
**Information technology —
Telecommunications and information
exchange between systems — High rate
60 GHz PHY, MAC and PALs**

*Technologies de l'information — Téléinformatique — PHY, MAC et
PALs 60 GHz à haut débit*



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Contents

Page

Foreword	ix
Introduction	x
1 Scope	1
2 Conformance	1
3 Normative references	1
4 Terms and definitions	1
5 Notational conventions	3
6 Abbreviated terms	4
7 General description (informative)	7
7.1 PHY general description	7
7.2 MAC general description	7
7.2.1 General description of the architecture	7
7.2.2 Device address	8
7.2.3 Features assumed from the PHY	8
7.2.4 Overview of MAC service functionality	9
7.2.5 MAC policies	12
7.2.6 Support for higher-layer timer synchronization	12
7.3 MUX general description	12
7.4 HDMI PAL description	13
8 PHY layer (informative)	13
9 Description of signal	13
9.1 Mathematical framework for SCBT, OFDM, DBPSK, DQPSK, UEP-QPSK, OOK and 4ASK	13
9.2 Mathematical framework for the narrow band section of the discovery mode preamble	14
10 PLCP sublayer	14
10.1 General PPDU frame format	14
10.1.1 PLCP preamble	16
10.1.2 PLCP header	16
10.1.3 PPDU payload	19
10.1.4 Antenna training sequence	20
10.2 Type A PPDU	20
10.2.1 Mode dependent parameters	20
10.2.2 SCBT	21
10.2.3 OFDM	42
10.2.4 Constellation mapping	60
10.2.5 Discovery mode	69
10.3 Type B PPDU	71
10.3.1 Mode dependent parameters	71
10.3.2 Single carrier (DBPSK, DQPSK, UEP-QPSK)	72
10.3.3 Channel bonding	80
10.3.4 Discovery mode	80
11 General requirements	80
11.1 Operating band frequencies	80
11.1.1 Operating frequency range	80
11.1.2 Channel numbering	80
11.2 PHY layer timing	81
11.2.1 Receive-to-transmit turnaround time	81
11.2.2 Transmit-to-receive turnaround time	82

11.2.3 Time between successive transmissions	82
12 Transmitter specifications	82
12.1 Transmit PSD mask	82
12.1.1 Transmit PSD	82
12.2 Transmit centre frequency tolerance	83
12.3 Symbol clock frequency tolerance	83
12.4 Clock synchronization	83
12.5 Transmit power control	83
12.6 Transmitter EVM	83
12.6.1 Type A	83
12.6.2 Type B	87
13 Receiver specification	87
13.1 Type A device	87
13.1.1 SCBT receiver sensitivity	87
13.1.2 OFDM receiver sensitivity	88
13.2 Type B device receiver sensitivity	88
13.3 Receiver CCA performance	89
14 Antenna training symbols and feedback methods	89
14.1 Antenna training sequence transmission	89
14.1.1 Training matrix in closed-loop mode	90
14.1.2 Tracking matrix	92
14.2 Antenna training feedback in closed-loop mode	92
14.2.1 Index feedback	92
14.2.2 Codebook based feedback	92
14.2.3 Quantised weights	95
15 MAC frame formats	95
15.1 Frame format conventions	95
15.1.1 Figures	95
15.1.2 Octet order	96
15.1.3 Encoding	96
15.2 General MAC frame format	96
15.2.1 Unaggregated MAC frame	96
15.2.2 Aggregated MAC frame	97
15.2.3 Frame control	98
15.2.4 DestAddr	99
15.2.5 SrcAddr	99
15.2.6 Sequence control	99
15.2.7 Access information	100
15.2.8 Frame payload	101
15.2.9 FCS	101
15.3 Beacon frames	102
15.4 Discovery frames	104
15.5 Control frames	105
15.5.1 Immediate acknowledgement (Imm-ACK)	106
15.5.2 Block acknowledgement (B-ACK)	107
15.5.3 Application-specific	108
15.5.4 B-Poll	108
15.5.5 B-Poll response frame	109
15.5.6 Antenna training/tracking control frames	109
15.6 Command frames	110
15.6.1 DRP reservation request	111
15.6.2 DRP reservation response	111
15.6.3 Channel selection	111
15.6.4 Link feedback	113
15.6.5 Probe	116
15.6.6 Pairwise temporal key (PTK)	117

15.6.7 Group temporal key (GTK)	118
15.6.8 Application-specific	119
15.6.9 Relay	119
15.6.10 Transmit switched diversity (TSD) request	119
15.6.11 Transmit switched diversity (TSD) set response	120
15.6.12 Transmit switched diversity (TSD) switch	120
15.6.13 Fast uplink channel allocation (FUCA)	121
15.7 Data frames	121
15.8 Aggregated MAC frames	122
15.8.1 Aggregated data frames	122
15.8.2 Aggregated tracking frames	122
15.9 Information elements	122
15.9.1 Application-specific IE (ASIE)	124
15.9.2 Application-specific probe IE	124
15.9.3 Antenna Capabilities IE (ACIE)	124
15.9.4 ATIE	125
15.9.5 ATTCIE	127
15.9.6 AFIE	128
15.9.7 Beacon period occupancy IE (BPOIE)	129
15.9.8 BP Switch IE	131
15.9.9 Channel bonding IE (CBOIE)	131
15.9.10 Channel change IE	132
15.9.11 Channel measurement IE	133
15.9.12 Distributed reservation protocol (DRP) IE	134
15.9.13 DRP availability IE	137
15.9.14 Hibernation anchor IE	137
15.9.15 Hibernation mode IE	137
15.9.16 Identification IE	138
15.9.17 Link feedback IE	139
15.9.18 MAC capabilities IE	140
15.9.19 Master key identifier (MKID) IE	141
15.9.20 Multicast address binding (MAB) IE	141
15.9.21 PHY capabilities IE	142
15.9.22 Probe IE	145
15.9.23 Relinquish request IE	145
15.9.24 Relay IE	146
15.9.25 Scan Timing IE	148
15.9.26 UEP information IE	149
16 MAC sublayer functional description	150
16.1 Frame processing	150
16.1.1 Frame addresses	150
16.1.2 Frame reception	151
16.1.3 Antenna training frame transaction	151
16.1.4 Frame transfer	151
16.1.5 Frame retry	152
16.1.6 Inter-frame space (IFS)	152
16.1.7 Duplicate detection	152
16.1.8 RTT/CTT use	152
16.1.9 MAC header fields	153
16.1.10 Information elements	154
16.2 Distributed contention access (DCA)	157
16.2.1 DCA medium availability	157
16.2.2 NAV	157
16.2.3 Medium status	158
16.2.4 Obtaining a TXOP	158
16.2.5 Using a TXOP	159
16.2.6 Invoking a backoff procedure	159

16.2.7 Decrementing a backoff counter	160
16.3 Device discovery	160
16.3.1 Power-up scan	161
16.3.2 Transmission and reception of discovery frames	162
16.4 Channel selection	164
16.4.1 Explicit channel selection	165
16.4.2 Implicit channel selection	166
16.5 Transmission and reception of beacons	166
16.5.1 Transmission and reception of Type A beacons	166
16.5.2 Transmission and reception of Type B beacon frames	167
16.5.3 Superframe	168
16.6 Distributed reservation protocol (DRP)	174
16.6.1 Reservation type	175
16.6.2 Reservation waveform	175
16.6.3 Medium access	175
16.6.4 DRP availability IE	176
16.6.5 DRP reservation negotiation	176
16.6.6 DRP reservation announcements	178
16.6.7 Resolution of DRP reservation conflicts	178
16.6.8 BPST realignment and existing DRP reservations	180
16.6.9 Modification and termination of existing DRP reservations	180
16.6.10 Retransmit procedures in DRP reservations	180
16.7 Coexistence and interoperability	181
16.7.1 Coexistence	181
16.7.2 Interoperability	181
16.8 Synchronization of devices	182
16.8.1 Clock accuracy	182
16.8.2 Synchronization for devices in hibernation mode	182
16.8.3 Guard times	182
16.9 Fragmentation and reassembly	184
16.10 Aggregation	184
16.11 Channel bonding	186
16.12 Acknowledgement policies	187
16.12.1 No-ACK	187
16.12.2 Immediate ACK	187
16.12.3 Block ACK	187
16.13 Probe	189
16.14 Multi-rate support	189
16.15 Transmit power control (TPC)	190
16.16 Power management mechanisms	190
16.16.1 Power management modes	190
16.16.2 Power state transitions at active mode	190
16.16.3 Hibernation mode operation	191
16.16.4 Hibernation anchor operation	192
16.17 ASIE operation	193
16.18 Antenna training and tracking	193
16.18.1 Announcement of antenna capabilities	193
16.18.2 Antenna training/tracking configuration	193
16.18.3 Iterative antenna training	194
16.18.4 Antenna tracking	195
16.19 Transmit switched diversity (TSD) operation	196
16.19.1 TSD initiating procedure	196
16.19.2 Antenna switching	196
16.20 MAC sublayer parameters	197
17 Security	198
17.1 Security mechanisms	198
17.1.1 Security operation	199

17.1.2	4-way handshake	199
17.1.3	Key transport	199
17.1.4	Freshness protection	199
17.1.5	Data encryption	199
17.1.6	Frame integrity protection	199
17.2	Security modes	200
17.2.1	Security mode 0	201
17.2.2	Security mode 1	201
17.2.3	Security mode 2	201
17.3	Temporal keys	202
17.3.1	Mutual authentication and PTK derivation	202
17.3.2	GTK exchange	203
17.3.3	Pseudo-random function (PRF) definition	204
17.3.4	PTK and KCK derivation	204
17.3.5	PTK MIC generation	205
17.3.6	Random number generation	205
17.4	Frame reception steps and replay prevention measures	206
17.4.1	Frame reception	206
17.4.2	Replay prevention	206
17.4.3	Implications on GTKs	207
17.5	AES-128 GCM inputs	207
17.5.1	Overview	207
17.5.2	Nonce	207
17.5.3	GCM blocks	208
17.6	Token authentication	209
17.6.1	Token issuance	209
17.6.2	Token revoke	210
18	HDMI PAL	210
18.1	Introduction	210
18.2	HDMI transmission	211
18.2.1	Identification of video vs. data	211
18.2.2	TMDs removal	211
18.2.3	Data type multiplexing	211
18.3	HDMI reception	213
18.3.1	TMDs encoding	213
18.3.2	Packet demultiplexing	213
18.4	PAL header format	217
18.4.1	Sub-packet header	218
18.5	PAL payload format	219
18.6	Block retransmission request	219
18.7	Type specific header fields	220
18.7.1	S-UEP	220
18.7.2	P-UEP	223
18.8	Video/audio format adaptation	224
18.8.1	Fast video format adaptation	224
18.8.2	Fast audio format adaptation	227
18.8.3	Control messages to support fast format adaptation	228
18.9	Fast uplink channel allocation (FUCA)	229
18.9.1	FUCA operation	230
18.9.2	The procedure of data exchange using FUCA	233
19	Out-of-band control channel	234
19.1	OOB operation	235
19.1.1	Ad hoc mode	235
19.1.2	Infrastructure mode	237
19.1.3	Other OOB functions	239
19.2	OOB frame format	240
19.2.1	General frame format	240

19.2.2	OOB-beacon	240
19.2.3	OOB-60GHz capability request	241
19.2.4	OOB-60GHz capability response	241
19.2.5	OOB-interference detection request	242
19.2.6	OOB-interference detection response	242
19.2.7	OOB-channel loss notification	242
19.2.8	OOB-block ACK	243
19.2.9	OOB-probe request	243
19.2.10	OOB-probe response	243
19.3	Convergence MAC sublayer parameters	244
20	Relay operation	244
20.1	Relay path setup	244
20.1.1	Identification of relay capabilities	244
20.1.2	Association with a relay device	244
20.1.3	Antenna training between the source and the destination	244
20.1.4	Antenna training between the source and the relay	244
20.1.5	Antenna training between the relay and the destination	245
20.1.6	Transition to data channel	245
20.2	Data transmission in relay operation	247
20.2.1	DRP reservation for relay operation in data channel	247
20.2.2	Usage of relay device	247
20.2.3	Frame transfer in relay operation	247
20.2.4	Frame reception in relay operation	248
20.2.5	Data exchange using relay device	248
20.2.6	Decision on path change	249
20.2.7	Path Change	249
20.2.8	Relay link feedback via relay device	250
20.2.9	Scan of idle path	251
20.2.10	Operation of relay device	251
Annex A	(normative) MUX sublayer	253
Annex B	(normative) MAC Policies	255
Annex C	(informative) Higher Layer Synchronization Support	258
Annex D	(informative) IP PAL	260
Annex E	(informative) USB PAL	263
Annex F	(informative) B-ACK buffer with fixed size elements	266
Bibliography		267

Foreword

ISO (the International Organization for Standardization) and IEC (the International Electrotechnical Commission) form the specialized system for worldwide standardization. National bodies that are members of ISO or IEC participate in the development of International Standards through technical committees established by the respective organization to deal with particular fields of technical activity. ISO and IEC technical committees collaborate in fields of mutual interest. Other international organizations, governmental and non-governmental, in liaison with ISO and IEC, also take part in the work. In the field of information technology, ISO and IEC have established a joint technical committee, ISO/IEC JTC 1.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of the joint technical committee is to prepare International Standards. Draft International Standards adopted by the joint technical committee are circulated to national bodies for voting. Publication as an International Standard requires approval by at least 75 % of the national bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO and IEC shall not be held responsible for identifying any or all such patent rights.

ISO/IEC 13156 was prepared by Ecma International (as ECMA-387) and was adopted, under a special "fast-track procedure", by Joint Technical Committee ISO/IEC JTC 1, *Information technology*, in parallel with its approval by national bodies of ISO and IEC.

This second edition cancels and replaces the first edition (ISO/IEC 13156:2009), which has been technically revised.

Introduction

This International Standard specifies PHY, MAC and PALs for flexible and heterogeneous multi-Gigabit Wireless Personal Area networks. The heterogeneous network consists of two types of devices (Types A and B) that can fully coexist and interoperate but at the same time are able to operate independently. As a result this standard enables a wide range of different implementations and applications ranging from simple and low-power data transfer at short ranges, suitable for handheld devices, to high-rate multimedia streaming at longer distances, when adaptive antenna arrays are employed. Applications include Sync-and-Go, Access points, Wireless desktops and docking stations and uncompressed video streaming.

The Type A device is designed to be the high-end, high-performance device and provides many features including high data rate, longer range, robustness against multipath, support for adaptive antenna arrays and multi-level QoS. On the other hand, Type B devices, designed for handheld devices, are simpler, low power and low cost, while offering high data rates.

Type A and Type B devices offer data rates up to 6,350 Gbps and 3,175 Gbps in a single channel, respectively. This International Standard defines four frequency channels with separation of 2,160 GHz, which may be bonded to each other to increase the data rates by a factor of 2, 3 or 4.

This International Standard defines a single decentralized MAC protocol for both device types, which provides interoperability and coexistence for the device types and features high bandwidth efficiency, QoS provisions, and spatial reuse capability (Figure 1).

Multiple PALs can reside on top of the MAC layer, which interact with the MAC layer through a multiplexing sublayer (MUX). This edition of ISO/IEC 13156 provides an HDMI¹ PAL as well as information regarding IP and USB PALs.

1. HDMI is the registered trademark of the HDMI LLC.

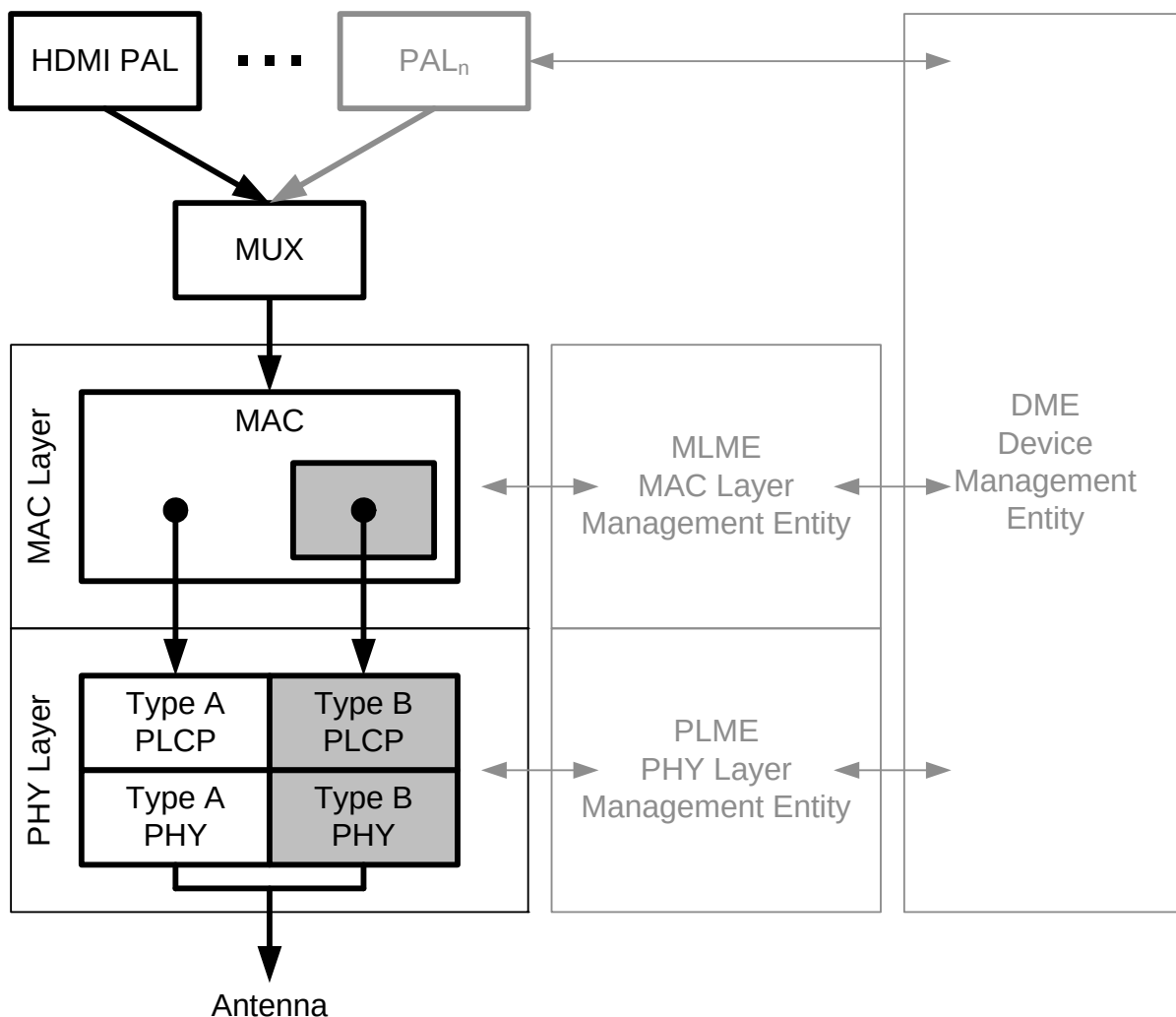


Figure 1 - Protocol structure

NOTE The DME, MLME, PLME, and PALs (except the HDMI PAL) are outside the scope of this International Standard and all references to these are informative.

Information technology — Telecommunications and information exchange between systems — High rate 60 GHz PHY, MAC and PALs

1 Scope

This International Standard specifies a physical layer (PHY), distributed medium access control (MAC) sublayer, and an HDMI protocol adaptation layer (PAL) for 60 GHz wireless networks.

2 Conformance

Conforming devices of Type A, B or C shall implement the MAC sublayer and the PHY layer and may implement the HDMI PAL as specified herein.

3 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC 8802-11:2005/Amd.6, *Information technology — Telecommunications and information exchange between systems — Local and metropolitan area networks — Specific requirements — Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications — Amendment 6: Medium Access Control (MAC) Security Enhancements*

IEEE 100, *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition

4 Terms and definitions

For the purposes of this document, the following terms and definitions apply. For terms and definitions not defined in this Clause, the term and definitions given in IEEE 100, *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition apply.

4.1

Beacon Group

BG

set of devices from which a device receives beacons that identify the same beacon period start time (BPST) as the device

4.2

Beacon Period

BP

period of time declared by a device during which it sends or listens for beacons

4.3

Beacon Period Start Time

BPST

start of the beacon period

4.4

channel

medium over which cooperating entities exchange information

4.5

data integrity

assurance that the data has not been modified from its original form

4.6

device

entity containing an implementation of this International Standard

4.7

Distributed Reservation Protocol

DRP

protocol implemented in each device to support negotiation and maintenance of channel time reservations binding on all neighbours of the reservation participants

4.8

Equivalent Isotropic Radiated Power

EIRP

amount of power that a theoretical isotropic antenna (that evenly distributes power in all directions) would emit to produce the peak power density observed in the direction of maximum antenna gain

4.9

Equivalent Isotropic Received Power

EIRxP

amount of power that a theoretical isotropic antenna (that evenly receives power in all directions) would receive

4.10

extended beacon group

union of a device's beacon group and the beacon groups of all devices in the device's beacon group

4.11

frame

unit of data transmitted by a device

4.12

frame protection

security service provided for a frame, including (but not limited to) payload encryption, message authentication, and replay attack protection

4.13

MAC client

entity above the MAC sublayer that generates MAC service data units for delivery to corresponding entities in other devices, and receives MAC service data units from such entities

4.14

MAC Command Data Unit

MCDU

unit of data exchanged between peer medium access control sublayers in order to manage medium access control functions

4.15

MAC Protocol Data Unit

MPDU

unit of data exchanged between two peer medium access control sublayers using the physical layer

4.16

MAC Service Data Unit

MSDU

information that is delivered as a unit between medium access control service access points (SAPs)

4.17**Master-Slave Pair****MSPr**

device-to-device link in which a first device acts as the master (initiates polling) and a second device acts as a slave (responds to a polling inquiry)

4.18**Message Integrity Code****MIC**

cryptographic checksum generated using a symmetric key that is typically appended to data in order to provide data integrity and source authentication similar to a digital signature

4.19**neighbour**

any device in a device's beacon group

4.20**reservation**

named set of one or more medium access slots (MASs) within a superframe during which a device has preferential access to the medium

4.21**reservation block**

one or more temporally contiguous medium access slots (MASs) within a reservation not adjacent to other MASs in the reservation

4.22**secure frame**

frame in which frame protection is applied

4.23**stream**

logical flow of MSDUs from one device to one or more other devices

4.24**superframe**

periodic time interval used in this International Standard to coordinate frame transmissions between devices, which contains a beacon period followed by a data period

4.25**symmetric key**

secret key shared between two or more parties that may be used for both encryption and decryption as well as for message integrity code computation and verification

4.26**Time Domain Spreading Factor****TDSF**

bandwidth expansion ratio due to the application of time domain spreading sequence

5 Notational conventions

The use of the word *shall* is meant to indicate a requirement which is mandated by the Standard, i.e. it is required to implement that particular feature with no deviation in order to conform to the Standard.

The use of the word *should* is meant to recommend one particular course of action over several other possibilities, however without mentioning or excluding these others.

The use of the word *may* is meant to indicate that a particular course of action is permitted.

The use of the word *can* is synonymous with *is able to* – it is meant to indicate a capability or a possibility.

All floating-point values have been rounded to 3 decimal places.

6 Abbreviated terms

AC	Access Category
ACK	Acknowledgment
AES	Advanced Encryption Standard
ASK	Amplitude Shift Keying
ASIE	Application-Specific Information Element
AWGN	Additive White Gaussian Noise
B-ACK	Block Acknowledgment
BcstAddr	Broadcast Device Address
BP	Beacon Period
BPOIE	Beacon Period Occupancy Information Element
BPSK	Binary Phase Shift Keying
BPST	Beacon Period Start Time
CC	Convolutional Code
CCA	Clear Channel Assessment
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTT	Clear To Train
DAC	Digital-to-Analogue Converter
DBPSK	Differential Binary Phase Shift Keying
DBS	Discovery Block Set
DCA	Distributed Contention Access
DestAddr	Destination Device Address
DevAddr	Device Address
DME	Device Management Entity
DQPSK	Differential Quadrature Phase Shift Keying
DRP	Distributed Reservation Protocol
EO	Encryption Offset
EUI	Extended Unique Identifier
FEC	Forward Error Correction
FER	Frame Error Rate
FFT	Fast Fourier Transform
FZ	Frank-Zadoff Sequence
GCM	Galois/Counter Mode

GF	Galois Field
Gbps	Gigabits per second
Gsps	Gigasymbols per second
GTK	Group Temporal Key
HCS	Header Check Sequence
ID	Identifier
IDFT	Inverse Discrete Fourier Transform
IE	Information Element
IFFT	Inverse Fast Fourier Transform
IFS	Inter-Frame Space
Imm-ACK	Immediate Acknowledgment
KCK	Key Confirmation Key
LIFS	Long Inter-frame space
LQE	Link Quality Estimator
LQI	Link Quality Indicator
LSB	Least-Significant Bit
MAC	Medium Access Control
MAS	Medium Access Slot
MCDU	MAC Command Data Unit
Mbps	Megabits per second
McstAddr	Multicast Device Address
MIB	Management Information Base
MIC	Message Integrity Code
MIFS	Minimum Interframe Spacing
MKID	Master Key Identifier
MLME	MAC Sublayer Management Entity
MPDU	MAC Protocol Data Unit
MSB	Most-Significant Bit
MSC	Message Sequence Chart
MSPr	Master-Slave Pair
MSDU	MAC Service Data Unit
No-ACK	No Acknowledgement
OFDM	Orthogonal Frequency Division Modulation
OOB	Out of Band
OOK	On-Off Keying
OUI	Organizationally Unique Identifier
PAA	Phased Array Antenna
PAN	Personal Area Network

PAL	Protocol Adaptation Layer
PDU	Protocol Data Unit
PER	Packet Error Rate
PHY	Physical (layer)
PHY-SAP	Physical Layer Service Access Point
PLCP	Physical Layer Convergence Protocol
PLME	Physical Layer Management Entity
PMK	Pair-wise Master Key
PPDU	PLCP Protocol Data Unit
PPM	Parts Per Million
PRBS	Pseudo-Random Binary Sequence
PRF	Pseudo-Random Function
PSD	Power Spectral Density
PSDU	PHY Service Data Unit
PT	Preamble Type
PTK	Pair-wise Temporal Key
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RMS	Root Mean Square
RS	Reed-Solomon
RTT	Request To Train
RX	Receive or Receiver
SAP	Service Access Point
SBA	Switched Beam Antenna
SCS	Segment Check Sequence
SFC	Secure Frame Counter
SFN	Secure Frame Number
SIFS	Short Interframe Spacing
SrcAddr	Source Device Address
TCM	Trellis Coded Modulation
TDSF	Time Domain Spreading Factor
TKID	Temporal Key Identifier
TX	Transmit or Transmitter
TXOP	Transmission Opportunity
WPAN	Wireless Personal Area Network

7 General description (informative)

7.1 PHY general description

This International Standard specifies a physical layer (PHY) for a Wireless Personal Area Network (WPAN), utilizing the unlicensed 60 GHz frequency band. Two types of devices are defined: Type A and Type B. both device types coexist and interoperate with other device types. Furthermore, all device types can operate independently. That is, neither device type requires the presence of another type for operation.

Type A devices operate at an SCBT mandatory mode (A0) at 0.397 Gbps with other optional SCBT modes at data rates 0.794 Gbps to 6.350 Gbps (without channel bonding) and optional OFDM modes at data rates 1.008 Gbps to 4.032 Gbps. Type B devices operate using DBPSK at data rates of 0.794 Gbps to 1.588 Gbps (without channel bonding); with optional modes of DQPSK and UEP-QPSK at data rates of 3.175 Gbps.

Type A devices also support directional antennas via sector antennas or adaptive arrays. This International Standard specifies the necessary training and tracking waveforms and protocols.

There are multiple channels specified in this International Standard. Multiple adjacent channels may be bonded together for increased data rate for Type A (SCBT) and Type B devices. With bonded channels the data rates for these device types increase by a factor proportional to the number of bonded channels. One channel has been designated as the discovery channel. The discovery channel has a lower quality of service but supports the interference prone and time consuming antenna training process. The data channels are optimized for high throughput and spatial reuse.

7.2 MAC general description

7.2.1 General description of the architecture

As illustrated in Figure 2, the MAC is a sublayer of the Data Link Layer defined in the OSI basic reference model [1]. The MAC service is provided by means of the MAC service access point (MAC SAP) to a single MAC service client, usually a higher layer protocol or adaptation layer. In this International Standard the MAC sublayer is represented by a device address.

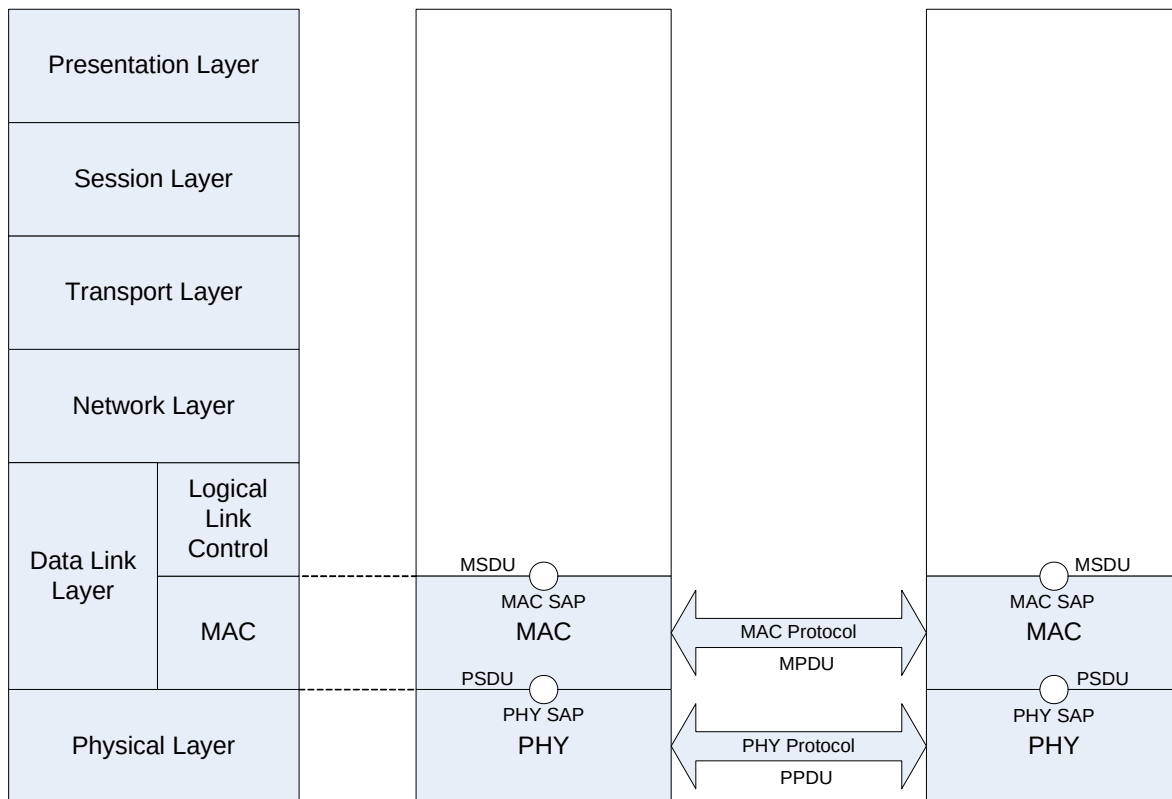


Figure 2 - Architectural reference model

The MAC sublayer in turn relies on the service provided by the PHY layer via the PHY service access point (PHY SAP). The MAC protocol applies between MAC sublayer peers.

7.2.2 Device address

Individual MAC sublayers are addressed via an EUI-48 [3], and are associated with a volatile abbreviated address called a DevAddr. Unicast frames carry a destination DevAddr that identifies a single MAC sublayer.

DevAddrs are 16-bit values, generated locally, without central coordination. Consequently, it is possible for a single value to ambiguously identify two or more MAC entities. This International Standard provides mechanisms for resolving ambiguous DevAddrs.

The MAC addressing scheme includes multicast and broadcast address values. A multicast address identifies a group of MAC entities. The broadcast address identifies all MAC entities.

7.2.3 Features assumed from the PHY

A MAC entity is associated with a single PHY entity via that entity's PHY SAP. The MAC sublayer requires the following features provided by the PHY:

- Frame transmission and reception;
- PLCP header error indication for both PHY and MAC header structures;
- Clear channel assessment for estimation of medium activity.

Frames are transmitted by the PHY from the source device and delivered to the destination device in identical bit order. Throughout this specification reference to the start of a frame refers to the leading

edge of the first symbol of the PHY frame at the local antenna and end of a frame refers to the trailing edge of the last symbol of the PHY frame.

Frame transmission and reception are supported by the exchange of parameters between the MAC sublayer and the PHY layer. These parameters are included in the PLCP header and allow the MAC entity to control, and be informed of, the MAC and PHY related parameters.

Depending on antennas used by the PHY, the MAC sublayer may use the following features provided by the PHY for directional frame transmission and reception:

- Antenna beam switching among different sectors
- Antenna beam steering toward a desired direction

7.2.4 Overview of MAC service functionality

The MAC service defined in this International Standard provides:

- A reservation-based channel access mechanism;
- A contention-based channel access mechanism for antenna training in the discovery channel;
- A synchronization facility among cooperating MAC entities;
- Coexistence and interoperability among Type A and B devices;
- Device power management by scheduling of frame transmission and reception;
- Secure communication with data authentication and encryption using cryptographic algorithms;

Each device provides required MAC functions based on the device type, and optional functions as determined by the application.

Coordination of devices within radio range is achieved by the transmission and reception of beacon and control frames. Periodic beacon transmission provides the basic timing for the network, supports dynamic network organization, and carries reservation and scheduling information for accessing the medium. Exchange of control frames enables antenna training among cooperating devices, and device discovery of Type A and B devices.

Coordination among devices that send periodic beacon frames (referred to as beaconing devices) is fully distributed. Coordination among beaconing devices and devices that do not send beacon frames is achieved by the beaconing devices acting as controllers. Coordination among devices that do not send beacon frames is not specified in this International Standard.

7.2.4.1 Logical groups

Logical groups are formed around each beaconing device to facilitate contention-free frame exchanges while exploring medium reuse over different spatial regions. In this International Standard, these logical groups are a beacon group and an extended beacon group. Both groups are determined with respect to an individual beaconing device, which has its own individual neighbourhood.

7.2.4.2 Device discovery

The MAC sublayer defined in this International Standard enables device discovery through one or more of the following mechanisms:

- Transmission and reception of discovery frames in the discovery channel;
- Exchange of antenna training control frames in the discovery channel;
- Exchange of interoperability control frames between Type A and Type B devices.

7.2.4.3 Channel selection

Once a device discovers another device with which it intends to communicate with, the pair of the devices use explicit channel selection procedure, as described in 16.4.1 to scan one or more channels and to select a channel for frame exchange in a coordinated manner.

If no beacons are detected in the selected channel, the device creates its beacon period (BP) by sending a beacon. If one or more beacons are detected in the selected channel, the device

synchronizes its BP to existing beacons in the selected channel. The device exchanges data with members of its beacon group using the same channel the device selected for beacons.

Each device operates in a dynamic environment and under unlicensed operation rules. Thus, it is subject to interference from other networks, and other unlicensed wireless entities in its channel. To enable the device to continue operation in this type of environment, each device has the capability to dynamically change the channel in which it operates without requiring disruption of links with its peers.

If at any time a device determines that the current channel is unsuitable, it uses the implicit channel selection procedure, as described in 16.4.2, to move to a new channel.

7.2.4.4 The superframe

Once a device finds its communication partner and selects a channel, the basic timing structure for frame exchange is a superframe. The superframe duration is specified as `mSuperframeLength`. The superframe is composed of 256 medium access slots (MASs), where each MAS duration is `mMASLength`.

Each superframe starts with a BP, which extends over one or more contiguous MASs. The start of the first MAS in the BP, and the superframe, is called the beacon period start time (BPST).

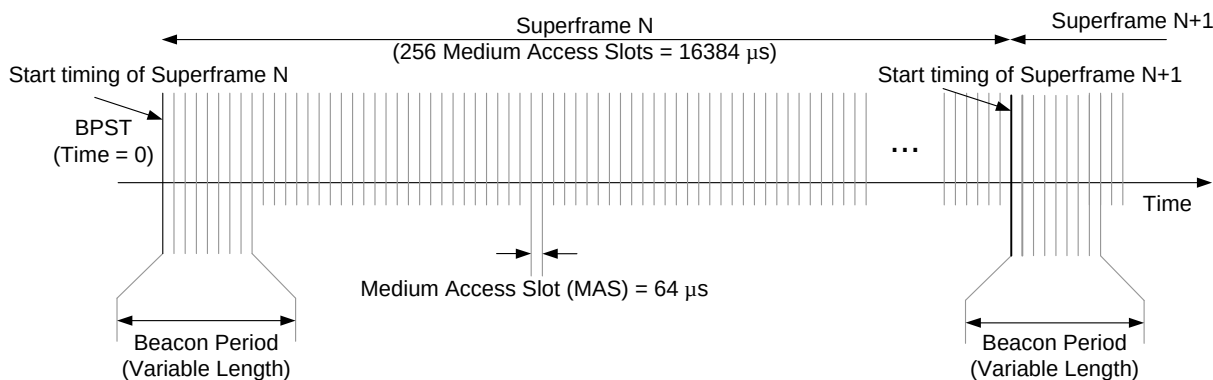


Figure 3 - MAC superframe structure

7.2.4.5 Beacon period protection

No transmissions other than beacons are attempted during the BP of any device.

A device may protect an alien BP, detected by reception of a beacon frame unaligned with the device's own BP, by announcing a reservation covering the alien BP in its beacon.

7.2.4.6 Medium access

The medium is accessed in one of three ways:

- During device discovery (16.3) and antenna training, devices send beacon and control frames in discovery channel using contention based access according to the rules specified in 16.2.
- During the BP, devices send only beacon frames, according to the rules specified in 16.5.
- During reservations, devices participating in the reservation send frames according to rules specified in 16.6.

7.2.4.7 Data communication between devices

Data is passed between the MAC entity and its client in MSDUs qualified by certain parameters. MSDUs are transported between devices in data frames. To reduce the frame error rate of a marginal link, data frames can be fragmented and reassembled, as described in 16.9. Fragments are numbered with an MSDU sequence number and a fragment number.

If the source device wishes to verify the delivery of a frame, then one of the acknowledgement policies is used, as described in 16.12. This International Standard provides for three types of acknowledgements to enable different applications. The No-ACK policy, described in 16.12.1, is

appropriate for frames that do not require guaranteed delivery, or are delay sensitive and a retransmitted frame would arrive too late. The Imm-ACK policy, described in 16.12.2, provides an acknowledgement process in which each frame is individually acknowledged following the reception of the frame. The B-ACK policy, described in 16.12.3, lets the source send multiple frames without intervening ACK frames. Instead, the acknowledgements of the individual frames are grouped into a single response frame that is sent when requested by the source device. The B-ACK process decreases the overhead of the Imm-ACK process while allowing the source device to verify the delivery of frames to the destination.

If the source device does not receive the requested acknowledgement, then it may retransmit the frame, as described in 16.1.5, or it may discard the frame. The decision to retransmit or discard the frame depends on the type of data or command that is being sent, the number of times that the source device has attempted to send the frame, the length of time it has attempted to send the frame, and other implementation-dependent factors.

7.2.4.8 MAC frame data rates

This International Standard specifies two common PHY modes for the two types of devices respectively. The frame payloads of MAC beacon frames are transmitted using one of the common PHY modes corresponding to its device type, and hence at the rate of the common mode. In device discovery or antenna training, MAC frames are transmitted using one of the discovery modes in the discovery channel. Payloads of other frames may be transmitted at higher data rates if possible.

7.2.4.9 Security

Wireless networks present unique security challenges due to the loss of protection provided by wires and shielding. Distributed wireless networks present additional challenges due to the wide range of applications and use models that they must support. To name a few, eavesdroppers can overhear data exchanges not intended for them, whereas imposters can send forged data not using its own identity, can replay previously transmitted data, and can transmit modified data captured from a previous transmission.

This International Standard defines two levels of security (Clause 17): no security and strong security protection. Security protection includes data encryption, message integrity, and replay attack protection. Secure frames are used to provide security protection to data and aggregated data frames as well as selected control and command frames.

Three security modes are defined to control the level of security for devices in their communications. This International Standard allows for a device to use one of the two security levels or a combination of them in communicating with other devices by selecting the appropriate security mode (see 17.2).

This International Standard further specifies a 4-way handshake mechanism to enable two devices to derive their pair-wise temporal keys (PTKs) while authenticating their identity to each other. A secure relationship is established following a successful 4-way handshake between two devices (see 17.3.1). A 4-way handshake between two devices is conducted based on a shared master key. How two devices obtain their shared master keys is outside the scope of this International Standard.

In addition, this International Standard provides means for the solicitation and distribution of group temporal keys (GTKs). While PTKs are used for protecting unicast frames exchanged between two devices, GTKs are employed for protecting multicast and broadcast frames transmitted from a source device to a multicast or broadcast group of recipient devices (see 17.3.2).

A pseudo-random function is defined based on the MIC generation by GCM using AES-128 (see 17.3.3). It can be made available to entities outside the MAC sublayer for random number generation.

Secure frame counters and replay counters are set up on a per-temporal key basis to guarantee message freshness (see 17.4). No specific mechanisms are created in this International Standard to address denial of service attacks given the open nature of the wireless medium.

In this International Standard, 128-bit symmetric temporal keys are employed based on AES-128 with GCM to provide payload encryption and message integrity code (MIC) generation (see 17.5).

In general, this International Standard specifies security mechanisms, not security policies.

7.2.4.10 Information discovery

The protocols and facilities of this International Standard are supported by the exchange of information between devices. Information can be broadcast in beacon frames or requested in Probe commands. For each type of information, an Information Element (IE) is defined. IEs can be included by a device in its beacon at any time and may optionally be requested or provided using the Probe command.

A device uses the MAC Capabilities IE and PHY Capabilities IE to announce information about its support of variable or optional facilities. Declaration of capabilities is especially useful when a device detects changes in its immediate neighbourhood.

7.2.4.11 Transmit rate and power adaptation

This International Standard provides transmit rate and power control mechanisms to select the optimal combination of transmit rate and power to increase throughput and/or reduce the frame error rate (FER).

A recipient device may recommend a transmit rate and/or power level change be used by a source device using explicit or implicit link feedback mechanisms. In addition, a source device may request a recipient device provide feedback on the quality of the link, base on which the source determines optimal transmit rate and power.

The transmit power and rate control mechanisms are described in 16.14 and 16.15.

7.2.4.12 Power management

An important goal of this International Standard is to enable long operation time for battery powered devices. An effective method to extend battery life is to enable devices to turn off completely or reduce power for long periods of time, where a long period is relative to the superframe duration.

This International Standard provides two power management modes in which a device can operate: active and hibernation. Devices in active mode transmit and receive beacons in every superframe. Devices in hibernation mode hibernate for multiple superframes and do not transmit or receive in those superframes.

In addition, this International Standard provides facilities to support devices that sleep for portions of each superframe in order to save power.

Power management mechanisms are described in 16.16.

7.2.5 MAC policies

It is desirable to allow and facilitate equitable and efficient coexistence of devices with varying medium access requirements. For this purpose, Annex B specifies policies governing channel selection and sharing of bandwidth. These policies impose, among other things, certain restrictions on the number and configuration of MASSs in DRP reservations, on the location of reserved MASSs within a superframe, and on channel selection order.

7.2.6 Support for higher-layer timer synchronization

Some applications, for example, the transport and rendering of audio or video streams, require synchronization of timers located at different devices. Greater accuracy (in terms of jitter bounds) or finer timer granularity than that provided by the synchronization mechanism described in 16.8 may be an additional requirement. In support of such applications, this International Standard defines an optional MAC facility in Annex C that enables layers above the MAC sublayer to accurately synchronize timers located in different devices. The facility is usable by more than one application at a time.

7.3 MUX general description

In order to enable the coexistence of concurrently active higher layer protocols within a single device, a multiplexing sublayer is defined. This sublayer routes outgoing and incoming MSDUs to and from their corresponding higher layers. The mandatory MUX sublayer is described in Annex A.

7.4 HDMI PAL description

This International Standard includes an HDMI pass-through PAL, Clause 18, which preserves the HDMI content protection scheme. The HDMI PAL interfaces with the wired HDMI interface's data channels, clock channel, display data channel and CE control. The HDMI PAL removes the data channels' TMDS encoding prior to wireless transmission and reinstates the TMDS coding prior to forwarding to the HDMI sink.

8 PHY layer (informative)

The PHY contains two functional entities: the PHY convergence function and the PHY layer management function. The PHY service is provided to the MAC through the PHY SAP.

9 Description of signal

9.1 Mathematical framework for SCBT, OFDM, DBPSK, DQPSK, UEP-QPSK, OOK and 4ASK

The transmitted RF signal can be written in terms of the complex baseband signal as follows:

$$s_{RF}(t) = \text{Re} \left\{ \sum_{n=0}^{N_{frame}-1} s_n(t - nT_{sym}) \exp(j2\pi f_c t) \right\} \quad (1)$$

where $\text{Re}\{\cdot\}$ represents the real part of the signal, T_{sym} is the symbol length, N_{frame} is the number of symbols in the frame, f_c is the centre frequency, and $s_n(t)$ is the complex baseband signal representation for the n^{th} symbol. The exact structure of the n^{th} symbol depends on its location within the frame:

$$s_n(t) = \begin{cases} s_{preamble,n}(t) & 0 \leq n < N_{preamble} \\ s_{header,n-N_{preamble}}(t) & N_{preamble} \leq n < N_{preamble} + N_{header} \\ s_{payload,n-N_{preamble}-N_{header}}(t) & N_{preamble} + N_{header} \leq n < N_{preamble} + N_{header} + N_{payload} \\ s_{ATS,n-N_{preamble}-N_{header}-N_{payload}}(t) & N_{preamble} + N_{header} + N_{payload} \leq n < N_{preamble} + N_{header} + N_{payload} + N_{ATS} \end{cases} \quad (2)$$

where $s_{preamble,n}(t)$ describes the n^{th} symbol of the preamble, $s_{header,n}(t)$ describes the n^{th} symbol of the header, $s_{payload}(t)$ describes the n^{th} symbol of the PPDU, $s_{ATS,n}(t)$ describes the n^{th} symbol of the antenna training sequence (ATS), $N_{preamble}$ is the number of symbols in the preamble, N_{header} is the number of symbols contained in the header, $N_{payload}$ is the number of symbols contained in the frame body, N_{ATS} is the number of symbols in the ATS, and $N_{frame} = N_{preamble} + N_{header} + N_{payload} + N_{ATS}$ is the number of symbols in the frame. The exact values of $N_{preamble}$, N_{header} , $N_{payload}$, N_{ATS} , and N_{frame} will be described in more detail in Clause 10.

The potentially complex time-domain signal $s_n(t)$ shall be created by passing the real and imaginary components of the discrete-time signal $s_n[k]$ through digital-to-analogue converters (DACs) and reconstruction filters as shown in Figure 4. When the discrete-time signal $s_n[k]$ is real, only the real digital-to-analogue converter and reconstruction filter need to be used. Clause 10 describes how to generate $s_n[k]$.

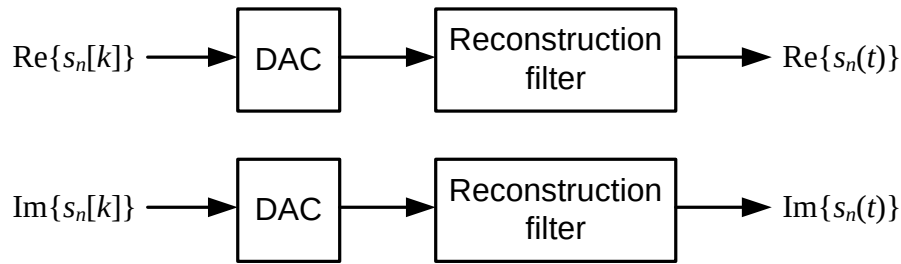


Figure 4 - Conversion from discrete-time signals to continuous-time signals

9.2 Mathematical framework for the narrow band section of the discovery mode preamble

The transmitted RF signal can be written in terms of the complex baseband signal as follows:

$$s_{RF}(t) = \text{Re} \left\{ \sum_{n=0}^{N_{NB}-1} s_{NB,n}(t - nT_{sym}) [\exp(j2\pi f_c t) + \exp(j2\pi [f_c - f_0]t) + \exp(j2\pi [f_c + f_0]t)] \right\} \quad (3)$$

where $\text{Re}\{.\}$ represents the real part of the signal, T_{sym} is the symbol length, $N_{NB} = 163839$ is the number of symbols in the narrow band preamble, f_c is the centre frequency, $f_0 = 720$ MHz is the offset frequency and $s_{NB,n}(t)$ describes the n^{th} symbol of the narrow band preamble.

The complex time-domain signal $s_{NB,n}(t)$ shall be created by passing the real and imaginary components of the discrete-time signal $s_{NB}[k]$ through digital-to-analogue converters (DACs) and reconstruction filters as shown in Figure 4. The sequence $s_{NB}[k]$ is described in Clause 10.

10 PLCP sublayer

10.1 General PPDU frame format

This Clause provides a method for converting a PSDU (PHY layer SDU) into a PPDU (PHY layer PDU). Figure 5 shows the general format for the PPDU, which may be composed of four major components: the PLCP preamble, the PLCP header, the PPDU payload, and the Antenna Training Sequence (ATS).

All device types shall follow this general frame format. However, particular parameters or components of the frame format may be different for different device types.

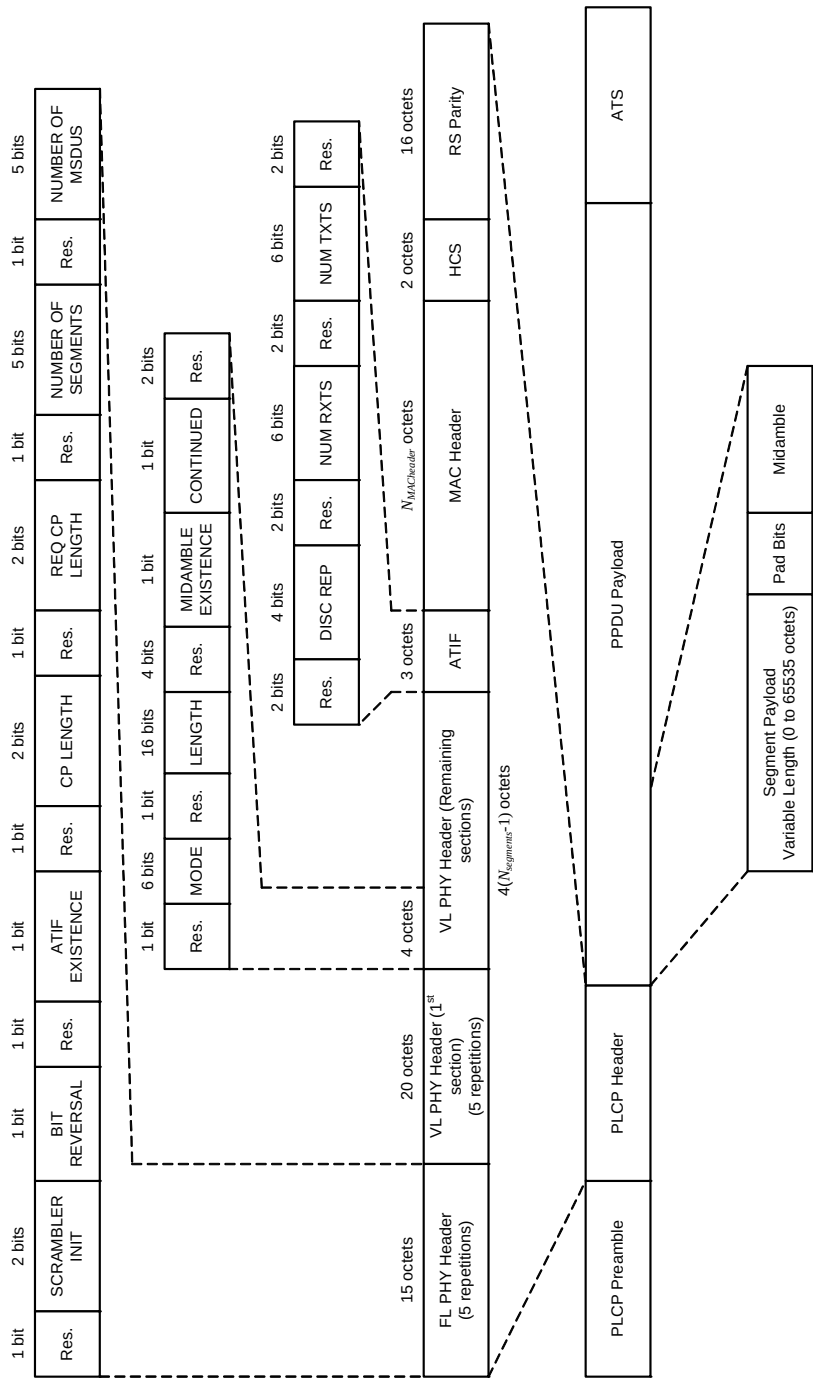


Figure 5 - General PPDU frame format

The components are listed in the order of transmission. The PLCP preamble shall be the first component of the PPDU. It consists of a frame synchronization sequence, and a channel estimation sequence (see 10.1.1). The goal of the PLCP preamble is to aid the receiver in timing synchronization, carrier offset recovery, and channel estimation.

The PLCP header shall be the second major component of the PPDU. The goal of this component is to convey necessary information about both the PHY and the MAC to aid in decoding of the PPDU payload at the receiver. The PLCP header may be further decomposed into PHY header, MAC header, HCS, and Reed-Solomon parity bits (see 10.1.2).

The PPDU payload may be the third major component of the PPDU. The PPDU may contain one or more segments as described in 10.1.3.

The ATS may be the last major component of the PPDU. This sequence is used to train an antenna array (see 10.1.4).

When transmitting the PPDU frame, the PLCP preamble shall be sent first, followed by the PLCP header, potentially the PPDU payload, and potentially the ATS.

10.1.1 PLCP preamble

A PLCP preamble shall be added prior to the PLCP header to aid the receiver in timing synchronization, carrier-offset recovery, and channel estimation.

The PLCP preamble for Type A (SCBT and OFDM) and Type B are different. The details of the PLCP preamble in each case can be found in 10.2.2.3, 10.2.3.3 and 10.3.2.3.

10.1.2 PLCP header

A PLCP header shall be added after the PLCP preamble to convey information about both the PHY and the MAC that is needed at the receiver in order to successfully decode the PPDU payload. The scrambled and Reed-Solomon encoded PLCP header shall be formed as shown in Figure 6:

- 1.Format the PHY header based on information provided by the MAC (See 10.1.2.1).
- 2.Calculate the HCS value (2 octets) over the combined PHY header and MAC header (See 10.1.2.2).
- 3.The resulting HCS value is appended to the MAC header. The resulting combination (MAC Header + HCS) is scrambled according to 10.2.2.5.1.1.
- 4.Apply a shortened Reed-Solomon code to the concatenation of variable length PHY header (except for the first section), ATIF, scrambled MAC header and HCS. The shortened Reed-Solomon code shall be as specified in 10.2.2.5.1.2.
- 5.Prepend five repetitions of the fixed length PHY header and the first section of the variable length PHY header and append the 16 parity octets at the end to form the scrambled and shortened Reed-Solomon encoded PLCP header.

Further encoding and modulation for the header is different for Type A (SCBT and OFDM) and Type B. The details of the further encoding and modulation for the header for each case can be found in 10.2.2.4, 10.2.3.4 and 10.3.2.4.

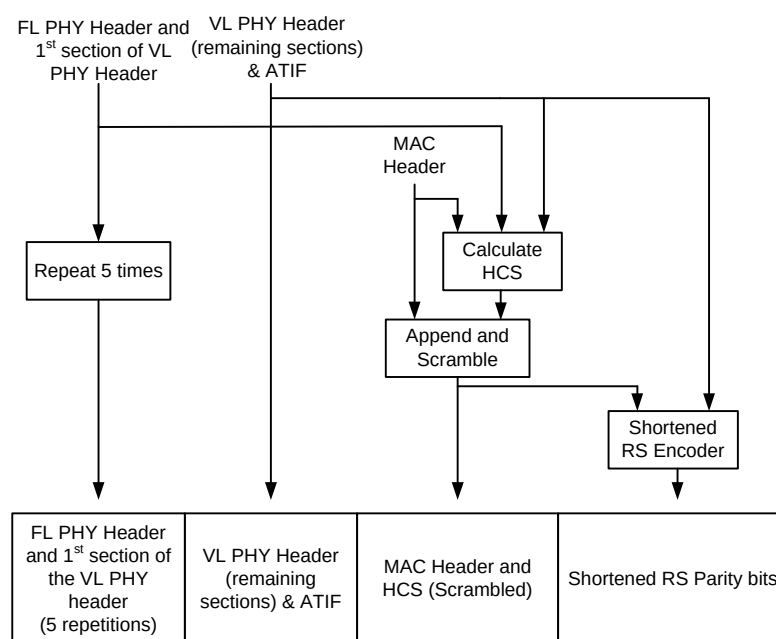


Figure 6- Formation of the header

10.1.2.1 PHY header

The PHY header shall be formed by concatenating five repetitions of the fixed length PHY header and five repetitions of the the first section of the variable length PHY header, followed by the remaining $N_{segments}-1$ sections of the variable length PHY Header and potentially an antenna training indicator field (ATIF). The overall length of the PHY header is therefore equal to $35+4(N_{segments}-1)+3I_{ATIF}$ octets, where I_{ATIF} is equal to zero when the header does not include the ATIF and is equal to one when the header includes the ATIF.

10.1.2.1.1 Fixed length PHY header

The fixed length PHY header contains information about the seed identifier for the data scrambler, the bit reversal state for PPDU payload, the existence of the ATIF, the CP length for the current frame, the requested CP length for the following frame, the number of segments in the frame, and the number of MSDUs in the frame.

The fixed length PHY header field shall be composed of 24 bits, numbered from 0 to 23 as illustrated in Figure 7. Bits 1-2 shall encode the seed value for the initial state of the scrambler, which is used to synchronize the descrambler of the receiver. Bit 3 shall encode whether or not all of the information data bits are inverted. Bit 5 shall encode whether or not the header includes an ATIF. Bits 7-8 shall encode the CP length for the current frame and bits 10-11 shall encode the requested CP length for the following frame. Bits 13-17 shall encode the number of segments in the frame. Bits 19-23 shall encode the number of MSDUs in the frame. All other bits which are not defined in this Clause shall be understood to be reserved for future use and shall be set to zero. The values of the defined fields are described in 10.2.2.4.1.1, 10.2.3.4.1.1 and 10.3.2.4.1.1.

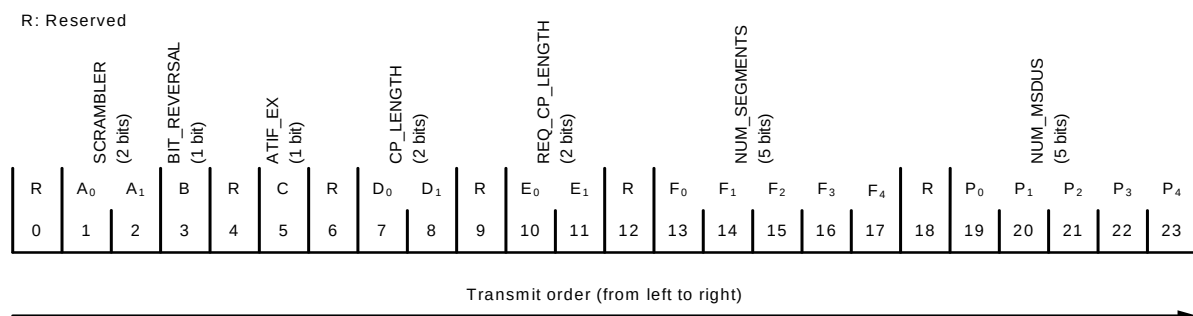


Figure 7 - Fixed length PHY header bit assignment

10.1.2.1.2 Variable length PHY header

Each section of the variable length PHY header contains information about the data rate of the corresponding segment, the length of the payload in the corresponding segment, whether the corresponding segment includes a midamble, and whether the corresponding segment is partitioned at the transmitter and should be reassembled at the receiver.

The variable length PHY header field shall be composed of $32N_{segments}$ bits and shall be constructed by concatenating $N_{segments}$ sections, each for one segment. Each section shall be composed of 32 bits, numbered from 0 to 31, as illustrated in Figure 8. Bits 1-6 shall encode the MODE field, which conveys the information about the type of modulation, the coding rate, and the spreading factor used in the segment. Bits 8-23 shall encode the LENGTH field, with the least-significant bit being transmitted first. Bit 28 shall encode whether the segment is appended by a midamble. Bit 29 shall encode whether the segment has partitioned at the transmitter, and should be reassembled at the receiver. All other bits

which are not defined in this Clause shall be understood to be reserved for future use and shall be set to zero. The values of the defined fields are described in 10.2.2.4.1.2, 10.2.3.4.1.2 and 10.3.2.4.1.2.

R: Reserved

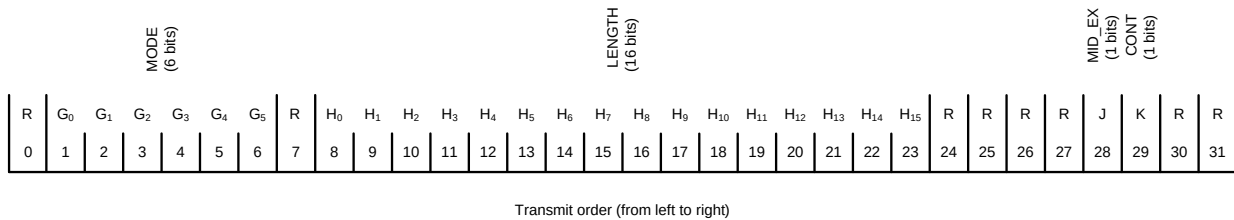


Figure 8 - Variable length PHY header bit assignment

10.1.2.1.3 Antenna training indicator field

The Antenna Training Indicator Field (ATIF) shall follow the variable length PHY header if the ATIF_EXISTENCE bit in the fixed length PHY header is set to 1 (see 10.1.2.1.1). The ATIF contains information about the number of block repetitions in the discovery mode, the number of training symbols for receive antenna training, and the number of training symbols for the transmit antenna training.

The ATIF shall be composed of 24 bits, numbered from 0 to 23, as illustrated in Figure 9. Bits 2-5 shall encode the DISC_REP field which conveys the number of repetitions in the discovery mode. Bits 8-13 shall encode the field NUM_RXTS which conveys the number of training symbols for receive antenna training. Bits 16-21 shall encode the field NUM_TXTS which conveys the number of training symbols for transmit antenna training. All other bits which are not defined in this Clause shall be understood to be reserved for future use and shall be set to zero. The values of the defined fields are described in 10.2.2.4.1.3, 10.2.3.4.1.3 and 10.3.2.4.1.3.

R: Reserved

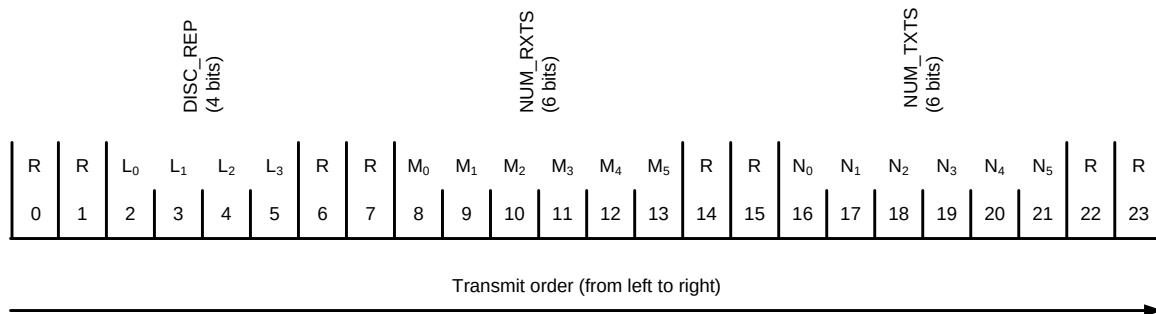


Figure 9 - Antenna Training Indicator Field bit assignment

10.1.2.2 Header check sequence (HCS)

The combination of PHY header and the MAC header shall be protected with a 2 octet CCITT CRC-16 header check sequence (HCS). The CCITT CRC-16 HCS shall be the ones complement of the remainder generated by the modulo-2 division of the combined PHY and MAC headers by the polynomial: $x^{16} + x^{12} + x^5 + 1$. The HCS bits shall be processed in the transmit order. All HCS

calculations shall be made prior to data scrambling. A schematic of the processing order is shown in Figure 10. The registers shall be initialized to all ones.

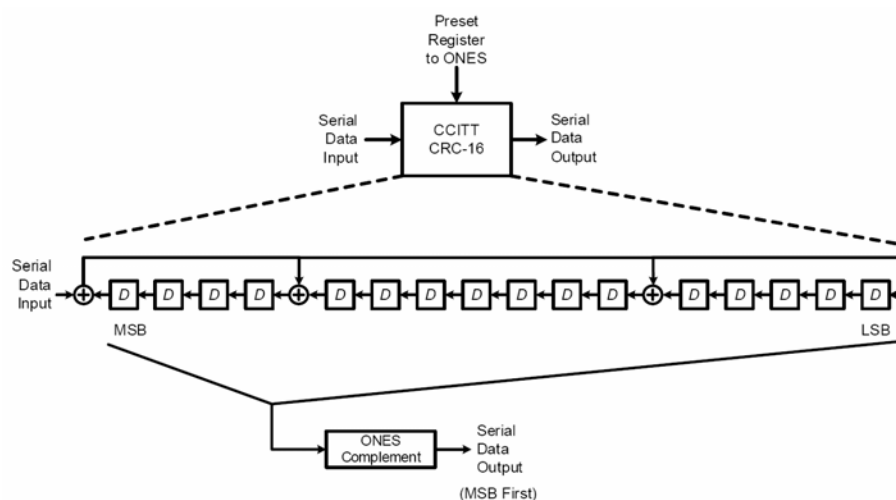


Figure 10 - CCITT CRC-16 block diagram

10.1.3 PPDU payload

The PSDU shall be split into the MAC header and up to 28 PSDU parts, where a PSDU part consists of an MSDU, an FCS and padding. Each PSDU part may be further split into two or more data bit blocks. The total number of PSDU parts and data bit blocks shall not be larger than 57. A number of consecutive PSDU parts that use the same transmission mode may be combined into one data bit block. The resulting data bit blocks shall be encoded and mapped according to the modulation and coding scheme of each device type to generate a transmit symbol block and may be appended by a midamble to form a segment. The details of each modulation and coding scheme is described in 10.2.2.5, 10.2.3.5 and 10.3.2.5. The resulting segments shall be joined consecutively to form the PPDU payload. Figure 11 depicts this operation. Each segment of the PPDU payload may be sent using a different data rate mode. The least-significant bit (LSB) of an octet shall be the first bit transmitted. Type A devices shall be capable of transmission and reception of multi-segment frames. Type B devices may be capable of transmission and reception of multi-segment frames.

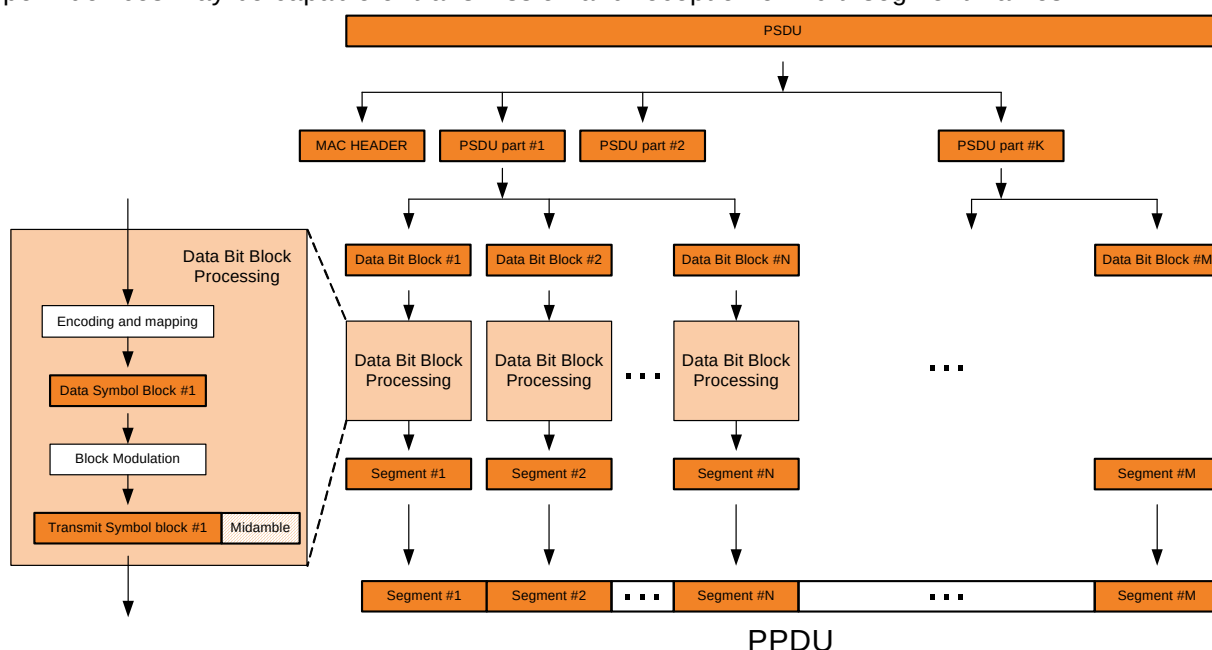


Figure 11 - Formation of the PPDU payload from the PSDU

10.1.3.1 Midamble

The midamble for Type A (SCBT and OFDM) and Type B are different. The details of the midamble for each case can be found in 10.2.2.5.4, 10.2.3.5.2, and 10.3.2.5.5.

10.1.4 Antenna training sequence

The Type A frames shall include the ATS, upon request. The Type B frames may include the ATS upon request. When included, the ATS shall be the concatenation of $N_{TXTS} + N_{RXTS}$ FZ sequences of length 256 (parameter $A_{FZ} = 16$). The FZ sequence is defined in 10.2.2.3, where N_{TXTS} and N_{RXTS} are the number of training sequences for transmitter and receiver antenna training, respectively (see Figure 12).

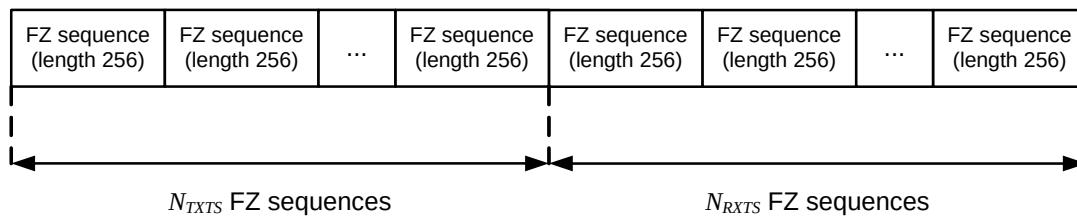


Figure 12 - Antenna training sequence

10.2 Type A PPDU

10.2.1 Mode dependent parameters

The PSDU mode dependent modulation parameters are listed in Table 1.

Table 1- PSDU mode dependent Parameters

Mode	Base Data Rate ¹ (Gbps)				Modulation	Constellation	Encoding	CC Code Rate (R)	TDSF (N_{TDS})	Tail bits (N_{tail})
	No channel bonding	2 bonded channels	3 bonded channels	4 bonded channels						
A0	0.397	0.794	1.191	1.588	SCBT	BPSK	RS & CC	1/2	2	4
A1	0.794	1.588	2.381	3.175	SCBT	BPSK	RS & CC	1/2	1	4
A2	1.588	3.175	4.763	6.350	SCBT	BPSK	RS	1	1	0
A3	1.588	3.175	4.763	6.350	SCBT	QPSK	RS & CC	1/2	1	4
A4	2.722	5.443	8.165	10.886	SCBT	QPSK	RS & CC	6/7	1	6
A5	3.175	6.350	9.526	12.701	SCBT	QPSK	RS	1	1	0
A6	4.234	8.467	13.701	16.934	SCBT	NS8QAM	RS & TCM	5/6	1	8
A7	4.763	9.526	14.288	19.051	SCBT	NS8QAM	RS	1	1	0
A8	4.763	9.526	14.288	19.051	SCBT	TCM-16QAM	RS & TCM	2/3	1	6
A9	6.350	12.701	19.051	25.402	SCBT	16QAM	RS	1	1	0
A10 ²	1.588	3.175	4.763	6.350	SCBT	QPSK	RS & UEP-CC	R_{MSB} : 1/2	1	4
A11	4.234	8.467	12.701	16.934	SCBT	16QAM	RS & UEP-CC	R_{MSB} : 4/7, R_{LSB} : 4/5	1	4
A12	2.117	4.234	6.350	8.467	SCBT	UEP-QPSK	RS & CC	2/3	1	4
A13	4.234	8.467	12.701	16.934	SCBT	UEP-16QAM	RS & CC	2/3	1	4

Table 1- PSDU mode dependent Parameters (concluded)

Mode	Base Data Rate ¹ (Gbps)				Modulation	Constellation	Encoding	CC Code Rate (R)	TDSF (N_{TDS})	Tail bits (N_{tail})
	No channel bonding	2 bonded channels	3 bonded channels	4 bonded channels						
A14	1.008	N/A	N/A	N/A	OFDM	QPSK	RS & CC	1/3	1	6
A15	2.016	N/A	N/A	N/A	OFDM	QPSK	RS & CC	2/3	1	6
A16	4.032	N/A	N/A	N/A	OFDM	16QAM	RS & CC	2/3	1	6
A17	2.016	N/A	N/A	N/A	OFDM	QPSK	RS & UEP-CC	R_{MSB} : 4/7, R_{LSB} : 4/5	1	6
A18	4.032	N/A	N/A	N/A	OFDM	16QAM	RS & UEP-CC	R_{MSB} : 4/7, R_{LSB} : 4/5	1	6
A19	2.016	N/A	N/A	N/A	OFDM	UEP-QPSK	RS & CC	2/3	1	6
A20	4.032	N/A	N/A	N/A	OFDM	UEP-16QAM	RS & CC	2/3	1	6
A21 ²	2.016	N/A	N/A	N/A	OFDM	QPSK	RS & CC	R_{MSB} : 2/3	1	6

NOTE 1 Base data rates assume a cyclic prefix length of zero.

NOTE 2 In modes A10 and A21 only the four MSB bits of each octet shall be transmitted, while the four LSB bits of each octet are discarded by the transmitter.

All Type A devices shall support mode A0 (without channel bonding), and may support mode A0 with channel bonding or modes A1 through A21. In addition all Type A devices shall support mode B0 (without channel bonding). Type A devices may support modes B0 (with channel bonding), B1, B2, or B3 (with or without channel bonding). See 10.3 for Type B modes.

10.2.2 SCBT

10.2.2.1 Timing related parameters

The timing parameters associated with the SCBT PHY are listed in Table 2.

Table 2 - Timing related parameters

Parameter	Description	Value
f_{sym}	Symbol frequency	1.728 Gsps
T_{sym}	Symbol duration	0.5787 ns
N_{SCBTB}	Number of symbols per SCBT block	256
N_D	Number of data symbols per SCBT block	252
N_P	Number of pilot symbols per SCBT block	4
N_{CP}	Number of symbols in the CP	0 32 64 96
N_{SCBTS}	Number of symbols per SCBT block	256 288 320 352

Table 2 - Timing related parameters (concluded)

Parameter	Description	Value
T_{SCBTB}	SCBT block interval	148.148 ns
T_{CP}	CP interval	0 18.5185 ns 37.037 ns 55.5556 ns
T_{SCBTS}	SCBT symbol interval	148.148 ns 166.667 ns 185.185 ns 203.707 ns

10.2.2.2 Frame related parameters

The frame related parameters associated with the PHY are listed in Table 3.

Table 3 - Frame Related Parameters

Parameter	Description	Value
N_{sync}	Number of symbols in the frame synchronization sequence	2048
T_{sync}	Duration of the frame synchronization sequence	1185.19 ns
N_{CE}	Number of symbols in the channel estimation sequence	768
T_{CE}	Duration of the channel estimation sequence	444.444 ns
$N_{preamble}$	Number of symbols in the PLCP preamble	2816
$T_{preamble}$	Duration of the PLCP preamble	1629.63 ns
N_{ATS}	Number of symbols in the ATS	$256(N_{TXTS} + N_{RXTS})N_{DISCREP}$
T_{ATS}	Duration of the ATS	$N_{ATS}T_{sym}$
N_{frame}	Number of symbols in the frame	$N_{preamble} + N_{header} + N_{payload} + N_{ATS}$
T_{frame}	Duration of the frame	$(N_{preamble} + N_{header} + N_{payload} + N_{ATS})T_{sym}$

10.2.2.3 PLCP preamble

The preamble for Type A SCBT frames can be subdivided into two distinct portions: a frame synchronization sequence, $S_{sync,A,SCBT}[\cdot]$, and a channel estimation sequence, $S_{CE,A,SCBT}[\cdot]$. Figure 13 shows the structure of the PLCP preamble for Type A SCBT frames.

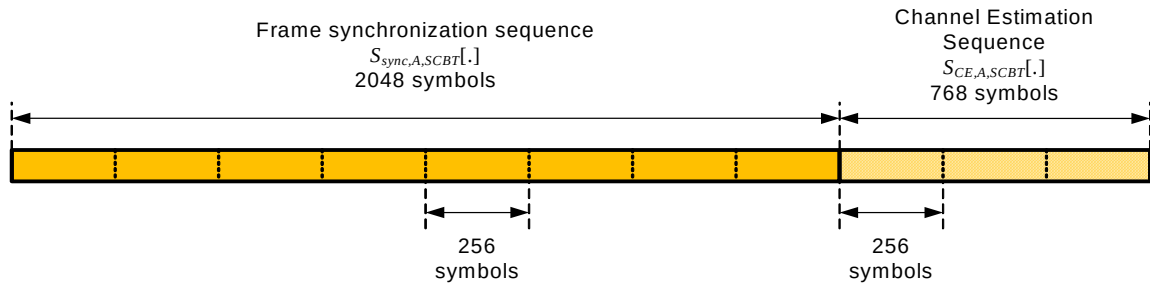


Figure 13 - Structure of the Type A PLCP preamble for Type A SCBT frames

Both the frame synchronization sequence and the channel estimation sequence are constructed based on the Frank-Zadoff (FZ) sequences. A Frank-Zadoff sequence with parameter A_{FZ} , which has length $N_{FZ}=A_{FZ}^2$, is defined as:

$$S_{FZ,A_{FZ}}[n] = \exp\left(j \frac{2\pi pq}{A_{FZ}}\right) \quad (4)$$

where $p=(n \bmod A_{FZ})+1$, and $q = \left\lfloor \frac{n}{A_{FZ}} \right\rfloor + 1$, for $n=0, \dots, A_{FZ}^2-1$, and $\lfloor \cdot \rfloor$ denotes the floor function, which returns the largest integer value smaller than or equal to its argument.

10.2.2.3.1 Frame synchronization sequence

The frame synchronization sequence for Type A SCBT frames consists of eight repetitions of a hierarchical sequence $S_h[\cdot]$, covered by sequence $S_{cover}[\cdot]$, as described in equation (7). The hierarchical sequence, $S_h[\cdot]$, is of length 256, and is defined as the Kronecker product of the Frank-Zadoff sequence of length 16, $S_{FZ,4}[\cdot]$, with itself. That is,

$$S_h[n] = S_{FZ,4}[n \bmod 16] S_{FZ,4}\left[\left\lfloor \frac{n}{16} \right\rfloor\right] \quad (5)$$

for $n=0, \dots, 255$. The cover sequence is of length eight and is defined as

$$S_{cover}[n] = \begin{cases} 1 & n = 0, \dots, 6 \\ -1 & n = 7 \end{cases} \quad (6)$$

The frame synchronization sequence is defined as the Kronecker product of the hierarchical sequence $S_h[\cdot]$ and the cover sequence $S_{cover}[\cdot]$. That is,

$$S_{sync,A,SCBT}[n] = S_{cover}\left[\left\lfloor \frac{n}{256} \right\rfloor\right] S_h[n \bmod 256] \quad (7)$$

for $n=0, \dots, 2047$.

10.2.2.3.2 Channel estimation sequence

The channel estimation sequence consists of three repetitions of the Frank-Zadoff sequence of length 256, $S_{FZ,16}[\cdot]$. That is, the channel estimation sequence is given by:

$$S_{CE,A,SCBT}[n] = S_{FZ,16}[n \bmod 256] \quad (8)$$

for $n=0,\dots,767$.

NOTE The frame synchronization sequence can be used for frame acquisition and detection, coarse carrier frequency estimation, coarse symbol timing, and for synchronization within the preamble. Whereas, the channel estimation sequence can be used for estimation of the channel frequency response, fine carrier frequency estimation, and fine symbol timing.

10.2.2.4 PLCP header

For Type A SCBT frames, the formed PLCP header (as described in 10.1.2) shall be first padded with N_{padhdr} bits where

$$N_{padhdr} = 192 \left\lceil \frac{N_{hdrbits}}{192} \right\rceil - N_{hdrbits} \quad (9)$$

where $N_{hdrbits}$ is the number of bits in the formed PLCP header (as described in 10.1.2). The padded header shall be encoded and modulated as described in 10.2.2.5, starting with the demultiplexing. Encoding and modulation parameters identical to mode A0 shall be used. The resulting data symbols shall be block modulated (see 10.2.2.5.3) in order to create the baseband signal.

10.2.2.4.1 PHY header

10.2.2.4.1.1 Fixed length PHY header

10.2.2.4.1.1.1 PLCP scrambler field (SCRAMBLER)

The bits A_0 and A_1 shall be set according to the scrambler seed identifier value. This two-bit value corresponds to the seed value chosen for the data scrambler (see 10.2.2.5.1.1).

10.2.2.4.1.1.2 Bit reversal field (BIT_REVERSAL)

The value of the BIT_REVERSAL bit shall be set to 0_B for all Type A SCBT frames.

10.2.2.4.1.1.3 ATIF existence field (ATIF_EX)

The ATIF_EX field determines whether or not an ATIF field exists at the end of the PHY header. The mapping between this field and existence of the ATIF is given in Table 4. The ATIF_EX value for Type A Beacon and Type B Beacon shall be 0

Table 4 - Mapping between the value of the ATIF_EX bit and existence of ATIF

ATIF_EX (C)	ATIF Existence
0	ATIF does not exist
1	ATIF does exist

10.2.2.4.1.1.4 CP length field (CP_LENGTH)

The mapping between the value of the CP_LENGTH field and N_{CP} for the current frame is given in Table 5. The default value of N_{CP} for the first frame, or for beacons, discovery mode frames and TRN frames shall be 96.

Table 5 - Mapping between the value of the CP_LENGTH field and N_{CP}

CP_LENGTH (D ₁ D ₀)	N_{CP}
00	0
01	32
10	64
11	96

10.2.2.4.1.1.5 Requested CP length field (REQ_CP_LENGTH)

The mapping between the value of the REQ_CP_LENGTH field and N_{CP} for the following frames is given in Table 6.

Table 6 - Mapping between the value of the REQ_CP_LENGTH field and N_{CP}

REQ_CP_LENGTH (E ₁ E ₀)	N_{CP}
00	0
01	32
10	64
11	96

10.2.2.4.1.1.6 Number of segments field (NUM_SEGMENTS)

Depending on the number of segments (NUM_SEGMENTS), bits F₀ to F₄ shall be set according to the values in Table 7. When a frame does not have a payload, this field shall be set to 0000_B.

Table 7 - Mapping between the value of the NUM_SEGMENTS field and number of segments

NUM_SEGMENTS (F ₄ F ₃ F ₂ F ₁ F ₀)	Number of segments (N _{segments})
00000	0
00001	1
00010	2
00011	3
00100	4
00101	5
00110	6
00111	7

Table 7 - Mapping between the value of the NUM_SEGMENTS field and number of segments (concluded)

NUM_SEGMENTS (F ₄ F ₃ F ₂ F ₁ F ₀)	Number of segments (N _{segments})
01000	8
01001	9
01010	10
01011	11
01100	12
01101	13
01110	14
01111	15
10000	16
10001	17
10010	18
10011	19
10100	20
10101	21
10110	22
10111	23
11000	24
11001	25
11010	26
11011	27
11100	28
11101	Reserved
11110	Reserved
11111	Reserved

NOTE Discovery mode frames and ACK frames may have zero segments (i.e. no payload).

10.2.2.4.1.1.7 Number of MSDUs field (NUM_MSDUS)

Depending on the number of MSDUs (NUM_MSDUS), bits P_0 to P_4 shall be set according to the values in Table 8. When a frame does not have a payload, this field shall be set to 00000_B.

Table 8 - Mapping between the value of the NUM_MSDUS field and number of MSDUs

NUM_MSDUS ($P_4P_3P_2P_1P_0$)	Number of MSDUs (N_{MSDUs})
00000	0
00001	1
00010	2
00011	3
00100	4
00101	5
00110	6
00111	7
01000	8
01001	9
01010	10
01011	11
01100	12
01101	13
01110	14
01111	15
10000	16
10001	17
10010	18
10011	19
10100	20
10101	21
10110	22
10111	23
11000	24
11001	25
11010	26
11011	27
11100	28

Table 8 - Mapping between the value of the NUM_MSDUS field and number of MSDUs (concluded)

NUM_MSDUS (P ₄ P ₃ P ₂ P ₁ P ₀)	Number of MSDUs (N _{MSDUs})
11101	Reserved
11110	Reserved
11111	Reserved

10.2.2.4.1.2 Variable length PHY header**10.2.2.4.1.2.1 Mode field (MODE)**

Depending on the mode (MODE), bits G₀ to G₅ shall be set according to the values in Table 9.

Table 9 - MODE field

Mode	MODE (G ₅ ...G ₀)	Mode	MODE (G ₅ ...G ₀)	Mode	MODE (G ₅ ...G ₀)	Mode	MODE (G ₅ ...G ₀)
A0	000000	A16	010000	Reserved	100000	Reserved	110000
A1	000001	A17	010001	Reserved	100001	Reserved	110001
A2	000010	A18	010010	Reserved	100010	Reserved	110010
A3	000011	A19	010011	Reserved	100011	Reserved	110011
A4	000100	A20	010100	Reserved	100100	Reserved	110100
A5	000101	A21	010101	Reserved	100101	Reserved	110101
A6	000110	Reserved	010110	Reserved	100110	Reserved	110110
A7	000111	Reserved	010111	Reserved	100111	Reserved	110111
A8	001000	Reserved	011000	Reserved	100111	Reserved	111000
A9	001001	Reserved	011001	B0	101001	Reserved	111001
A10	001010	Reserved	011010	B1	101010	Reserved	111010
A11	001011	Reserved	011011	B2	101011	Reserved	111011
A12	001100	Reserved	011100	B3	101100	Reserved	111100
A13	001101	Reserved	011101	Reserved	101101	Reserved	111101
A14	001110	Reserved	011110	Reserved	101110	Reserved	111110
A15	001111	Reserved	011111	Reserved	101111	Reserved	111111

10.2.2.4.1.2.2 Segment length field (LENGTH)

The segment length field shall be an unsigned 16-bit integer that indicates the number of octets in the uncoded segment payload (which does not include the tail bits, or the pad bits). The length of each segment shall not be larger than 65535 octets.

10.2.2.4.1.2.3 Midamble existence field (MID_EX)

The MID_EX field determines whether or not the segment is appended by a midamble. The mapping between this bit and existence of the midamble is given in Table 10.

Table 10 - Mapping between the value of the MID_EX bit and existence of midamble

MID_EX (J)	Midamble existence
0	Midamble does not exist
1	Midamble exists

10.2.2.4.1.2.4 Segment continued field (CONT)

The CONT field determines whether or not this segment is a fragment of the received PSDU, and should be reassembled at the receiver. The value of this bit shall be according to Table 11.

Table 11 - Value of the CONT bit

CONT (K)	Fragmentation
0	The segment is not a fragment or is the last fragment
1	The segment is a fragment

10.2.2.4.1.3 Antenna training indicator field**10.2.2.4.1.3.1 Discovery mode repetition field (DISC_REP)**

The discovery mode repetition field represents the number of repetitions in the discovery mode. The mapping between the value of DISC_REP and $N_{DISCREP}$ is given in Table 12. For all non-discovery mode frames the value of DISC_REP shall be set to $L_3L_2L_1L_0 = 0000_B$.

Table 12 - Mapping between the value of the DISC_REP field and number of discovery mode repetitions

DISC_REP ($L_3L_2L_1L_0$)	Number of repetitions in discovery mode ($N_{DISCREP}$)
0000	1
0001	2
0010	4
0011	8
0100	16
0101	32
0110	64
0111	128
1000	Reserved
1001	Reserved
1010	Reserved

Table 12 - Mapping between the value of the DISC_REP field and number of discovery mode repetitions (concluded)

DISC_REP (L ₃ L ₂ L ₁ L ₀)	Number of repetitions in discovery mode (N _{DISCREP})
1011	Reserved
1100	Reserved
1101	Reserved
1110	Reserved
1111	Reserved

10.2.2.4.1.3.2 Number of training symbols for RX training field (NUM_RXTS)

The number of training symbols for RX training field shall be an unsigned 6-bit integer. Its value shall indicate the number of training symbols for RX training in the ATS. The NUM_RXTS value for Discovery Mode Beacon shall be 0.

10.2.2.4.1.3.3 Number of training symbols for TX training field (NUM_TXTS)

The number of training symbols for TX training field shall be an unsigned 6-bit integer. Its value shall indicate the number of training symbols for TX training in the ATS. The NUM_TXTS value for Discovery Mode Beacon is 0.

10.2.2.5 PPDU payload

The PPDU payload consists of one or more segments as described in 10.1. The segments are formed as described in 10.1.3. Each data bit block shall be processed as follows:

1. The resulting bits shall be encoded and mapped as described in 10.2.2.5.1 or 10.2.2.5.2.
2. The resulting symbols shall be modulated into SCBT symbols as described in 10.2.2.5.3.

10.2.2.5.1 FEC and mapping (Equal error protection)

Figure 14 depicts the general overview of the encoding and mapping scheme for modes A0 through A9. For the payload, first, the data bits shall be scrambled as specified in 10.2.2.5.1.1. Then, $N_{padbits}$ zero pad bits shall be appended to the end of the data bit block, where

$$N_{padbits} = 1792 \left\lceil \frac{N_{bits}}{1792} \right\rceil - N_{bits} \quad (10)$$

and N_{bits} is the number of bits in the data bit block. The padded data bit block shall be encoded according to the Reed-Solomon code, as specified in 10.2.2.5.1.2.

The resulting RS coded payload bits or the formed header bits shall be demultiplexed into 4 groups, as described in 10.2.2.5.1.3. Depending on the data rate mode, each group of bits shall then be interleaved using the bit interleaver described in 10.2.2.5.1.4. The resulting bits shall be appended with N_{tail} tail bits (in each branch). They then shall be encoded using the convolutional code or trellis coded modulation described in 10.2.2.5.1.5 and 10.2.2.5.1.6. The resulting encoded bits from the 4 branches shall then be multiplexed together into one group of symbols as specified in 10.2.2.5.1.7. The multiplexed bits are then mapped to constellations as specified in 10.2.2.5.1.8. The data symbols shall be spread in time domain as described in 10.2.2.5.1.9. The resulting data symbols shall then be appended with N_{padsym} zero symbols, where

$$N_{padsyms} = 2N_D \left\lceil \frac{N_{sym}}{2N_D} \right\rceil - N_{sym} \quad (11)$$

At the end of each segment, the resulting data symbols shall be interleaved with the Dual Helical Scan (DHS) symbol interleaver as described in 10.2.2.5.1.10.

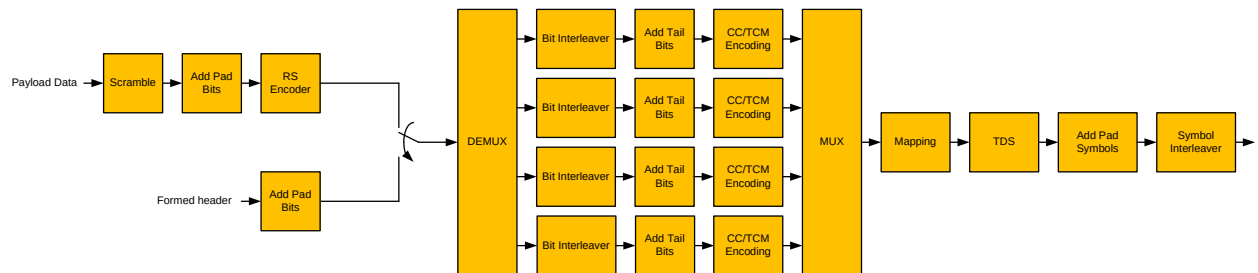


Figure 14 - General view of the encoding procedure

10.2.2.5.1.1 Data scrambler

A side-stream scrambler shall be used to whiten only portions of the PLCP header, i.e. the MAC header and HCS, and the entirety of each segment. In addition, the scrambler shall be initialized to a seed value specified by the MAC at the beginning of the MAC header and then re-initialized to the same seed value at the beginning of each segment.

The polynomial generator, $g(D)$, for the pseudo-random binary sequence (PRBS) generator shall be: $g(D) = 1 + D^{14} + D^{15}$, where D is a single bit delay element. Using this generator polynomial, the corresponding PRBS, $x[n]$, is generated as

$$x[n] = x[n - 14] \oplus x[n - 15], n = 0, 1, 2, \dots \quad (12)$$

where $\oplus$ denotes modulo-2 addition. The following sequence defines the initialization vector, x_{init} , which is specified by the parameter “seed value” in:

$$\mathbf{x}_{init} = [x_i[-1] \ x_i[-2] \ \dots \ x_i[-14] \ x_i[-15]] \quad (13)$$

where $x_i[-k]$ represents the binary initial value at the output of the k^{th} delay element. The scrambled data bits, v_m , are obtained as show in Figure 15.

$$v[n] = s[m] \oplus x[m], m = 0, 1, 2, \dots \quad (14)$$

where $s[m]$ represents the non-scrambled data bits.

The 15-bit initialization vector or seed value shall correspond to the seed identifier as shown in Table 13. The seed identifier value shall be set to 00 when the PHY is initialized and this value shall be incremented in a 2-bit rollover counter for *each* frame sent by the PHY.

Table 13 - Scrambler seed selection

Seed Identifier (A_1A_0)	Seed Value $x_{init} = x_i[-1] \ x_i[-2] \ \dots \ x_i[-15]$	PRBS Output First 16 bits $x[0] \ x[1] \ \dots \ x[15]$
00	0011 1111 1111 111	0000 0000 0000 1000

Table 13 - Scrambler seed selection (concluded)

01	0111 1111 1111 111	0000 0000 0000 0100
10	1011 1111 1111 111	0000 0000 0000 1110
Seed Identifier (A ₁ A ₀)	Seed Value $x_{init} = x_i[-1] \ x_i[-2] \dots x_i[-15]$	PRBS Output First 16 bits $x[0] \ x[1] \dots x[15]$
11	1111 1111 1111 111	0000 0000 0000 0010

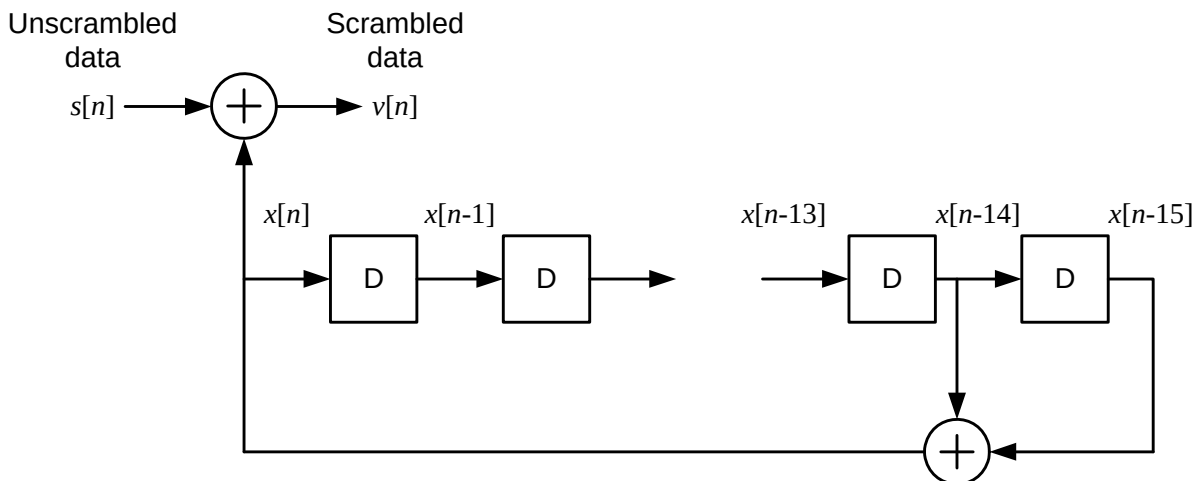


Figure 15 - Block diagram of the side-stream scramble

10.2.2.5.1.2 Reed-Solomon code

A systematic ($N=255$, $K=239$, $T=8$) Reed-Solomon code is shortened to different lengths to be used for the header and the payload. The RS(255,239) shall be shortened to RS($255-N_{RSpad}$, $239-N_{RSpad}$) by first padding a block of $239-N_{RSpad}$ data octets with N_{RSpad} zero octets. The resulting block shall be coded using the RS(255,239) Reed-Solomon code described below. The resulting 16 parity octets $r_{15}, \dots, r_0$ shall be appended to the data block to form the coded data block of length $255-N_{RSpad}$.

For the header, the N_{RSpad} shall be equal to $237-4N_{segments}-3I_{ATIF}-N_{MACheader}$, where $N_{MACheader}$ is the length of the MAC header (refer to 15.2.1 and 15.2.2). For the payload, the N_{RSpad} shall be equal to 15.

The RS(255,239) code is defined over $GF(2^8)$ with a primitive polynomial $p(z) = z^8 + z^4 + z^3 + z^2 + 1$. As notation, the element $M = b_7z^7 + b_6z^6 + b_5z^5 + b_4z^4 + b_3z^3 + b_2z^2 + b_1z + b_0$, where $M \in GF(2^8)$, has the following binary representation $b_7b_6b_5b_4b_3b_2b_1b_0$, where b_7 is the MSB and b_0 is the LSB.

The code is specified by the generator polynomial $g(x)$ defined over $GF(2^8)$.

$$g(x) = \prod_{i=0}^{2T-1} (x - \alpha^i) \quad (15)$$

where $\alpha = \alpha_{2^8-1}$ is the root of the polynomial $p(z)$.

The mapping of the information octets $m = (m_{238}, m_{237}, \dots, m_0)$ to codeword octets $c = (m_{238}, m_{237}, \dots, m_0, r_{15}, r_{14}, \dots, r_0)$ is achieved by computing the remainder polynomial $r(x)$

$$r(x) = \prod_{i=0}^{15} r_i x^i = x^{16} m(x) \bmod g(x) \quad (16)$$

where $m(x)$ is the information polynomial

$$m(x) = \prod_{i=0}^{238} m_i x^i \quad (17)$$

and $r_i, i = 0, \dots, 15$, and $m_i, i = 0, \dots, 238$, are elements of $GF(2^8)$.

10.2.2.5.1.3 Demultiplexer

The Reed-Solomon encoded bits $b[.]$ shall be demultiplexed to create four bit streams $c_m[.]$, $m=0,\dots,3$. The $c_m[.]$ shall be obtained from $b[.]$ from $c_m[k] = b[4k+m]$.

10.2.2.5.1.4 Bit interleaver

The bit streams shall be interleaved by a bit interleaver of length 48. The interleaved bit $d_m[l]$ shall be equal to $c_m[k]$ by

$$l = \left[6 \left\lfloor \frac{k}{6} \right\rfloor + 7(k \bmod 6) \right] \bmod 48 \quad (18)$$

10.2.2.5.1.5 Convolutional code

The convolutional encoder shall use the rate $R=1/2$ code with generator polynomials, $g_0 = 23_O$, and $g_1 = 35_O$, as shown in Figure 16. The bit denoted as "A" shall be the first bit generated by the encoder, followed by the bit denoted as "B". Additional coding rates are derived from the "mother" rate $R=1/2$ convolutional code by employing "puncturing". Puncturing is a procedure for omitting some of the encoded bits at the transmitter (thus reducing the number of transmitted bits and increasing the coding rate) and inserting a dummy "zero" metric into the decoder at the receiver in place of the omitted bits. The puncturing patterns are illustrated in Figure 17, Figure 18, Figure 19, Figure 20, and Figure 21. In each of these cases, the tables shall be filled in with encoder output bits from left to right. For the last block of bits, the process shall be stopped at the point at which encoder output bits are exhausted, and the puncturing pattern applied to the partially filled block.

The encoder shall start from the all-zero state. After the encoding process for the PLCP header has been completed, the encoder shall be reset to the all-zero state before the encoding starts for each segment; in other words, the encoding of each segment shall also start from the all-zero state. The PSDU shall be encoded using the appropriate coding rate of $R = 4/7, 2/3, 4/5, 5/6$, or $6/7$.

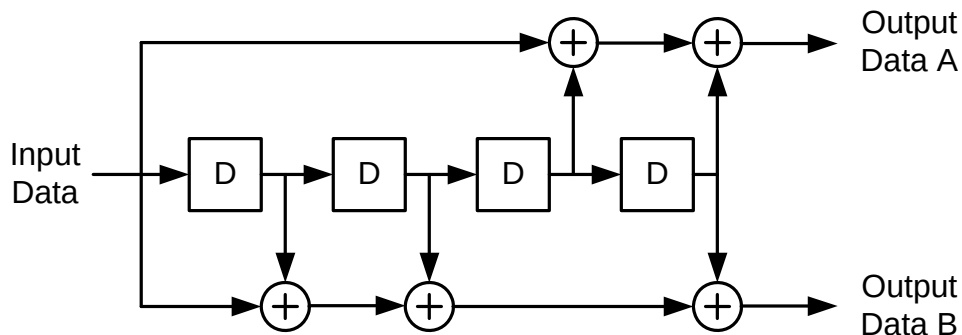


Figure 16 - Convolutional encoder: rate $R=1/2$, constraint length $K=5$

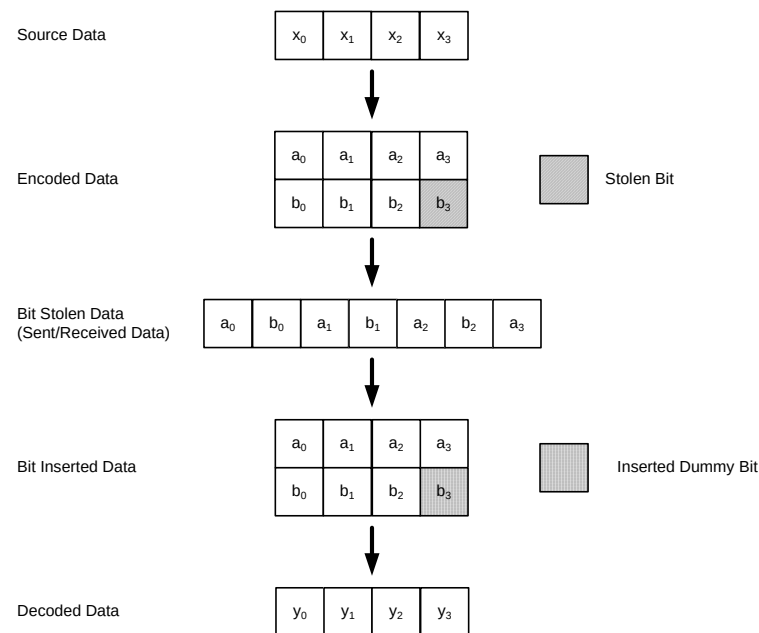


Figure 17 - An example of bit stealing and bit insertion for R=4/7 code

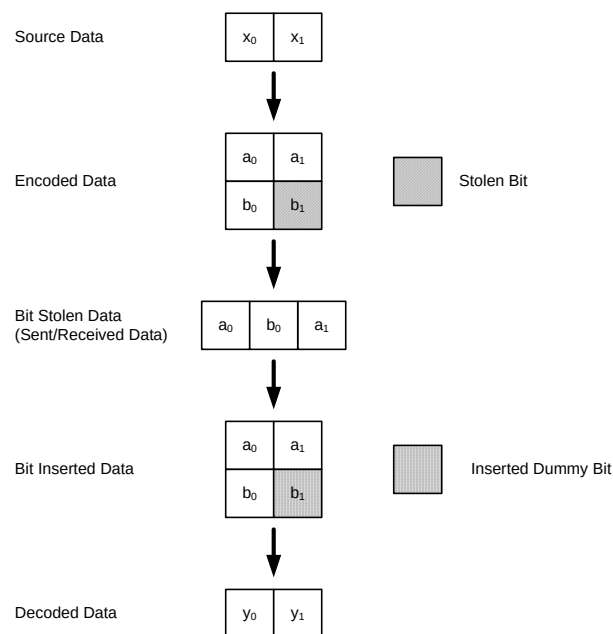


Figure 18- An example of bit-stealing and bit-insertion for R=2/3 code

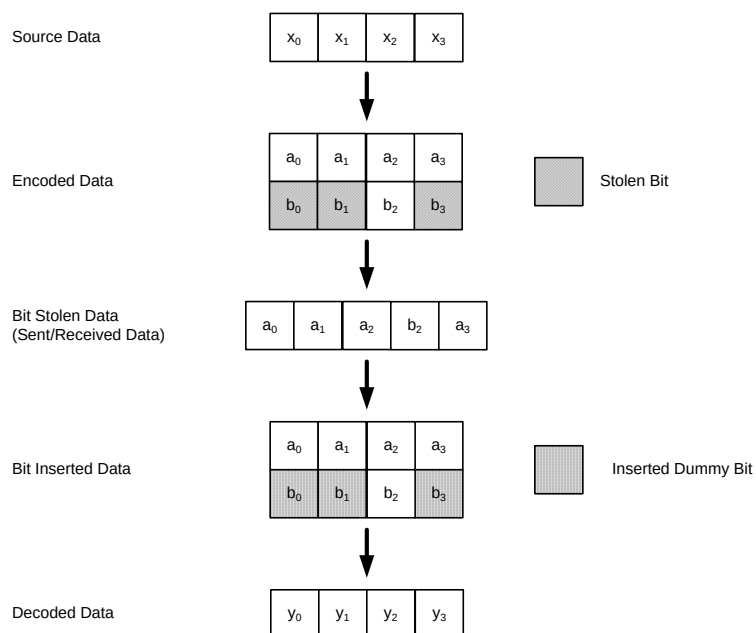


Figure 19 - An example of bit-stealing and bit-insertion for R=4/5 code



Figure 20 - An example of bit-stealing and bit-insertion for R=5/6 code

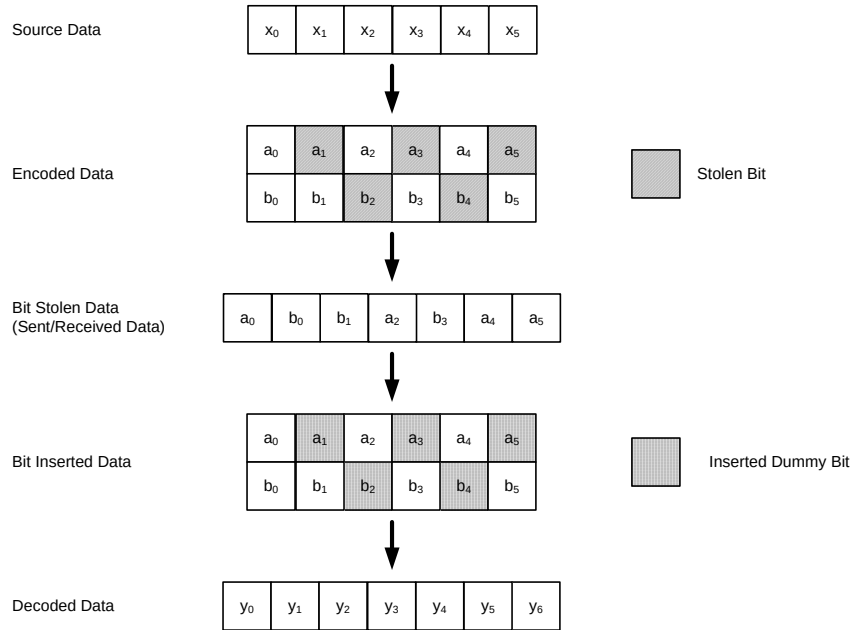


Figure 21 - An example of bit-stealing and bit-insertion for R=6/7 code

NOTE Decoding by the Viterbi algorithm is recommended

10.2.2.5.1.6 Trellis coded modulation

For NS8QAM and 16QAM constellations, a "pragmatic" trellis coded modulation (TCM) is employed by using the convolutional code and the puncturing patterns as described in 10.2.2.5.1.5.

Before the convolutional encoding, the bits $e_m[.]$ shall be demultiplexed into two groups $e_{c,m}[.]$ and $e_{u,m}[.]$, where

$$e_{u,m}[i] = e_m \left[\left\lfloor \frac{i}{U} \right\rfloor (U + C) + i \bmod U \right] \quad (19)$$

and

$$e_{c,m}[i] = e_m \left[\left\lfloor \frac{i}{C} \right\rfloor (U + C) + i \bmod C + U \right] \quad (20)$$

The bits $e_{c,m}[.]$ shall be encoded and punctured to produce the bits $p_m[.]$. The resulting bits, $p_m[.]$, shall then be multiplexed with bits $e_{u,m}[.]$ to generate $f_m[.]$, where

$$f_m[i] = \begin{cases} e_{u,m}[i/P] & i \bmod P = 0 \\ e_{c,m}[\lfloor i/P \rfloor (P-1) + i \bmod P - 1] & i \bmod P \neq 0 \end{cases} \quad (21)$$

For a given data rate mode, the convolutional code rate (including encoding and puncturing) and C , P and U shall be as described in Table 14.

Table 14 - Parameters for trellis coded modulation

Mode	R	U	C	P
A6	5/6	3	5	3
A8	2/3	1	2	4

An example of this operation for data rate mode A6 is depicted in Figure 22.

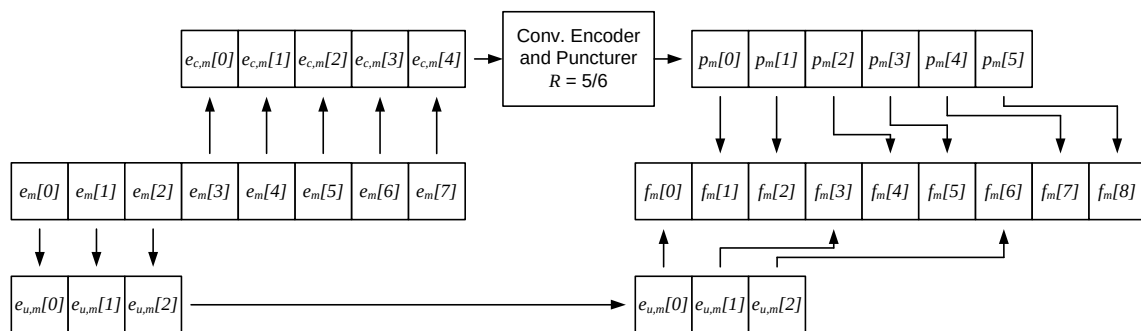


Figure 22 - An example of encoding for trellis coded modulation for mode A6

10.2.2.5.1.7 Multiplexer

The coded bits from the four branches $f_m[.]$, $m=0,...,3$ shall be multiplexed to create a single stream $g[.]$. The $g[.]$ shall be obtained from $f_m[.]$ from

$$g[k] = f_{\lfloor k/k_{MUX} \rfloor \bmod 4} \left[k \bmod k_{MUX} + k_{MUX} \left\lfloor \frac{k}{4k_{MUX}} \right\rfloor \right] \quad (22)$$

where $k_{MUX} = 1$ for modes A0 to A5, A7 and A9, $k_{MUX} = 3$ for mode A6, and $k_{MUX} = 4$ for mode A8.

10.2.2.5.1.8 Mapping

The data bits shall be mapped to the constellations according to the data rate mode. The constellation mappings are given in 10.2.4.

10.2.2.5.1.9 Time domain spreading (TDS)

The data symbols shall be consecutively repeated N_{TDS} times, that is the output of the spread symbols $s[.]$ shall be derived from the data symbols $v[.]$ by

$$s[n] = v \left[\left\lfloor \frac{n}{N_{TDS}} \right\rfloor \right] \quad (23)$$

where N_{TDS} is the time domain spreading factor (TDSF) defined for each mode in Table 48.

10.2.2.5.1.10 Symbol interleaver

The data symbols, $u[.]$, shall be interleaved using a 21 by 24 dual helical scan (DHS) interleaver. The DHS interleaver interleaves the data symbols by writing and reading the data symbols in a memory

block with a helical scan pattern. Each block of 504 data symbols, $u[0], \dots, u[503]$, shall be interleaved separately to form the interleaved symbols $w[0], \dots, w[503]$.

The interleaving operation is described by defining the auxiliary symbols $r[m, n]$. The $r[m, n]$ are then given by $r[m, n] = u[k]$ where

$$m = \left[(k \bmod 21) + \left\lfloor \frac{k}{21} \right\rfloor \right] \bmod 24 \quad (24)$$

and

$$n = k \bmod 21 \quad (25)$$

and $w[k]$ are given by $w[k] = r[m, n]$, where

$$m = 23 - \left[(k \bmod 21) + \left\lfloor \frac{k}{21} \right\rfloor \right] \bmod 24 \quad (26)$$

and

$$n = k \bmod 21 \quad (27)$$

10.2.2.5.2 FEC and mapping (Unequal error protection)

Figure 23 depicts the general overview of the encoding and mapping scheme for modes A10 through A13. For the payload, first, the MSB and LSB bits of the each octet is separated as described in 10.2.2.5.2.1. Then, for each group, the data bits shall be scrambled as specified in 10.2.2.5.2.2. Then, $N_{padbits}$ shall be appended to the end of the data bit block, where

$$N_{padbits} = 1792 \left\lceil \frac{N_{bits}}{1792} \right\rceil - N_{bits} \quad (28)$$

and N_{bits} is the number of bits in the data bit block. The padded data bit block shall be encoded according to the Reed-Solomon code, as specified in 10.2.2.5.2.3.

The resulting RS coded payload bits or the formed header bits shall be demultiplexed into 4 groups, as described in 10.2.2.5.2.4. Depending on the data rate mode, each group of bits shall then be interleaved using the bit interleaver described in 10.2.2.5.2.5. The resulting bits shall be appended with N_{tail} tail bits (in each branch). Then they shall be encoded using the convolutional code described in 10.2.2.5.2.6. The resulting encoded bits from all 8 branches shall then be multiplexed together into one group of bits as specified in 10.2.2.5.2.7. The multiplexed bits are then mapped to constellations as specified in 10.2.2.5.2.8. The resulting data symbols shall then be appended with N_{padsym} zero symbols, where

$$N_{padsym} = 2N_D \left\lceil \frac{N_{sym}}{2N_D} \right\rceil - N_{sym} \quad (29)$$