

International Telecommunication Union

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

G.9903

(08/2017)

SERIES G: TRANSMISSION SYSTEMS AND MEDIA,
DIGITAL SYSTEMS AND NETWORKS

Access networks – In premises networks

**Narrowband orthogonal frequency division
multiplexing power line communication
transceivers for G3-PLC networks**

Recommendation ITU-T G.9903

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Recommendation ITU-T G.9903

Narrowband orthogonal frequency division multiplexing power line communication transceivers for G3-PLC networks

Summary

Recommendation ITU-T G.9903 contains the physical layer (PHY) and data link layer (DLL) specification for the G3-PLC narrowband orthogonal frequency division multiplexing (OFDM) power line communication transceivers, for communications via alternating current and direct current electric power lines over frequencies below 500 kHz.

The control parameters that determine spectral content, power spectral density (PSD) mask requirements, and the set of tools and procedures to support the measurement and reduction of the transmit PSD can be found in Recommendation ITU-T G.9901.

This Recommendation adds several corrections of and improvements to the PHY, the DLL, and the routing parts of the specification. It also integrates Amendment 1 to Recommendation ITU-T G.9903 (2014), adding support for coexistence with other narrowband PLC technologies via the preamble-based coexistence mechanism specified in clause 10 of IEEE 1901.2.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
1.0	ITU-T G.9903	2012-10-29	15	11.1002/1000/11823
1.1	ITU-T G.9903 (2012) Amd. 1	2013-05-07	15	11.1002/1000/11897
2.0	ITU-T G.9903	2013-05-07	15	11.1002/1000/12049
3.0	ITU-T G.9903	2014-02-22	15	11.1002/1000/12088
3.1	ITU-T G.9903 (2014) Amd. 1	2015-08-13	15	11.1002/1000/12539
4.0	ITU-T G.9903	2017-08-13	15	11.1002/1000/13333

Keywords

Narrowband power line communications, G3-PLC, OFDM, PHY, physical layer, MAC medium access control, routing, LOADng

* To access the Recommendation, type the URL <http://handle.itu.int/> in the address field of your web browser, followed by the Recommendation's unique ID. For example, <http://handle.itu.int/11.1002/1000/11830-en>.

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Recommendation ITU-T G.9903

Narrowband orthogonal frequency division multiplexing power line communication transceivers for G3-PLC networks

1 Scope

Recommendation ITU-T G.9903 contains the physical layer (PHY) and data link layer (DLL) specification for the G3-PLC narrowband orthogonal frequency division multiplexing (OFDM) power line communication transceivers, for communications via alternating current and direct current electric power lines over frequencies below 500 kHz. This Recommendation supports indoor and outdoor communications over low-voltage lines, medium-voltage lines, through transformer low-voltage to medium-voltage and through transformer medium-voltage to low-voltage power lines in both urban and long distance rural communications. This Recommendation addresses grid to utility meter applications, advanced metering infrastructure (AMI), and other 'Smart Grid' applications such as the charging of electric vehicles, home automation, and home area networking (HAN) communications scenarios.

This Recommendation supports coexistence with other narrowband PLC technologies via frequency division and via the preamble-based coexistence mechanism specified in clause 10 of [IEEE 1901.2].

This Recommendation does not contain the control parameters that determine spectral content, power spectral density (PSD) mask requirements and the set of tools and procedures to support the reduction and measurement of the transmit PSD; all of which are detailed in Recommendation [ITU-T G.9901].

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

- [ITU-T G.9901] Recommendation ITU-T G.9901 (2014), *Narrowband orthogonal frequency division multiplexing power line communication transceivers – Power spectral density specification*.
- [ITU-T G.9905] Recommendation ITU-T G.9905 (2013), *Centralized metric-based source routing*.
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- [IEEE 802-2001] IEEE Std 802-2001 (R2007), *IEEE Standard for Local and Metropolitan Area Networks. Overview and Architecture*.
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- [IEEE 802.15.4] IEEE 802.15.4:2006, *IEEE Standard for Information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 15.4: Wireless Medium Access (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs)*.
- [IEEE 1901.2] IEEE 1901.2 (2013), *IEEE Standard for Low-Frequency (less than 500 kHz) Narrowband Power Line Communications for Smart Grid Applications*.
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- [IETF RFC 2284] IETF RFC 2284 (1998), *PPP Extensible Authentication Protocol (EAP)*.
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- [IETF RFC 5444] IETF RFC 5444 (2009), *Generalized Mobile Ad Hoc Network (MANET) Packet/Message Format*.
- [IETF RFC 6282] IETF RFC 6282 (2011), *Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks*.
- [IETF RFC 6775] IETF RFC 6775 (2012), *Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)*.
- [TTC JJ-300.11] TTC standard JJ-300.11 (2014): *Homenetwork Communication Interface for ECHONET Lite (ITU-T G.9903 Narrow band OFDM PLC), version 2.0*.

3 Conventions and definitions

3.1 Conventions

Binary numbers are indicated by the prefix '0b' followed by the binary digits.

Hexadecimal numbers are indicated by the prefix '0x' followed by the hexadecimal digits.

3.2 Terms defined elsewhere

None.

3.3 Terms defined in this Recommendation

This Recommendation defines the following terms:

3.3.1 active tone: A tone that carries data according to the tone map field. Masked tones and pilot tones are not active tones.

3.3.2 inactive tone: A tone that carries dummy data according to the tone map field. Masked tones and pilot tones are not inactive tones.

3.3.3 masked tone: A tone with a null amplitude according to the tone mask parameter. Thus, it contributes neither to the OFDM signal's power spectrum density nor to the LQI calculation.

3.3.4 modulation scheme: Two modulation schemes are defined: differential and coherent.

3.3.5 modulation type: The following modulation types are defined: robust modes, BPSK, DBPSK, QPSK, DQPSK, 8-PSK, D8PSK, and 16-QAM.

3.3.6 pilot tone: A tone used in coherent modulation schemes that carries a specific pattern in order to help the receiver with clock recovery and channel estimation.

3.3.7 tone map: A bitmap containing a list of the sub-bands (groups of tones) that are either active (bit set to 1) or inactive (bit set to zero). A bit in the bitmap represents a group of consecutive tones and the number of tones per group depends on the bandplan.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

6LoWPAN	IPv6 over Low power Wireless Personal Area Network
8-PSK	8 Phase Shift Keying
16-QAM	16 Quadrature Amplitude Modulation
AAA	Authentication, Authorization and Accounting
ACK	Acknowledge
ADP	Adaptation
AFE	Analogue Front End
AGC	Automatic Gain Control
AMM	Automated Meter Management
AMN	Artificial Mains Network
ARQ	Automatic Repeat Request
BPSK	Binary Phase Shift Keying
CIFS	Contention Inter-Frame Space
CP	Cyclic Prefix
CRC	Cyclic Redundancy Check
D8PSK	Differential 8 Phase Shift Keying
DBPSK	Differential Binary Phase Shift Keying
DCI	Destination Context Identifier
DQPSK	Differential Quadrature Phase Shift Keying
DSI	Device Specific Information
EAP	Extensible Authentication Protocol
ED	End Device
EIFS	Extended Inter-frame Space
FCH	Frame Control Header
FEC	Forward Error Correction

FFT	Fast Fourier Transform
FL	Frame Length
GF	Galois Field
GI	Guard Interval
GMK	Group Master Key
GTS	Guaranteed Time Slot (see [IEEE 802.15.4])
HPCW	High Priority Contention Window
IB	Information Base
ICI	Inter-Carrier Interference
IFFT	Inverse Fast Fourier Transform
IFS	Inter-frame Spacing
IS	Information System
LBA	LoWPAN Bootstrapping Agent
LBD	LoWPAN Bootstrapping Device
LBP	LoWPAN Bootstrapping Protocol
LBS	LoWPAN Bootstrapping Server
LFSR	Linear Feedback Shift Register
LQ	Link Quality
LSB	Least Significant Bit
LSF	Last Segment Flag
MAC	Media Access Control
MIB	Management Information Base
MPDU	MAC Protocol Data Unit
MSB	Most Significant Bit
MSE	Mean Square Error
NACK	Negative Acknowledgement
NIB	Neighbour Information Base
NPCW	Normal Priority Contention Window
NSDU	Network Service Data Unit
OFDM	Orthogonal Frequency Division Multiplexing
PAN	Personal Area Network
PAR	Peak to Average Ratio
PCS	Physical Carrier Sense
PDC	Phase Detection Counter
PHY	Physical layer
PIB	PAN Information Base
PICS	Protocol Implementation Conformance Statement

PLC	Power Line Communication
PN	Pseudo Noise
POS	Personal Operating Space
PPDU	PHY Protocol Data Unit
PPM	Parts Per Million
PSDU	PHY Service Data Unit
PSI	PAN Specific Information
PSK	Pre-Shared Key
QPSK	Quadrature Phase Shift Keying
RA	Router Advertisement
RADIUS	Remote Authentication Dial in User Service
RERR	Route Error
RES	Reserved (bit fields)
RIFS	Response Inter-frame Space
rms	Root Mean Square
RREP	Route Reply
RREQ	Route Request
RS	Reed-Solomon
RX	Receiver
SC	Segment Count
SCI	Source Context Identifier
S-FSK	Spread Frequency Shift Keying
SN	Sequence Number
SNR	Signal to Noise Ratio
SSCS	Service-Specific Convergence Sublayer
TMI	Tone Map Index
TMR	Tone Map Request
TX	Transmitter
TX	Transmit
VCS	Virtual Carrier Sense

Furthermore, the abbreviations given in the following clauses also apply:

- clause 4 of [IEEE 802.15.4].
- clause 1.2 of [IETF RFC 4944].

5 Introduction to OFDM and the power line channel

Power line communication has been used for many decades, but a variety of new services and applications require greater reliability and higher data rates. However, the power line channel is very hostile. Channel characteristics and parameters vary with frequency, location, time and the



type of equipment connected to it. The lower frequency regions from 10 kHz to 200 kHz are especially susceptible to interference. Besides background noise, the power line channel is subject to impulsive noise and narrowband interference and group delays of up to several hundred microseconds.

OFDM is a modulation technique that efficiently utilizes the assigned bandwidth, allowing the use of advanced channel coding techniques. This combination enables a very robust communication in the presence of narrowband interference, impulsive noise and frequency selective attenuation. OFDM-based ITU-T G.9903 specifications address the following main objectives:

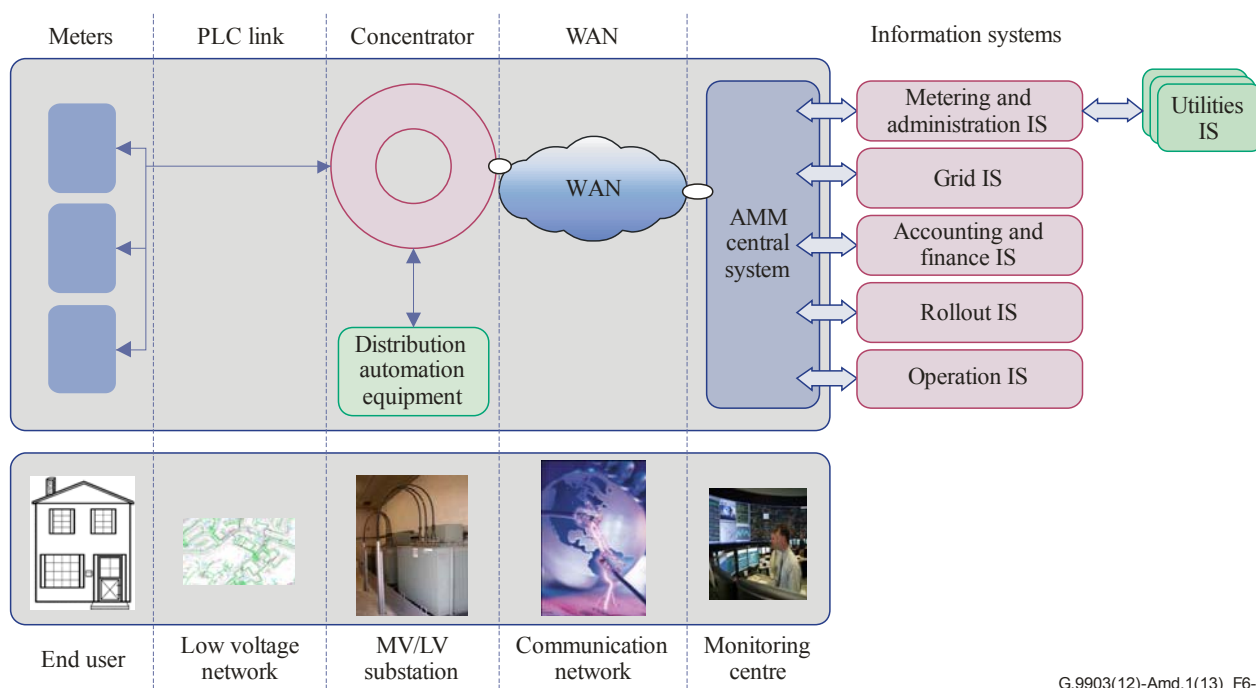
- 1) provide robust communication in extremely harsh power line channels;
- 2) provide a minimum of 20 kbit/s effective data rate in the normal mode of operation;
- 3) provide the ability of notching selected frequencies, allowing the cohabitation with S-FSK narrow-band communication;
- 4) provide a dynamic tone adoption capability to varying power line channel to ensure a robust communication.

6 General description

6.1 Overall infrastructure

The following diagram illustrates an example of an automated meter management (AMM) system.

The system provides a reliable two-way communication using an OFDM-based PLC link between the meters installed at the customer's premises and the concentrator, communicating in a master and slave configuration.



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Figure 6-1 – Network architecture

The AMM architecture consists of the five following main components:

- The meter which needs to integrate the capability of measuring power consumption, simple load control and customer remote information.

- The hub which acts as an intermediary between the AMM information system (IS) and the meters. Complementary equipment supplied by the electrical network that can be connected downstream of the hub.
- The PLC (LAN) technology which allows the use of a low-voltage electrical network to exchange data and commands between meters and hubs.
- A remote connection (WAN) allows connection between the hubs and the AMM central IS.
- The central system, which not only handles its own functional services but also supplies metering services to the existing or forthcoming enterprise services (deployment IS, network IS, management-finance IS, customer-supplier IS-Intervention management IS, etc.). The customer-supplier IS is the interface between the suppliers and AMM for handling their requirements.

6.2 Coexistence with other PLC networks

Two mechanisms are defined to allow coexistence between ITU-T G.9903 devices and other narrowband PLC technologies operating in the same frequency band:

- frequency division coexistence;
- preamble-based coexistence.

6.2.1 Frequency division coexistence mechanism

A first method consists in assigning non-overlapping bandplans to devices complying with this Recommendation within communication range. A second method is to exploit the tone masking feature (see clause 7.15 and description of macToneMask attribute in Table 9-15) to avoid any overlapping frequencies. Frequency division coexistence provides a means to ensure coexistence between devices complying with this Recommendation and both single (e.g., existing narrowband Frequency Shift Keying/Phase Shift Keying systems) and multiple carrier PLC systems.

6.2.2 Preamble-based coexistence mechanism (optional)

Devices complying with this Recommendation may support the preamble-based coexistence mechanism specified in clauses 10.2.2 and 10.3 to 10.5 of [IEEE 1901.2] to fairly share the medium with other types of narrowband PLC technologies supporting the same preamble-based coexistence mechanism. Support for this coexistence mechanism is optional in this Recommendation, with the exception given in Annex G.

If devices complying with this Recommendation support the preamble-based coexistence mechanism, then Tables 10-2 and 10-3 of [IEEE 1901.2] shall be revised as specified below.

The IDs (identifiers) listed in Table 10-2 of [IEEE 1901.2] shall be replaced by the identifiers listed in Table 6-1.

Table 6-1 – Attributes for the preamble-based coexistence mechanism

Attribute	Identifier
Beta	0x0117
aMacMaxCoexistenceBackoffs	0x0118
macAlpha	0x0119
K	0x011A
macNdcTime	0x011B

NOTE – The other attributes listed in Table 10-2 of [IEEE 1901.2] (aCEIFS, macLongPreambleDuration, macDCEIFS, macMinChannelIdleTime) do not require an identifier as their values depend exclusively on the values of other attributes which have their own identifier.

The IDs (identifiers) and default values listed in Table 10-3 of [IEEE 1901.2] shall be replaced by the ones listed in Table 6-2.

Table 6-2 – Coexistence control PIB attributes

Attribute	Identifier	Default value
macCoexPreambleDetectionEnabled	0x011C	FALSE
macCoexPreambleEnabled	0x011D	FALSE

7 Physical layer specification

This clause specifies the physical layer block using the orthogonal frequency division multiplexing (OFDM) system in the CENELEC and FCC bandplans.

7.1 Introduction

The power line channel is very hostile. Channel characteristics and parameters vary with frequency, location, time and the type of equipment connected to it. The lower frequency regions from 10 kHz to 200 kHz are especially susceptible to interference. Furthermore, the power line is a very frequency selective channel. Besides background noise, it is subject to impulsive noise often occurring at 50/60 Hz and narrowband interference and group delays of up to several hundred microseconds.

OFDM can efficiently utilize limited bandwidth channels allowing the use of advanced channel coding techniques. This combination facilitates a very robust communication over a power line channel.

Figure 7-1 shows the block diagram of an OFDM transmitter. The available bandwidth is divided into a number of sub-channels, which can be viewed as many independent Phase Shift Keying modulated subcarriers with different non-interfering (orthogonal) subcarrier frequencies. Convolutional and Reed-Solomon coding provide redundancy bits allowing the receiver to recover lost bits caused by background and impulsive noise. A time-frequency interleaving scheme is used to decrease the correlation of received noise at the input of the decoder, providing diversity.

The OFDM signal is generated by performing inverse fast Fourier transform (IFFT) on the complex-valued signal points produced by differentially encoded phase modulation that are allocated to individual subcarriers. An OFDM symbol is built by appending a cyclic prefix to the beginning of each block generated by IFFT. The length of a cyclic prefix is chosen so that the channel group delay does not cause excessive interference between successive OFDM symbols. Windowing reduces the out-of-band leakage of the transmit signals.

Channel estimation is used for link adaptation. Based on the quality of the received signal, the receiver (if requested by the transmitter) shall feed back the suggested modulation scheme to be used by the transmitting station in subsequent packets transmitted to the same receiver. Moreover, the system differentiates the subcarriers with insufficient SNR and does not transmit data on them.

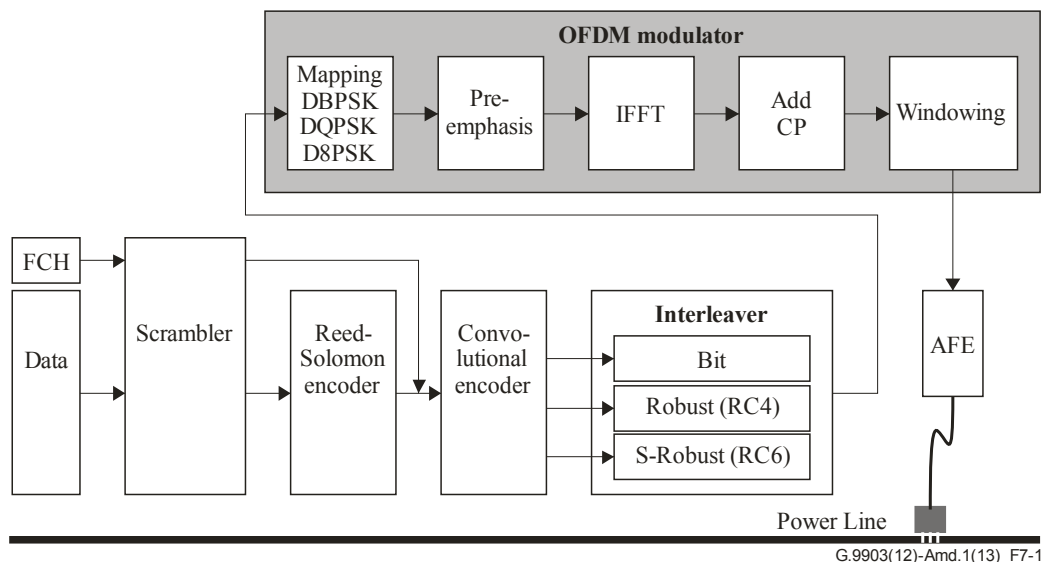


Figure 7-1 – Block diagram of an OFDM transceiver

7.2 System parameters

The differential modulations (DBPSK, DQPSK, and D8PSK) for each subcarrier make the receiver design significantly simpler compared to coherent modulations (BPSK, QPSK, 8-PSK and 16-QAM) since no tracking circuitry is required at the receiver for detecting the phase of each subcarrier. Instead, the phases of subcarriers in the adjacent symbol are taken as reference for detecting the phases of the subcarriers in the current symbol. However, coherent modulation, which offers greater robustness, is an option available to ITU-T G.9903 devices (see clause 7.16).

As specified in Annex B of [ITU-T G.9901], the maximum number of subcarriers that can be used is selected to be 128, resulting in an IFFT size of 256. This yields a frequency spacing between the OFDM subcarriers equal to 1.5625 kHz (F_s/N) for CENELEC bandplans and 4.6875 kHz (F_s/N) for the FCC bandplan, where F_s is the sampling frequency and N is the IFFT size. Note that imperfection such as sampling clock frequency variation can cause inter-carrier interference (ICI). In practice, the ICI caused by a typical sampling frequency variation of about 2% of the frequency spacing is negligible. In other words, considering ± 25 ppm sampling frequency in transmitter and receiver clocks, the drift of the subcarriers is approximately equal to 8 Hz that is approximately 0.5% of the selected frequency spacing. Considering these selections, the number of usable subcarriers is 36 for the CENELEC-A bandplan, 16 for the CENELEC-B bandplan and 72 for the FCC bandplan.

The system works in two different modes namely normal and robust modes.

In normal mode, the FEC is composed of a Reed-Solomon encoder and a convolutional encoder. The system also supports Reed-Solomon code with a parity of 8 and 16 bytes.

In robust mode, the FEC is composed of Reed-Solomon and convolutional encoders followed by a repetition code. The repetition code, repeats each bit four times making the system more robust to channel impairments.

A super robust mode is used for the FCH only (see clause 7.9.3.2).

7.3 Data rate, Reed-Solomon block size and maximum PSDU length

7.3.1 Data rate calculation and RS block size

The data rate is calculated based on the number of symbols per PHY frame (N_s), number of subcarrier per symbol (N_{CAR}) and the number of parity bits added by FEC blocks.

An example of how to calculate the data rate is given below using the following CENELEC-A bandplan parameters:

– Number of FFT points	$N = 256$
– Number of subcarriers	$N_{CAR} = 36$
– Number of overlapped samples	$N_O = 8$
– Number of cyclic prefix samples	$N_{CP} = 30$
– Number of FCH symbols	$N_{FCH} = 13$
– Sampling frequency	$F_s = 0.4 \text{ MHz}$
– Number of symbols in preamble	$N_{PRE} = 9.5$

Consider the system in the CENELEC-A band working in the robust mode. The total number of bits carried by the whole PHY frame is equal to:

$$\text{Total_No_Bits} = N_S \times N_{CAR} = 40 \times 36 = 1\,440 \text{ bits}$$

The number of bits required at the input of the robust encoder is given by:

$$\text{No_Bits_Robust} = 1440 \times \text{RobustRate} = 1440 \times 1/4 = 360 \text{ bits}$$

Considering the fact that the convolutional encoder has a rate equal to $1/2$ ($CC_{Rate} = 1/2$) and also consider adding $CC_{ZeroTail} = 6$ bits of zeros to terminate the states of the encoder to all zero states then the maximum number of symbols at the output of the Reed-Solomon encoder ($MAXRS_{bytes}$) shall be equal to:

$$MAXRS_{Bytes} = \text{floor}\left(\frac{\text{NoBitsRobust} \times CC_{Rate} - CC_{ZeroTail}}{8}\right) = \text{floor}\left(\frac{360 \times 0.5 - 6}{8}\right) = 21$$

Removing 8 bytes associated with the parity bits (in robust mode) we obtain:

$$\text{DataLength} = (21 - \text{ParityLength}) \times 8 = 104 \text{ bits}$$

These 104 bits are carried within the duration of a PHY frame. The duration of a PHY frame is calculated by the following formula:

$$T_{\text{Frame}} = \frac{(N_S + N_{FCH}) \times (N_{CP} + N - N_O) + (N_{PRE} \times N)}{F_s}$$

Where N_{PRE} , N , N_O and N_{CP} are the number of symbols in the preamble, FFT length, the number of samples overlapped at each side of one symbol and the number of samples in the cyclic prefix, respectively. N_{FCH} is the number of symbols in the FCH. The F_s is the sampling frequency.

Substituting the above numbers in the equation, T_{Frame} (PHY frame duration) for a 40-symbol frame is obtained as follows:

$$T_{\text{Frame}} = \frac{(40 + 13) \times (256 + 22) + (9.5 \times 256)}{400000} = 0.043 \text{ s}$$

Therefore the data rate is calculated as:

$$\text{Data rate} = 104/0.042 \sim 2.4 \text{ kbit/s}$$

7.3.1.1 CENELEC-A bandplan

Mandatory values for the OFDM control parameters for the CENELEC-A bandplan are given in Table B.1 of [ITU-T G.9901]. The frequency band used for the CENELEC-A bandplan is defined in Table B.2 of [ITU-T G.9901].

The number of symbols in each PHY (physical layer) frame is selected based on two parameters, the required data rate and the acceptable robustness. The number of symbols, Reed-Solomon block sizes and data rate associated with 36 tones is tabulated in Tables 7-1 and 7-2.

Table 7-3 shows the rate including the data transmitted in the FCH. To calculate the data rate, it is assumed that the packets are continuously transmitted with no inter-frame time gap.

Table 7-1 – RS block size for various modulations

CENELEC-A Number of symbols	Reed-Solomon blocks (bytes) D8PSK (Out/In) (Note 1)	Reed-Solomon blocks (bytes) DQPSK (Out/In) (Note 1)	Reed-Solomon blocks (bytes) DBPSK (Out/In) (Note 1)	Reed-Solomon blocks (bytes) Robust (Out/In) (Note 2)
12	(80/64)	(53/37)	(26/10)	N/A
20	(134/118)	(89/73)	(44/28)	N/A
32	(215/199)	(143/127)	(71/55)	N/A
40	N/A	(179/163)	(89/73)	(21/13)
52	N/A	(233/217)	(116/100)	(28/20)
56	N/A	(251/235)	(125/109)	(30/22)
112	N/A	N/A	(251/235)	(62/54)
252	N/A	N/A	N/A	(141/133)
NOTE 1 – Reed-Solomon with 16 bytes parity. NOTE 2 – Reed-Solomon with 8 bytes parity.				

Table 7-2 – Data rate for various modulations (excluding FCH)

CENELEC-A	Data rate per modulation type, bit/s			
Number of symbols	D8PSK, P16 (Note 1)	DQPSK, P16 (Note 1)	DBPSK, P16 (Note 1)	Robust, P8 (Note 2)
12	21 829	12 619	3 410	N/A
20	32 534	20 127	7 720	N/A
32	42 619	27 198	11 778	N/A
40	N/A	30 385	13 608	2 423
52	N/A	33 869	15 608	3 121
56	N/A	34 792	16 137	3 257
112	N/A	N/A	20 224	4 647
252	N/A	N/A	N/A	5 592
NOTE 1 – Reed-Solomon with a 16 byte parity. NOTE 2 – Reed-Solomon with an 8 byte parity. NOTE – N/A means not applicable and the reason for this is that the corresponding number of symbols specified results in an RS encoder block length that exceeds the maximum allowable limit of 255.				

Table 7-3 – Data rate for various modulations (including FCH)

CENELEC-A	Data rate per modulation type, bit/s			
Number of symbols	D8PSK, P16 (Note 1)	DQPSK, P16 (Note 1)	DBPSK, P16 (Note 1)	Robust, P8 (Note 2)
12	23 235	14 026	4 817	N/A
20	33 672	21 264	8 857	N/A
32	43 501	28 081	12 662	N/A
40	N/A	31 154	14 377	3 192
52	N/A	34 513	16 252	3 765
56	N/A	35 402	16 748	3 867
112	N/A	N/A	20 579	5 002
252	N/A	N/A	N/A	5 765

NOTE 1 – Reed-Solomon with a 16 byte parity.
NOTE 2 – Reed-Solomon with an 8 byte parity.
NOTE – N/A means not applicable and the reason for this is that the corresponding number of symbols specified results in an RS encoder block length that exceeds the maximum allowable limit of 255.

7.3.1.2 CENELEC-B bandplan

Mandatory values for the OFDM control parameters for the CENELEC-B bandplan are given in Table B.1 of [ITU-T G.9901].

The frequency band used for the CENELEC-B bandplan is defined in Table B.3 of [ITU-T G.9901]. The number of symbols, Reed-Solomon block sizes, and data rate associated with 16 tones is tabulated in Tables 7-4 and 7-5.

Table 7-6 shows the rate including the data transmitted in the FCH. To calculate the data rate, it is assumed that the packets are continuously transmitted with no inter-frame time gap.

Table 7-4 – RS block size for various modulations

CENELEC B	Reed-Solomon blocks (bytes)	Reed-Solomon blocks (bytes)	Reed-Solomon blocks (bytes)	Reed-Solomon blocks (bytes)
Number of symbols	D8PSK (Out/In) (Note 1)	DQPSK (Out/In) (Note 1)	DBPSK (Out/In) (Note 1)	Robust (Out/In) (Note 2)
12	35/19	23/7	N/A	N/A
20	59/43	39/23	19/3	N/A
32	95/79	63/47	31/15	N/A
40	119/103	79/63	39/23	9/1
52	155/139	103/87	51/35	12/4
56	167/151	111/95	55/39	13/5
112	N/A	223/207	111/95	27/19
252	N/A	N/A	251/235	62/54

NOTE 1 – Reed-Solomon with a 16 byte parity.
NOTE 2 – Reed-Solomon with an 8 byte parity.

Table 7-5 – Data rate for various modulations (excluding FCH)

CENELEC B	Data rate per modulation type, bps			
Number of symbols	D8PSK, P16 (Note 1)	DQPSK, P16 (Note 1)	DBPSK, P16 (Note 1)	Robust, P8 (Note 2)
12	4309	1587	N/A	N/A
20	8425	4506	587	N/A
32	12853	7646	2440	N/A
40	15055	9208	3361	146
52	17631	11035	4439	507
56	18344	11541	4738	607
112	N/A	15806	7253	1450
252	N/A	N/A	9303	2137
NOTE 1 – Reed-Solomon with a 16 byte parity. NOTE 2 – Reed-Solomon with an 8 byte parity. NOTE – N/A means not applicable and the reason for this is that the corresponding number of symbols specified results in an RS encoder block length that exceeds the maximum allowable limit of 255.				

Table 7-6 – Data rate for various modulations (including FCH)

CENELEC B	Data rate per modulation type, bps			
Number of symbols	D8PSK, P16 (Note 1)	DQPSK, P16 (Note 1)	DBPSK, P16 (Note 1)	Robust, P8 (Note 2)
12	5245	2523	N/A	N/A
20	9233	5314	1396	N/A
32	13524	8318	3111	N/A
40	15658	9811	3964	749
52	18154	11558	4962	1030
56	18845	12042	5239	1108
112	N/A	16121	7568	1765
252	N/A	N/A	9467	2301
NOTE 1 – Reed-Solomon with a 16 byte parity. NOTE 2 – Reed-Solomon with an 8 byte parity. NOTE – N/A means not applicable and the reason for this is that the corresponding number of symbols specified results in an RS encoder block length that exceeds the maximum allowable limit of 255.				

7.3.1.3 FCC bandplan

Mandatory values for the OFDM control parameters for the FCC bandplan are given in Table B.4 of [ITU-T G.9901]. The frequency bands used for the FCC bandplan are defined in Table B.5 of [ITU-T G.9901].

As specified in Table B.5 of [ITU-T G.9901], the subcarrier spacing is 4.6875 kHz and the number of usable subcarriers is 72. DBPSK, DQPSK and D8PSK modulation schemes are supported, resulting in an up to 300 kbit/s data rate in the normal mode of operation.

The number of symbols in each PHY frame is selected based on two parameters, the required data rate and the acceptable robustness. The number of symbols, Reed-Solomon block sizes and data rate associated with 72 tones are tabulated for several values as examples in Tables 7-7 and 7-8.

Table 7-7 – RS block size for various modulations

FCC Number of symbols	Reed-Solomon blocks (bytes) D8PSK (Out/In) (Note 1)	Reed-Solomon blocks (bytes) DQPSK (Out/In) (Note 1)	Reed-Solomon blocks (bytes) DBPSK (Out/In) (Note 1)	Reed-Solomon blocks (bytes) Robust (Out/In) (Note 2)
12	(161/145)	(107/91)	(53/37)	(12/4)
20	N/A	(179/163)	(89/73)	(21/13)
28	N/A	(251/235)	(125/109)	(30/22)
NOTE 1 – Reed-Solomon with a 16 byte parity. NOTE 2 – Reed-Solomon with an 8 byte parity.				

Table 7-8 – Data rate for various modulations (excluding FCH)

FCC Number of symbols	Data rate (bit/s) D8PSK (Note 1)	Data rate (bit/s) DQPSK (Note 1)	Data rate (bit/s) DBPSK (Note 1)	Data rate (bit/s) Robust (Note 2)
12	152,899	95,957	39,015	4,217
20	N/A	138,135	61,864	11,016
28	N/A	166,469	77,213	15,584
NOTE 1 – Reed-Solomon with a 16 byte parity. NOTE 2 – Reed-Solomon with an 8 byte parity.				

7.3.2 Maximum PSDU length calculation

The maximum PSDU length in bytes for an ITU-T G.9903 PHY packet (Max_PSDUBytes) is a function of the PHY configuration comprising of the number of available subcarriers per symbol (NCAR), modulation type (MOD) and other dependent parameters. Given a PHY configuration, Max_PSDUBytes can be calculated using the following set of equations:

$$N_S = FL_{Band} \times \min \left[FL_{max}, \text{ceil} \left(\frac{(MaxRSBlockSize \times 8 + CC_{ZeroTail}) \times Rep_Code}{FL_{Band} \times N_{car} \times mod_size \times CC_{Rate}} \right) \right]$$

where:

- MaxRSBlockSize = 255 bytes,
- N_S is the number of symbols in the PHY packet,
- $CC_{Rate} = 0.5$,
- $CC_{ZeroTail} = 6$,
- $FL_{Band} = 4$ for CENELEC bandplans and $FL_{Band} = 1$ for FCC bandplan,
- FL_{max} is the maximum possible frame length ($FL_{max} = 63$ for CENELEC bandplans, $FL_{max} = 511$ for FCC bandplan),
- Rep_Code denotes the repetition coding (Rep_Code = 4 for Robust mode; Rep_Code = 1 for all other modes),

- mod_{size} is the number of bits per constellation symbol, i.e.:
 - 1 for Robust, DBPSK or BPSK
 - 2 for DQPSK or QPSK
 - 3 for D8PSK or 8-PSK
 - 4 for 16-QAM

Adjust the number of symbols in the PHY packet if Reed-Solomon block size per calculated NS is more than MaxRSBlockSize, i.e.,

$$if \left[\left\lfloor \left((N_S \times N_{car} \times mod_{size}) - CC_{ZeroTail} \times \frac{Rep_Code}{CC_{Rate}} \right) \times \frac{CC_{Rate}}{8 \times Rep_Code} \right\rfloor > MaxRSBlockSize \right]$$

then { NS = NS - 4; }

Max_PSDU_{Bytes}

$$= \max \left[0, \left\lfloor \left((N_S \times N_{car} \times mod_{size}) - CC_{ZeroTail} \times \frac{Rep_Code}{CC_{Rate}} \right) \times \frac{CC_{Rate}}{8 \times Rep_Code} - ParityLength \right\rfloor \right]$$

The PHY interleaver bit padding is calculated using the following equation:

$$Interleaver_padding = \frac{N_S \times N_{car} \times Bits_per_subCarrier}{Rep_Code} - \frac{(RSBlockSize \times 8 + CC_{ZeroTail})}{CC_{Rate}}$$

7.4 Frame structure

The PHY supports two types of frames. A typical data frame for the OFDM PHY is shown in Figure 7-2. Each frame starts with a preamble which is used for synchronization and detection in addition to AGC adaptation. SYNCP simply refers to symbols that are multiplied by +1 in the sign function above, and SYNCM refers to symbols multiplied by -1. The preamble consists of eight SYNCP symbols followed by one and a half SYNCM symbols with no cyclic prefix between adjacent symbols. The preamble is followed by 13 data symbols allocated to the frame control header (FCH). The FCH has the important control information required to demodulate the data frame. Data symbols are transmitted next. The first FCH symbol uses the phase from the last preamble SYNCP symbol and the first data symbol uses the phase from the last FCH symbol. In the figures, "GI" stands for guard interval, which is the interval containing the cyclic prefix.

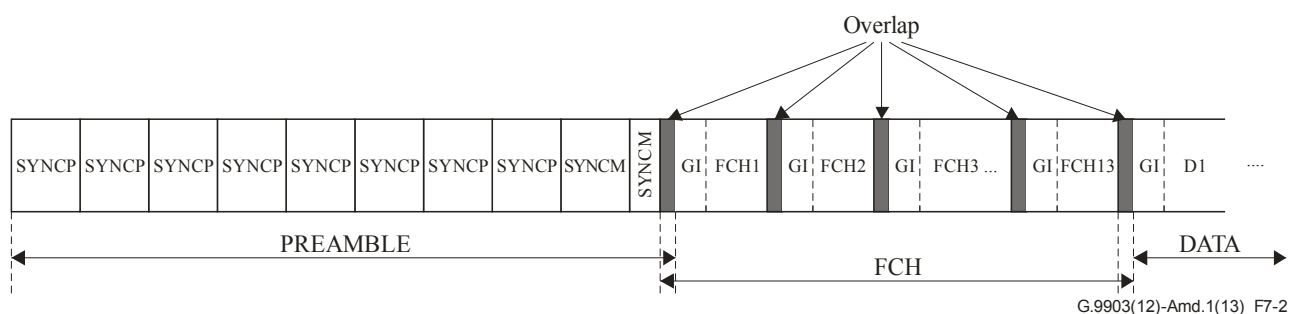


Figure 7-2 – Typical data frame structure

The PHY also supports an ACK/NACK frame which only consists of the preamble and the FCH. The frame structure of the ACK frame is shown in Figure 7-3. The bit fields in the FCH, explained in clause 7.6, will perform the ACK/NACK signalling.

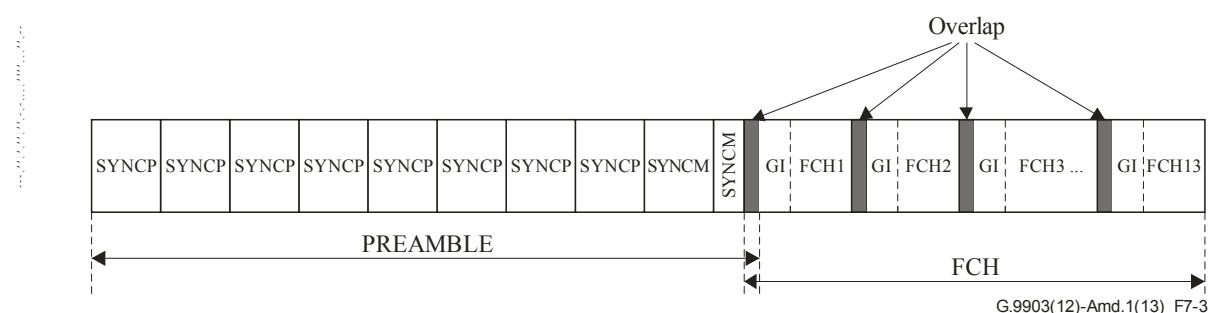


Figure 7-3 – ACK/NACK frame structure

7.5 Preamble

The preamble is composed of 8 identical SYNCp symbols and 1½ identical SYNCm symbols. Each of the SYNCp and SYNCm symbols is 256 samples and is pre-stored in the transmitter and transmitted right before the data symbols. The SYNCp symbols are used for AGC adaptation, symbol synchronization, channel estimation and initial phase reference estimation. The SYNCm symbols are identical to the SYNCp symbols except that all the subcarriers are π phase shifted. At the receiver, the phase distance between symbol SYNCp and symbol SYNCm waveforms is used for frame synchronization. A SYNCp symbol is generated by creating the desired number of equally spaced subcarriers with the phase of each subcarrier given by ϕ_c . One way to generate this signal is to start in the frequency domain and create complex subcarriers with the initial phases ϕ_c , as shown in Tables 7-9, 7-10 and 7-11. Figure 7-15 shows how the subcarriers are mapped to the IFFT input.

All preamble symbols (SYNCp and SYNCm) shall have the same gain factor compared to data symbols. The gain is defined to be 3 dB.

Table 7-9 – Preamble phase vector for CENELEC-A bandplan

c	ϕ_c	c	ϕ_c	c	ϕ_c
23	$2(\pi/8)$	35	$1(\pi/8)$	47	$13(\pi/8)$
24	$1(\pi/8)$	36	$11(\pi/8)$	48	$2(\pi/8)$
25	$0(\pi/8)$	37	$5(\pi/8)$	49	$6(\pi/8)$
26	$15(\pi/8)$	38	$14(\pi/8)$	50	$10(\pi/8)$
27	$14(\pi/8)$	39	$7(\pi/8)$	51	$13(\pi/8)$

Table 7-9 – Preamble phase vector for CENELEC-A bandplan

c	ϕ_c	c	ϕ_c	c	ϕ_c
28	$12(\pi/8)$	40	$15(\pi/8)$	52	0
29	$10(\pi/8)$	41	$7(\pi/8)$	53	$2(\pi/8)$
30	$7(\pi/8)$	42	$15(\pi/8)$	54	$3(\pi/8)$
31	$3(\pi/8)$	43	$6(\pi/8)$	55	$5(\pi/8)$
32	$15(\pi/8)$	44	$13(\pi/8)$	56	$6(\pi/8)$
33	$11(\pi/8)$	45	$2(\pi/8)$	57	$7(\pi/8)$
34	$6(\pi/8)$	46	$8(\pi/8)$	58	$7(\pi/8)$

Table 7-10 – Preamble phase vector for CENELEC B bandplan

C	ϕ_c	c	ϕ_c	c	ϕ_c
63	$2(\pi/8)$	69	$15(\pi/8)$	75	$5(\pi/8)$
64	$1(\pi/8)$	70	$8(\pi/8)$	76	$7(\pi/8)$
65	$15(\pi/8)$	71	0	77	$9(\pi/8)$
66	$13(\pi/8)$	72	$7(\pi/8)$	78	$10(\pi/8)$
67	$10(\pi/8)$	73	$13(\pi/8)$		
68	$5(\pi/8)$	74	$2(\pi/8)$		

Table 7-11 – Preamble phase vector for FCC bandplan

C	ϕ_c	C	ϕ_c	C	ϕ_c	c	ϕ_c
				52	$10(\pi/8)$	77	$8(\pi/8)$
				53	$5(\pi/8)$	78	$14(\pi/8)$
				54	0	79	$3(\pi/8)$
				55	$12(\pi/8)$	80	$9(\pi/8)$
				56	$6(\pi/8)$	81	$15(\pi/8)$
				57	$1(\pi/8)$	82	$3(\pi/8)$
		33	$2(\pi/8)$	58	$12(\pi/8)$	83	$8(\pi/8)$
		34	$(\pi/8)$	59	$6(\pi/8)$	84	$13(\pi/8)$
		35	$(\pi/8)$	60	0	85	$\pi/8$
		36	0	61	$10(\pi/8)$	86	$5(\pi/8)$
		37	0	62	$3(\pi/8)$	87	$9(\pi/8)$
		38	$15(\pi/8)$	63	$13(\pi/8)$	88	$13(\pi/8)$
		39	$14(\pi/8)$	64	$6(\pi/8)$	89	$\pi/8$
		40	$12(\pi/8)$	65	$15(\pi/8)$	90	$4(\pi/8)$
		41	$11(\pi/8)$	66	$7(\pi/8)$	91	$7(\pi/8)$



Table 7-11 – Preamble phase vector for FCC bandplan

C	ϕ_c	C	ϕ_c	C	ϕ_c	c	ϕ_c
		42	$9(\pi/8)$	67	0	92	$10(\pi/8)$
		43	$7(\pi/8)$	68	$8(\pi/8)$	93	$13(\pi/8)$
		44	$4(\pi/8)$	69	0	94	$15(\pi/8)$
		45	$\pi/8$	70	$8(\pi/8)$	95	$\pi/8$
		46	$15(\pi/8)$	71	$15(\pi/8)$	96	$3(\pi/8)$
		47	$12(\pi/8)$	72	$6(\pi/8)$	97	$4(\pi/8)$
		48	$9(\pi/8)$	73	$14(\pi/8)$	98	$5(\pi/8)$
		49	$5(\pi/8)$	74	$4(\pi/8)$	99	$7(\pi/8)$
		50	$(\pi/8)$	75	$11(\pi/8)$	100	$7(\pi/8)$
		51	$14(\pi/8)$	76	$2(\pi/8)$	101	$8(\pi/8)$
						102	$9(\pi/8)$
						103	$10(\pi/8)$
						104	$10(\pi/8)$

7.6 Frame control header

The FCH is a data structure transmitted at the beginning of each PHY data frame and contains information regarding the current frame. It has information about the type of frame, the tone map index of the frame, the length of the frame, etc. The FCH data is protected with CRC5 for CENELEC bandplans and CRC8 for FCC bandplan. Clauses 7.6.1 and 7.6.2 define the structure of the FCH and the calculation of the associated CRC. The FCH shall use the default tone map (all unmasked subcarriers).

7.6.1 CENELEC bandplans

The thirteen data symbols immediately after the preamble are used for the frame control header (FCH). They are transmitted in super robust mode (see clause 7.9.3.2) regardless of the modulation type and scheme of the payload. Its structure is given in Table 7-12 for the data frame and Table 7-14 for the ACK/NACK frame.

7.6.1.1 FCH for a data frame

Bandplans are divided into sub-bands (groups of tones) to selectively adapt to the quality of the media (see clause 7.15). For the CENELEC bandplans, each sub-band contains 6 tones. Each bit of the tone map field is associated with one sub-band (a group of 6 tones), indicating if it carries data. The 6-bit tone map field covers all the CENELEC bandplans. Each bit set to one indicates that the associated group of tones carries data in the payload of the PHY frame.

The tone map splitting for CENELEC bandplans is given in Table 7-13.

Table 7-12 – FCH bit fields for data frames for CENELEC bandplans

Field	Byte	Bit number	Bits	Description
PDC	0	7-0	8	Phase detection counter (see clause 8.10)
MOD	1	7-6	2	Modulation type: 0: Robust Mode (see clause 7.9.3) 1: DBPSK or BPSK 2: DQPSK or QPSK 3: D8PSK or 8-PSK
FL	1	5-0	6	PHY frame length in PHY symbols FL gives the number of symbols in the frame according to the formula $FL = \text{Number of symbols}/4$
Reserved by ITU-T	2	7-6	2	Shall be set to zero
TM[5:0]	2	5-0	6	TM[5:0] – Tone map In CENELEC-B bandplan, TM[5:3] are reserved by ITU-T and shall be set to zero
Payload modulation scheme	3	7	1	0: Differential 1: Coherent Note – The coherent modulation scheme specified in clause 7.16 is optional
DT	3	6-4	3	Delimiter type: 0: Acknowledgment is not requested 1: Acknowledgment is requested 2-7: Reserved by ITU-T
FCCS	3	3-0	4	Frame control check sequence (CRC5) (see clause 7.6.1.3)
	4	7	1	
ConvZeros	4	6-1	6	6 zeros for convolutional encoder

Table 7-13 – Tone map field mapping for CENELEC bandplans

Tone map field	CENELEC-A bandplan	CENELEC-B bandplan
TM[0]	35.9375 to 43.75 kHz	98.4375 to 106.25 kHz
TM[1]	45.3125 to 53.125 kHz	107.8125 to 115.625 kHz
TM[2]	54.6875 to 62.5 kHz	117.1875 to 121.875 kHz
TM[3]	64.0625 to 71.875 kHz	Unused in CENELEC-B band
TM[4]	73.4375 to 81.25 kHz	Unused in CENELEC-B band
TM[5]	82.8125 to 90.625 kHz	Unused in CENELEC-B band

7.6.1.2 FCH for ACK/NACK frame

Table 7-14 shows the structure of a positive acknowledgment (ACK) or a negative acknowledgment (NACK). A node shall send an ACK or a NACK after receiving a data frame with an FCH requiring an answer (with the delimiter type field set to 1).

Table 7-14 – FCH bit fields for ACK/NACK frames for CENELEC bandplans

Field	Byte	Bit number	Bits	Description
FCS-1	0	7-0	8	MAC FCS[7:0]
SSCA	1	7	1	Subsequent segment collision avoidance (see clause 9.3.2): 0: No further segment is expected 1: Further segments are expected
Reserved by ITU-T	1	6-0	7	Shall be set to zero
FCS-2	2	7-0	8	MAC FCS[15:8]
Reserved by ITU-T	3	7	1	Shall be set to zero
DT	3	6-4	3	Delimiter type: 0-1: Reserved by ITU-T 2: Positive acknowledgement (ACK) 3: Negative acknowledgement (NACK) 4-7: Reserved by ITU-T
FCCS	3	3-0	4	Frame control check sequence (CRC5) (see clause 7.6.1.3)
	4	7	1	
ConvZeros	4	6-1	6	6 zeros for convolutional encoder

7.6.1.3 CRC5

A 5-bit cyclic redundancy check (CRC) is used for error detection in the FCH. The CRC5 is computed using an initial value of 0b11111. The CRC5 is calculated using the following standard generator polynomial of degree 5:

$$G(x) = x^5 + x^2 + 1$$

Data bits are shifted to the CRC5 register starting with the most significant bit of the first byte of the FCH. The CRC5 is the remainder of the division of the FCH polynomial by the generator polynomial. The one's complement of the remainder is used as the FCCS for the FCH, where the FCCS field is packed as follows: bit 3 to bit 0 of Byte 3 are packed with FCCS bit 3 to bit 0, respectively, and bit 7 of Byte 4 is packed with FCCS bit 4 (MSB).

7.6.2 FCC bandplan

The twelve data symbols immediately after the preamble constitute the frame control header (FCH). They are transmitted in super robust mode (see clause 7.9.3.2) using BPSK with coherent modulation regardless of the modulation type and scheme of the payload. However, no pilot tone shall be inserted in the frame control header. If the payload modulation scheme is differential, the S1 and S2 symbols shall not be included after the FCH. Its structure is given in Table 7-15 for the data frame and Table 7-16 for the ACK/NACK frame.

7.6.2.1 FCH for a data frame

The bandplan is divided into sub-bands (groups of tones) to selectively adapt to the quality of the media (see clause 7.15). For the FCC bandplan, each sub-band contains 3 tones. Each bit of the tone map field is associated with one sub-band, indicating if it carries data. The tone map field is a 24 bit field which covers the FCC bandplan. Each bit set to one indicates that the associated group of tones carries data in the payload of the PHY frame.

Table 7-15 – FCH bit fields for data frames for the FCC bandplan

Field	Byte	Bit Number	Bits	Description
PDC	0	7-0	8	Phase detection counter (see clause 8.10)
MOD	1	7-5	3	Modulation type 0: Robust mode (differential or coherent) 1: DBPSK or BPSK 2: DQPSK or QPSK 3: D8PSK or 8-PSK 4: 16-QAM 5-7: Reserved by ITU-T
Payload modulation scheme	1	4	1	Payload modulation scheme: 0: Differential 1: Coherent NOTE – The coherent modulation scheme, specified in clause 7.16, is optional.
DT	1	3-1	3	Delimiter type: 0: Start of frame with no response expected 1: Start of frame with response expected 2-7: Reserved by ITU-T
FL	2	7-0	8	PHY frame length in PHY symbols. FL represents the number of symbols in the frame
		0	1	
TM[7:0]	3	7-0	8	TM[7:0]: Tone map
TM[15:8]	4	7-0	8	TM[15:8]: Tone map
TM[23:16]	5	7-0	8	TM[23:16]: Tone map
Reserved by ITU-T	6	7-5	3	Shall be set to zero
Two RS Blocks	6	4	1	0: Transmitter is transmitting two RS blocks. 1: Transmitter is transmitting one RS block.
Reserved by ITU-T	6	3-0	4	Shall be set to zero
Reserved by ITU-T	7	7-6	2	Shall be set to zero
FCCS	7	5-0	6	Frame control check sequence (CRC8)
	8	7-6	2	
ConvZeros	8	5-0	6	Zeros for convolutional encoder

7.6.2.2 FCH for ACK/NACK frame

Table 7-16 shows the structure of a positive acknowledgment (ACK) or a negative acknowledgment (NACK) that a node shall send after receiving a data frame with an FCH requiring an answer (with the delimiter type field set to 1).

Table 7-16 – FCH bit fields for ACK/NACK frames for FCC bandplan

Field	Byte	Bit Number	Bits	Description
FCS-1	0	7-0	8	MAC FCS[7:0]
SSCA	1	7	1	Subsequent segment collision avoidance (see clause 9.3.2): 0: No further segment is expected 1: Further segments are expected
Reserved by ITU-T	1	6 – 4	3	Shall be set to zero
DT	1	3 - 1	3	Delimiter type: 0-1 : Reserved by ITU-T 2: Positive acknowledgement (ACK) 3: Negative acknowledgement (NACK) 4-7: Reserved by ITU-T
Reserved by ITU-T	1	0	1	Shall be set to zero
Reserved by ITU-T	2	7-0	8	Shall be set to zero
FCS-2	3	7-0	8	MAC FCS[15:8]
Reserved by ITU-T	4	7-0	8	Shall be set to zero
Reserved by ITU-T	5	7-0	8	Shall be set to zero
Reserved by ITU-T	6	7-0	8	Shall be set to zero
Reserved by ITU-T	7	7-6	2	Shall be set to zero
FCCS	7	5-0	6	Frame control check sequence (CRC8) (see clause 7.6.2.3)
	8	7-6	2	
ConvZeros	8	5-0	6	Zeros for convolutional encoder

7.6.2.3 CRC8

An 8-bit cyclic redundancy check (CRC) is used for error detection in the FCH. The CRC8 is computed as a function of the 58-bit sequence using an initial value of 0xFF. The CRC8 is calculated using the following eighth degree generator polynomial:

$$G(x) = x^8 + x^2 + x + 1$$

Data bits are shifted to the CRC8 register starting with the most significant bit of the first byte of the FCH. The CRC8 is the remainder of the division of the FCH polynomial by the generator polynomial. The one's complement of the remainder is used as the FCCS for the FCH, where the FCCS field is packed as follows: bit 5 to bit 0 of Byte 7 are packed with FCCS bit 7 to bit 2, respectively, and bit 7 to bit 6 of Byte 8 are packed with FCCS bit 1 to bit 0 (LSB).

7.7 Payload of PHY frame

The data to transport in a physical frame (PSDU) is provided by the upper layer as a byte stream and is read most significant bit first into the scrambler. The upper layer shall be responsible for padding the data to accommodate the requirement of the PHY layer (see clause I.1).

7.8 Scrambler

The data scrambler block helps give the data a random distribution. The data stream is 'XOR-ed' with a repeating PN sequence using the following generator polynomial:

$$S(x) = x^7 \oplus x^4 \oplus 1$$

This is illustrated in Figure 7-4. The bits in the scrambler are initialized to all-ones at the start of processing the FCH and at the start of processing the PHY payload.

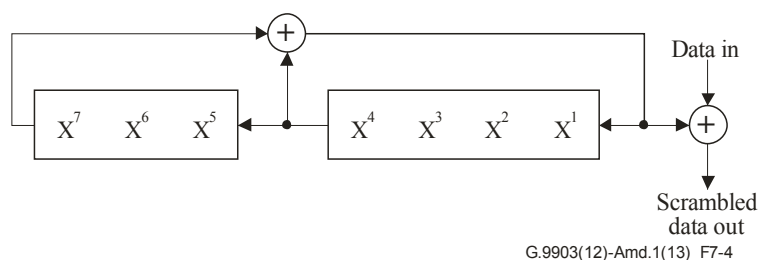


Figure 7-4 – Data scrambler

7.9 FEC coding

The FEC encoder is composed of a Reed-Solomon encoder followed by a convolutional encoder. In robust mode, an encoder, namely, repetition code by 4, is used after the convolutional encoder in order to repeat the bits at the output of convolutional encoder four times. In super robust mode, an encoder, namely, repetition code by 6, is used after the convolutional encoder in order to repeat the bits at the output of the convolutional encoder six times.

7.9.1 Reed-Solomon encoder

For the data portion of a frame, data from the scrambler is encoded by shortened systematic codes using Galois field $GF(2^8)$. Only one RS block is used by a frame. Depending on the mode used the following parameters are applied:

- Normal mode: RS(N = 255, K = 239, T = 8)
- Robust mode: RS(N = 255, K = 247, T = 4) The RS symbol word length (i.e., the size of the data words used in the Reed-Solomon block) is fixed at 8 bits. The value of T (number of correctable symbol errors) can be either 4 or 8 for different configurations. For the robust mode, the code with T=4 is used. The number of parity words in an RS-block is 2T bytes.

Code generator polynomial $g(x) = \prod_{i=1}^{2T} (x - \alpha^i)$

Field generator polynomial: $p(x) = x^8 + x^4 + x^3 + x^2 + 1$ (435 octal)

The representation of α^0 is "00000001", where the left most bit of this RS symbol is the MSB and is the first in time from the scrambler and is the first in time out of the RS encoder.

The arithmetic is performed in the Galois field $GF(2^8)$, where α^1 is a primitive element that satisfies the primitive binary polynomial $x^8 + x^4 + x^3 + x^2 + 1$. A data byte ($d^7, d^6, \dots, d^1, d^0$) is identified with the Galois field element $d^7\alpha^7 + d^6\alpha^6 + \dots + d^1\alpha + d^0$.

The first bit in time from the data scrambler becomes the most significant bit of the symbol at the input of the RS encoder. Each RS encoder input block is formed by one or more fill symbols ("00000000") followed by the message symbols. Output of the RS encoder (with fill symbols discarded) proceeds in time from the first message symbol to the last message symbol followed by parity symbols, with each symbol shifted out most significant bit first.

ITU-TG.9903 devices have the option to split a packet of any size into two RS blocks. The "Two RS Blocks" bit in its FCH shall be set to specify whether one or two RS blocks are being transmitted.

7.9.2 Convolutional encoder

The bit stream at the output of the Reed-Solomon block is encoded with a standard rate $=1/2$, $K=7$ convolutional encoder. The tap connections are defined as $x = 0b1111001$ and $y = 0b1011011$, as shown in Figure 7-5.

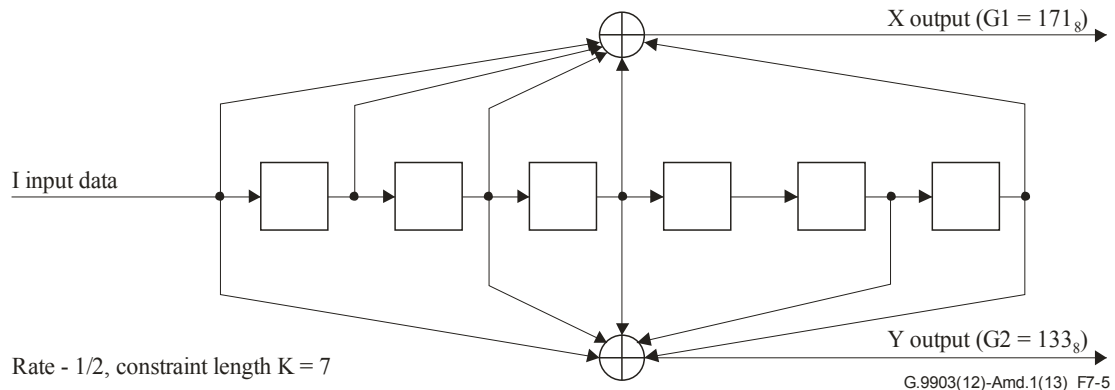


Figure 7-5 – Convolutional encoder

When the last bit of data to the convolutional encoder has been received, the convolutional encoder inserts six tail bits which are required to return the convolutional encoder to the "zero state". This improves the error probability of the convolutional decoder, which relies on future bits when decoding. The tail bits are defined as six zeros.

For CENELEC bandplans, zero bit padding is used to fit the encoded bits into a number of OFDM symbols that is a multiple of 4. The location of the bit padding shall be at the end of the convolutional encoder output and, in case of the robust mode, the bit padding is done before the repetition block.

7.9.2.1 Encoding 2 Reed-Solomon blocks

If the transmitter decides to divide the PSDU it shall be divided into two equal-size RS blocks, neither of which shall exceed the maximum size of 255 octets (including the parity octets). The bit padding is done for each RS block separately.

The PHY shall split the PSDU into two RS blocks after the scrambler, and then it shall pass each block to the RS encoder separately. The resulting two consecutive RS blocks shall then be passed to the convolutional encoder and each block shall be encoded separately. The output of the convolutional encoder has two equal-size segments and each segment shall be independently repetition encoded (if needed), zero bit padded (if needed), and interleaved. In other words, each RS block in the two RS blocks case shall be processed in the same way as in the single RS block case. All interleaver output is then treated as a whole. There shall be no re-initialization of the PN sequence for mapping or pilot tone computation between the two RS blocks.

7.9.3 Robust and super robust modes

Robust and super robust modes provide extensive time and frequency diversity to improve the ability of the system to operate under adverse conditions.

7.9.3.1 Repetition coding by 4

In robust mode, every bit at the output of the convolutional encoder is repeated four times and then passed as input to the interleaver as described in clause 7.10. This encoder (RC4) is only activated in robust mode. The underlying modulation type may be either DBPSK or BPSK according to the modulation scheme used for the payload.

7.9.3.2 Repetition coding by 6

In the super robust mode, every bit at the output of the convolutional encoder is repeated six times and then passed as input to the interleaver as described in clause 7.10. Only the FCH uses the super robust mode but without Reed-Solomon encoding. The underlying modulation type shall always be DBPSK.

7.10 Interleaver

The interleaver is designed as such so that it can provide protection against two different sources of error:

- A burst error that corrupts a few consecutive OFDM symbols.
- A frequency deep fade that corrupts a few adjacent frequencies for a large number of OFDM symbols.

To fight both problems at the same time, interleaving is done in two steps. In the first step, each column is circularly shifted a different number of times. Therefore, a corrupted OFDM symbol is spread over different symbols. In the second step, each row is circularly shifted a different number of times, which prevents a deep frequency fade from disrupting the whole column.

The elementary interleaver is used for CENELEC and FCC bandplans when `macCENELECLegacyMode` or `macFCCLegacyMode` is set to 0. Otherwise, the full block interleaver is processed for all bandplans.

7.10.1 Elementary interleaver

We define m as the number of used data carriers in each OFDM symbol, n as the number of OFDM symbols used by the frame and `total_number_of_bits` as the total number of coded bits without zero padding bits in the frame.

$$n = \text{ceil} \left(\frac{\text{Total_number_of_bits}}{FL_{\text{Band}} * m * \text{mod_size}} \right) * FL_{\text{Band}}$$

with:

- $\text{mod_size}=1, 2, 3, 4$ is the modulation size, i.e., the number of bits per constellation symbol and
- $FL_{\text{Band}} = 4$ for CENELEC bandplans and $FL_{\text{Band}} = 1$ for FCC bandplan.

From m and n the circular shift parameters m_i , m_j , n_i and n_j are derived.

To get a proper parameter set, m_i , m_j , n_i and n_j should be the smallest figures to comply with these conditions:

- $\text{GCD}(m_i, m) = \text{GCD}(m_j, m) = 1$
- $m_i < m_j < m$
- $\text{GCD}(n_i, n) = \text{GCD}(n_j, n) = 1$
- $n_j < n_i < n$

These parameters form an elementary permutation matrix (dimensions are m columns and n rows) taking input bits from their original position to the interleaved position following the formula below:

$$J_{(i,j)} = (j \times n_j + i \times n_i) \% n$$

$$I_{(i,j)} = (i \times m_i + j \times m_j) \% m$$

where:

- (i,j) are the original bit position ($i = 0, 1, \dots, m-1$ and $j = 0, 1, \dots, n-1$)
- (I,J) are their corresponding interleaved position.

When `macCENELECLegacyMode` or `macFCCLegacyMode` is different from 0, and if the initial value $I_{(1,0)}$ is zero, the circular shift parameters n_j and n_i shall be swapped before performing interleaving. $I_{(1,0)}$ is computed as:

$$I_{(1,0)} = (1 \times m_i + J_{(1,0)} \times m_j) \% m \text{ and } J_{(1,0)} = (0 \times n_j + 1 \times n_i) \% n.$$

In this case, the interleaved position follows the formula below:

$$J_{(i,j)} = (j \times n_i + i \times n_j) \% n$$

$$I_{(i,j)} = (i \times m_i + J_{(i,j)} \times m_j) \% m$$

where:

(i,j) are related to the original bit position ($i = 0, 1, \dots, m-1$ and $j = 0, 1, \dots, n-1$)

(I,J) are related to the corresponding interleaved position.

For DBPSK or BPSK modulation, the permutation matrix corresponds to the elementary permutation matrix while other modulations use multiple times the elementary permutation matrix. Thus, the dimensions of the permutation matrix for DQPSK, QPSK, D8PSK and 8-PSK modulations are m columns and $n \times \text{mod_size}$ rows.

The data to be interleaved are stored in the input buffer and shows which dimensions are m columns and $n \times \text{mod_size}$ rows.

The data bits are put in the input buffer row by row, as shown in Figure 7-6. Zero padding will be used to match permutation matrix dimensions.

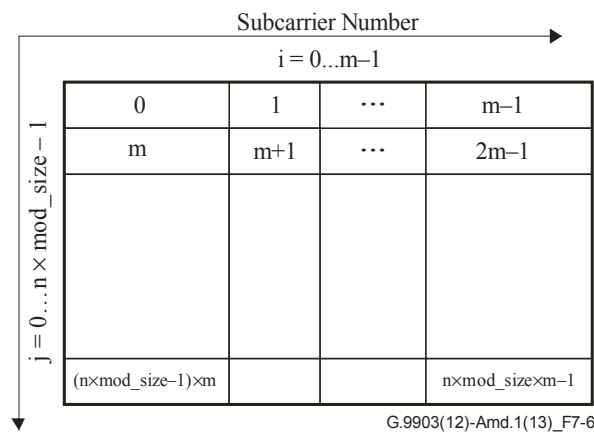


Figure 7-6 – Bit order input into the input buffer

Once interleaved each bit is stored in an output buffer as shown in Figure 7-7.

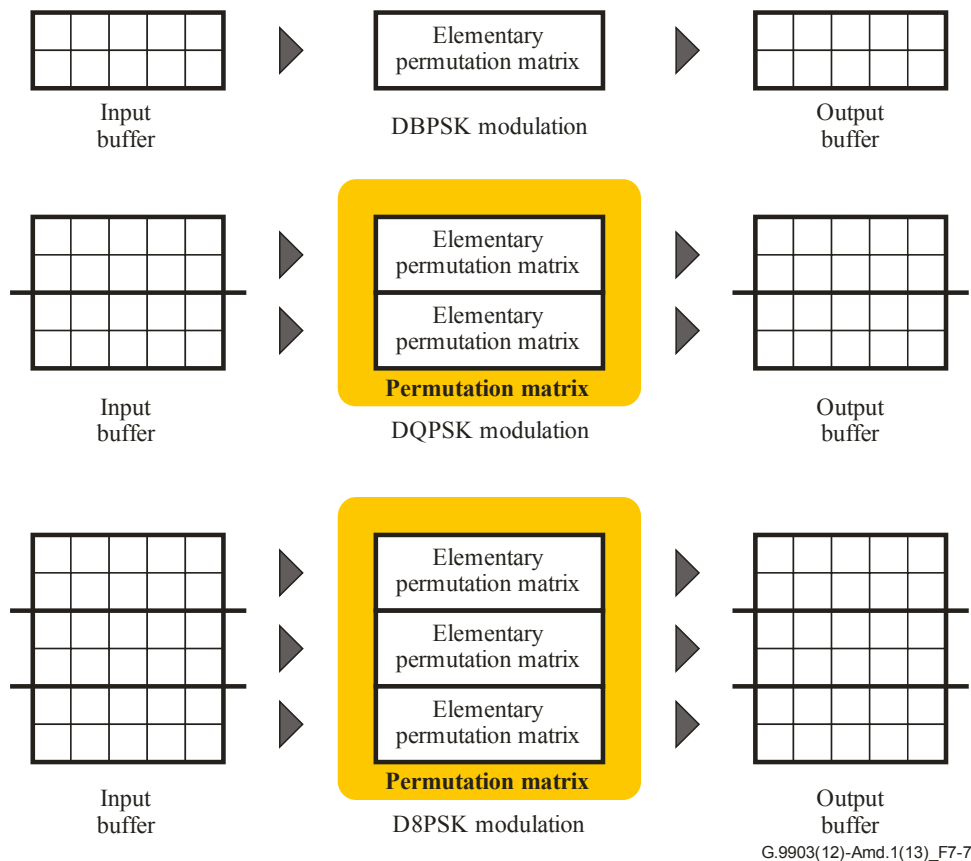


Figure 7-7 – Permutation matrix used with different modulations

After interleaving, the mapping functions used for modulation read the output buffer row by row. Each sequence of mod_{size} bit(s) is (are) computed to form a symbol.

An example is given here for information purposes.

A simple search is done to find a good set of parameters based on m and n .

For a given value of n , n_j shall be the first co-prime larger than 2 and n_i shall be the second co-prime larger than 2. When $\text{macCENELECLegacyMode}$ or macFCCLegacyMode is different from 0 and if the initial value $I_{(1,0)}$ is zero, the circular shift parameters n_i and n_j shall be swapped. Similarly, for a given value of m , m_i shall be the first co-prime larger than 2 and m_j shall be the second co-prime larger than 2. If it is not possible to find (a) required co-prime number(s) in normal or swapping case, a default value of 1 shall be used. In this special case, the condition n_j less than n_i or m_i less than m_j does not apply.

Figure 7-8 displays the spreading behaviour of the interleaver for $n = 8$, $m = 10$, $n_i = 5$, $n_j = 3$, $m_i = 3$ and $m_j = 7$.

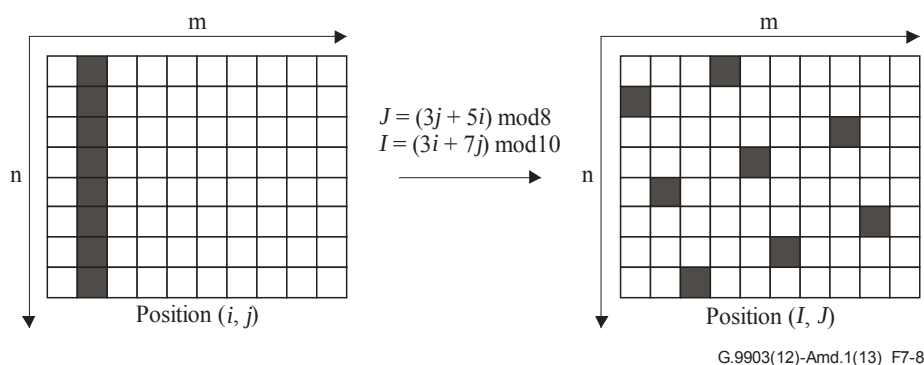


Figure 7-8 – Example of spreading behaviour

The calculation of n_i , n_j , m_i and m_j are explained as below:

- $n = 8$ (co-prime numbers for 8 except 1 and 2 are: 3, 5, 7). The first number is 3, so $n_j = 3$; and the next co-prime with 8 is 5, so $n_i = 5$; that is the first co-prime number other than 1 and 2 of n shall be n_j , and the second co-prime of n other than 1 and 2 shall be n_i ;
- $m = 10$ (co-prime numbers for 10 except 1 and 2 are: 3, 7, 9). The first number we meet in the set is 3, so $m_i = 3$; and the next is 7, so $m_j = 7$; that is the first co-prime of m other than 1 and 2 shall be m_i , and the next co-prime shall be m_j .

Here, we use DBPSK and DQPSK as examples. Suppose we have 3 active tones ($m = 3$) and 2 symbols ($n = 2$).

With DBPSK modulation:

If the input bit stream is "123456", the input bit stream will be loaded into the matrix as Figure 7-9(a). The vertical dimension of the matrix is $n \times \text{mod}_{\text{size}}$ (i.e., $2 \times 1 = 2$). After that, interleaving is done with interleaving block size $n \times m$ (i.e., 2×3). After all the bits have been processed, the bits 1'2'3'...6' are mapped to the modulator as shown in Figure 7-9(c).

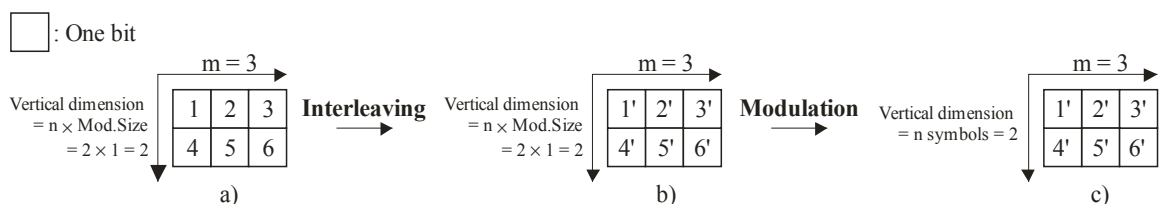


Figure 7-9 – Example of interleaving with DBPSK

With DQPSK modulation:

If the input bit stream is "1 2 3 4 5 6 ... 12", the input bit stream will be loaded into the matrix as Figure 7-10(a). The vertical dimension of the matrix is $n \times \text{mod}_{\text{size}}$ (i.e., $2 \times 2 = 4$). After that, interleaving is done with interleaving block size $n \times m$ (i.e., 2×3). After all the bits have been processed, the bits 1' 2' 3'...11' 12' are mapped to the modulator as shown in Figure 7-10(c).

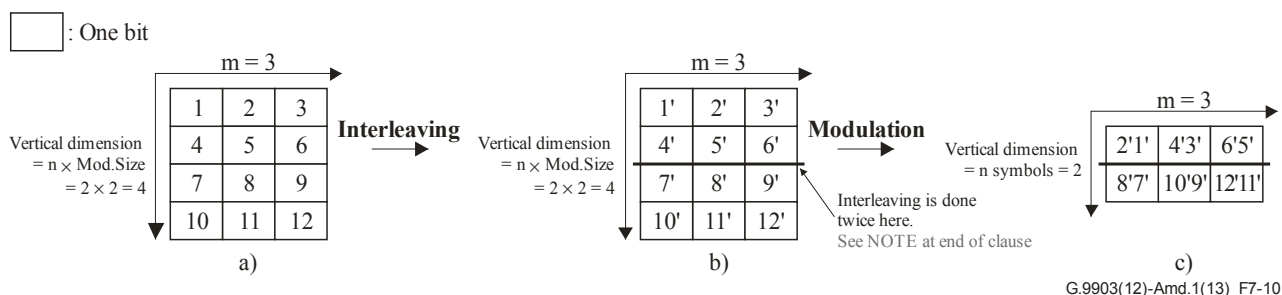


Figure 7-10 – Example of interleaving with DQPSK

Interleaving itself can be done using the following piece of code:

```
for ( i = 0; i < size; i += ILV_SIZE ) //See note below
```

```
for ( j = 0; j < ILV_SIZE; j++ )
```

```
y[ i + ILV_TBL[j] ] = (i+j) < size ? x[i+j]: 0;
```

where the interleaving table ILV_TBL and the interleaving size ILV_SIZE are defined as follows:

```
ILV_SIZE = m * n
```

```
for ( j = 0; j < n; j++ )
```

```
{
```

```
for ( i = 0; i < m; i++ )
```

```
{
```

```
J = ( j * nj + i * ni ) % n;
```

```
I = ( i * mi + J * mj ) % m;
```

```
ILV_TBL[ i + j * m ] = I + J * m;
```

```
}
```

```
}
```

NOTE – For the above DBPSK example, ILV_SIZE = $m \times n = 3 \times 2 = 6$, size = $3 \times 2 = 6$, so the loop runs once. For the above DQPSK example, ILV_SIZE = $m \times n = 3 \times 2 = 6$, size = $3 \times 4 = 12$, so the loop runs twice.

7.10.2 Full block interleaver

In the full block interleaver, the value of n is computed as:

$$n = \text{ceil} \left(\frac{\text{Total_number_of_bits}}{m \times \text{mod_size}} \right) \times \text{mod_size}$$

The derivation and computation of co-prime numbers are as described in the elementary interleaver clause.

Suppose the input bit stream to the interleaver is "ABCDEFGH IJKL...", and it is put into the interleaver block as shown in Figure 7-11. Then, after interleaving, the bit stream becomes "A'B'C'D'E'F'G'H'I'J'K'L'..."

Finally, the interleaved bit stream is mapped to the modulator as shown below for the DQPSK case, where two consecutive bits are put into the same DQPSK symbol. The same exact procedure is applied to D8PSK as shown in Figure 7-12.

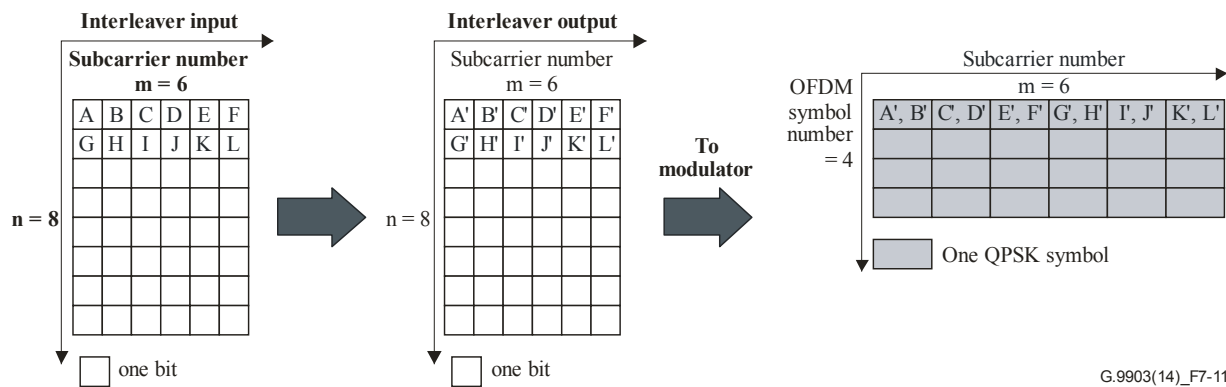


Figure 7-11 – Interleaving process for QPSK/DQPSK case

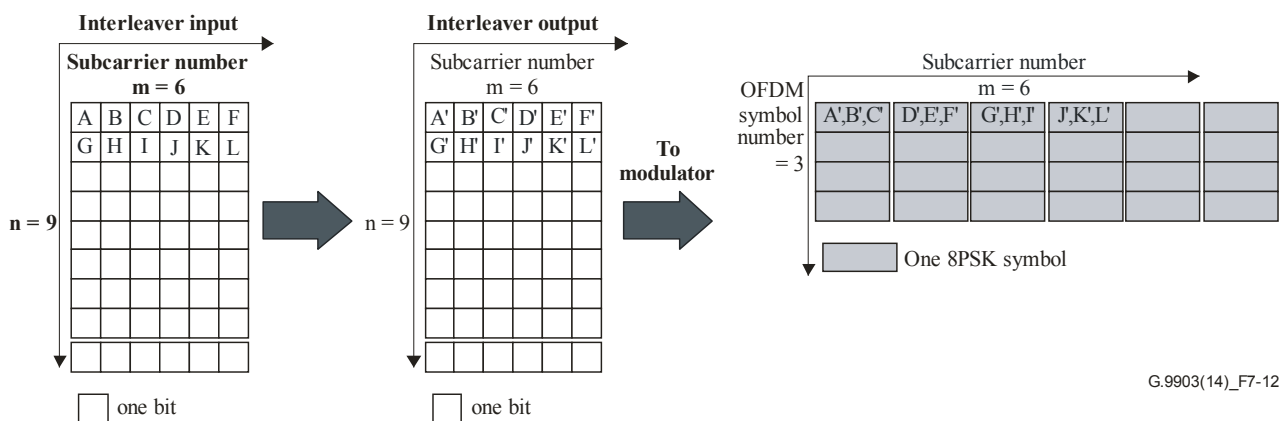


Figure 7-12 – Interleaving process for 8-PSK/D8PSK case

In the case where some subcarriers are masked i.e., some tones are notched, or serve as pilots – interleaving is done in the same way as shown above, except that the m and n values shall be adjusted based on how many tones are actually used (i.e., active). For example, in Figure 7-11, where certain tones are masked or serve as pilots, in the above example, m (where m is the number of active carriers in an OFDM symbol) is less than 6 and n is larger than 8.

7.11 Mapping for DBPSK/DQPSK/D8PSK

Each subcarrier is modulated with differential binary or differential quadrature phase shift keying (DBPSK or DQPSK or D8PSK). Forward error correction (FEC) is applied to both the frame control information (super robust encoding) and the data (concatenated Reed-Solomon and convolutional encoding) in the communication packet.

The mapping block is also responsible for assuring that the transmitted signal conforms to the given tone map and tone mask. The tone map and mask are discussed in clause 7.15.

Data bits are mapped for differential modulation (DBPSK, DQPSK, D8PSK). Instead of using the phase reference vector ϕ , each phase vector uses the same subcarrier, previous symbol, as its phase reference. The first FCH symbol uses the phase from the last preamble SYNC/P symbol and the first data symbol uses the phase from the last FCH symbol. The data encoding for DBPSK DQPSK and D8PSK is defined in Tables 7-17, 7-18 and 7-19, where Ψ_k is the phase of the k -th subcarrier from the previous symbol. In DBPSK a phase shift of 0 degrees represents a binary "0" and a phase shift of 180 degrees represent a binary "1". In DQPSK a pair of 2 bits is mapped to 4 different output phases. The phase shifts of 0, 90, 180 and 270 degrees represent binary "00", "01", "11" and "10", respectively. In D8PSK a triplet of 3 bits is mapped to one of 8 different output phases. The phase

shifts of 0, 45, 90, 135, 180, 225, 270 and 315 degrees represent binary 000, 001, 011, 010, 110, 111, 101 and 100 respectively.

Table 7-17 – DBPSK encoding table of k-th subcarrier

Input bit	Output phase
0	Ψ_k
1	$\Psi_k + \pi$

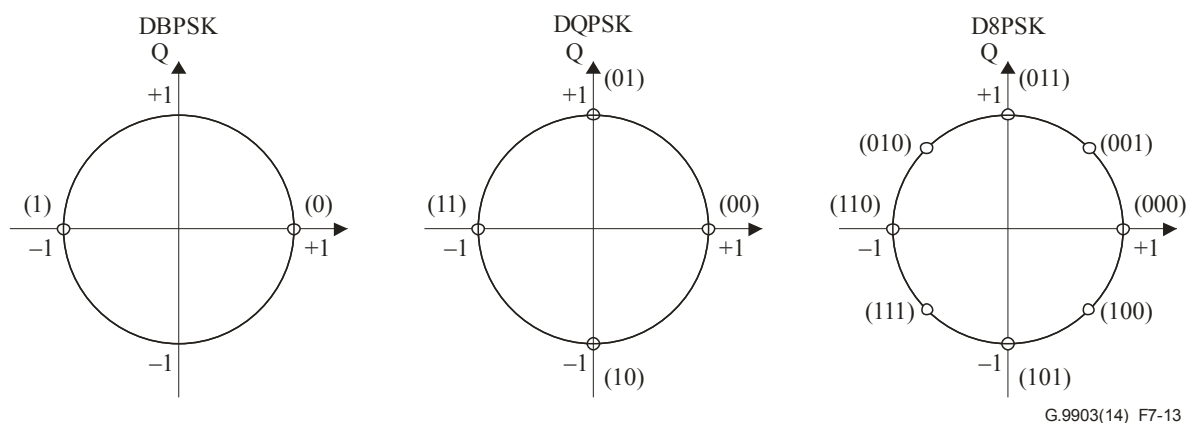
Table 7-18 – DQPSK encoding table of k-th subcarrier

Input bit pattern (X, Y), Y is from first interleaver matrix	Output phase
00	Ψ_k
01	$\Psi_k + \pi/2$
11	$\Psi_k + \pi$
10	$\Psi_k + 3\pi/2$

Table 7-19 – D8PSK encoding table of k-th subcarrier

Input bit pattern (X, Y, Z), Z is from first interleaver matrix	Output phase
000	Ψ_k
001	$\Psi_k + \pi/4$
011	$\Psi_k + \pi/2$
010	$\Psi_k + 3\pi/4$
110	$\Psi_k + \pi$
111	$\Psi_k + 5\pi/4$
101	$\Psi_k + 3\pi/2$
100	$\Psi_k + 7\pi/4$

Alternatively, the phase differences used to compute "output phases" in Tables 7-17, 7-18 and 7-19 can be represented in a constellation diagram (with reference phase assumed equal to 0 degrees), as shown in Figure 7-13.



G.9903(14)_F7-13

Figure 7-13 – Constellation encoding

7.12 Frequency domain pre-emphasis

Frequency domain pre-emphasis provides a mechanism to frequency shape the transmit signal. This mechanism may be used for spectral shaping of the transmitted signal, compensation for frequency-dependent attenuation introduced to the signal as it goes through the power line or transmission of signal over a noisy channel.

The frequency shaping of the signal may be computed from the TXRES and TXCOEF parameters that are part of the neighbour table appropriate for the band of operation. Pre-emphasis has to be applied to all OFDM symbols (including preamble, FCH and data symbols).

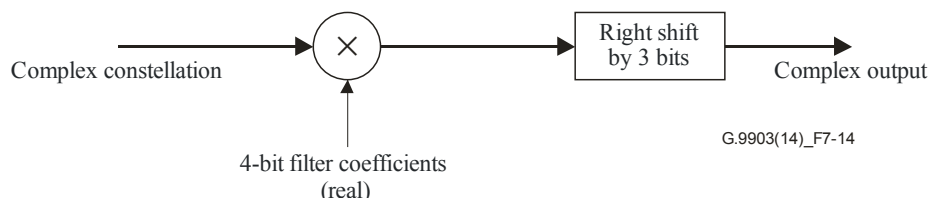


Figure 7-14 – Block diagram of the pre-emphasis filter

7.13 OFDM generation (IFFT and CP addition)

The OFDM signal can be generated using IFFT. The IFFT block takes the 256-point IFFT of the input vector and generates the main 256 time-domain OFDM words pre-pended by 30 samples of cyclic prefix. In other words, we take the last 30 samples at the output of the IFFT and place them in front of symbol. The useful output is the real part of the IFFT coefficients. The input/output configuration is as depicted in Figure 7-15.

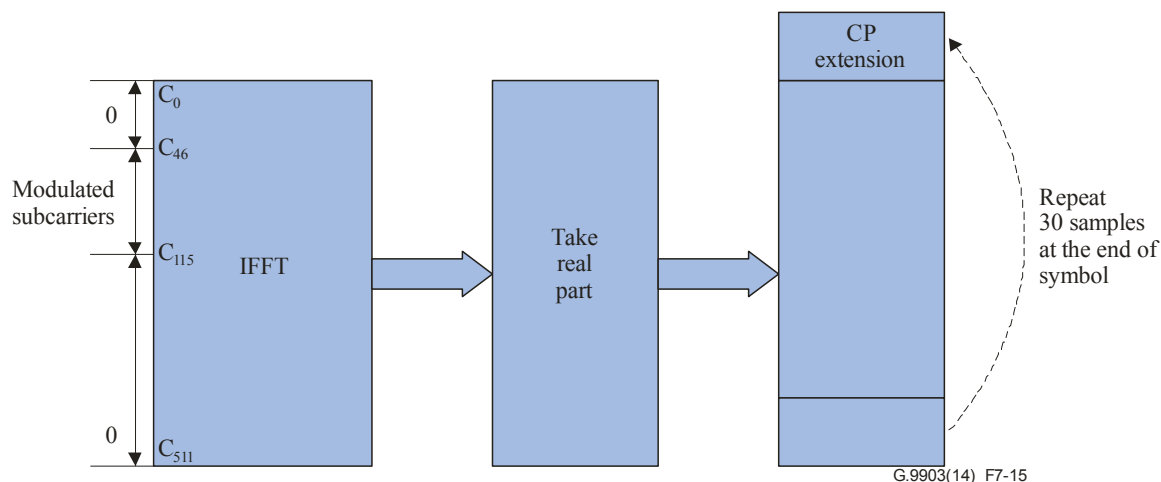


Figure 7-15 – IFFT input/output and CP addition

7.14 Windowing

In order to reduce the out-of-band emission and to reduce the spectral side lobe, the shaping is applied to all the FCH and payload symbols. Then the tails and heads of successive symbols are overlapped and added together. This process is described below. Each side of a symbol is first shaped as shown in Figure 7-16 (a raised cosine function is used in this example).

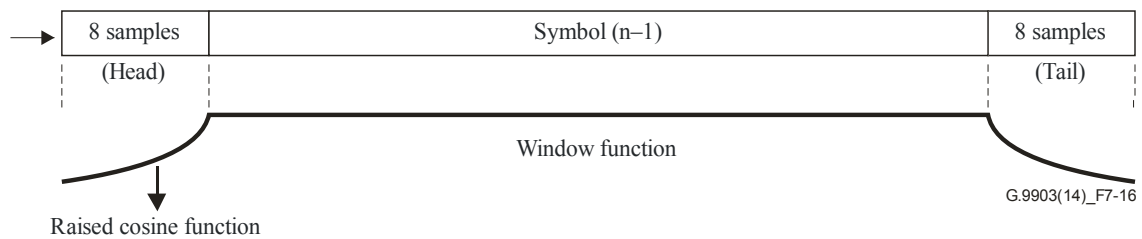


Figure 7-16 – Windowing using a raised cosine for the shaping function

The windowing function should have the sum of the overlapped head and tail samples equal to one. The window function has a value equal to one at all the remaining samples of the symbol. The 8 tail and 8 head shaped samples of the symbol from each side of the symbol are overlapped with the tail and head samples of adjacent symbols as shown in Figure 7-17.

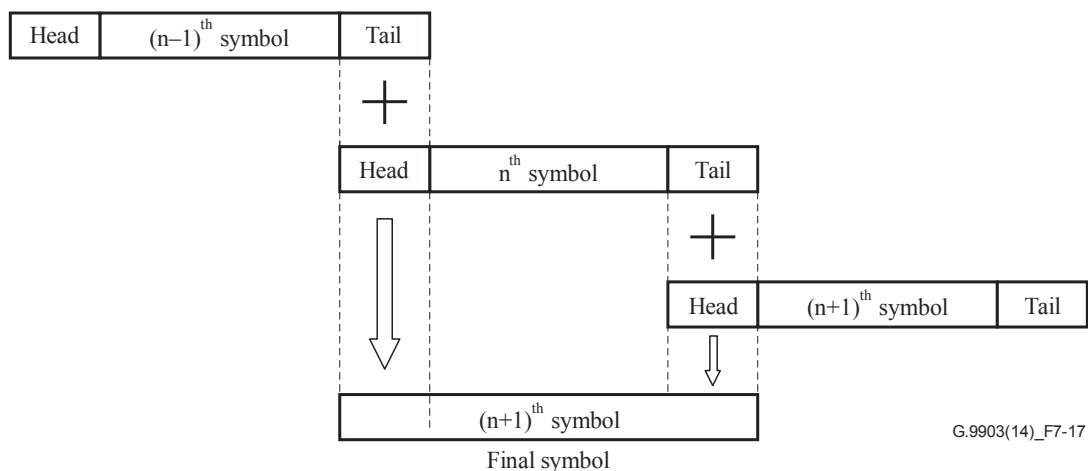


Figure 7-17 – Overlap/add

In other words, to construct the n -th symbol, first its 8 head samples are overlapped with the 8 tail samples of the $(n-1)$ -th symbol and its 8 tail samples are overlapped with the 8 head samples of the $(n+1)$ -th symbol. Finally, the corresponding overlapped parts are added together. Note that the head of the first symbol is overlapped with the tail of the preamble. And the tail of the last symbol is sent out with no overlapping applied.

7.15 Tone masking and tone mapping

The tone mask is a static PAN-wide parameter defined by `macToneMask` – see Table 9-15. Each bit set to one in the tone mask indicates that the associated tone will be used for the communication (less the significant bit representing the lowest frequency of the CENELEC or FCC bandplans). Thus, masked subcarriers are not assigned phase symbols and their amplitude is zero. The tone mask is applied to the preamble, FCH and payload.

The tone map is an adaptive parameter that, based on channel estimation, contains a list of subcarriers that are to be used for communication between two ITU-T G.9903 devices. For example, the tone map contains information on which subcarriers shall not carry information, for example those subcarriers that suffer deep fades or very low SNR. The tone map shall apply only to the payload. In the case where the robust mode is used, all subcarriers are used to carry information (the tone map is all ones).

ITU-T G.9903 devices shall estimate the SNR of the received signal subcarriers and adaptively select the usable tones, optimum modulation and code rate to ensure reliable communication over the power line channel. It shall also specify which power level the remote transmitter shall use and

which gain values it should apply for various sections of the spectrum. The per-tone quality measurement enables the system to adaptively avoid transmitting data on subcarriers with poor quality. Using a tone map indexing system, where the index is passed from receiver to transmitter and vice versa, allows the receiver to adaptively select which group of subcarriers will be used for data transmission and which ones will be used to send dummy data that the receiver shall ignore.

The goal of the adaptive tone mapping is to allow the ITU-T G.9903 receiver to achieve the greatest possible throughput given the channel conditions existing between them. In order to accomplish this goal, the receiver shall inform the remote transmitter which tones it should use to send data bits on and which tones it should use to send dummy data bits that the receiver shall ignore. The receiver shall also inform the remote transmitter how much amplification or attenuation it should apply to each of the tones.

The source station's MAC layer may request a destination station to estimate a channel condition by setting the TMR bit of the MAC header as described in Table 9-5.

The destination station has to estimate this particular communication link between two points and choose optimal PHY parameters. This information will be sent back to the originator as a tone map response.

The parameters of the tone map response message are shown in Table 9-9.

The number of tones after tone masking and tone mapping shall always be 6 or more.

7.15.1 PN modulating unused subcarriers

For inactive tones (subcarriers that carry no information), the mapping function shall use binary values taken from a pseudo noise (PN) sequence. The number of required bit outputs of the PN sequence depends on the modulation types. For example, DBPSK, DQPSK and D8PSK require 1, 2 and 3 bit outputs from the PN sequence, respectively.

The PN sequence shall be generated using the same generator polynomial introduced in clause 7.5. Based on Figure 7-18, the bits in the PN sequence generator shall all be initialized to ones at the start of the FCH and sequenced to the next value according to tone modulation and for every inactive, pilot, or masked carrier.

For every m consecutive bits output by the LFSR for a single constellation symbol of size 2^m , the first bit shall be mapped to the LSB and the last bit shall be mapped to the MSB of the constellation symbol, respectively.

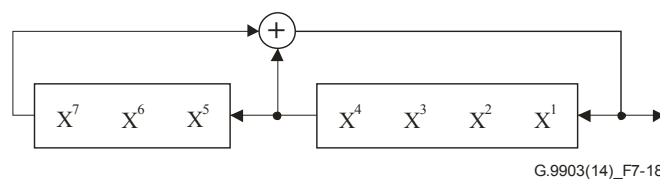


Figure 7-18 – PN sequence generator using linear feedback shift register (LFSR)

7.16 Coherent modulation scheme

For CENELEC bands, ITU-T G.9903 devices operate using a differential modulation scheme for FCH and payload. However, the device may support a coherent modulation scheme for the payload. If requested by the tone map response received from a neighbour node, a coherent modulation scheme shall be used with this neighbour (if supported). Otherwise, the differential modulation scheme shall be used.

For an FCC band, the FCH is coded using super robust mode with BPSK modulation.

This clause describes the operation of ITU-T G.9903 devices when operating in the optional coherent scheme. This clause only describes the portions of the standard that are different from the

main differential scheme. Portions of the coherent transmitter that are not described here shall operate exactly as described in the differential scheme.

7.16.1 Frame structure – Coherent modulation scheme

In a similar way to differential mode, the coherent mode shall support two types of frames: data frames and ACK/NACK frames. The frame structure of data frames shall be identical to the one used in differential mode except for two changes:

- a) The data portion of the PHY frame shall be preceded by an S1 symbol followed by an S2 symbol, where both symbols shall be inserted between the last FCH symbol and the first data symbol. The S2 symbol shall have the same phase reference vector used in differential mode for a SYNCP symbol. The only difference from a SYNCP symbol is that the S2 symbol consists of a SYNCP symbol plus a cyclic prefix of 30 samples and an overlap of 8 samples, resulting in 278 samples when an IFFT size of 256 is used. Hence, the duration of the S2 symbol shall be the same as for that of an FCH symbol or a data symbol. The S1 symbol shall be an inverted S2 symbol (i.e., $-S2$), hence it will also consist of 278 samples.
- b) Pilot tones shall be inserted in the data symbols as described in clause 7.16.10 on pilot tones.

The frame structure of the ACK/NACK frames for coherent mode shall be identical to the one used in differential mode.

7.16.2 Preamble – Coherent modulation scheme

The preamble for the coherent scheme is composed of 8 or $(8+4=12)$ identical SYNCP symbols followed by a SYNCM symbol that is followed by a half SYNCM symbol. The SYNCP and SYNCM symbols for the coherent scheme are identical to the ones generated in the differential scheme. The initial phases used for both schemes are shown in Table 7-11.

All coherent mode preamble symbols (SYNCP, SYNCM and the additional symbols between the last FCH symbol and the first data symbol) shall have the same gain factor compared to data symbols and their gain is defined to be 3 dB, the same as in the differential mode – see clause 7.5.

7.16.3 Frame control header – Coherent modulation scheme

The thirteen (CENELEC bandplans) or twelve (FCC bandplan) symbols following immediately after the preamble constitute the frame control header (FCH). The FCH has the same structure in both differential and coherent modulation schemes. The "Payload Modulation Scheme" bit in the FCH for data frames shall be used to indicate whether the payload is modulated coherently or not.

7.16.4 CRC – Coherent modulation scheme

The CRC used in coherent mode shall be identical to the one used in differential mode.

7.16.5 Data scrambler – Coherent modulation scheme

The data scrambler used in coherent mode shall be identical to the one used in differential mode.

7.16.6 FEC coding – Coherent modulation scheme

The FEC encoder for coherent mode shall be identical to the one used for differential mode.

7.16.7 Payload padding – Coherent modulation scheme

The payload padding for coherent mode shall be identical to the one used for differential mode.

7.16.8 Interleaver – Coherent modulation scheme

The interleaver for coherent mode shall be identical to the interleaver in differential mode where the pilot tones shall not be considered part of the active tones and hence shall be completely ignored by

the interleaver. This means that the number of subcarriers 'm' shall not include in it the pilot tones (nor the masked tones as is the case for differential mode).

7.16.9 Coherent mapping for BPSK, QPSK, 8-PSK, 16-QAM and robust modes – Coherent modulation scheme

The mapping block is responsible for assuring that the transmitted signal conforms to the given tone map and tone mask. The tone map and tone mask are discussed in clause 7.15. The tone mask is a predefined (static) system-wide parameter defining the start, stop and notch frequencies. The tone map is an adaptive parameter that, based on channel estimation, contains a list of carriers that are to be used for a particular communication between two modems.

Data bits are mapped for coherent modulation (BPSK, QPSK, 8-PSK, 16-QAM or robust) as follows: For a given symbol, instead of using the same carrier, the previous symbol as its phase reference, it uses the preamble phase of the same carrier as its reference. This predefined phase reference is identical to the one that is specified for differential modulation as shown in Table 7-11. Both the FCH symbols and data symbols use the same phase reference vector.

7.16.9.1 Mapping for BPSK and robust mode – Coherent modulation scheme

In BPSK (and robust) modulation a phase shift of 0° represents a binary "0" and a phase shift of 180° represents a binary "1" as illustrated in Table 7-20.

Table 7-20 – BPSK and robust encoding table of k-th subcarrier

Input bit	Output phase
0	Ψ_k
1	$\Psi_k + \pi$

The constellation shall be identical to the one used for differential mode.

7.16.9.2 Mapping for QPSK modulation – Coherent modulation scheme

In QPSK a pair of 2 bits is mapped to 4 different output phases. The phase shifts of 0° , 90° , 180° and 270° represent binary "00", "01", "11" and "10" respectively, as illustrated in Table 7-21.

Table 7-21 – QPSK encoding table of k-th subcarrier

Input bit pattern (X, Y), Y leaves interleaver first	Output phase
00	Ψ_k
01	$\Psi_k + \pi/2$
11	$\Psi_k + \pi$
10	$\Psi_k + 3\pi/2$

The constellation shall be identical to the one used for differential mode.

7.16.9.3 Mapping for 8-PSK modulation – Coherent modulation scheme

In 8-PSK a triplet of 3 bits is mapped to one of 8 different output phases. The phase shifts of 0° , 45° , 90° , 135° , 180° , 225° , 270° and 315° represent binary 000, 001, 011, 010, 110, 111, 101 and 100 respectively, as illustrated in Table 7-22.

Table 7-22 – 8-PSK encoding table of k-th subcarrier

Input bit pattern (X, Y, Z), Z leaves interleaver first	Output phase
000	Ψ_k
001	$\Psi_k + \pi/4$
011	$\Psi_k + \pi/2$
010	$\Psi_k + 3\pi/4$
110	$\Psi_k + \pi$
111	$\Psi_k + 5\pi/4$
101	$\Psi_k + 3\pi/2$
100	$\Psi_k + 7\pi/4$

The constellation shall be identical to the one used for differential mode.

7.16.9.4 Mapping for 16-QAM modulation (applies only to FCC bandplan) – Coherent modulation scheme

The 16-QAM modulation is optional.

In 16-QAM modulation, 4 bits are mapped to one of sixteen different constellation points. The mapping is shown in Figure 7-19 and Table 7-23.

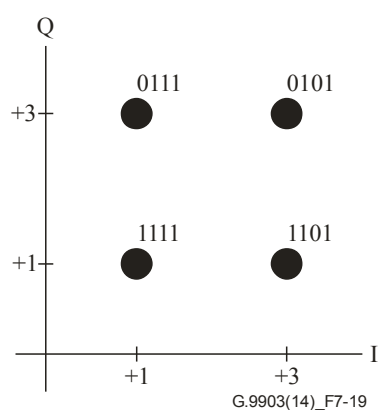


Figure 7-19 – 16-QAM constellation diagram

The complete constellation description is given in Table 7-23.

Table 7-23 – Mapping for 16-QAM

Bits [d ₁ d ₀]	I	Bit [d ₃ d ₂]	Q
00	–3	00	–3
10	–1	10	–1
11	1	11	1
01	3	01	3

The resulting outputs values "d" are formed by multiplying the resulting (I+jQ) value by a normalization factor equal to $1/\sqrt{(10)}$:

$$d = (I + jQ) \times \frac{1}{\sqrt{(10)}}$$

The purpose of the normalization factor is to achieve the same average power for all mappings.

7.16.10 Pilot tones – Coherent modulation scheme

Pilot tones can be used in coherent mode to help with clock recovery and channel estimation, particularly in harsh environments where strong noise and frequent channel variations occur. Pilot tones shall only be inserted in data symbols and shall not be inserted in FCH symbols.

For pilot tone assignment, the pilot indices shall be sequentially enumerated over only the active subcarrier set:

$$P(i,j) = (\text{OFFSET} + (\text{FreqSpacing} \times i) + 2 \times j) \% M_{\text{ACTIVE}} \quad (7-1)$$

Where:

- $P(i,j)$ is the relative position of pilot i in symbol j within the set of active subcarriers. The set of active subcarriers is enumerated as 0, 1, 2, ..., $M_{\text{ACTIVE}}-1$
- M is the number of subcarriers per symbol in a given band ($M=36$ for CENELEC A; $M=16$ for CENELEC B; $M=72$ for FCC)
- M_{ACTIVE} is the number of subcarriers in the bandplan that are not masked nor inactive ($M_{\text{ACTIVE}} \leq M$)
- FreqSpacing = Frequency spacing between pilots within the same symbol expressed in multiples of the subcarrier spacing (12 for CENELEC A; 8 for CENELEC B; 12 for FCC band)
- i = pilot index = 0, 1, 2, ..., $\text{ceil}(M_{\text{ACTIVE}} / \text{FreqSpacing}) - 1$
- j = symbol number = 0, 1, 2, 3, ..., $N-1$
- N = total number of data symbols per frame.
- OFFSET (6 for CENELEC A and CENELEC B; 36 for FCC).

The absolute pilot tone index with respect to FFT numbering is given by:

$$P_{\text{abs}}(i,j) = \text{STARTINDEX} + Q_{\text{ACTIVE}}(P(i,j)) \quad (7-2)$$

Where:

- $Q = [0, 1, 2, \dots, M-1]$ is a vector of the relative indices of the subcarriers of a given band. $\text{Length}(Q) = M$
- Q_{ACTIVE} is a vector of the relative indices of the active subcarriers of the given band. Q_{ACTIVE} is derived from Q by excluding inactive and masked subcarriers. $\text{Length}(Q_{\text{ACTIVE}}) = M_{\text{ACTIVE}}$
- STARTINDEX is the absolute index with respect to FFT numbering of the first subcarrier in the bandplan (23 for CENELEC A; 63 for CENELEC B; 33 for FCC).

The pilot tones shall consist of sine waves at the specified tone frequencies modulated in QPSK using the constellation specified in clause 7.16.9.2. The bits that get mapped to the constellation points shall be generated following the PN sequence generation procedure described in clause 7.15.1.

The pilot tones' indexes shall be ordered first in ascending order, and then each pilot tone shall be modulated with the output of the PN sequence generator.

For every two consecutive output bits for pilot tones from the PN sequence generator, the first bit shall be mapped to the LSB of the QPSK symbol and the second bit shall be mapped to the MSB of the QPSK symbol.

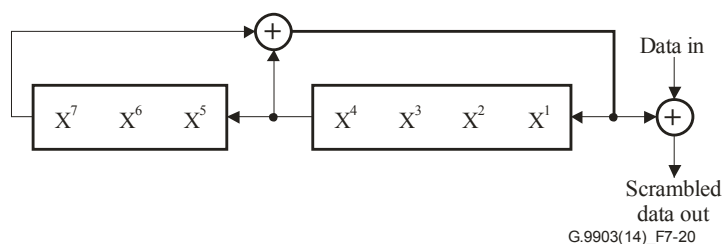


Figure 7-20 – LFSR used to generate the data bits that are used to modulate the pilot tones

7.16.10.1 Example of pilot tone assignment

Below is an example of the application of Equations (7-1) and (7-2).

With the CENELEC A bandplan we have the following initial parameters:

$$M = 36;$$

$$\text{FreqSpacing} = 12;$$

$$\text{OFFSET} = 6;$$

$$\text{STARTINDEX} = 23;$$

If neither masked nor inactive (ToneMap equal to 0x3F) subcarriers are present, the derived parameters are:

$$M_{\text{ACTIVE}} = M = 36;$$

$$i = [0:2] = [0 \quad 1 \quad 2]$$

$$Q = [0:M] = [0:35] = [0 \quad 1 \quad 2 \quad 3 \quad 4 \quad \dots \quad 34 \quad 35];$$

$$Q_{\text{ACTIVE}} = Q = [0:35];$$

$$\text{Length}(Q_{\text{ACTIVE}}) = M_{\text{ACTIVE}} = 36$$

Given $N = 10$ OFDM symbols, pilot tones are allocated as follows:

$$j = [0:9] = [0 \quad 1 \quad 2 \quad 3 \quad 4 \quad \dots \quad 8 \quad 9]$$

$$P(i,j) =$$

6	8	10	12	14	16	18	20	22	24
18	20	22	24	26	28	30	32	34	0
30	32	34	0	2	4	6	8	10	12

$$P_{\text{abs}}(i,j) =$$

29	31	33	35	37	39	41	43	45	47
41	43	45	47	49	51	53	55	57	23
53	55	57	23	25	27	29	31	33	35

7.16.11 Frequency domain pre-emphasis – Coherent modulation scheme

For further study.

7.16.12 OFDM generation (IFFT and CP addition) – Coherent modulation scheme

OFDM generation for coherent mode shall be identical to the procedure used for differential mode.

7.16.13 Windowing – Coherent modulation scheme

Windowing for coherent mode shall follow the identical procedure used for differential mode and shall apply to S1 and S2 symbols accordingly.

7.16.14 Adaptive tone mapping and transmit power control – Coherent modulation scheme

Adaptive tone mapping and transmit power control shall follow the identical procedure used for differential mode. However, transmit power scaling per sub band shall not be allowed for coherent modulation. In particular, pilot tones shall not have any special treatment when it comes to transmit power control and shall follow the same mechanism applied to data tones.

7.17 PHY primitives

7.17.1 Data primitive

The receipt of the PD-DATA.request primitive by the PHY entity will cause the transmission of the supplied PSDU to be attempted. The PHY will first construct a PHY protocol data unit (PPDU) containing the supplied PSDU, and then transmit the PPDU. If the PD-DATA.request primitive is received by the PHY while the receiver is not enabled, or the transmitter is busy transmitting, the PHY shall first construct a PPDU containing the supplied PSDU, and then transmit the PPDU. When the PHY entity has completed the transmission successfully, it shall issue the PD-DATA.confirm primitive with a status of SUCCESS. If a PD-DATA.request primitive is received while the receiver is enabled (TXOFF_RXON state), the PHY entity shall discard the PSDU and issue the PD-DATA.confirm primitive with a BUSY_RX status. If a PD-DATA.request primitive is received while the transmitter is already busy transmitting (BUSY_TX state), the PHY entity shall discard the PSDU and issue the PD-DATA.confirm primitive with a BUSY_TX status. If the processing or transmission of PHY is not possible due to invalid parameters or for any other reason, the PHY entity shall discard the PSDU and issue the PD-DATA.confirm primitive with a FAILED status.

The receipt of the PD-ACK.request primitive by the PHY entity will cause the transmission of the ACK/NACK frame to be attempted. The PHY will first construct an ACK/NACK frame and then transmit it. When the PHY entity has completed the transmission successfully, it shall issue the PD-ACK.confirm primitive with a SUCCESS status. If a PD-ACK.request primitive is received while the receiver is enabled (TXOFF_RXON state), the PHY entity shall discard the constructed ACK/NACK frame and issue the PD-ACK.confirm primitive with a BUSY_RX status. If a PD-ACK.request primitive is received while the transmitter is already busy transmitting (BUSY_TX state), the PHY entity shall discard the constructed ACK/NACK frame and issue the PD-ACK.confirm primitive with a BUSY_TX status. If the processing or transmission of PHY is not possible due to invalid parameters or for any other reason, the PHY entity shall discard the constructed ACK/NACK frame and issue the PD-ACK.confirm primitive with a FAILED status.

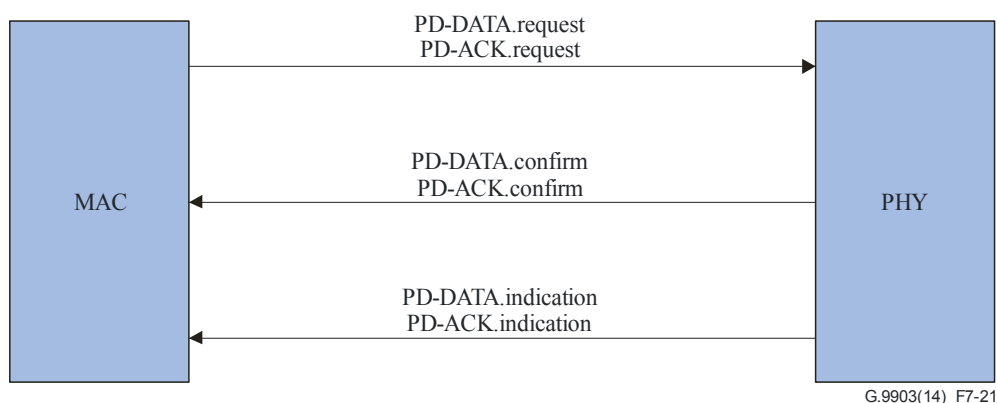


Figure 7-21 – Data or ACK primitive flow

7.17.1.1 PD-DATA.request

The PD-DATA.request primitive is generated by a local MAC sublayer entity and issued to its PHY entity to request the transmission of an MPDU. The semantics of the PD-DATA.request primitive is as follows:

```
PD-DATA.request (  
    psduLength  
    psdu  
)
```

Table 7-24 specifies the parameters for the PD-DATA.request primitive.

Table 7-24 – The parameters for the PD-DATA.request primitive

Name	Type	Valid range	Description
psduLength	Integer	0x00-0xEF for CENELEC bandplans 0x00-0x1EE for FCC bandplan	The number of bytes contained in the PSDU to be transmitted by the PHY entity. The effective maximum PSDU length can be derived as described in clause 7.3.2.
Psdu	Integer Array	Any	The set of bytes forming the PSDU request to be transmitted by the PHY entity.

The PHY should start the transmission no later than $0.1 \times aSlotTime$ after the PD-DATA.request is issued by the MAC. The aSlotTime is defined in Table 9-14.

7.17.1.2 PD-DATA.confirm

The PD-DATA.confirm primitive confirms the end of the transmission of an MPDU (i.e., PSDU) from a local PHY entity to a peer PHY entity. The semantics of the PD-DATA.confirm primitive is as follows:

```
PD-DATA.confirm (  
    status  
)
```

Table 7-25 specifies the parameters for the PD-DATA.confirm primitive.

Table 7-25 – The parameters for the PD-DATA.confirm primitive

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS, BUSY_RX, BUSY_TX, FAILED	The result of the request to transmit a packet

7.17.1.3 PD-DATA.indication

The PD-DATA.indication primitive indicates the transfer of an MPDU (i.e., PSDU) from the PHY to the local MAC sublayer entity. The semantics of the PD-DATA.indication primitive is as follows:

```
PD-DATA.indication (  
    psduLength,  
    psdu,
```

ppduLinkQuality
CarrierSNR,
PhaseDifferential,
PayloadModulationType,
PayloadModulationScheme
ToneMap,
DT

)

Table 7-26 specifies the parameters for the PD-DATA.indication primitive.

Table 7-26 – The parameters for the PD-DATA.indication primitive

Name	Type	Valid range	Description
psduLength	Integer	0x00-0xEF for CENELEC bandplans 0x00-0x1EE for FCC bandplan	The number of bytes contained in the PSDU received by the PHY entity
Psdu	Integer	–	The set of bytes forming the PSDU received by the PHY entity
ppduLinkQuality	Integer	0x00-0xFF	Link quality (forward LQI) value measured during reception of the PPDU
CarrierSNR	Array	0x00-0x3F	The PHY provides the SNR value per each carrier of the last received frame (see clause 7.17.2.4).
PhaseDifferential	Integer	0x00-0x05	The PHY computes and provides the phase difference in multiples of 60 degrees to the MAC layer of the last received frame. 0: local node and neighbour node are in phase 1: local node leads neighbour node by 60 degrees 2: local node leads neighbour node by 120 degrees 3: neighbour node and local node are in phase opposition 4: neighbour node leads local node by 120 degrees 5: neighbour node leads local node by 60 degrees
PayloadModulation Type	Integer	0x00-0x04	The modulation type used in the last received frame. 0: Robust mode 1: DBPSK or BPSK 2: DQPSK or QPSK 3: D8PSK or 8-PSK 4: 16-QAM