles consist of sequences for synchronization (SYNC) and channel estimation (CE)
 - SYNC in long preamble
 - **36** 'repetition' of Golay code of 128 chips
 - SYNC in middle preamble (original short preamble)
 - **20** 'repetition' of Golay code of 128 chips
 - SYNC in short preamble (added)
 - **12** 'repetition' of Golay code of 128 chips
 - CE in the three preambles
 - **4** repetition of Golay code of 256 chips: used for CE and fine AFC
 - $[a]$ and $[b]$ are Golay codes and complimentary pairs of each other
 - $[a_{256}]$ and $[b_{256}]$: Golay codes of 256@ 1.728 Gcps
 - $[a']$ is a copy of last half part of $[a_{256}]$, and $[a'']$ is a copy of first half part of $[a_{256}]$
 - $[b_{256}][b']][b'']$ is set to the same manners as $[a_{256}][a']][a'']$



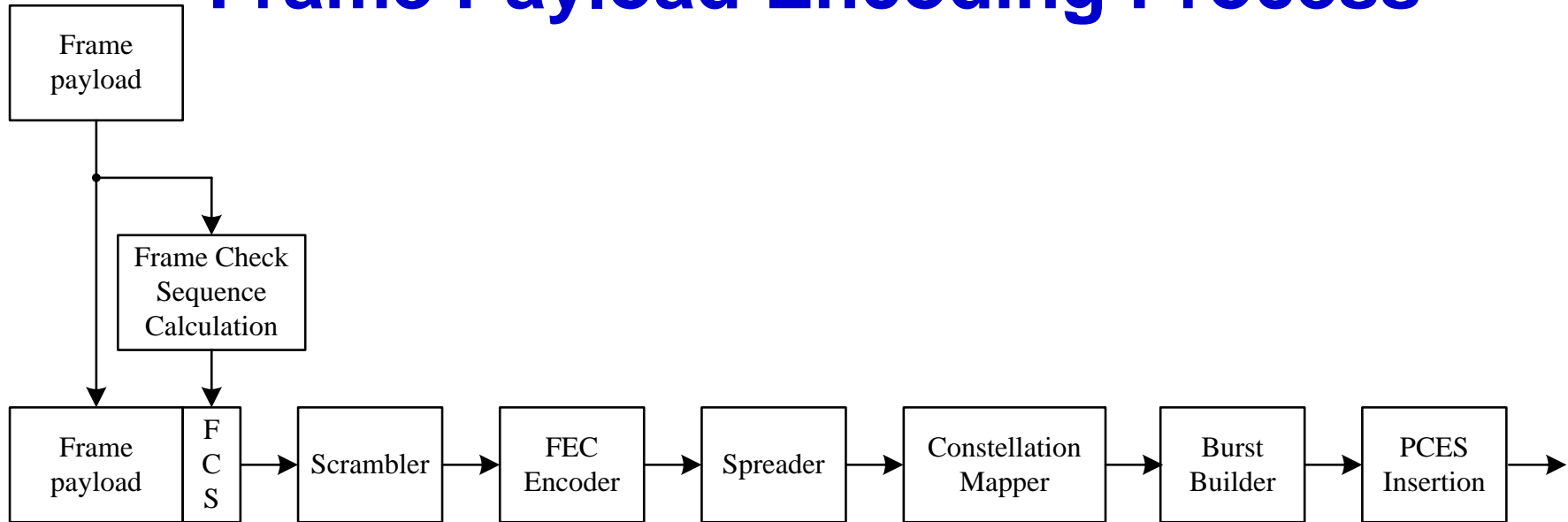
CR Frame Header Construction



•Form the base frame header as follows:

1. Construct the PHY header
2. Compute the HCS append to Mac Header
3. Scramble the combined MAC header and HCS,
4. Compute the Reed Solomon parity bits (16 octets)
5. Form the base frame header by concatenating the PHY header, scrambled MAC header, scrambled HCS and Reed Solomon parity bits.

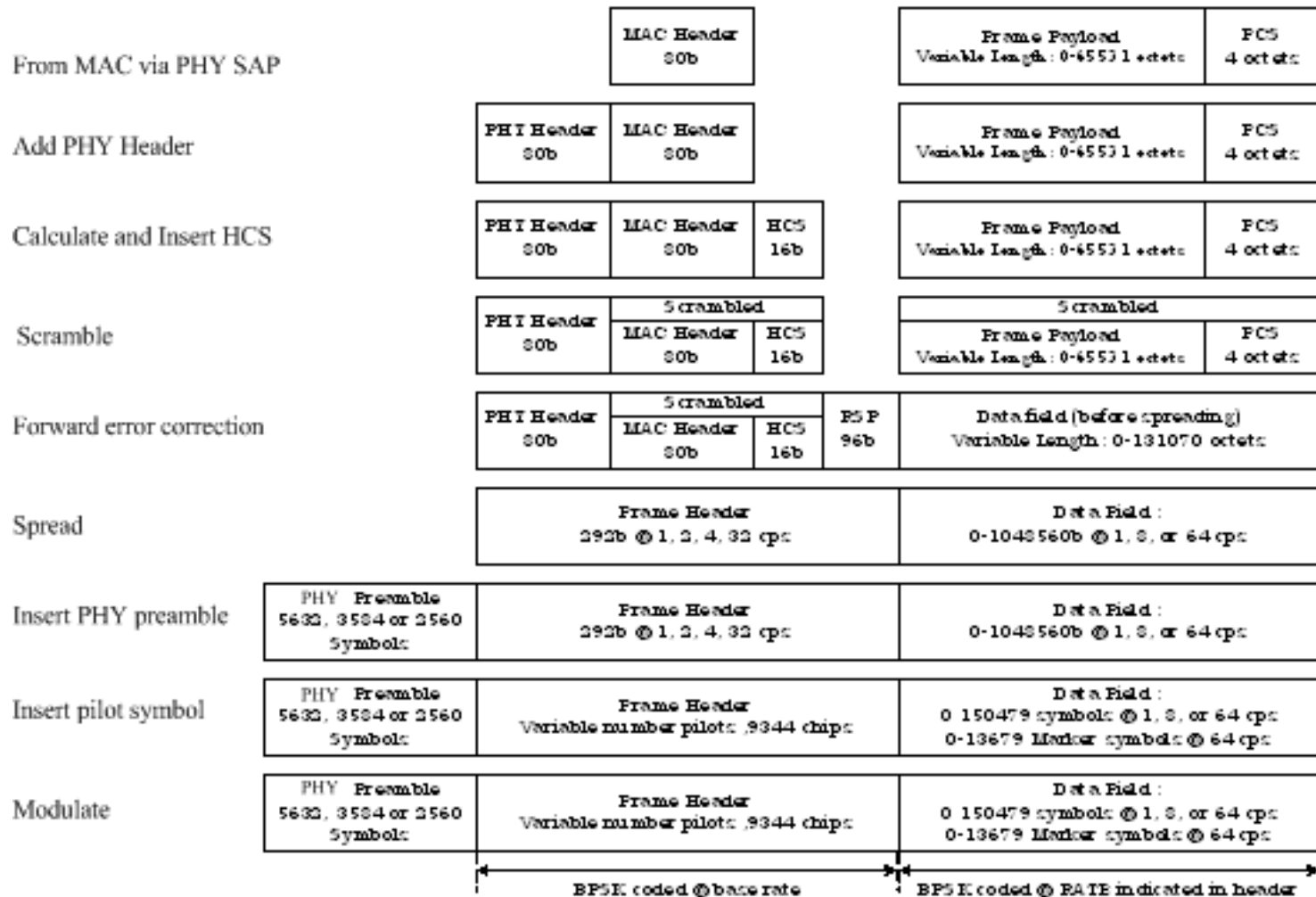
Frame Payload Encoding Process



Frame payload encoding process:

- Computing FCS over frame payload,
- Appending the FCS to the frame payload,
- Scrambling the resulting combination
- Encoding the scrambled data
- Spreading the encoded and scrambled data
- Modulating the encoded and scrambled data
- Building bursts from the spread, encoded and scrambled data
- Inserting Pilot Channel Estimation Symbol fields into the data

Packet Construction



Base header rate-dependent parameters

Header Rate	Chip Rate	Modulation	Spreading	FEC	FEC	Pilot Word	Burst Length	Coded Bits
Mbps	MHz	Scheme	Code Length	Type	Rate	Length (chips)	(chips)	Per Burst
R_H	R_C		L		R_{FEC}	N_{PW}	N_{BURST}	N_{CBPS}
28.4	864	$\pi/2$ -BPSK / (G)MSK	32	RS(38,22)	0.579	0	256	8
540.0	864	$\pi/2$ -BPSK / (G)MSK	1	RS(38,22)	0.579	64	256	192
28.4	1728	$\pi/2$ -BPSK / (G)MSK	32	RS(38,22)	0.579	0	256	8
540.0	1728	$\pi/2$ -BPSK / (G)MSK	1	RS(38,22)	0.579	0	256	256

Timing-related parameters

Parameter	Description	value				Unit	Formula
R_C	Chip rate	1728				MHz	
T_C	Chip duration	0.579				ns	$= 1/R_C$
N_{burst}	Burst length	256				chips	
N_{UW}	Pilot word length	0	16	32	64	chips	
N_{DC}	Number of data chips per burst	256	240	224	192	chips	
T_{burst}	Burst duration	148.15				ns	$= N_{burst} \times T_C$
F_{burst}	Burst rate	6.75				MHz	$= 1/T_{burst}$

MAC – Difference and Addition

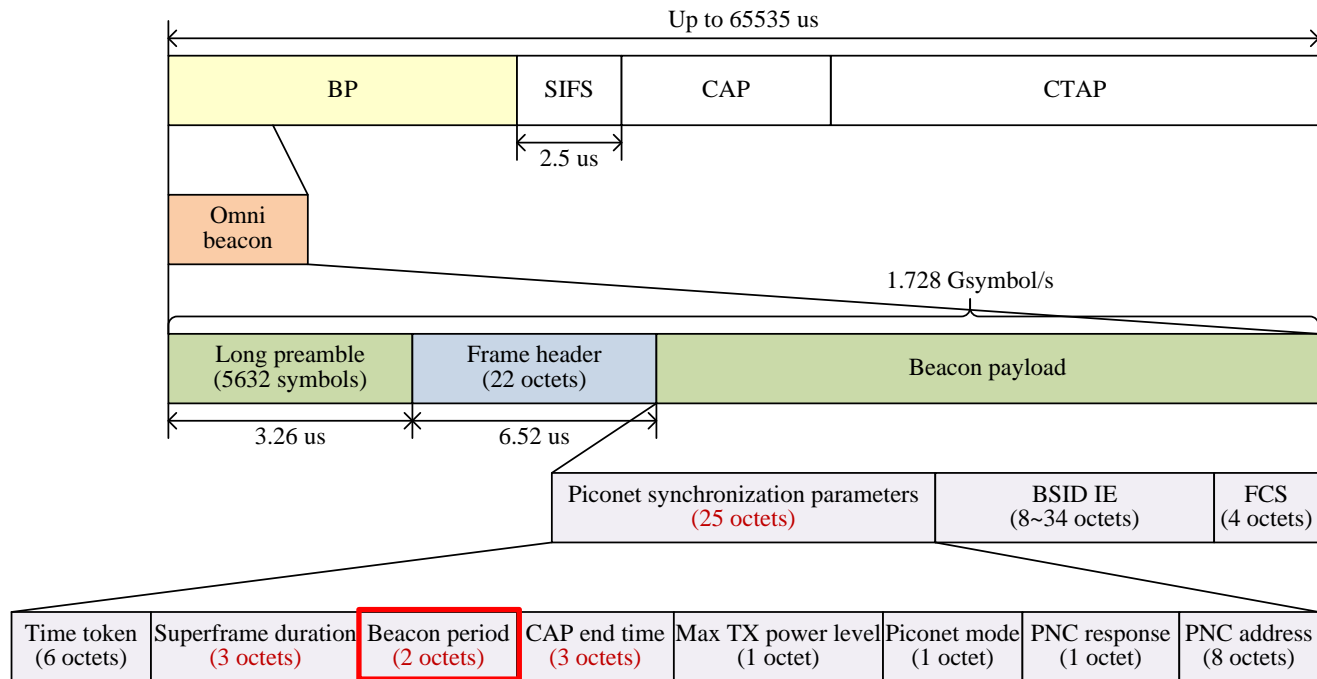
Features of 802.15.3cMAC

1. Superframe structure
 - Newly defined variable beacon period
 - Improved time resolution for superframe timing control
2. Frame aggregation
 - Frame aggregation with dedicated subheader
 - Definition of Blk-ACK for aggregation
3. Four new procedures to realize 15.3c functions
 - Option : Beamforming, Channel probing, DEV-DEV directional communications, UEP

Superframe structure

- Newly defined variable beacon period (BP) up to 256us
Multiple beacon support of “omni”* and directional beacons in CR, OFDM/OOK beacons as well
- Contention Access Period (CAP) based on CSMA/CA
- Channel Time Allocation Period (CTAP) based on TDMA
- Improved time resolution of 9ns (16symbols/1.728Gbps) for superframe timing control
Modification of piconet synchronization parameters
 - Superframe duration (3 octets from 2 octets in 15.3b)
 - CAP end time (3 octets from 2 octets in 15.3b)

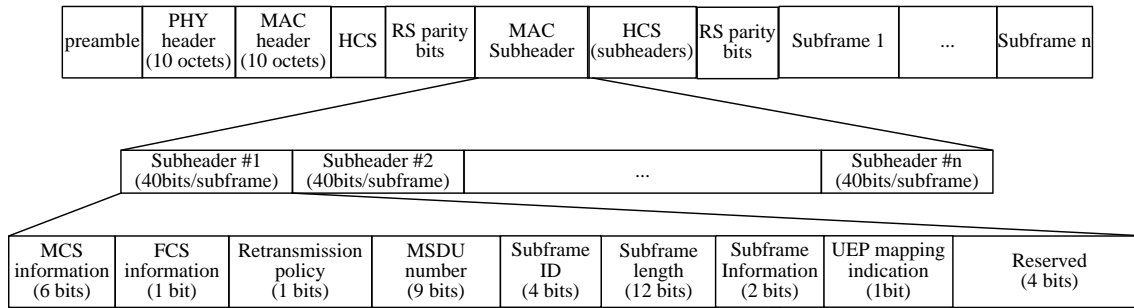
“Omni”: meaning to cover all directions by omni antenna or part of omni antenna coverage which is planned to be covered by the directional antenna



Aggregation and Blk-ACK

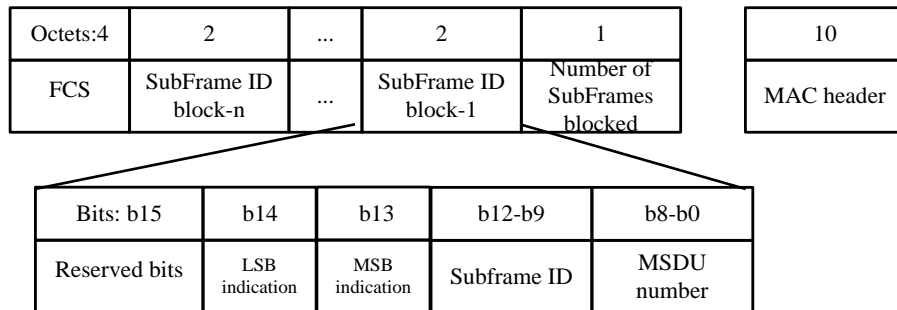
- Frame aggregation for High throughput
 - Subheader for each subframe protected by HCS
 - When subframe information in subheader indicates the subframe contains MSB and LSB together, the corresponding subframe shall have two FCSs (MSB FCS and LSB FCS) attached to it. FCS information shall be set to 1 in this case
- Newly defined Block ACK (Blk-ACK)
 - Independent retransmission for each subframe
 - Scalability for other function such as UEP

Subheader



- MSB subframe
- LSB subframe
- MSB and LSB combined subframe

Block ACK



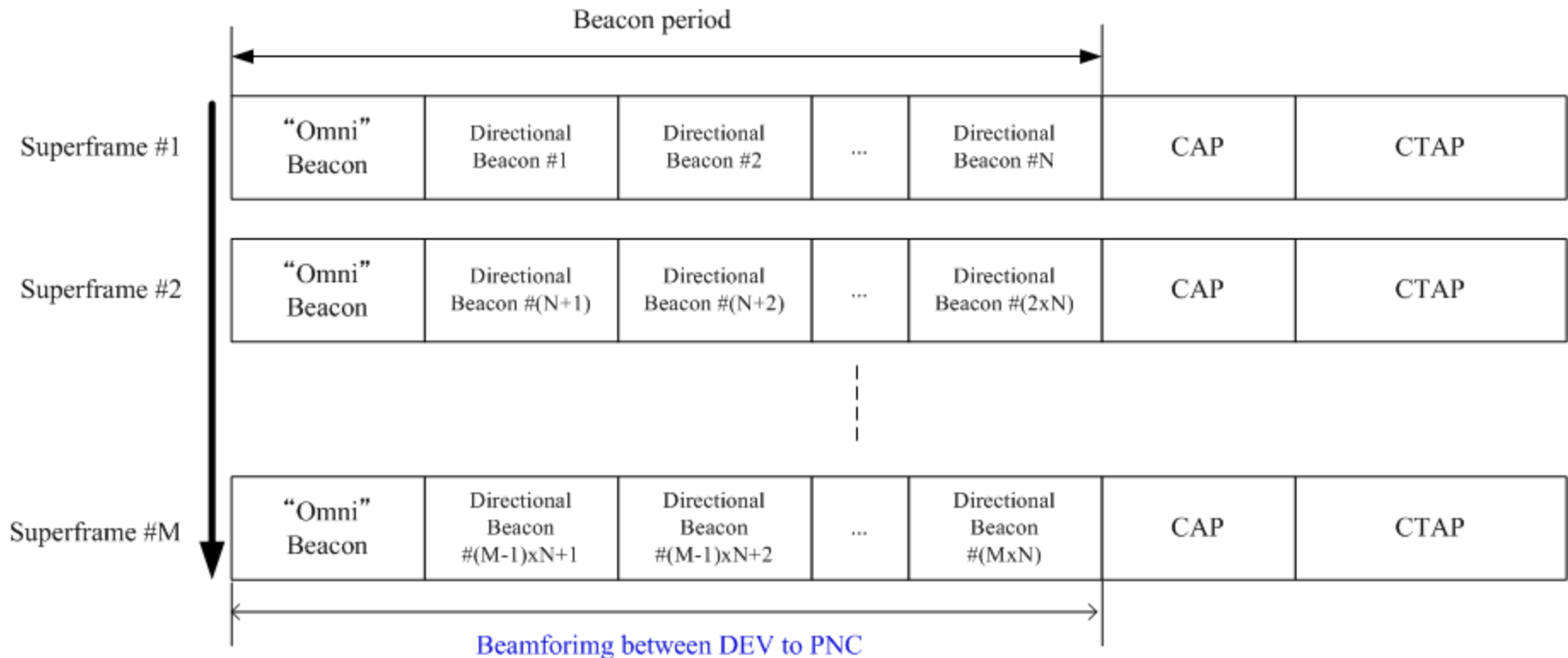
MAC New operation procedures and primitives

Four procedure additions

- **Beamforming (Option)**
 - Beamforming by receiving beam training sequence
- **Channel probing (Option)**
 - Determination of most suitable PHY transmission mode
 - Forward and backward channel probing by transmitting channel probing sequence
- **DEV-DEV directional communications (Option)**
 - DEV-DEV beamforming, channel probing and streaming
 - Peer discovery for capability confirmation
- **UEP (Option)**
 - MCS (modulation and coding scheme) control by the subheaders

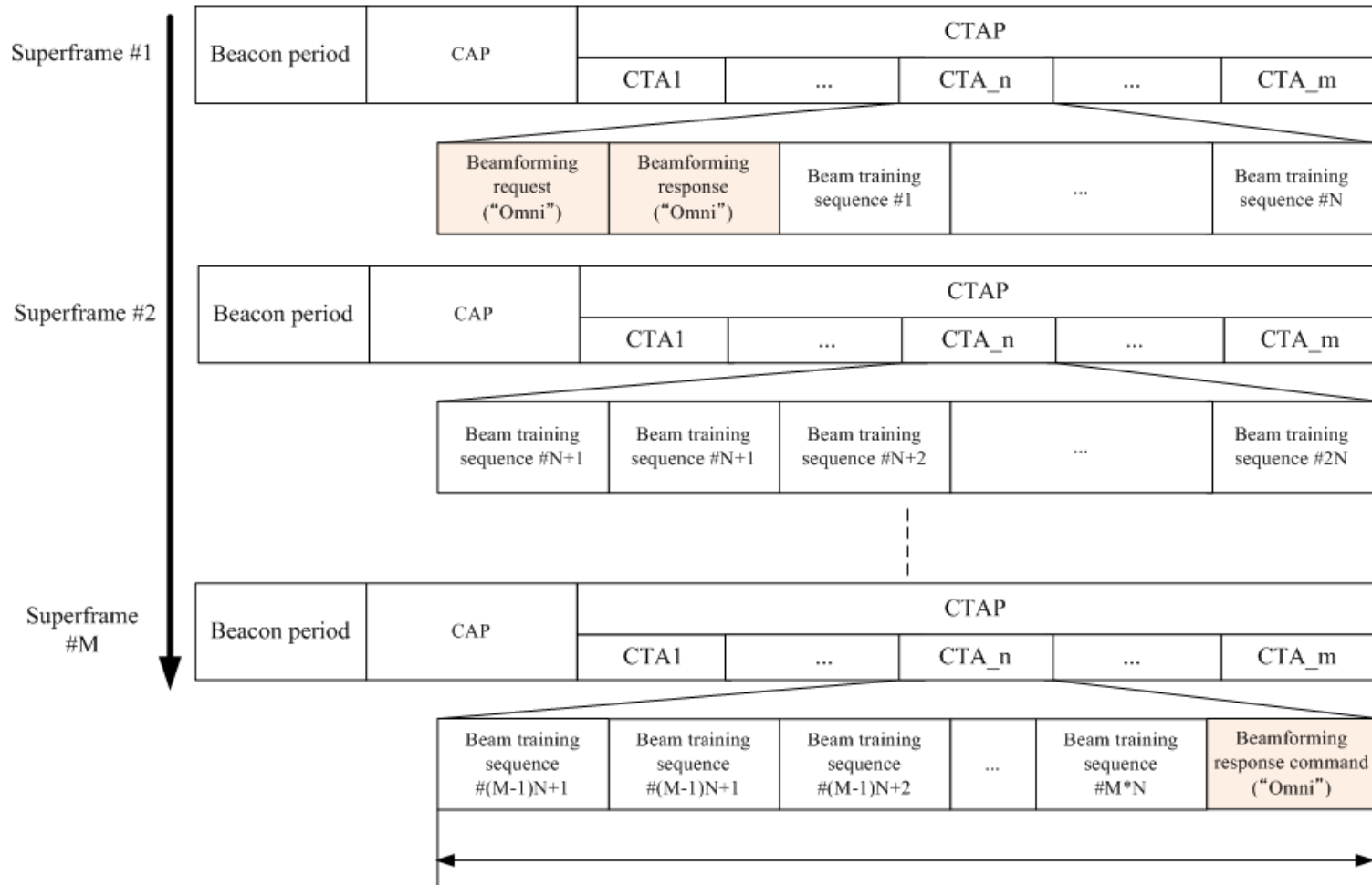
Beamforming (1/2)

- **Two types of beamforming** are defined
 - **Type 1 : PNC and DEV beamforming by using “omni” and directional beacons in beacon period**



Beamforming (2/2)

- **Type 2 : DEV and DEV beamforming by beam training sequences in CTA**



Channel probing

- **Channel probing** is defined to find the highest data rate transmission mode
 - **Channel probing between DEVs in CTA**
 - DEV request intended DEV to send channel probing sequence in allocated CTA
 - DEV measure channel status by processing channel probing sequence from intended DEV
 - DEV informs the measurement result to the intended DEV in the same CTA

Unequal Error Protection (UEP) (1/3)

– Three types of UEP are defined

- UEP 1
 - MSB data or LSB data occupies a whole subframe
 - MSB subframes and LSB subframes can be aggregated into one frame
 - Different MCS and FCS can be selected subframe by subframe
 - 6bits in subheader to indicate different MCS
- UEP 2
 - MSB and LSB data are separately put into different aggregated frame
 - MSB and LSB frames are allowed to be transmitted on different antenna (using transmit switched diversity)
 - One bit in subheader to indicate the aggregated frame is MSB data or not

UEP (2/3)

• UEP 3

- Two UEP schemes are available: UEP mapping and UEP coding
- Two bits in subheader to indicate using UEP mapping or coding
- Additional transmission mode (MCS) for UEP

Transmission Mode	PHY-SAP data rate	Modulation	Constellation	MSB coding	LSB coding
SC Mode	2040 Mbps	QPSK	normal	LDPC (576,288)	LDPC (576,432)
SC Mode	2562 Mbps	QPSK	normal	LDPC (576,432)	LDPC (576, 504)

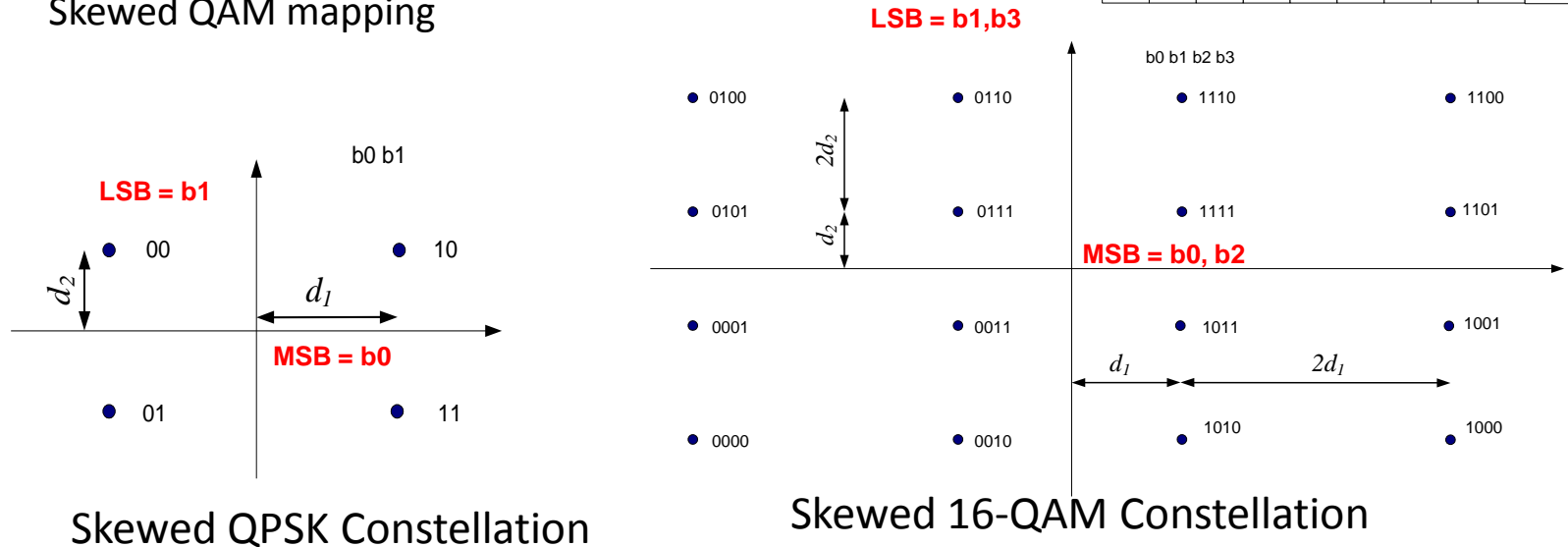
• Interleaver for UEP mapping

– Bit interleaving pattern

- A,B,C and D denote output of any FEC encoder for MSB's
- E,F,G and H denote output of any FEC encoder for LSB's

A1	C3	A5	B1	D3	B5	C1	A3	C5	D1	B3	D5
B2	D4	B6	C2	A4	C6	D2	B4	D6	A2	C4	A6
E1	G3	E5	F1	H3	F5	G1	E3	G5	H1	F3	G5
F2	H4	F6	G2	E4	G6	H2	F4	H6	E2	G4	E6

• Skewed QAM mapping



UEP (3/3)

- UEP information request command : This command is sent by any DEV to other DEV including PNC to request UEP scheme supported and UEP MCSs supported at the target DEV

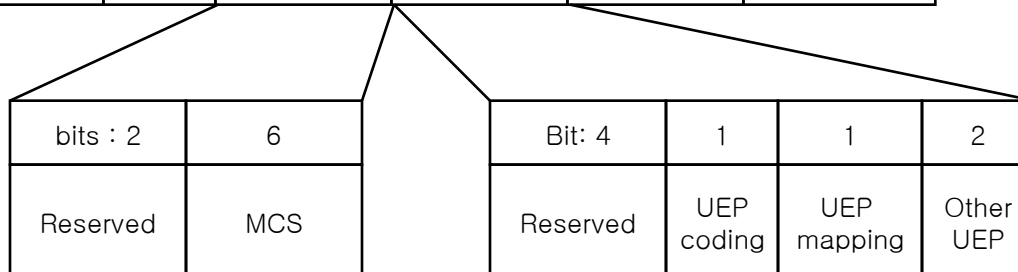
2	2
Length=Ln	Command type

Fig. UEP information request command format

- UEP information response command : This command is sent by the target DEV in response to originating DEV's request to let the originating DEV know which UEP schemes are supported and which UEP MCSs are supported at the target DEV.

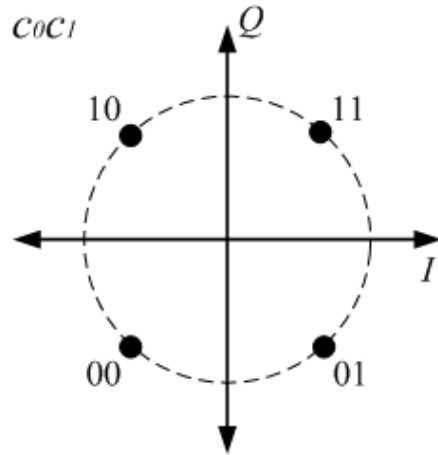
Octets : 1	...	1	1	2	2
UEP MCS Block-n	...	UEP MCS Block-1	UEP information	Length=Ln	Command type

Fig. UEP information response command format

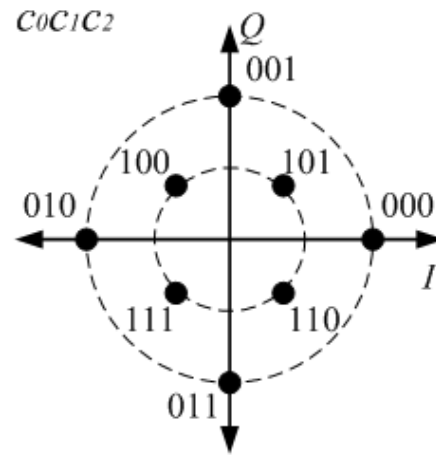


Optional Modulation Schemes (1/2)

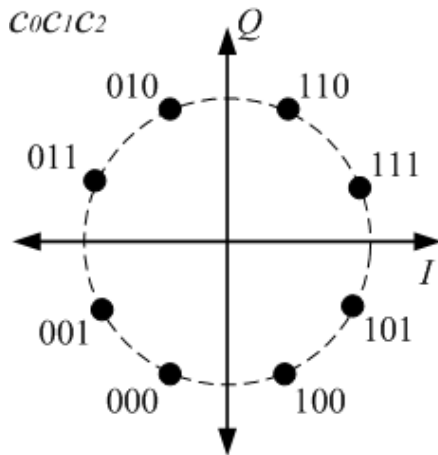
$\pi/2$ QPSK



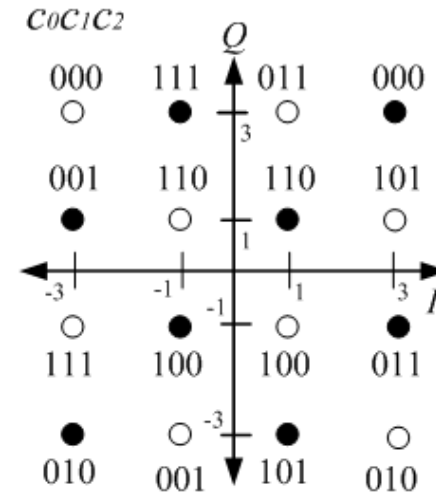
$\pi/2$ star 8QAM



$\pi/2$ 8PSK



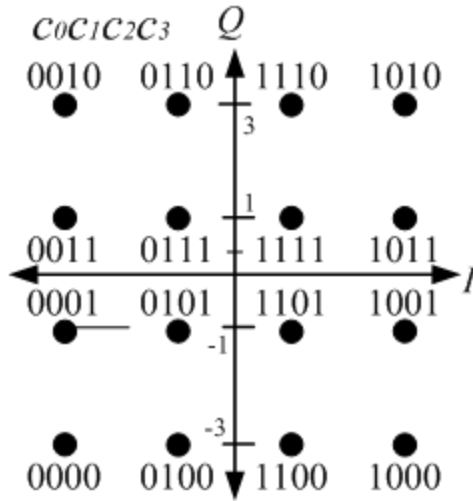
$\pi/2$ NS8QAM



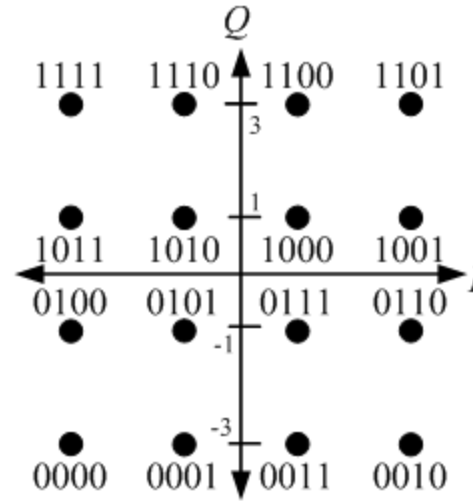
Solid dots: k is even
Hollow dots: k is odd

Optional Modulation Schemes (2/2)

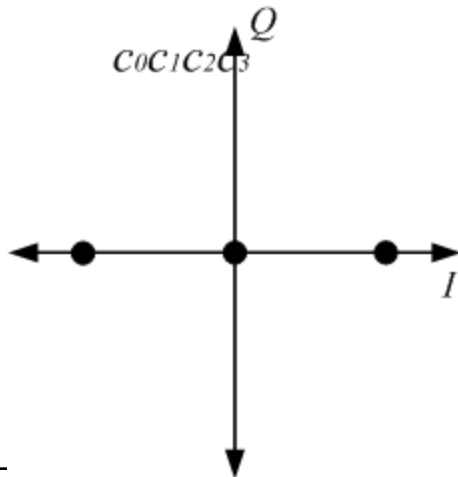
16QAM with Gray coding



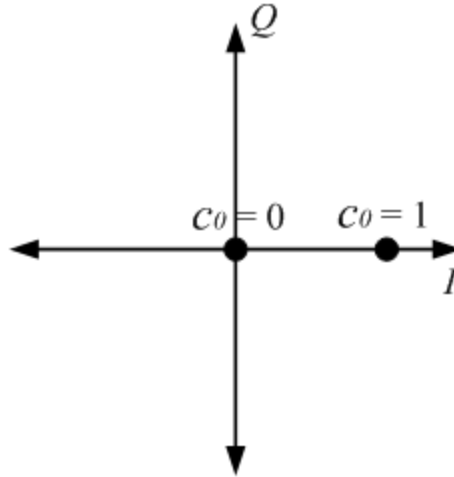
16QAM for TCM



Dual rail bipolar



OOK



Optional FEC Schemes(1/4)

Block Coding

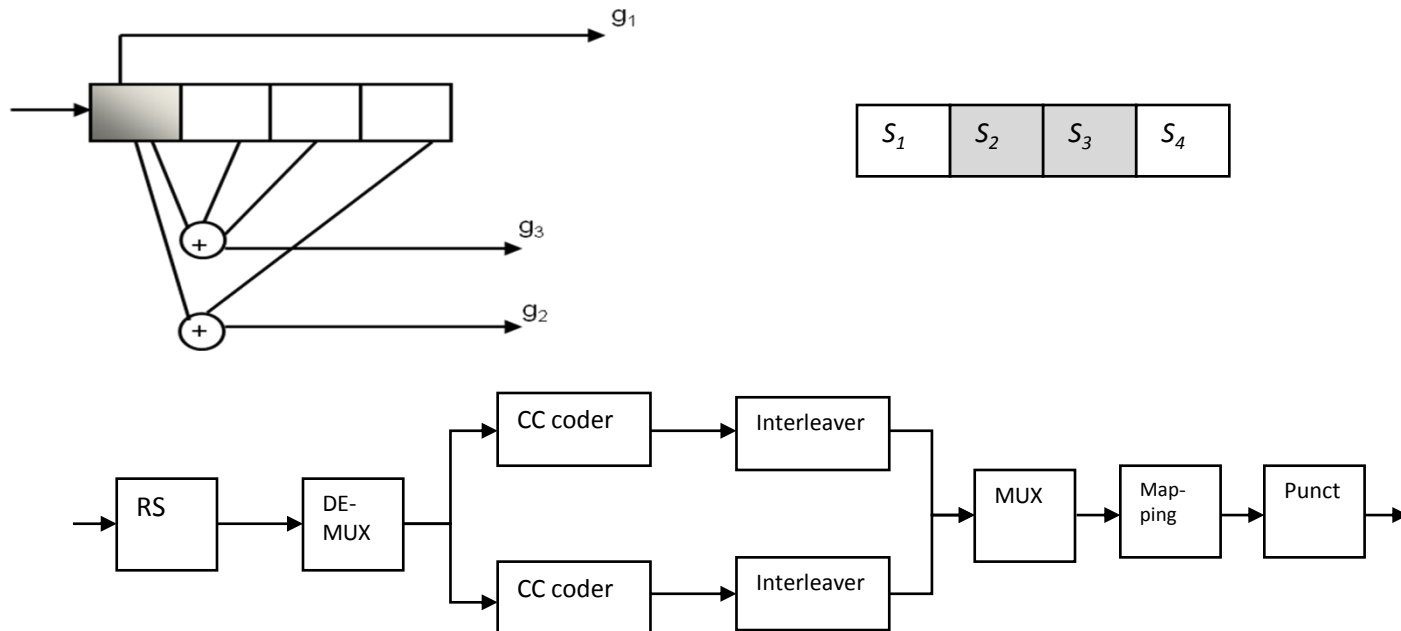
- **RS(63,55):**
Reed Solomon block code in $GF(2^6)$
- **LDPC(576, 288), LDPC(576, 432), LDPC(576, 504):** Irregular low density parity check codes
- **LDPC(1440,1344):**
Quasi-cyclic regular LDPC code

Optional FEC Schemes(2/4)

Convolutional Coding

Rate 2/3 convolutional coding with puncturing and two path parallel encoding

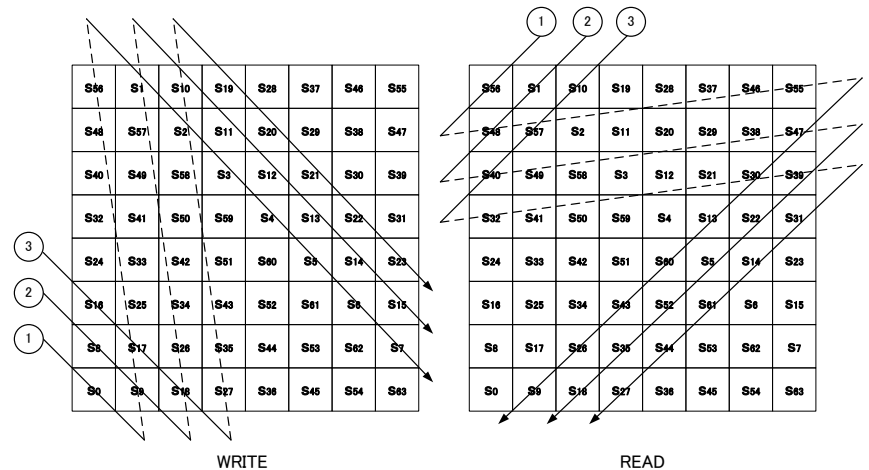
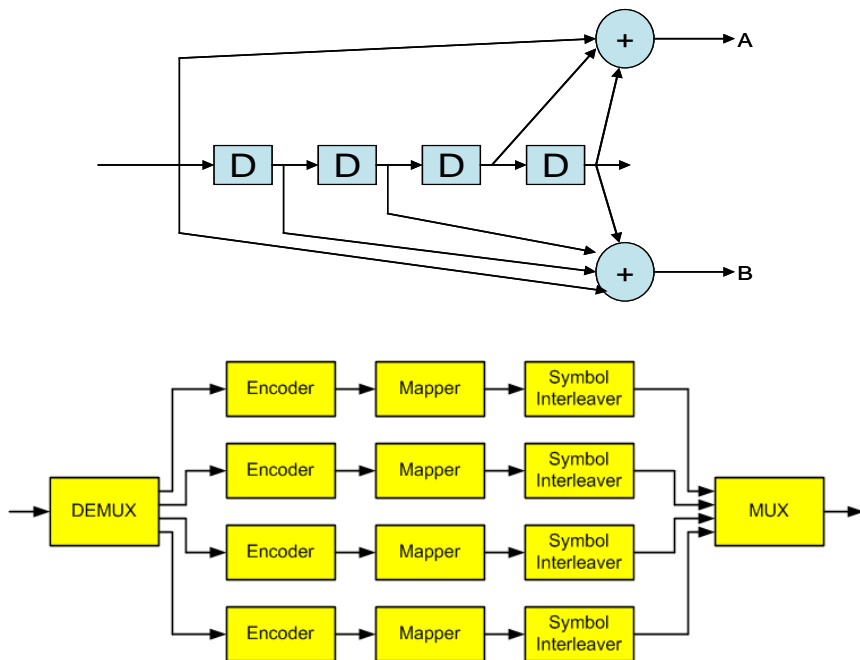
$K=4$



Optional FEC Schemes(3/4)

Convolutional Coding

Rate 1/2 convolutional coding with four path parallel encoding and interleaving (K=5)

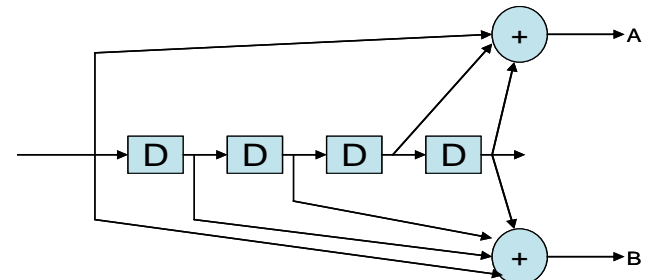
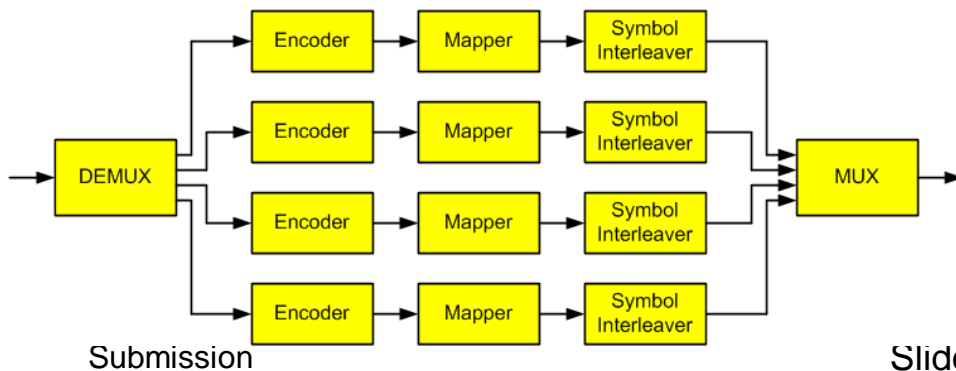
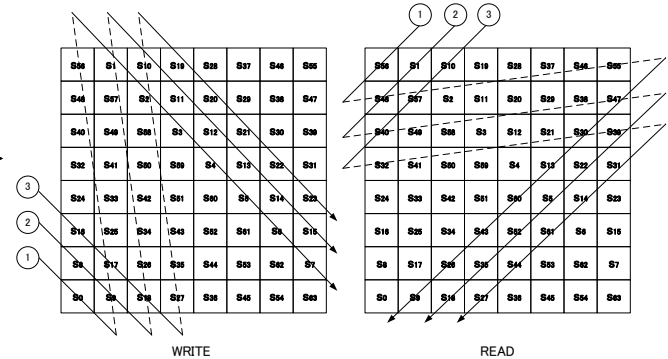
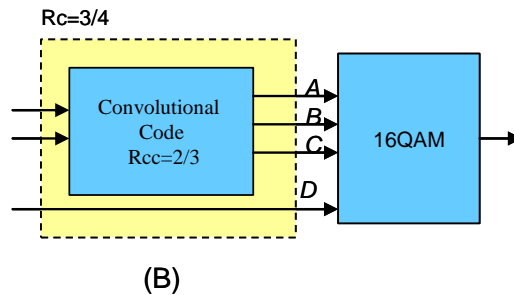
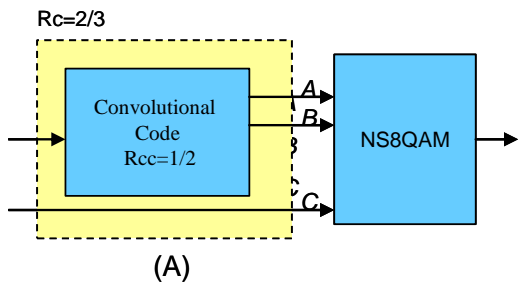


Optional FEC Schemes(4/4)

Trellis Coded Modulation

Mother code: Rate 1/2 convolutional coding with four path parallel encoding $K=5$

Modulation schemes NS-8QAM 16QAM

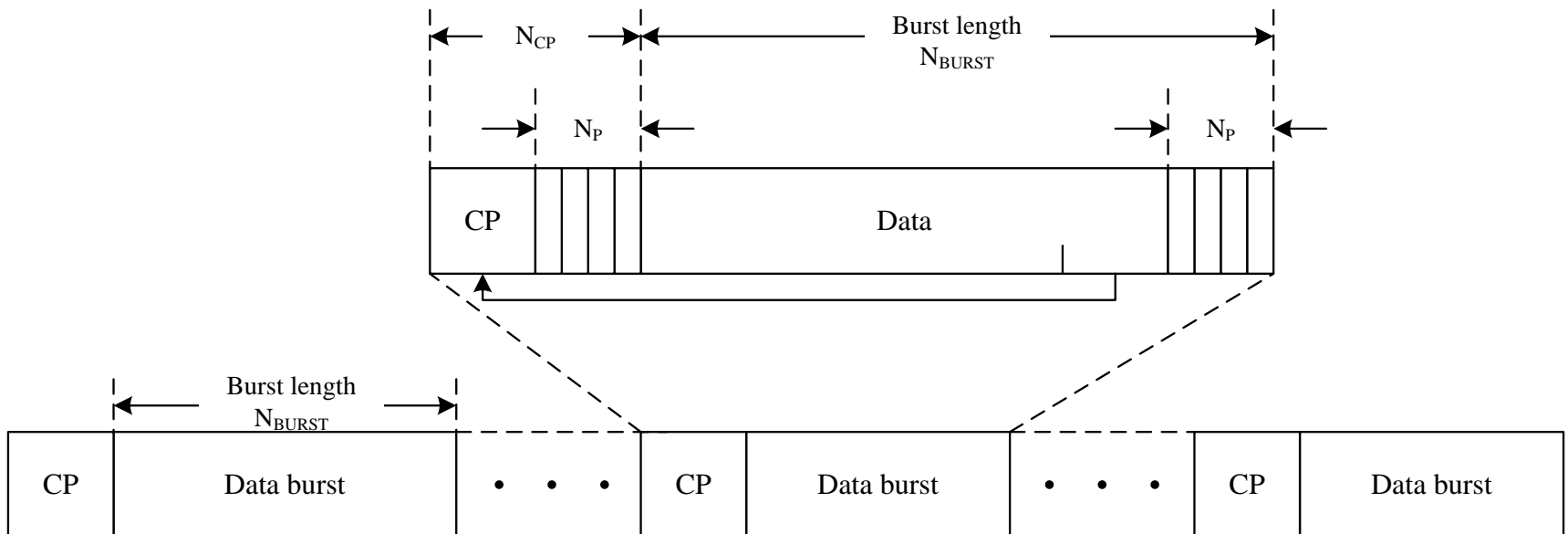


Optional Cyclic Prefix

Burst length options: 256,512

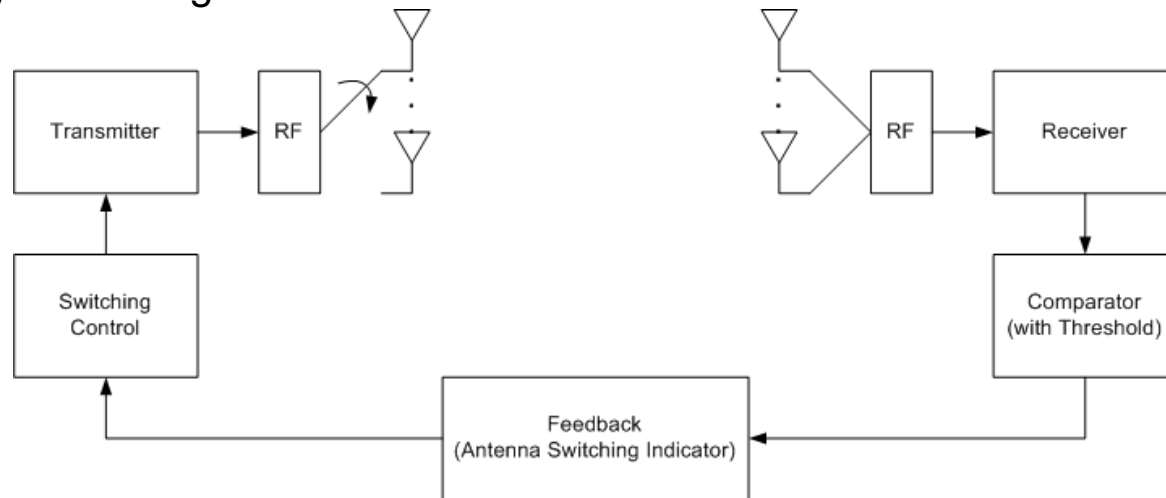
CP length options: 0,16,32,64, 96, 128

Number of Pilot Symbols: 4 The value of this pilot symbols shall be $[-1 \ 1 \ 1 \ 1]$ and modulated using $\pi/2$ -BPSK.



Optional Transmit Switched Diversity

- Transmit antenna switch diversity may be used to achieve diversity gain from shadowing or blockage.



- Transmitter will inform the receiver of the number of antennas, L .
- At first transmission, transmitter arbitrarily selects one antenna from L transmit antennas.
- At each stage, receiver will compare the received SNR with a predetermined threshold, γ .
- If the SNR is larger than γ , receiver will feedback a “no switch” signal.
- If the SNR is smaller than γ , receiver will feedback a “switch” signal.
- If the SNR for all L available antennas, is less than γ , the receiver will then feedback the antenna number with largest SNR. The transmitter will use this antenna for

OFDM

Mandatory Rates

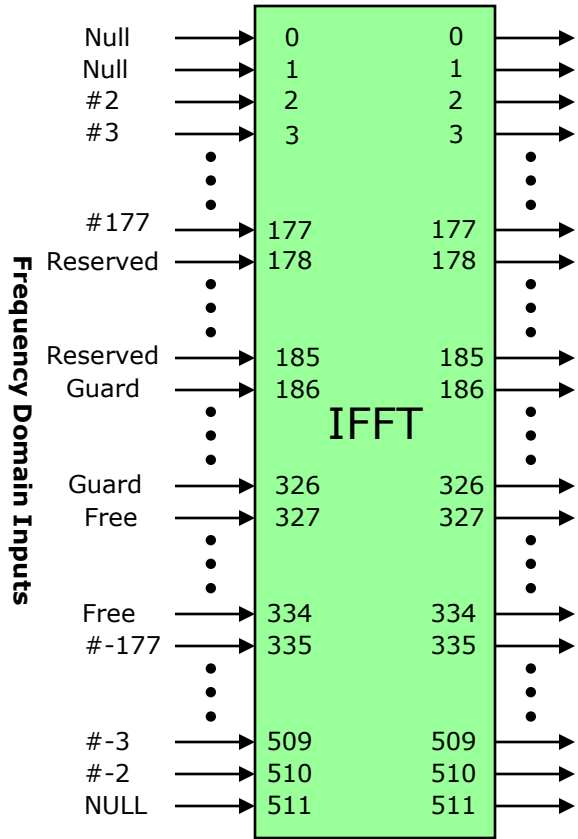
- Common Rate (CR 50 Mbps) and Mandatory Low Rate (MLR 1.5Gbps) are mandatory for all SC devices and all OFDM and OOK PNC capable devices.
- All 802.15.3c compliant PNC capable DEVs that support the mmWave PHY shall support dependent piconets both as a parent PNC and as a dependent PNC. A DEV that supports the mmWave PHY may start a dependent piconet, as described in 8.2.5 and 8.2.6 to enable communication with and among entities that do not support the mmWave PHY base rate.

OFDM Mode Overview

- Same Channel Plan as Single Carrier
- Homogeneous Sampling frequency with Single Carrier
 - OFDM : 2592 MHz = 1.5 x 1728 MHz (SC)
 - Optional OFDM Rate: 2538 MHz (same XTAL)
- Data Rates up to 0.7 Gbps to 7.3 Gbps
- Beaconing & Signaling modes from 58 Mbps to 900 Mbps
 - Low Latency Shortened RS + Hamming
- Two high performance FEC schemes
 - Concatenated Outer RS, Inner LDPC Block Code
 - Concatenated Outer RS, Inner Convolutional Code
- Multiple Preamble Types for improved efficiency & Beamforming Support
- Aggregation & UEP support
- Beamforming support in Beacon & CTAP

The OFDM Modulator

IFFT Inputs & Outputs



- CP Default value is 64, Optional: 32, 96, & 128

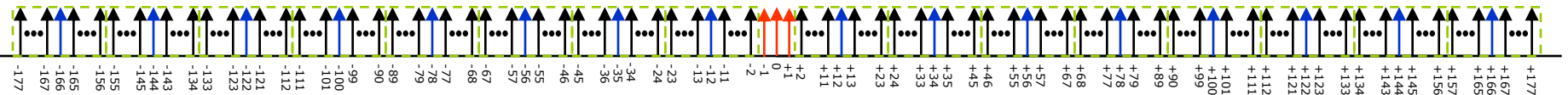
$$s_k^{(n)} = \frac{1}{\sqrt{N_{FFT}}} \sum_{m=-N_u/2}^{N_u/2} Y_m^{(n)} e^{j \frac{2\pi mk}{N_{FFT}}} \quad k = 0 : 511$$

$Y_m^{(n)}$: frequency domain inputs with $m = -184 : 184$

$s_k^{(n)}$: time domain outputs

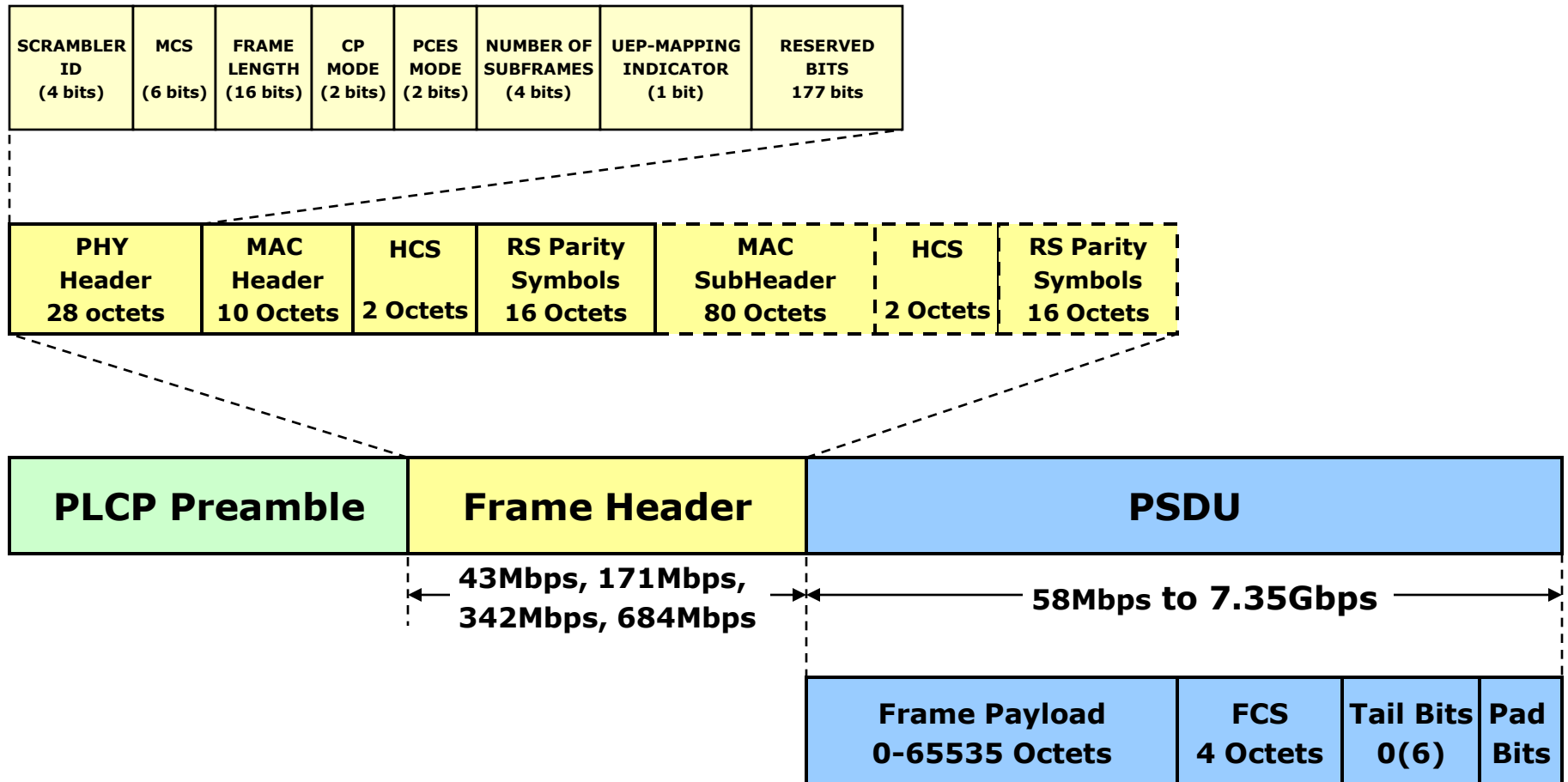
Description	#	location
Zero subcarriers	3	-1,0,1
Guard subcarriers	141	[-186:-256]U[186:255]
Pilot subcarriers	16	[-166:22:-12]U[12:22:166]
User defined subcarriers	16	[-185:-178]U[178:185]
Data subcarriers	336	[-177:-2]U[2:177] - [-166:22:-12]U[12:22:166]

Subcarrier frequency allocation:
16 groups, 22 subcarriers per group (21 data & 1 pilot)

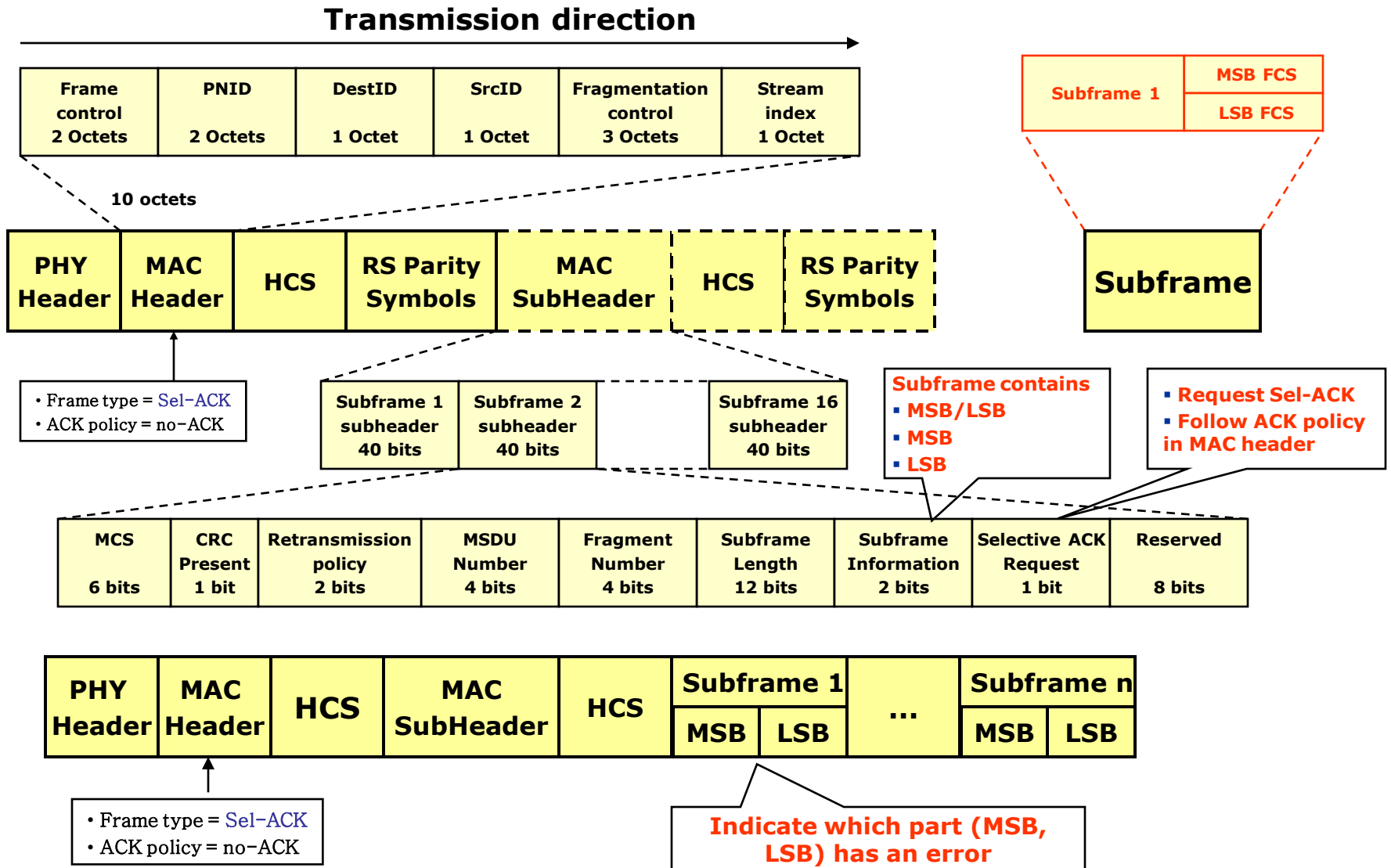


Packet Structure

Transmit Order (from left to right) →



MAC SubHeader & Sel-ACK (Selective ACK)

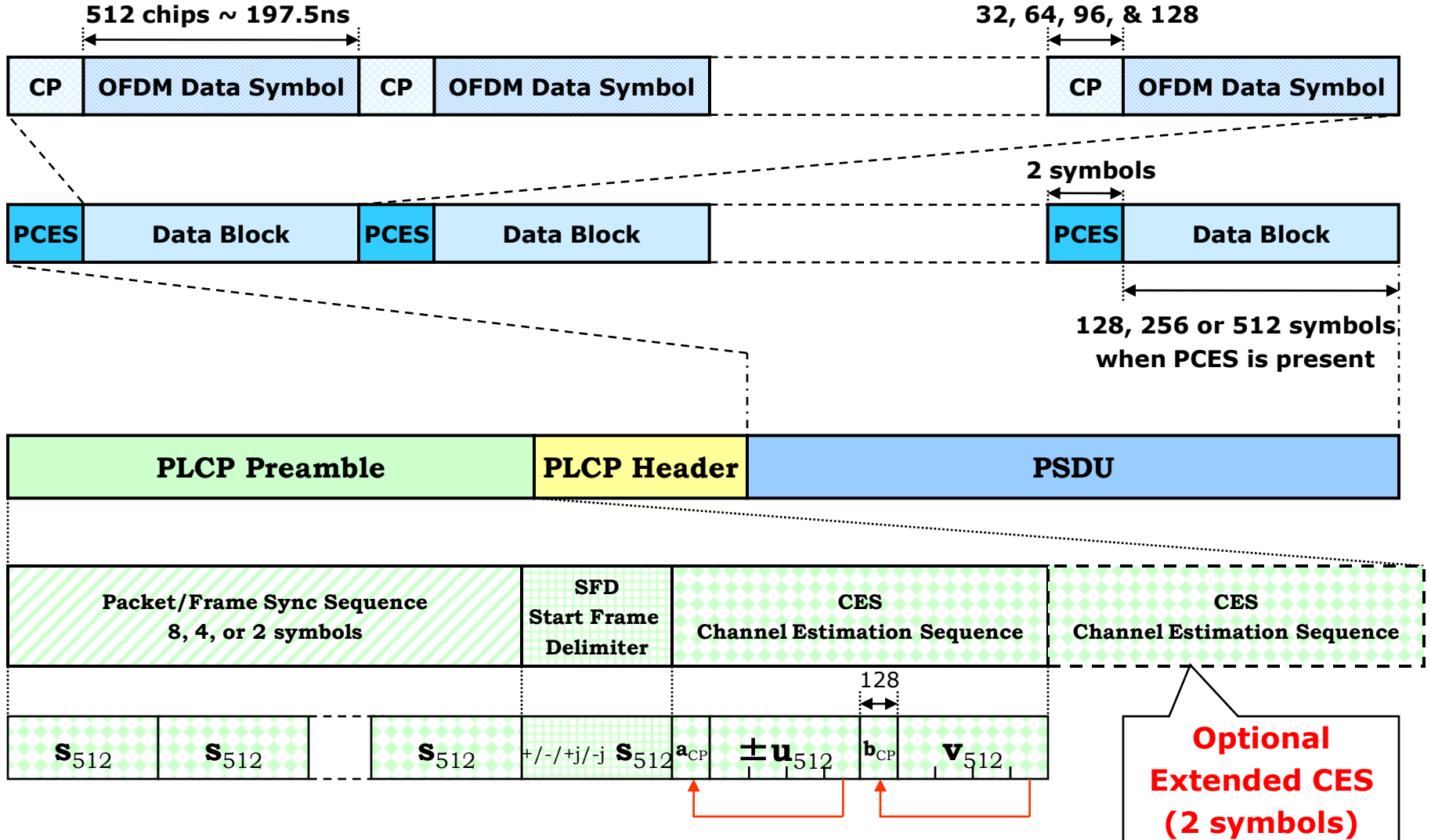


PHY Header

SCRAMBLER ID (4 bits)	MCS (6 bits)	FRAME LENGTH (16 bits)	CP MODE (2 bits)	PCES MODE (2 bits)	NUMBER OF SUBFRAMES (4 bits)	UEP-MAPPING INDICATOR (1 bit)	RESERVED BITS 177 bits
---------------------------------	------------------------	----------------------------------	----------------------------	------------------------------	--	---	----------------------------------

- **SCRAMBLER ID**: Scrambler Seed in current packet
- **MCS** : of current packet
- **CP Mode** : of current packet body (not header)
- **PCES Mode** : of current packet
- **UEP-Mapping** : of current packet (0 means EEP, 1 means UEP-Constellation)

Frame Format



OFDM signaling Mode

- Outer Reed Solomon (K+16,K)
- Inner Hamming(12,8)
- Spreading in Frequency Domain to allow 4 non-overlapping tone sets

Data Rates

Data Rate Mbps R_d	Header Rate Mbps R_h	Chip Rate MHz R_C	Modulation Scheme	Frequency Spreading Factor: L_f	Outer FEC Type	Outer FEC Rate R_{OFEC}	Inner FEC Type	Inner FEC Rate R_{IFEC}	FEC Rate R_{FEC}	Spread & Coded Bits/symbol N_{SCBPS}	Coded Bits Per Symbol N_{CBPS}	Data Info Bits* Per Symbol N_{IBPSD}
58	43	2592	QPSK	32	RS(216,200)	0.926	Ham(12,8)	0.667	0.617	672	21	14
117	43	2592	QPSK	16	RS(216,200)	0.926	Ham(12,8)	0.667	0.617	672	42	28
467	171	2592	QPSK	4	RS(216,200)	0.926	Ham(12,8)	0.667	0.617	672	168	112
933	342	2592	QPSK	2	RS(216,200)	0.926	Ham(12,8)	0.667	0.617	672	336	224

Header Rates

Base header Rate (Mbps) R_{BH}	Base+optional Header Rate R_H	Chip Rate MHz R_C	Modulation Scheme	Frequency Spreading Factor: L_f	Outer FEC Rate R_{OFEC}	Outer FEC Type	Inner FEC Type	Inner FEC Rate R_{IFEC}	FEC Rate R_{FEC}	pread & Code Bits/symbol N_{SCBPS}	Coded Bits Per Symbol N_{CBPS}	Data Info Bits* Per Symbol N_{IBPSD}	Number of Used Symbols	
													Base header	Optional header
43	48	2592	QPSK	32	RS(56,40)	0.714	Ham(12,8)	0.667	0.476	672	21	14	32	56
171	193	2592	QPSK	8	RS(56,40)	0.714	Ham(12,8)	0.667	0.476	672	84	56	8	14
342	386	2592	QPSK	4	RS(56,40)	0.714	Ham(12,8)	0.667	0.476	672	168	112	4	7
684	708	2592	QPSK	2	RS(56,40)	0.714	Ham(12,8)	0.667	0.476	672	336	224	2	4

Rate-Dependent Parameters (LDPC)

Data Rate Mbps R_d	Header Rate Mbps R_h	Chip Rate MHz R_C	Modulation Scheme	Frequency Spreading Factor: L_f	Outer FEC Type	Outer FEC Rate R_{OFEC}	Inner FEC Type	Inner FEC Rate R_{IFEC}	FEC Rate R_{FEC}	Spread & Coded Bits/symbol N_{SCBPS}	Coded Bits Per Symbol N_{CBPS}	Data Info Bits* Per Symbol N_{IBPSD}
700	342	2592	QPSK	2	RS(216,200)	0.926	LDPC(672,336)	0.500	0.463	672	336	168
1400	684	2592	QPSK	1	RS(216,200)	0.926	LDPC(672,336)	0.500	0.463	672	672	336
2100	684	2592	QPSK	1	RS(216,200)	0.926	LDPC(672,504)	0.750	0.694	672	672	504
2450	684	2592	QPSK	1	RS(216,200)	0.926	LDPC(672,588)	0.875	0.810	672	672	588
2800	684	2592	16QAM	1	RS(216,200)	0.926	LDPC(672,336)	0.500	0.463	1344	1344	672
4200	684	2592	16QAM	1	RS(216,200)	0.926	LDPC(672,504)	0.750	0.694	1344	1344	1008
4900	684	2592	16QAM	1	RS(216,200)	0.926	LDPC(672,588)	0.875	0.810	1344	1344	1176
6300	684	2592	64QAM	1	RS(216,200)	0.926	LDPC(672,504)	0.750	0.694	2016	2016	1512
7350	684	2592	64QAM	1	RS(216,200)	0.926	LDPC(672,588)	0.875	0.810	2016	2016	1764

- **RS encoded data bits with an outer RS(216,200)**

UEP Mode

Data Rate(Mbps)	Modulation	MSB Coding rate	LSB Coding Rate
1750 Mbps	QPSK	LDPC(672,336)	LDPC(672,504)
2625 Mbps	QPSK	LDPC(672,504)	LDPC(672,588)

Rate-Dependent Parameters (Convolutional)

HRC mode index	Coding Mode	Modulation	Convolutional Code Rate								Net data rate (Gbps)
			MSB				LSB				
			[7]	[6]	[5]	[4]	[3]	[2]	[1]	[0]	
0	EEP	QPSK	1/3								1.0
1			1/2								1.5
2			2/3								2.0
3		16QAM	1/2								3.0
4			2/3								4.0
5		64QAM	1/2								4.5
6	2/3								6.0		
7	UEP	QPSK	4/7				4/5				2.0
8		16QAM	4/7				4/5				4.0
9		64QAM	4/7				4/5				6.0
10	MSB/(LSB)-only transmission	QPSK	1/3				(1/3)				1.0
11			2/3				(2/3)				2.0

Timing-Related Parameters

Parameter	Description	value				Unit	Formula
R_C	Chip rate	2592				MHz	
T_C	Chip duration	0.386				ns	$= 1/R_C$
N_{FFT}	FFT Size	512				subcarriers	
N_D	Number of data subcarriers	336				subcarriers	
N_P	Total number of pilot subcarriers	16				subcarriers	
N_G	Number of guard subcarriers	141				subcarriers	
N_{DC}	Number of DC subcarriers	3				subcarriers	
N_{RES}	Number of reserved subcarriers*	16				subcarriers	
N_U	Number of useful subcarriers	352				subcarriers	
N_{CP}	Cyclic prefix length	32	64	96	128	Chips	
D_f	Subcarrier frequency spacing	5.0625				MHz	$= R_C/N_{FFT}$
B_U	Used bandwidth	1782				MHz	$= N_U \times D_f$
T_{FFT}	IFFT/FFT duration	197.53				ns	$= 1/D_f$
T_{CP}	Cyclic prefix duration	12.35	24.69	37.04	49.38	ns	$= N_{CP} \times T_C$
T_{SYM}	Symbol duration	209.88	222.22	234.57	246.91	ns	$= T_{FFT} + T_{CP}$
F_{SYM}	Symbol rate	4.765	4.5	4.263	4.05	MHz	$= 1/T_{SYM}$
N_{CPSYM}	Number of chips per symbol	544	576	608	640	Chips	$= N_{FFT} + N_{CP}$

Frame-Related Parameters

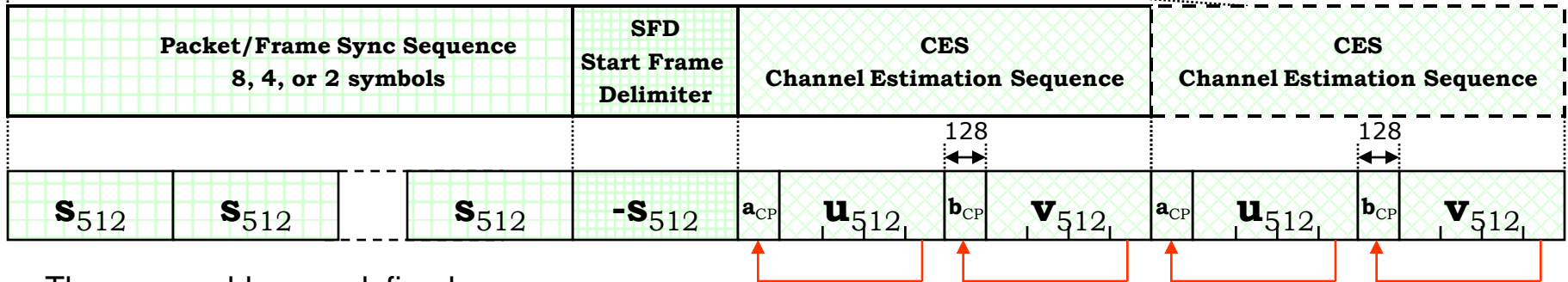
Parameter	Description	Value
N_{sync}	Number of symbols in the packet/frame synchronization sequence	Long preamble: 9 Medium preamble: 5 Short preamble: 3
T_{sync}	Duration of the packet/frame synchronization sequence	Long preamble: 1.778 μ S Medium preamble: 0.988 μ S Short preamble: 0.593 μ S
N_{ces}	Number of symbols in the channel estimation sequence	Long preamble: 2 Medium preamble: 2 Short preamble: 1
T_{ces}	Duration of the channel estimation sequence	Long preamble: 0.395 μ S Medium preamble: 0.395 μ S Short preamble: 0.198 μ S
N_{pre}	Number of symbols in the PLCP preamble	Long preamble: 11 medium preamble: 7 short preamble: 4
T_{pre}	Duration of the PLCP preamble	Long preamble: 2.173 μ S Medium preamble: 1.383 μ S Short preamble: 0.790 μ S
N_{hdr}	Number of symbols in the header	Long header: 84 Medium I Header: 8 Medium II Header: 2 Short Header: 1
T_{hdr}	Duration of the PHY header ⁽¹⁾	Long header: 1.580 μ S Medium I header: 0.395 μ S Medium II header: 0.198 μ S Short header: 0.312 μ S
N_{RS}	Number of Reed solomon Blocks	$\text{ceil}[(\text{LENGTH}+4)/200]$
N_{LDPC}	Number of LDPC Blocks	$\text{ceil}[(\text{LENGTH}+4+16 \times N_{RS})/(84 \times R_{Inner})]$
N_{frame}	Number of symbols in the data field	$\text{ceil}\{[8 \times \text{LENGTH} + 32 + 128 \times N_{RS} + 676 \times (1 - \text{Rinner}) \times N_{LDPC}]/N_{SCBPS}\}$
T_{frame}	Duration of the data field	$N_{frame} \times T_{SYM}$
N_{packet}	Number of symbols in the packet	$N_{pre} + N_{hdr} + N_{frame}$
T_{packet}	Duration of the packet	$T_{pre} + T_{hdr} + T_{frame}$

(1) Duration is based on the default CP of 64

The Preambles

Long: $T_{pre} = 2.173\mu\text{s}$, $N_{pre} = 11$
 Medium: $T_{pre} = 1.383\mu\text{s}$, $N_{pre} = 07$
 Short: $T_{pre} = 0.790\mu\text{s}$, $N_{pre} = 04$

PLCP Preamble



- Three preambles are defined:
 - Long preamble : 8 sync symbols, 1 SFD symbol, 2 CES symbols
 - Medium preamble : 4 sync symbols, 1 SFD symbol, 2 CES symbols
 - Short preamble : 2 sync symbols, 1 SFD symbol, 1 CES symbol
- Different preamble lengths reduces overhead and latency and enable efficient beamforming
- For data transmission, switching from long to medium or short preamble is upon device request.
 - First packet shall use the long PLCP preamble, the remaining packets may use either one of the three preambles.
 - When using medium or short preamble, packets shall be separated by MIFS.
- For beamforming, different preamble lengths are used to maintain a balanced spreading gain-antenna gain
- A unique preamble sequence set is assigned to each piconet within the same frequency channel (frequency & spatial reuse).

The Preambles

- Four preamble sequence sets (labeled by the parameter m) are provided for the purpose of frequency/spatial reuse
- A preamble sequence set consists of a base sequence $\mathbf{s}_{512,m}$ and two CES sequences $\mathbf{u}_{512,m}$ and $\mathbf{v}_{512,m}$.
- The length 512 base sequence $\mathbf{s}_{512,m}$ is the Kronecker product of a length 4 cover sequence, $\mathbf{c}_{4,m}$ and a length 128 modified Golay sequence $\mathbf{u}_{128,m}$.

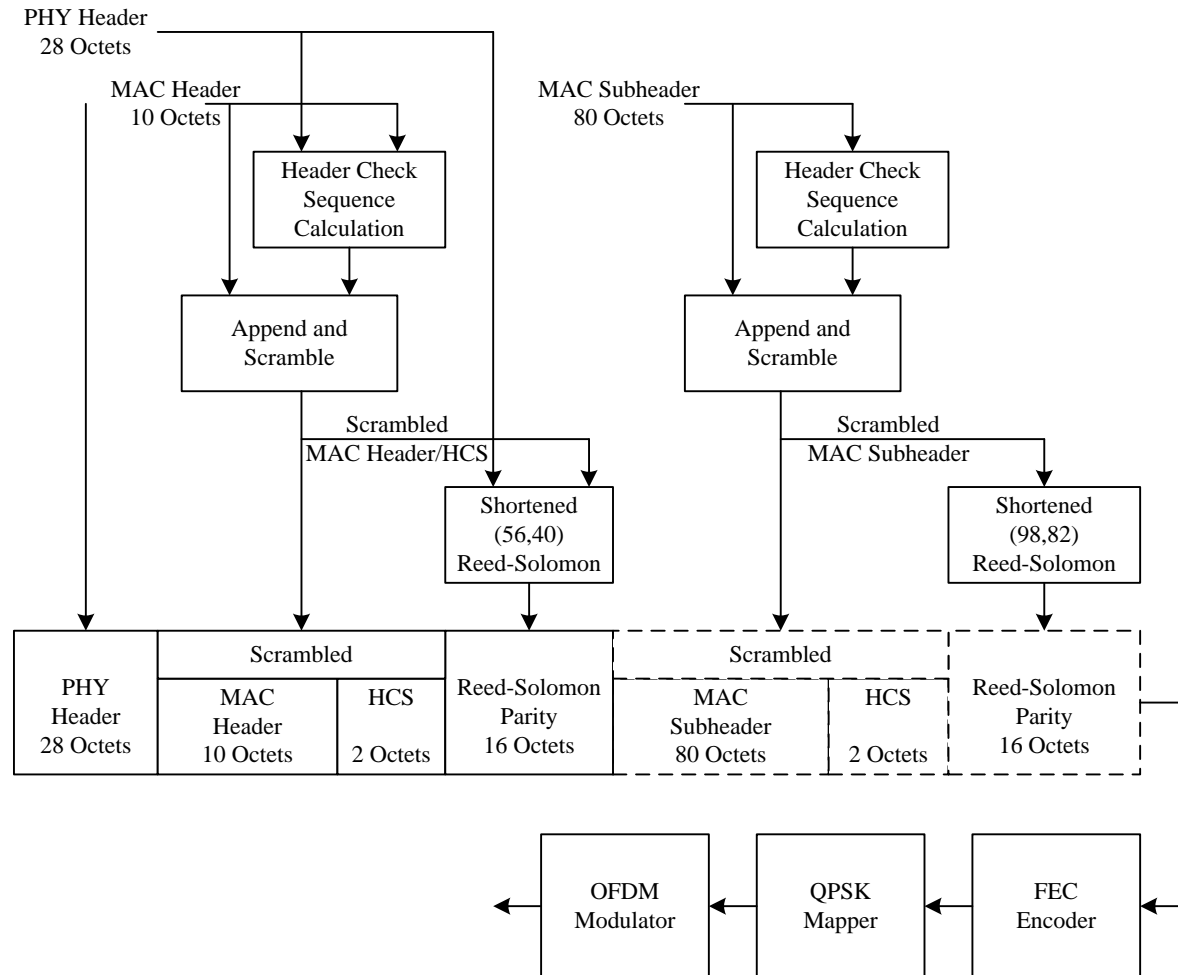
$$s_{512,m}[n] = c_{4,m}[\text{floor}(n/128)] \times u_{128,m}[n \bmod 128] \quad n=0:511$$

- The cover sequences and modified Golay sequences are listed in Tables 1 & 2 respectively.
- The base sequences occupy four non-overlapping frequency bin sets, and therefore are orthogonal in time and frequency domain. The m th base sequence occupies frequency bins $m, m+4, m+8, m+12, \dots$
- Modified Golay sequences, are obtained from Golay sequences using time (or frequency) domain filtering to guarantee that only the used subcarriers are populated rather than the entire 512 subcarriers.

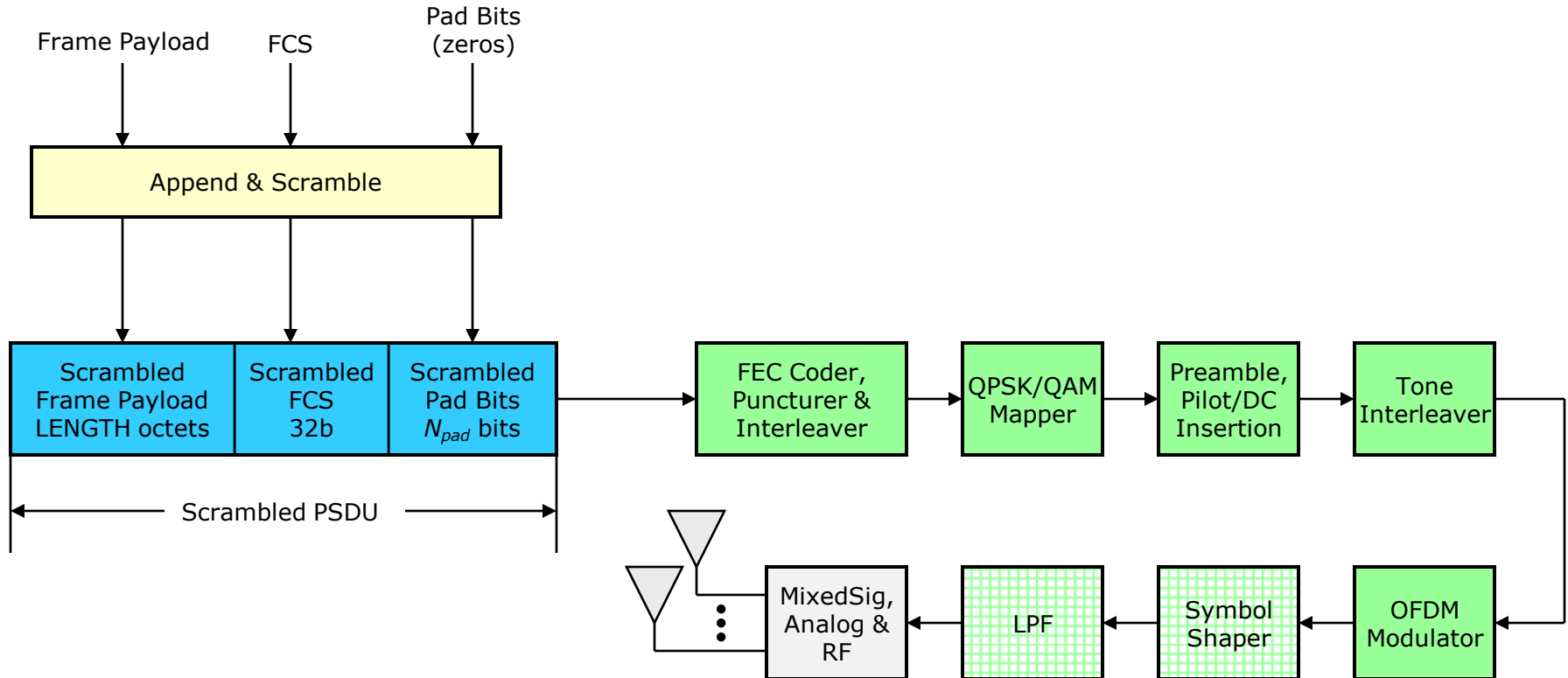
The Preambles

- The length 512 CES sequences $\mathbf{u}_{512,m}$ and $\mathbf{v}_{512,m}$ are modified complementary Golay sequences derived from Golay sequences $\mathbf{a}_{512,m}$ and $\mathbf{b}_{512,m}$. They are listed in Table 3.
- Modified complementary Golay sequences enable perfect channel estimation in both time and frequency domains
 - The Golay matched filter (shown before) can be used to provide simultaneously matched filter outputs to codes \mathbf{a} and \mathbf{b} . Combining the two outputs appropriately provide a perfect channel estimation in time domain;
 - Frequency domain channel estimation is done in the conventional way. The complementarity property is conserved in frequency domain.
- OFDM systems can benefit from time-domain channel estimation due to dimensionality (rank) issue;
- The Pilot CES (PCES) field is an optional field. When present, it is equivalent to the CES field and is repeated periodically to allow channel tracking. Three periods are provided which correspond to pedestrian speeds of 1, 3, and 6m/s.
- The receiver may use the efficient 2-levels (on I & Q) low-complexity Golay matched filter shown above for packet and frame detection.

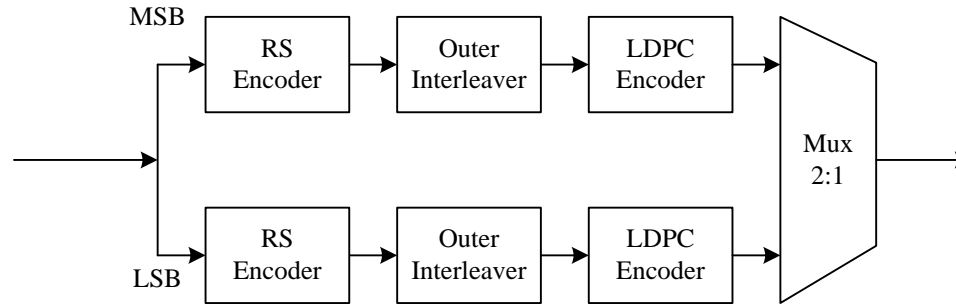
Frame Header Encoding Process



Transmitter Reference diagram



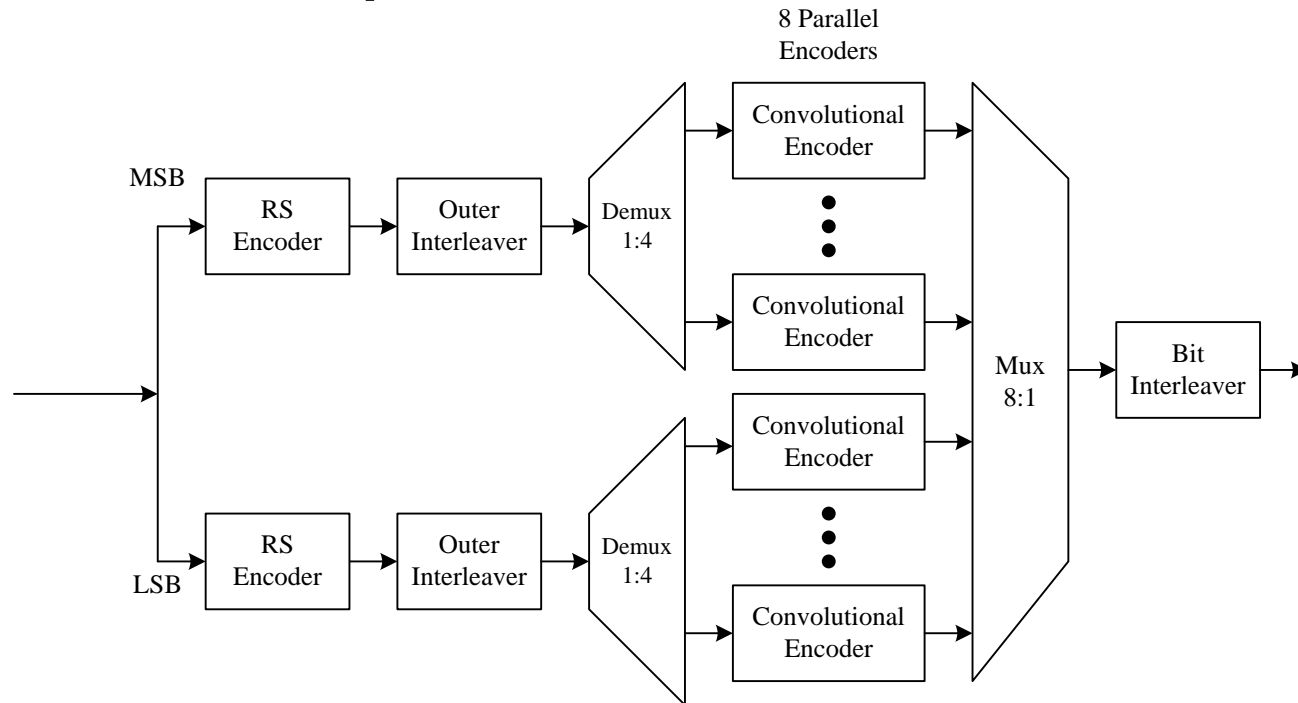
FEC Option I: RS-LDPC



- Outer Block Interleaver: 4×216 bytes
- No bit interleaving is required
- Supports rates $\frac{1}{2}$, $\frac{3}{4}$, and $\frac{7}{8}$
- Very low complexity systematic encoder
- Low complexity highly parallelizable decoder (gate count ~ 105K gates)
- Throughput matched to that of RS
- 1 RS and 1 LDPC Decoder engine is needed for LDR devices
- Throughput of ~ 6 Gbps with Master clock of 324 MHz (BW/8) and 32 iterations
- Parity Check Matrices (Same as SC LDPC)

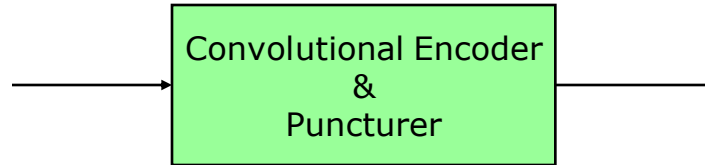
Rate	$1/2$	$3/4$	$7/8$
KK	336	504	588
NN	672	672	672
d_{min}	14	10	6

FEC Option II: RQ-Convolutional



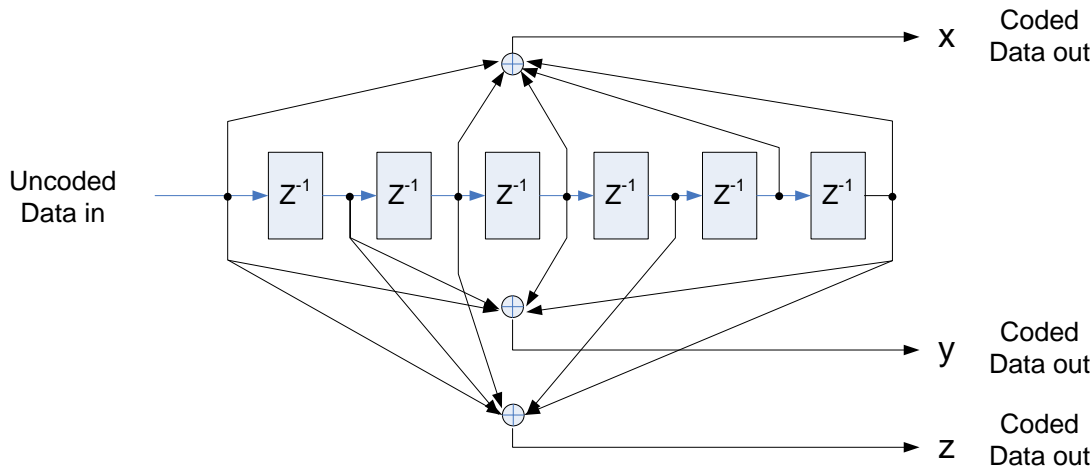
- Inner convolutional codes combined with outer Reed Solomon codes
- Outer-interleaver in-between : 4x224 bytes block interleaver
- Outer code rate : RS(224, 216)

FEC Option II: RS-Convolutional



Convolutional encoder : $R = 1/3, K = 7$

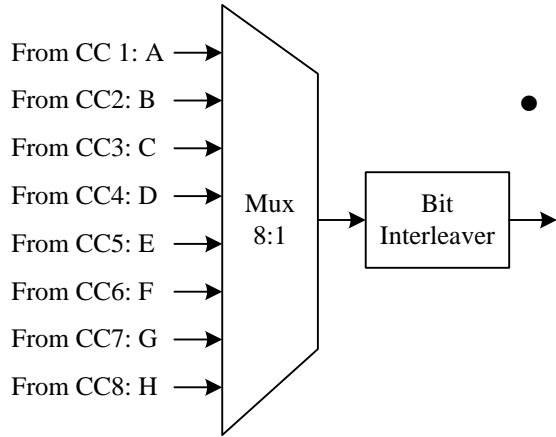
Generator polynomial :
 $g_0 = 133_8, g_1 = 171_8, g_2 = 165_8$



Code rate	Puncturing pattern	Transmitted sequence
1/3	X:1 Y:1 Z:1	$X_1Y_1Z_1$
1/2	X:1 Y:1 Z:0	X_1Y_1
4/7	X:1 1 1 1 Y:1 0 1 1 Z:0 0 0 0	$X_1Y_1X_2X_3Y_3X_4Y_4$
2/3	X:1 1 Y:1 0 Z:0 0	$X_1Y_1X_2$
4/5	X:1 1 1 1 Y:1 0 0 0 Z:0 0 0 0	$X_1Y_1X_2X_3X_4$

FEC Option II: RS-Convolutional

- Data multiplexer combines data from all convolutional encoders



- EEP Mux / Interleaver
 - Bit interleaver size: 48
 - A1...A6 come from encoder A, and similarly for others

A1	E5	D3	C1	G5	F3	E1	A5	H3	G1	C5	B3	→ I
B2	F6	E4	D2	H6	G4	F2	B6	A4	H2	D6	C4	→ MSB
C3	B1	F5	E3	D1	H5	G3	F1	B5	A3	H1	D5	→ I
D4	C2	G6	F4	E2	A6	H4	G2	C6	B4	A2	E6	→ I

LSB

Q

MSB

Q

LSB

- UEP-Mapping Mux/Interleaver: Overall bit interleaver size 48

A1	C3	A5	B1	D3	B5	C1	A3	C5	D1	B3	D5
B2	D4	B6	C2	A4	C6	D2	B4	D6	A2	C4	A6
E1	G3	E5	F1	H3	F5	G1	E3	G5	H1	F3	G5
F2	H4	F6	G2	E4	G6	H2	F4	H6	E2	G4	E6

FEC Option II: RS-Convolutional

- UEP-Coding Mux/Interleaver

- Overall bit interleaver size 96
- For first half cycle of 48 bits: A1...A7 come from encoder A, similarly for BCD; E1...E5 come from encoder E, similarly for FG

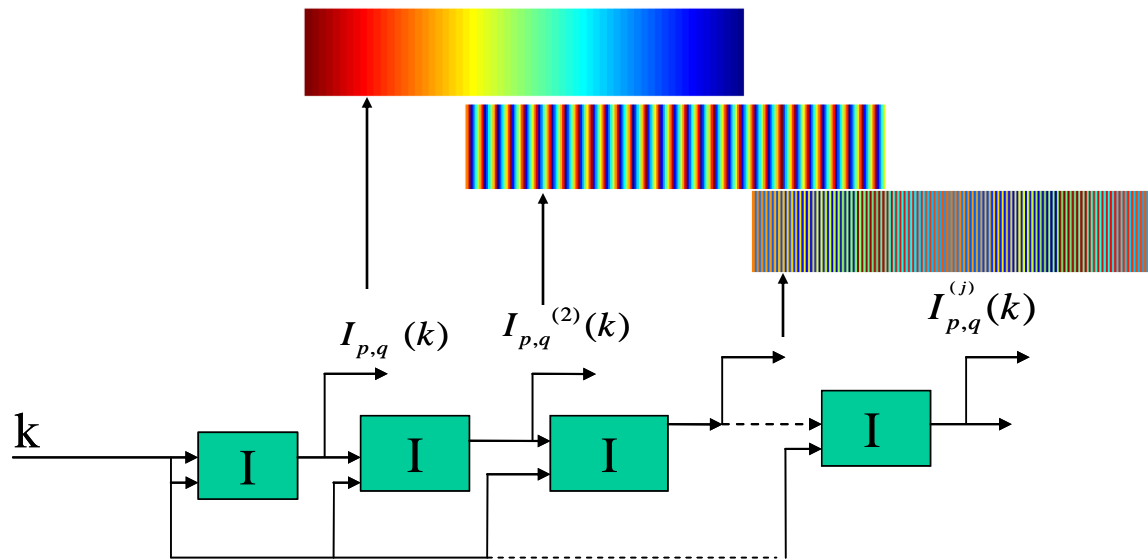
A1	E1	C7	B6	G3	E5	D4	A5	H2	F4	C3	B2
B2	F3	D7	C6	H5	G2	E4	B5	B5	H1	D3	C2
C1	A7	F2	D6	C5	H4	G1	E3	E3	A3	G5	D2
D1	B7	G4	F1	D5	A6	H3	F5	F5	B3	A2	E2

- For second half cycle of 48 bits: A1...A7 come from encoder A, similarly for BCD; E1...E5 come from encoder E, similarly for FG

B1	E1	C7	B6	G3	E5	D4	A5	H2	F4	C3	B2
C1	F3	D7	C6	H5	G2	E4	B5	B5	H1	D3	C2
C1	A7	F2	D6	C5	H4	G1	E3	E3	A3	G5	D2
D1	B7	G4	F1	D5	A6	H3	F5	F5	B3	A2	E2

FEC Option II: Binary Interleaving

- Optimized binary interleaver based on an iterative structure [1-4]
- Effectively maximizes both intra- and inter- symbols interleaving spreading
- Efficiently improves decoder performance



$$X_{OUT}(k) = X_{IN}(I_{p,q}^{(j)}(k))$$

$$I_{p,q}^{(0)}(k) = \left[\alpha + k + q \cdot p \cdot \left[-k - p \cdot k \right]_K \right]_K$$

$$I_{p,q}^{(j)}(k) = \left[\alpha + k + q \cdot p \cdot \left[-k - p \cdot I_{p,q}^{(j-1)} \right]_K \right]_K$$

K : Block size,

p, q, j : Interleaver parameters

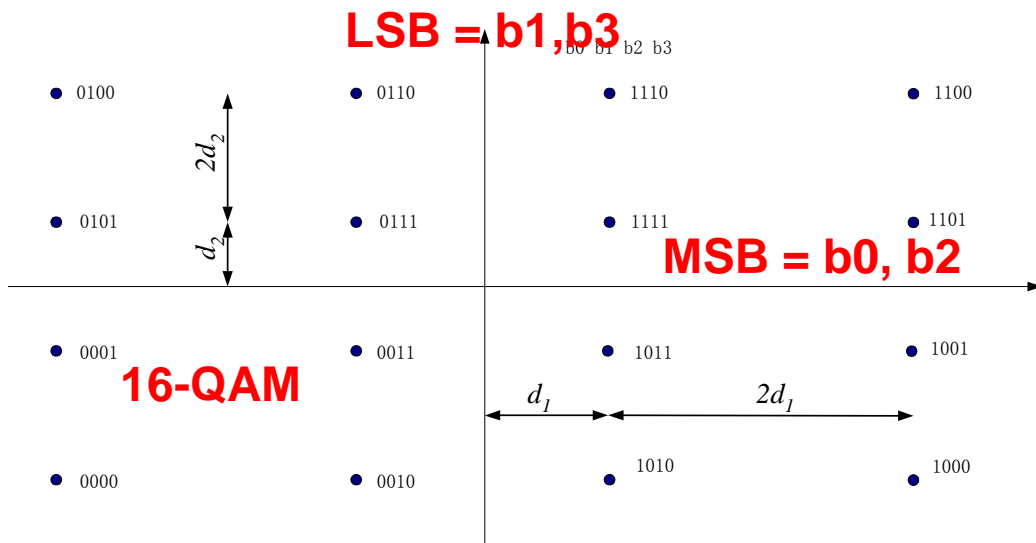
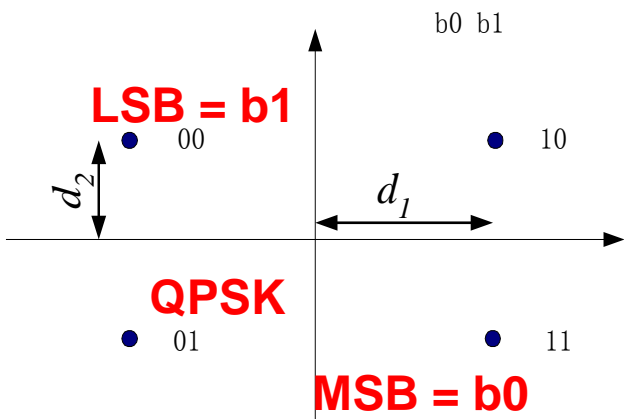
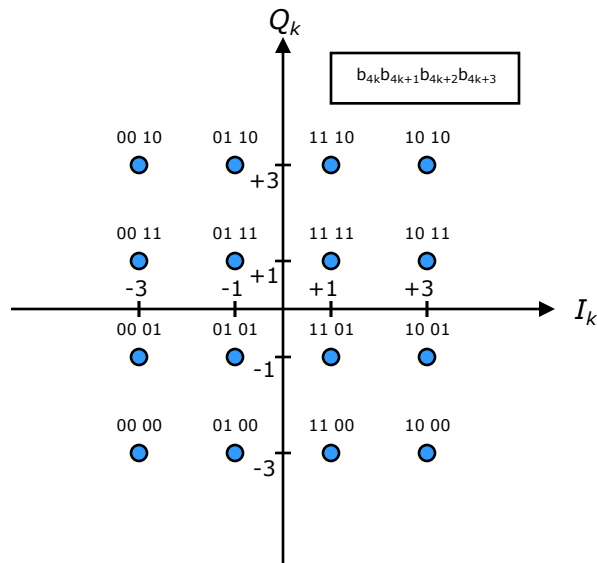
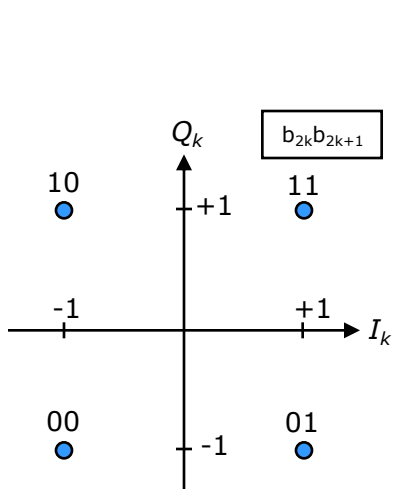
$\alpha < \frac{K}{p}$: Offset parameter

FEC Option II: The Tone Interleaver

- Normal FFT requires a bit-reversal operation before “butterflying”
- Bit-reversal interleaving pattern can be combined with FFT operation to reduce complexity
- Interleaving Rule :

Before Interleaving		After Interleaving	
0	000	000	0
1	001	100	4
2	010	010	2
3	011	110	6
4	100	001	1
5	101	101	5
6	110	011	3
7	111	111	7

Normal & Skewed Constellation for UEP-Mapping

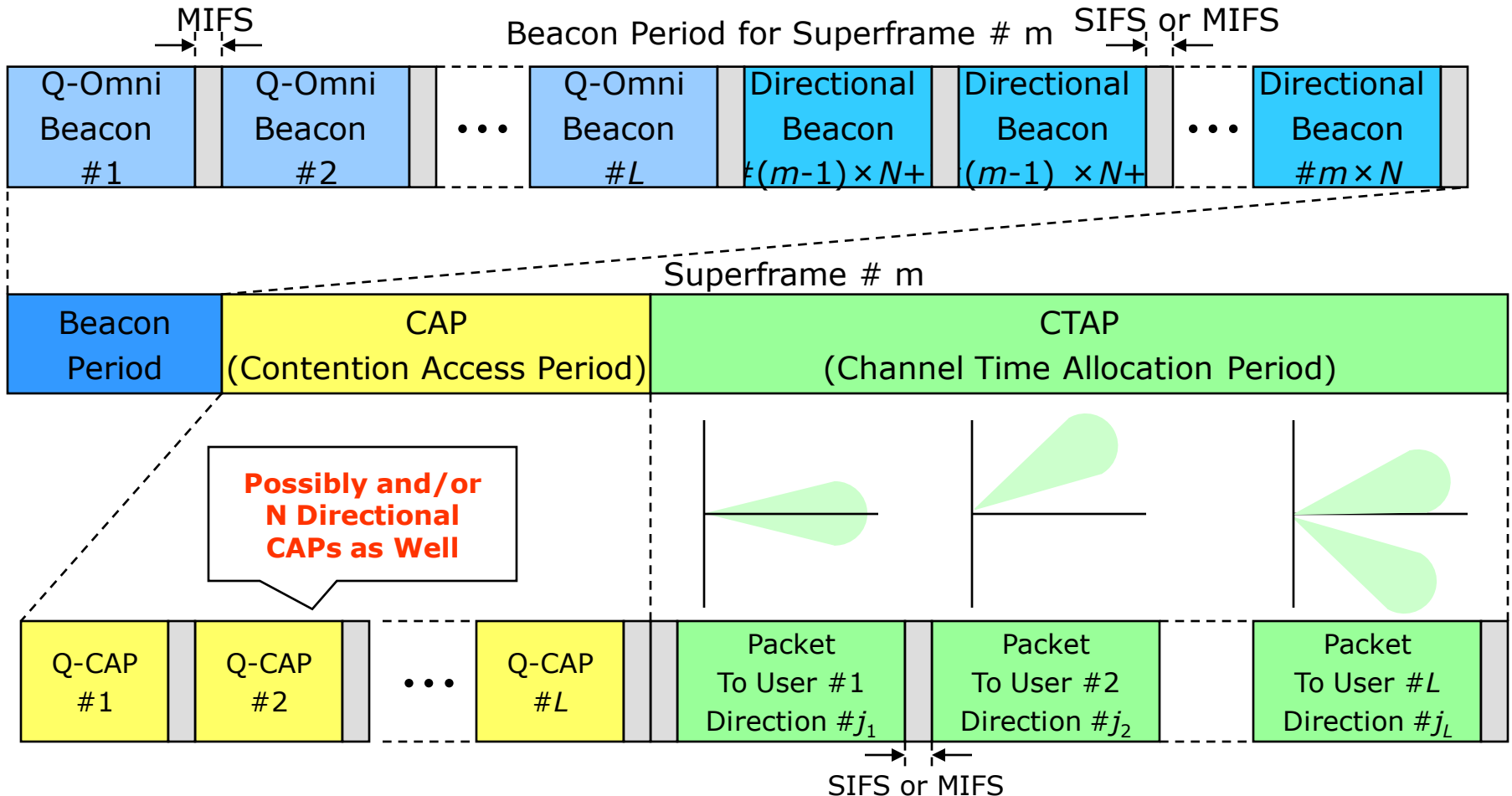


Optional Beamforming I

Beamforming Requirements

- A unified messaging protocol that supports :
 - 1. Different antenna configurations on either side (Tx or Rx):
 - Omni or quasi-omni antennas
 - Directional single antenna
 - Switch diversity antennas
 - Sectorized antennas
 - Beamforming antennas
 - Etc,...
 - 2. Both pro-active and on-demand beamforming
 - 3. Different usage models
 - Per packet beamforming from PNC to multiple DEVs and DEVs to PNC
 - PNC to one DEV
 - DEV-DEV
 - Others,...
- The unified messaging protocol should be independent of the specifics of the beamforming algorithm and antenna configuration implementation. Therefore, the actual beamforming algorithm will be left to the implementer.
- However, the tools enabling the beamforming should be defined. These tools should support all scenarios while enabling:
 - 1. Reduced latency
 - 2. Reduced overhead
 - 3. Fast beamforming
- The tools: four types of signaling packets with different preamble options

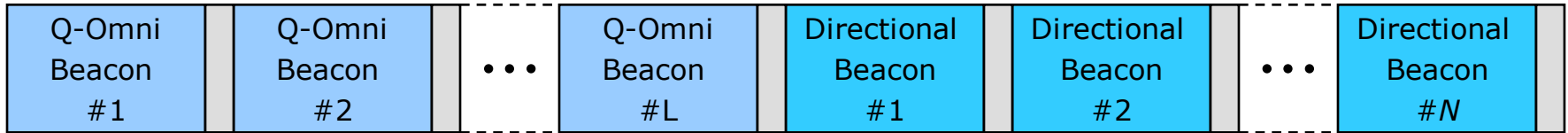
Pro-Active Beamforming



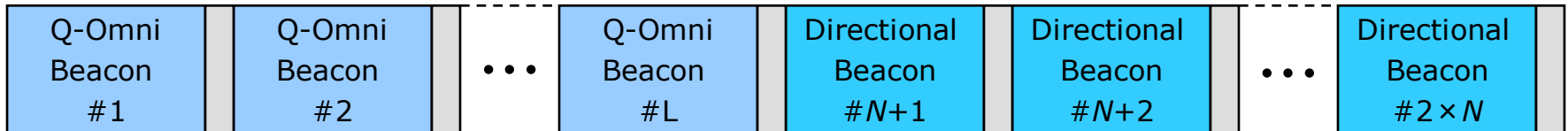
- Pro-active beamforming is useful when the PNC is the source of data to one or multiple DEVs.
- Usage model example: Kiosk, STB, Laptop:
 - The PNC is the source of data to multiple DEVs;
 - The PNC can send each packet in a different direction, optimized to the destined device.

Pro-Active Beamforming

Beacon Period for Superframe # 1

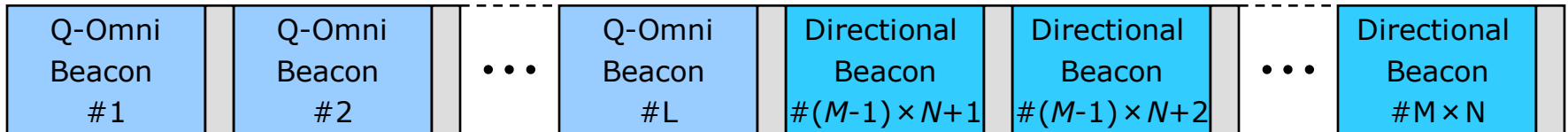


Beacon Period for Superframe # 2



⋮

Beacon Period for Superframe # M



⋮

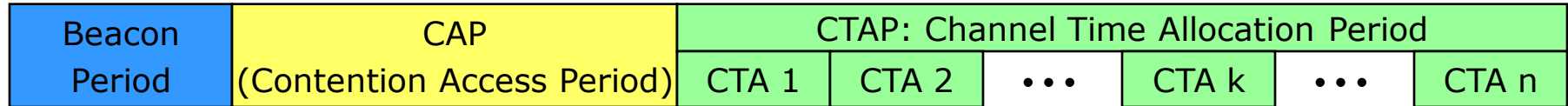
- The first L transmissions in each superframe use Quasi-Omni (Q-Omni) beacons that together provide a Quasi-omni pattern;
- For a PNC capable of a Quasi-omni coverage, $L = 1$;
- For a PNC with sectorized antennas, L would be the number of sectors;
- For a PNC with switching transmit diversity antennas, L would be the number of transmit antennas;
- It is assumed that the PNC can beamform in $J = N \times M$ directions;
- A direction does not necessarily mean a single beam; it can be any number of beams.
- The directional beacons are distributed over M superframes with N directional beacons per superframe;
- The structure is periodic of period M superframes;
- The CAP is divided into L sub-CAP periods corresponding to the L Q-omni beacons. During the l^{th} Q-CAP, the PNC antenna is in the same direction it used to transmit the l^{th} Q-Omni beacon.

On-Demand Beamforming

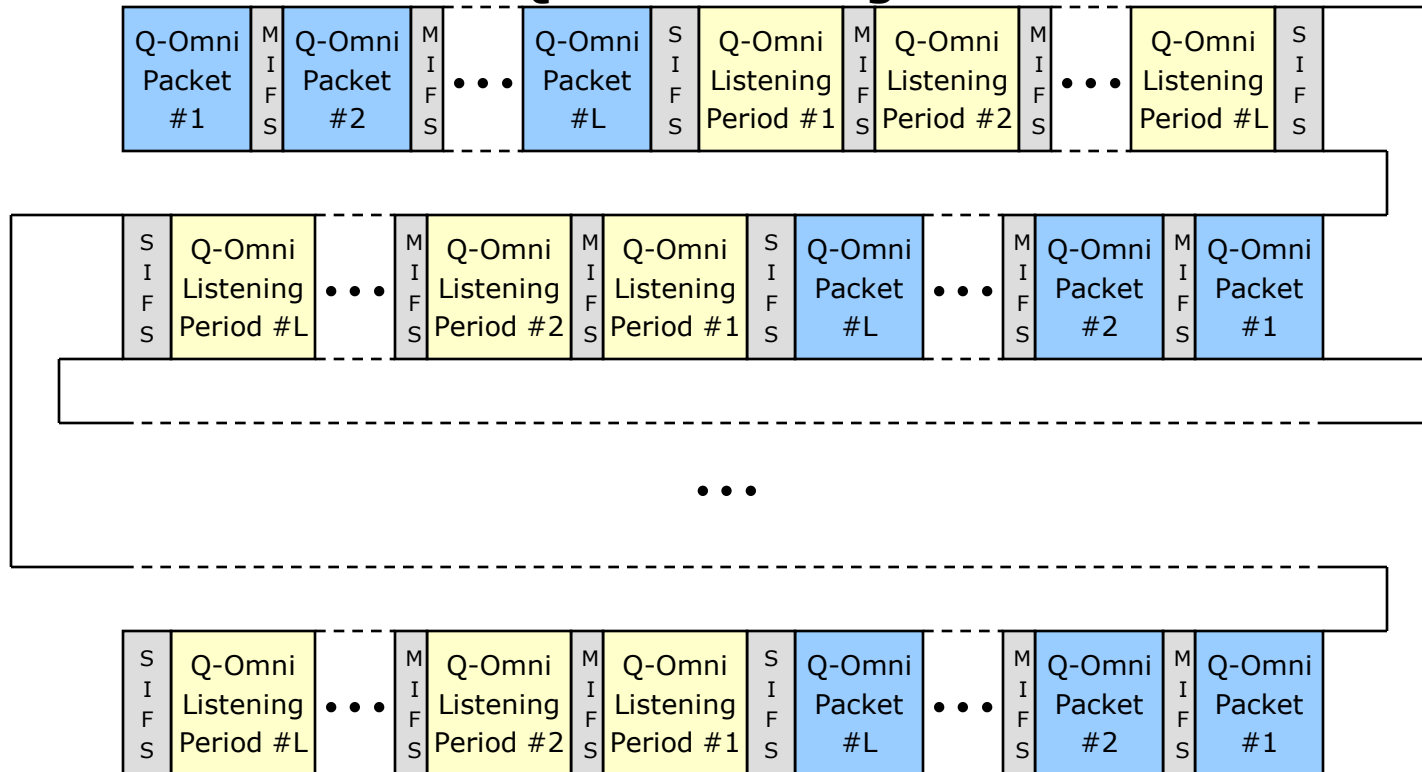
- On-demand beamforming will take place in the CTA allocated to the link between the TWO DEVs or PNC and a DEV;
- Q-omni phase:
 - DEV1 starts its first transmission with L_1 Q-omni packets followed by L_1 corresponding Q-omni listening periods;
 - DEV1 keeps repeating this section until DEV2 sends back a response
 - Each Q-omni training packet would contain the “Q-omni training packet IE”;
 - DEV2, capable of L_2 Q-Omni directions, will set its reception direction to one of the L_2 directions and listens to DEV1 first L_1 transmissions and stores L_1 LQFs. DEV2 moves to a new direction and listen to DEV1 second period of L_1 transmissions. DEV2 continue to do so until an adequate LQF. Alternatively, DEV2 may choose to listen using all L_2 directions than find the best LQF.
 - At the end of this phase, DEV1 and DEV2 would know the best Q-Omni directions combination to exchange further data.
 - Using the “Q-omni training response packet IE”, DEV2 would inform DEV1 of its Q-omni capabilities, i.e. L_2 , as well as its own best 1st direction and 2nd direction that it will use for all messaging. Furthermore, DEV2 would inform DEV1 of the best 1st and 2nd direction it found out from the L_1 direction. DEV1 best Q-omni direction would be labeled I_1 , and DEV2 best Q-omni-direction would be labeled I_2 . DEV2 informs DEV1 of its directional capability as well.

On-Demand Beamforming

Superframe Structure



Q-omni training section



Proactive & On-Demand Beamforming IEs

Q-Omni Training Packet IE: DEV1→DEV2

3	1	1	1	1
Q-OMIN LISTENING PERIOD DURATION	NUMBER OF Q-OMIN LISTENING PERIODS	CURRENT Q-OMIN PACKET IDENTIFIER	Length (=5)	Element ID

Directional Beacon

**PLCP Preamble
Type I, II or III**

Q-Omni Training Response Packet IE: DEV2→DEV1

1	1	1	1	1	1	1	1
DEV2 DIRECTIONAL CAPABILITY	DEV1 PREFERRED DIRECTION #2	DEV1 PREFERRED DIRECTION #1	DEV2 PREFERRED DIRECTION #2	DEV2 PREFERRED DIRECTION #1	DEV2 NUMBER OF Q-OMNI DIRECTIONS	Length (=11)	Element ID

Piconet synchronization parameters field format: 21+3n octets

Octets:8	1	1	1	3	3	3	3	6
PNC address	PNC response	Piconet Mode	MAX TX Power Level	Duration per Q-CAP	Number of Q-CAP Periods	CAP end time	Superframe duration	Time token

Beamforming Information Element

Element ID hex value	Element	Subclause	Present in beacon
0x14	Beamforming Information	Add as 7.4.22	In every beacon

Beamforming Information Element Format

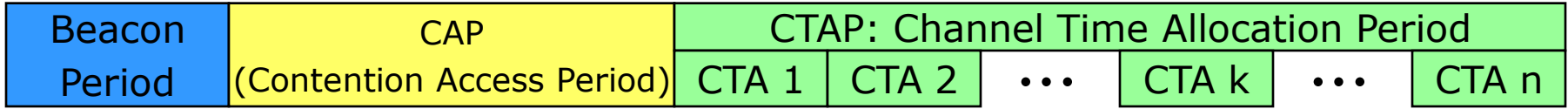
1	1	1	1	1	1	1	1
DIRECTIONAL PACKET TYPE	CURRENT DIRECTIONAL BEACON IDENTIFIER	NUMBER OF SUPERFRAMES PER BEAMFORMING CYCLE	NUMBER OF DIRECTIONAL BEACONS PER SUPERFRAME	CURRENT Q-OMIN BEACON IDENTIFIER (4bits)	NUMBER OF Q-OMNI BEACONS (4bits)	Length (=5)	Element ID

On-Demand Beamforming

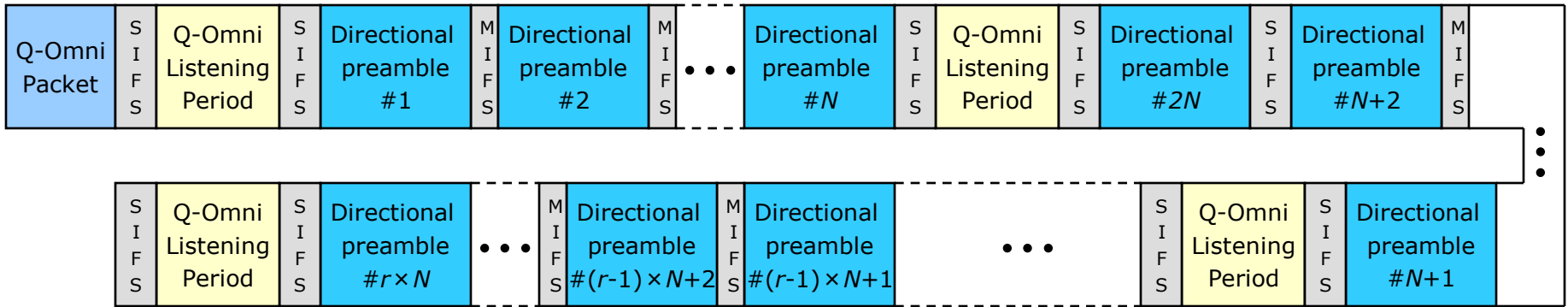
- Directional phase:
 - DEV1 uses an R -cycle procedure to do the beamforming;
 - The R cycles may happen within one CTA or may be distributed over M superframes;
 - Each cycle is made from K sub-cycles, where N and K can change from one cycle to another. This will allow for different search algorithms such as random and binary search, and differentiating between acquisition and tracking;
 - Each cycle is preceded by an Q-omni transmission outlining the structure of the current cycle;
 - Each sub-cycle consists of N directional preambles followed by an Q-omni listening period;
 - During data communication, DEV1 may still choose to transmit a sub-cycle every superframe to allow DEV2 to continuously track the beams. If DEV2 finds a better direction, it can inform DEV1 to transmit next packets using the new direction by encoding the field “Antenna Direction” in the header appropriately.

On-Demand Beamforming

Superframe Structure



CTA k Sub-cycle



Q-Omni Packet Information Element

1	1	1	1	3	1	3	1	1
DIRECTIONAL PREAMBLE TYPE	NUMBER OF SUPERFRAMES PER BEAMFORMING CYCLE	NUMBER OF SUB-CYCLES PER SUPERFRAME	NUMBER OF DIRECTIONAL PREAMBLES PER SUB-CYCLE	Q-OMIN LISTENING PERIOD DURATION	CURRENT Q-OMIN PACKET IDENTIFIER	CTA END TIME	Length (=11)	Element ID

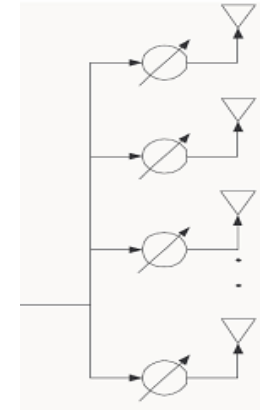
Beamforming Report Information Element

1	...	1	1	1	1
LQF-N	...	LQF-2	LQF-1	Length (=N)	Element ID

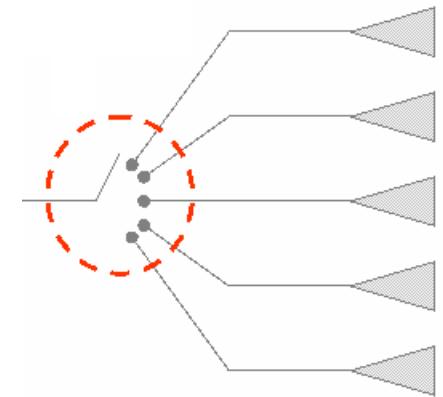
Optional Beamforming II

Antenna Configuration & Number of Antenna elements

- Two major antenna configurations identified
 - Phased antenna array: beams can be formed with most versatility to almost arbitrary directions
 - Switched antenna: beams can be formed toward only a finite number of pre-defined directions
 - Single antenna can be viewed as a special case of the switched antenna
- Antenna training protocol should support different antenna configurations
- In both cases of phased antenna array (PAA) and switched antenna array (SAA), number of antenna elements in the array can not be pre-fixed
 - Standard simply does not specify how many antenna elements a device should implement
- Number of antenna elements thus should be exchanged over the air inside the training process



Antennas



Antenna Info Exchange

- Antenna info (antenna type and number of antennas) are exchanged in the association stage. Example:

Octets: 1	1	2	2	1	3
IE index	Length	SC mode support	OFDM mode support	Explicit / implicit	Antenna Support

Bits: 8	8	4	4
Number of TX elements	Number of RX elements	TX antenna type	RX antenna type

- Depending on the antenna types of STA1, and STA2;
- 4 possible combinations
 - 1) PAA to PAA
 - 2) PAA to SAA
 - 3) SAA to PAA
 - 4) SAA to SAA
- Apply optimized training sequence for each combination

Appendix LDPC Parity Check Matrix

E78: Rate 7/8

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	2	11	9	10	4	15	2	5	12	16	16	10	5	13	2	8	10	5	10	6	5	17	10	8	6	7	16	0	2	∞	∞	∞
2	10	2	11	9	5	4	15	2	10	12	16	16	8	5	13	2	6	10	5	10	8	5	17	10	0	6	7	16	7	2	∞	∞
3	9	10	2	11	2	5	4	15	16	10	12	16	2	8	5	13	10	6	10	5	10	8	5	17	16	0	6	7	8	7	2	∞
4	11	9	10	2	15	2	5	4	16	16	10	12	13	2	8	5	5	10	6	10	17	10	8	5	7	16	0	6	5	8	7	2

E34: Rate 3/4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	
1	2	∞	9	∞	4	∞	∞	5	12	∞	16	∞	5	∞	2	∞	10	5	∞	∞	∞	∞	10	8	∞	7	∞	∞	∞	∞	∞	∞	
2	∞	11	∞	10	∞	15	2	∞	∞	16	∞	10	∞	13	∞	8	∞	∞	10	6	5	17	∞	∞	6	∞	∞	∞	∞	∞	∞	∞	
3	∞	2	∞	9	5	4	∞	∞	∞	12	∞	16	∞	5	∞	2	∞	10	5	∞	8	∞	∞	10	∞	∞	7	16	∞	2	∞	∞	
4	10	∞	11	∞	∞	∞	15	2	10	∞	16	∞	8	∞	13	∞	6	∞	∞	10	∞	5	17	∞	0	6	∞	∞	7	∞	∞	∞	
5	9	∞	2	∞	∞	5	4	∞	16	∞	12	∞	2	∞	5	∞	∞	∞	10	5	10	8	∞	∞	16	∞	∞	7	∞	∞	∞	∞	
6	∞	10	∞	11	2	∞	∞	15	∞	10	∞	16	∞	8	∞	13	10	6	∞	∞	∞	∞	∞	5	17	∞	0	6	∞	∞	∞	∞	∞
7	∞	9	∞	2	∞	∞	5	4	∞	16	∞	12	∞	2	∞	5	5	∞	∞	10	∞	10	8	∞	7	16	∞	∞	5	∞	∞	2	
8	11	∞	10	∞	15	2	∞	∞	16	∞	10	∞	13	∞	8	∞	∞	10	6	∞	17	∞	∞	5	∞	∞	0	6	∞	8	7	∞	

E12: Rate 1/2

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	
1	2	∞	∞	∞	4	∞	∞	∞	∞	∞	2	∞	∞	5	∞	∞	∞	∞	10	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	
2	∞	∞	9	∞	∞	∞	∞	5	5	∞	∞	∞	10	∞	∞	∞	∞	∞	∞	8	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	
3	∞	11	∞	∞	∞	15	∞	∞	∞	∞	∞	8	∞	∞	∞	6	∞	17	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	
4	∞	∞	∞	10	∞	∞	2	∞	∞	13	∞	∞	∞	10	∞	5	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	
5	∞	2	∞	∞	∞	4	∞	∞	∞	∞	∞	2	∞	∞	5	∞	∞	∞	∞	10	∞	∞	7	∞	∞	∞	5	∞	∞	∞	∞	∞	
6	∞	∞	∞	9	5	∞	∞	∞	∞	5	∞	∞	∞	10	∞	∞	8	∞	∞	∞	∞	∞	∞	16	∞	2	∞	∞	∞	∞	∞	∞	∞
7	∞	∞	11	∞	∞	∞	15	∞	8	∞	∞	∞	6	∞	∞	∞	∞	∞	17	∞	∞	6	∞	∞	7	∞	∞	∞	∞	∞	∞	∞	
8	10	∞	∞	∞	∞	∞	∞	2	∞	∞	13	∞	∞	∞	∞	10	∞	5	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	8	∞	∞	∞	
9	∞	∞	2	∞	∞	∞	4	∞	2	∞	∞	∞	∞	∞	∞	5	10	∞	∞	∞	∞	∞	∞	7	∞	∞	∞	∞	∞	∞	∞	∞	
10	9	∞	∞	∞	∞	5	∞	∞	∞	∞	5	∞	∞	10	∞	∞	8	∞	∞	∞	16	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
11	∞	∞	∞	11	∞	∞	15	∞	8	∞	∞	∞	6	∞	∞	∞	∞	∞	17	∞	∞	6	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
12	∞	10	∞	∞	2	∞	∞	∞	∞	∞	∞	13	10	∞	∞	∞	∞	∞	5	∞	∞	0	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
13	∞	∞	∞	2	∞	∞	4	∞	2	∞	∞	∞	5	∞	∞	∞	∞	10	∞	∞	7	∞	∞	∞	5	∞	∞	∞	∞	∞	∞	∞	12
14	∞	9	∞	∞	∞	∞	5	∞	∞	∞	∞	5	∞	∞	∞	10	∞	∞	8	∞	∞	16	∞	∞	∞	∞	∞	2	∞	16	∞	∞	∞
15	11	∞	∞	∞	15	∞	∞	∞	∞	∞	8	∞	∞	∞	6	∞	17	∞	∞	∞	∞	∞	∞	6	∞	∞	7	∞	∞	∞	10	∞	∞
16	∞	∞	10	∞	∞	2	∞	∞	13	∞	∞	∞	∞	10	∞	∞	∞	∞	5	∞	∞	∞	0	∞	∞	8	∞	∞	16	∞	∞	∞	∞