International Telecommunication Union

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

G.9955

(12/2011)

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

Access networks – In premises networks

Narrowband orthogonal frequency division multiplexing power line communication transceivers – Physical layer specification

Recommendation ITU-T G.9955 (2011)

ITU-T

ITU-T G-SERIES RECOMMENDATIONS

TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

INTERNATIONAL TELEPHONE CONNECTIONS AND CIRCUITS	G.100–G.199
GENERAL CHARACTERISTICS COMMON TO ALL ANALOGUE CARRIER-TRANSMISSION SYSTEMS	G.200–G.299
INDIVIDUAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON METALLIC LINES	G.300–G.399
GENERAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON RADIO-RELAY OR SATELLITE LINKS AND INTERCONNECTION WITH METALLIC LINES	G.400–G.449
COORDINATION OF RADIOTELEPHONY AND LINE TELEPHONY	G.450–G.499
TRANSMISSION MEDIA AND OPTICAL SYSTEMS CHARACTERISTICS	G.600–G.699
DIGITAL TERMINAL EQUIPMENTS	G.700–G.799
DIGITAL NETWORKS	G.800–G.899
DIGITAL SECTIONS AND DIGITAL LINE SYSTEM	G.900–G.999
MULTIMEDIA QUALITY OF SERVICE AND PERFORMANCE – GENERIC AND USER-RELATED ASPECTS	G.1000–G.1999
TRANSMISSION MEDIA CHARACTERISTICS	G.6000–G.6999
DATA OVER TRANSPORT – GENERIC ASPECTS	G.7000–G.7999
PACKET OVER TRANSPORT ASPECTS	G.8000–G.8999
ACCESS NETWORKS	G.9000–G.9999
In premises networks	**G.9950–G.9999**

For further details, please refer to the list of ITU-T Recommendations.

Recommendation ITU-T G.9955

Narrowband orthogonal frequency division multiplexing power line communication transceivers – Physical layer specification

Summary

Recommendation ITU-T G.9955 contains the physical layer specification for narrowband OFDM power line communications 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 in long distance rural communications. This Recommendation addresses grid to utility meter applications, advanced metering infrastructure (AMI), and other Smart Grid applications such as charging of electric vehicle, home automation, and home area networking (HAN) communications scenarios.

This version integrates Recommendation ITU-T G.9955 (12/2011) with its Amendment 1.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
1.0	ITU-T G.9955	2011-12-16	15	11.1002/1000/11324
1.1	ITU-T G.9955 (2011) Amd. 1	2012-09-21	15	11.1002/1000/11684

* 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.

FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications, information and communication technologies (ICTs). The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

In this Recommendation, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

Compliance with this Recommendation is voluntary. However, the Recommendation may contain certain mandatory provisions (to ensure, e.g., interoperability or applicability) and compliance with the Recommendation is achieved when all of these mandatory provisions are met. The words "shall" or some other obligatory language such as "must" and the negative equivalents are used to express requirements. The use of such words does not suggest that compliance with the Recommendation is required of any party.

INTELLECTUAL PROPERTY RIGHTS

ITU draws attention to the possibility that the practice or implementation of this Recommendation may involve the use of a claimed Intellectual Property Right. ITU takes no position concerning the evidence, validity or applicability of claimed Intellectual Property Rights, whether asserted by ITU members or others outside of the Recommendation development process.

As of the date of approval of this Recommendation, ITU had received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementers are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database at http://www.itu.int/ITU-T/ipr/.

© ITU 2014

All rights reserved. No part of this publication may be reproduced, by any means whatsoever, without the prior written permission of ITU.

Table of Contents

Recommendation ITU-T G.9955

Narrowband orthogonal frequency division multiplexing power line communication transceivers – Physical layer specification

1 Scope

This Recommendation contains the physical layer specification for narrowband OFDM power line communications 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 in long distance rural communications. This Recommendation addresses grid to utility meter applications, advanced metering infrastructure (AMI), and other Smart Grid applications such as charging of electric vehicle, home automation, and home area networking (HAN) communications scenarios.

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.9956] Recommendation ITU-T G.9956 (2011), *Narrowband OFDM power line communication transceivers – Data link layer specification.*

[CISPR 16-1] IEC CISPR 16-1 (1993), *Specification for radio disturbance and immunity measuring apparatus and methods. Part 1: Radio disturbance and immunity measuring apparatus*.

[CISPR 16-2] IEC CISPR 16-2 (1996), *Specification for radio disturbance and immunity measuring apparatus and methods. Part 2: Methods of measurement of disturbances and immunity*.

[EN50065-1] CENELEC EN 50065-1 (2011), *Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz – Part 1: General requirements, frequency bands and electromagnetic disturbances.*

3 Definitions

This Recommendation defines the following terms:

3.1 advanced metering infrastructure (AMI): Primary means for utilities to interact with meters on customer sites. In addition to basic meter reading, AMI provides two-way communications allowing to collect and analyse energy usage, and interact with advanced devices such as electricity meters, gas meters, heat meters, and water meters, through various communication media.

3.2 alien domain: Any group of non-ITU-T G.9955 nodes connected to the same or a different medium (wired or wireless) operating in a close proximity. These domains can be used as backbones to the ITU-T G.9955 network or as separate networks. The L3 bridging function to an alien domain, as well as coordination with an alien domain to avoid mutual interference is beyond the scope of this Recommendation.

3.3 bandplan: A specific range of the frequency spectrum that is defined by a lower frequency and upper frequency.

3.4 baseband: A frequency band defined by an up-convert frequency $F_{UC} = 0$ and an up-shift frequency $F_{US} = F_{SC} \times N/2$ (see Table 7-27).

3.5 bridge to alien domain/network: An application device implementing an L2 or L3-bridging function to interconnect an ITU-T G.9955 domain to an alien domain (or alien network). Bridging to alien domains/networks is beyond the scope of this Recommendation.

3.6 broadcast: A type of communication where a node sends the same frame simultaneously to all other nodes in the home network or in the domain.

3.7 carrier sense (CRS): Generated by the receiver, CRS indicates that the medium is busy, i.e., a PHY frame, or sequence of PHY frames, or a special signal (e.g., INUSE, PR) is currently transmitted on the medium by another node. CRS may be either a physical carrier sense signal or a virtual carrier sense indicator.

– Physical carrier sense is generated by analysing physical signals present on the medium.
– Virtual carrier sense is generated based on the information on the PHY frame duration or PHY frame sequence duration derived from the frame header or communicated to a node by other means (e.g., in another frame).

3.8 *ceiling(x)*: A function that returns the minimum integer value bigger than or equal to *x*.

3.9 CENELEC band: Frequency band between 3 kHz and 148.5 KHz allowed to be used for power line communications by Annex F. Four CENELEC bands are defined: A: 3-95 kHz, B: 95-125 kHz, C: 125-140 kHz, and D: 140-148.5 kHz.

3.10 channel: A transmission path between nodes. One channel is considered to be one transmission path. Logically a channel is an instance of communications medium used for the purpose of passing data between two or more nodes.

3.11 coding overhead: A part of the overhead used to carry the coding redundancy (such as redundancy bits of error correction coding or CRC).

3.12 data: Bits or bytes transported over the medium or via a reference point that individually convey information. Data includes both user (application) data and any other auxiliary information (overhead, including control, management, etc.). Data does not include bits or bytes that, by themselves, do not convey any information, such as preamble.

3.13 data rate: The average number of data elements (bits, bytes, or frames) communicated (transmitted) in a unit of time. Depending on the data element, data bit rate, data byte rate, and symbol frame rate may be used. The usual unit of time for data rate is 1 second.

3.14 domain: A part of an ITU-T G.9955 home network comprising a domain master and all those nodes that are registered with this same domain master. In the context of this Recommendation, use of the term 'domain' without a qualifier means 'ITU-T G.9955 domain', and use of the term 'alien domain' means 'non-ITU-T G.9955 domain'.

3.15 domain ID: A unique identifier of a domain.

3.16 domain master (DM): A node that manages (coordinates) all other nodes of the same domain. Domain master is a node with extended management capabilities that enables to form, control, and maintain the nodes associated with its domain.

3.17 end-node: A node that is not a domain master; all nodes in the domain except the domain master are end-nodes.

3.18 FCC band: Frequency band between 9 kHz and 490 KHz allowed to be used for power line communications.

3.19 *floor(x)*: A function that returns the maximum integer value smaller than or equal to *x*.

3.20 global master (GM): A function that provides coordination between different domains of the same network (such as communication resources, priority setting, policies of domain masters, and interference mitigation). A GM may also convey management functions initiated by the remote management system. Detailed specification and use of this function is for further study.

3.21 guard interval (GI): The time interval intended to mitigate corruption of data carried by the symbol due to ISI from the preceding symbols. In this Recommendation, the guard interval is implemented as a cyclic prefix.

3.22 home area network (HAN): A network at customer premises that interconnects customer-owned devices for energy management and communications with the utility.

3.23 inter-domain bridge (IDB): A bridging function to interconnect nodes of two different domains.

3.24 inter-network bridge (INB): A bridging function to interconnect nodes of two different ITU-T G.9955 networks.

3.25 latency: A measure of the delay from the instant when the last bit of a frame has been transmitted through the assigned reference point of the transmitter protocol stack to the instant when a whole frame reaches the assigned reference point of receiver protocol stack. Mean and maximum latency estimations are assumed to be calculated on the 99th percentile of all latency measurements. If retransmission is required for a frame, the retransmission time is a part of latency for the protocol reference points above the MAC.

3.26 logical (functional) interface: An interface in which the semantic, syntactic, and symbolic attributes of information flows are defined. Logical interfaces do not define the physical properties of signals used to represent the information. It is defined by a set of primitives.

3.27 medium: A wire-line facility allowing physical connection between nodes. Nodes connected to the same medium may communicate on the physical layer, and may interfere with each other unless they use orthogonal signals (e.g., different frequency bands, different time periods).

3.28 mod(a,b): A function that returns the remainder when *a* is divided by *b*.

3.29 multicast: A type of communication when a node sends the same frame simultaneously to more than one node in the network.

3.30 net data rate: The data rate at the A-interface of the transceiver reference model.

3.31 network: Two or more nodes that can communicate with each other either directly or through a relay node at the physical layer, or through an inter-domain bridge above the physical layer.

3.32 node: Any network device that contains an ITU-T G.9955 transceiver. In the context of this Recommendation, use of the term 'node' without a qualifier means 'ITU-T G.9955 node', and use of the term 'alien node' means 'non-ITU-T G.9955 node'. Additional qualifiers (e.g., 'relay') may be added to either 'node' or 'alien node'.

3.33 node ID: A unique identifier allocated to a node within the domain.

3.34 physical interface: An interface defined in terms of physical properties of the signals used to represent the information transfer. A physical interface is defined by signal parameters like power (power spectrum density), timing, and connector type.

3.35 primitives: Variables and functions used to define logical interfaces and reference points.

3.36 quality of service (QoS): A set of quality requirements on the communications in the network.

3.37 reference point: A location in a signal flow, either logical or physical, that provides a common point for observation and or measurement of the signal flow.

3.38 subcarrier (OFDM subcarrier): The centre frequency of each OFDM sub-channel onto which bits may be modulated for transmission over the sub-channel.

3.39 subcarrier spacing: The difference between frequencies of any two adjacent OFDM subcarriers.

3.40 sub-channel (OFDM sub-channel): A fundamental element of OFDM modulation technology. The OFDM modulator partitions the channel bandwidth into a set of non-overlapping sub-channels.

3.41 symbol (OFDM symbol): A fixed time-unit of an OFDM signal. An OFDM symbol consists of multiple sine-wave signals or subcarriers. Each subcarrier can be modulated by certain number of data bits and transmitted during the fixed time called symbol period.

3.42 symbol frame: A frame composed of bits of a single OFDM symbol period. Symbol frames are exchanged over the δ-reference point between the PMA and PMD sub-layers of the PHY.

3.43 symbol rate: The rate, in symbols per second, at which OFDM symbols are transmitted by a node onto a medium. Symbol rate is calculated only for time periods of continuous transmission.

3.44 throughput: The amount of data transferred from the A-interface of a source node to the A-interface of a destination node over some time interval, expressed as the number of bits per second.

3.45 transmission overhead: A part of the overhead used to support transmission over the line (e.g., samples of cyclic prefix, inter-frame gaps, and silent periods).

3.46 unicast: A type of communication when a node sends the frame to another single node.

3.47 utility access network (UAN): A power line communications network that operates under control of the electric utility over the utility-owned electricity distribution lines, and provides communications between the utility and the utility-controlled devices and network infrastructure at the customer premises.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

AC	Alternating Current
ACK	Acknowledgement
AE	Application Entity
AFE	Analogue Front End
AMI	Advanced Metering Infrastructure
AMM	Automated Meter Management
APC	Application Protocol Convergence

BAT	Bit Allocation Table
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CENELEC	European Committee for Electrotechnical Standardization
CP	Customer Premise
CRC	Cyclic Redundancy Check
DLL	Data Link Layer
DM	Domain Master
EMS	Energy Management System
ESI	Energy Service Interface
EV	Electrical Vehicle
EVCF	Electrical Vehicle Charging Facility
EVSE	Electrical Vehicle Supply Equipment
FCS	Frame Check Sequence
FEC	Forward Error Correction
FFT	Fast Fourier Transform
GF	Galois Field
GI	Guard Interval
GM	Global Master
HAN	Home Area Network
HCS	Header Check Sequence
IDB	Inter-Domain Bridge
IEC	International Electrotechnical Committee
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
INB	Inter-Network Bridge
ISI	Inter-Symbol Interference
LISN	Line Impedance Stabilization Network
LSB	Least Significant Bit
LLC	Logical Link Control
MAC	Medium Access Control
MDI	Medium-Dependent Interface
MIB	Management Information Base
MPDU	MAC Protocol Data Unit
MSB	Most Significant Bit
MSDU	MAC Service Data Unit
OFDM	Orthogonal Frequency Division Multiplexing

PCS	Physical Coding Sub-layer
PEV	Plug-in Electrical Vehicle
PFH	PHY Frame Header
PHY	Physical Layer
PLC	Power Line Communications
PMA	Physical Medium Attachment
PMD	Physical Medium Dependent
PMI	Physical Medium-independent Interface
PPM	parts per million
PSD	Power Spectral Density
PSDU	PHY Service Data Unit
PST	Programmable Smart Thermostat
QoS	Quality of Service
RCM	Robust Communication Mode
RMS	Root Mean Square
RS	Reed-Solomon
RX	Receiver
SNR	Signal to Noise Ratio
TX	Transmitter
UAN	Utility Access Network

5 Network architecture and reference models

5.1 Network architecture and topology

5.1.1 Basic principles of ITU-T G.9955 networking

The followings are the basic principles of ITU-T G.9955 network architecture:

1) The network is divided into domains:
   - The division of physical network into domains is logical; no physical separation is required, so domains may fully or partially overlap, i.e., some nodes of one domain may directly (on the physical layer) communicate with some nodes of another domain.
   - The number of domains within the physical network may be up to *N*.
   - Each domain is identified by a domain ID that is unique inside the network.
   - Nodes of different domains can communicate with each other via inter-domain bridges (IDB). The IDB functions are provided by one or more nodes dedicated to operate as an IDB.
   - Besides ITU-T G.9955 domains, a network may include alien domains. Connection between ITU-T G.9955 domains and alien domains is via L3 bridges.
   - Operation of different domain in the same network may be coordinated by the global master (GM). The function of the GM is associated with one of the nodes in one of the network's domains.

2) The domain is a set of nodes connected to the same medium:

- One node in the domain operates as a domain master.
- Each domain may contain up to *M* nodes (including the domain master).
- Each node in the domain is identified by a node ID that is unique inside the domain.
- All nodes that belong to the same domain indicate that by using the same domain ID. A particular single node can belong to only one domain.
- Nodes of the same domain can communicate with each other either directly or via other nodes of the same domain, called relay nodes. Domains where not all nodes can directly communicate to each other are called "partially connected".

3) Nodes of different ITU-T G.9955 networks:

- Can communicate via inter-network bridges (INB). The INB function is L3 bridging function associated with one or more dedicated nodes of network domains.

Generic network architecture of ITU-T G.9955 network is presented in Figure 5-1.

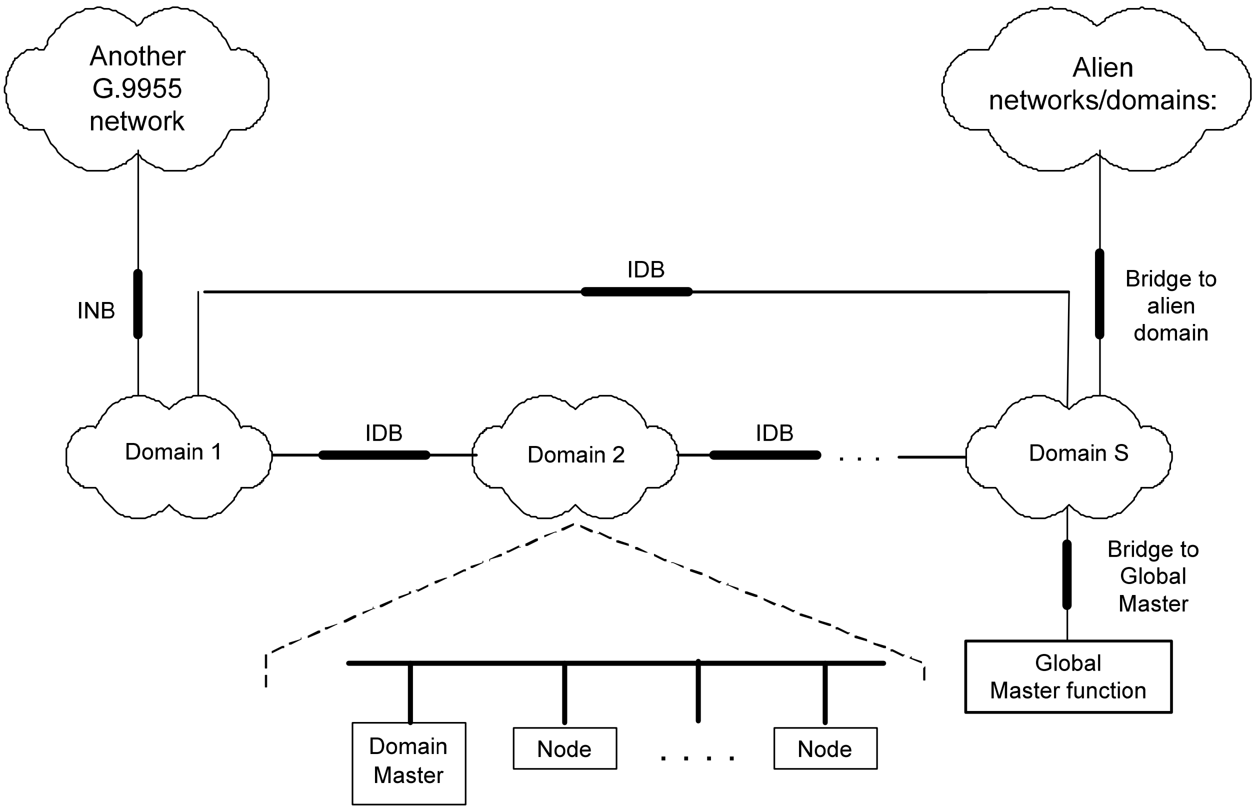


Figure 5-1 – Generic network architecture

The details of domain operation rules, types of communications inside a domain, and functionalities of domain master and endpoint nodes are beyond the scope of this Recommendation and described in [ITU-T G.9956], clause 5.1.3. An ITU-T G.9955-based network supports a mesh topology, that allows each node to communicate with any other node either directly, or via one or more relays, or via relays and IDBs. This allows supporting of any type of network topology, such as star, tree, multiple trees, and others. Maximum number of domains, N and maximum number of nodes per domain, *M* depend on the particular type of the network.

Alien domains and bridges to alien domains are beyond the scope of this Recommendation. [ITU-T G.9956] defines all necessary means to support the IDB and INB functionality and the exchange of relevant information.

The scope of this Recommendation is limited to the PHY layer of ITU-T G.9955 transceivers capable of operating either with extended capabilities (e.g., domain master, relay node, or combinations thereof) or without extended capabilities, as end-nodes.

5.1.2 Energy management network architecture and topology

An example architectural model of the EM network is presented in Figure 5-2. It contains the utility head-end, the multi-domain utility access network (UAN) and energy-management home area networks (EM-HAN) at customer premises (CP). Each EM-HAN can include one or more domains (not shown in Figure 5-2 – see clause 5.1.2.2 for EM-HAN architecture).

The domains of UAN incorporate all devices that are owned and physically belong to UAN (e.g., metres), while the HAN includes all customer-owned and some utility-owned devices related to energy management (e.g., home appliances, PSTs, EVSEs) that reside at the CP. In this example, each HAN is connected to a UAN via an INB; the INB function is implemented by the energy service interface (ESI).

NOTE – This architectural model is exclusively for reference purposes and does not limit the use of ITU-T G.9955 transceivers for other network configurations.

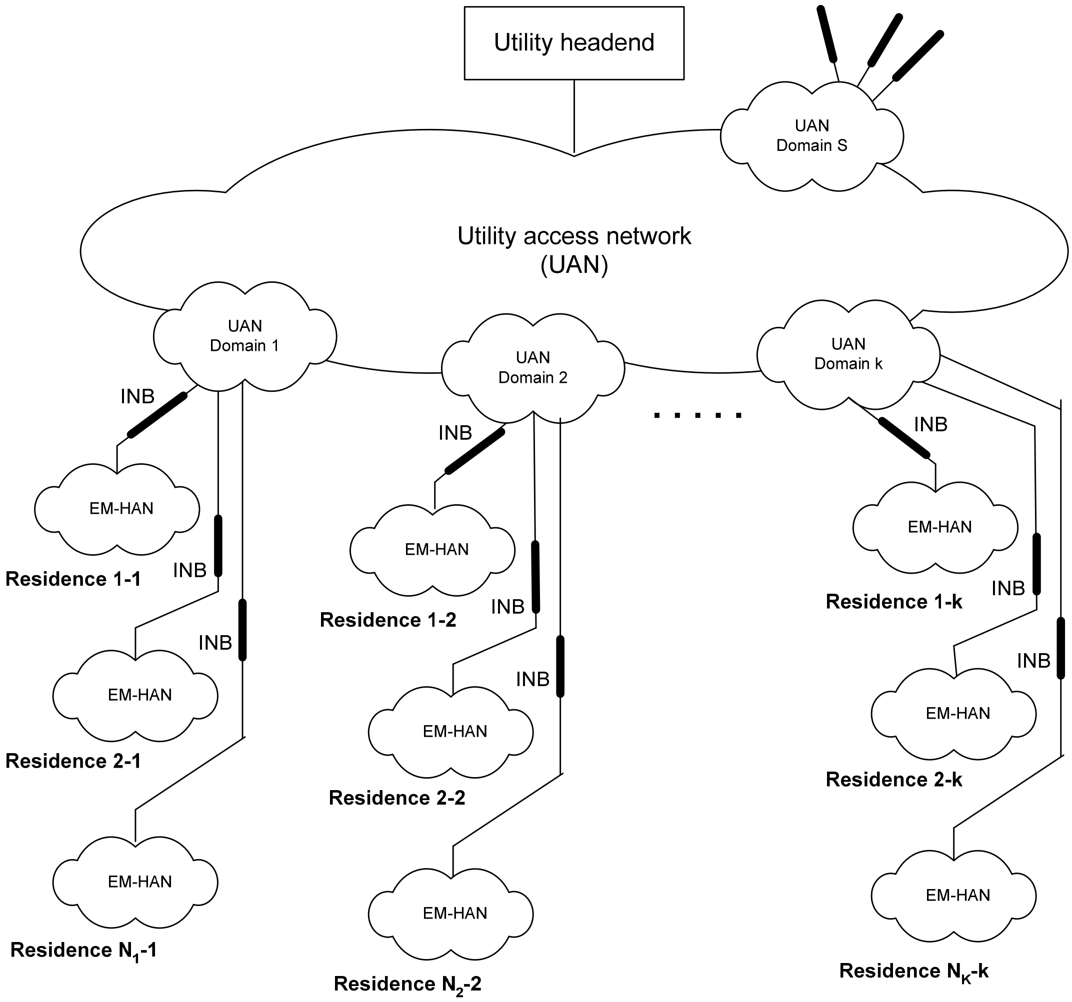


Figure 5-2 – Generic EM network architecture

5.1.2.1 Generic UAN architecture

The UAN is logically divided into domains. Each domain is associated with a particular set of ITU-T G.9955-based nodes connected to the same medium (usually, power line). A particular node can belong to only one domain (this does not preclude a physical device incorporating multiple logical nodes belonging to different domains).

All nodes of a UAN domain are controlled by a domain master; other nodes are called end-nodes.

Nodes of the same UAN domain can communicate to each other directly or via other nodes of the same domain (relay nodes). Two or more UAN domains may overlap: nodes of overlapping domains may "see" transmissions of each other and thus may interfere with each other.

The UAN domains may be connected to each other by one or more IDBs (see example in Figure 5-5) that allow nodes each domain to get connected at least to the utility head-end. Nodes of different UAN domains may communicate to each other using one or multiple IDBs. The GM function of the UAN coordinates operation of all UAN domains (resources, priorities, operational characteristics) via the corresponding domain masters. This high-level management function can be performed by one of the nodes of the UAN.

NOTE – The typical structure of UAN is a tree (see Appendix II, Figure II.3) and the utility head-end functions such as a global master of the UAN. There might be one or more nodes per CP, including a node implementing ESI to connect between UAN and EM-HAN.

Besides ITU-T G.9955 domains, a UAN may also include alien domains. These domains are established by non-ITU-T G.9955 technologies, wired and wireless. Alien UAN domains can be bridged to the ITU-T G.9955 domains using L3 bridges. The specification of bridges to alien UAN domains is beyond the scope of this Recommendation.

5.1.2.2 Generic HAN architecture

The EM-HAN (further called "HAN") is logically divided into domains. Each domain shall be associated with a particular set of ITU-T G.9955 nodes. A particular node can belong to only one domain. Nodes of the same HAN domain communicate via the medium over which the domain is established. The nodes of different HAN domains communicate to each other via IDBs. The HAN is connected to the UAN (if necessary) via an INB which is a part of the gateway between the HAN and the UAN. The interface between the UAN and the HAN is called ESI.

The domains of the HAN are established using in-home wiring, usually power line, but may also use other type of wired media. One of the HAN domain devices is the domain master, while all other nodes are called end-nodes. Two or more HAN domains may overlap: nodes of overlapping domains may "see" transmissions of each other and may interfere with each other.

Besides ITU-T G.9955 domains, a HAN may include alien domains. These domains can be established using in-home wireline or wireless media. Alien HAN domains can be bridged to the ITU-T G.9955 domains using L3 bridges. The specification of bridges to alien HAN domains is beyond the scope of this Recommendation.

When coordination between domains of the HAN (resources, priorities, operational characteristics) is required, it is provided by the GM function of one of the nodes, which is a high-level management function that may also convey the relevant functions initiated by a remote management system.

Generic architecture of a HAN containing both ITU-T G.9955 domains and alien domains is presented in Figure 5-3.

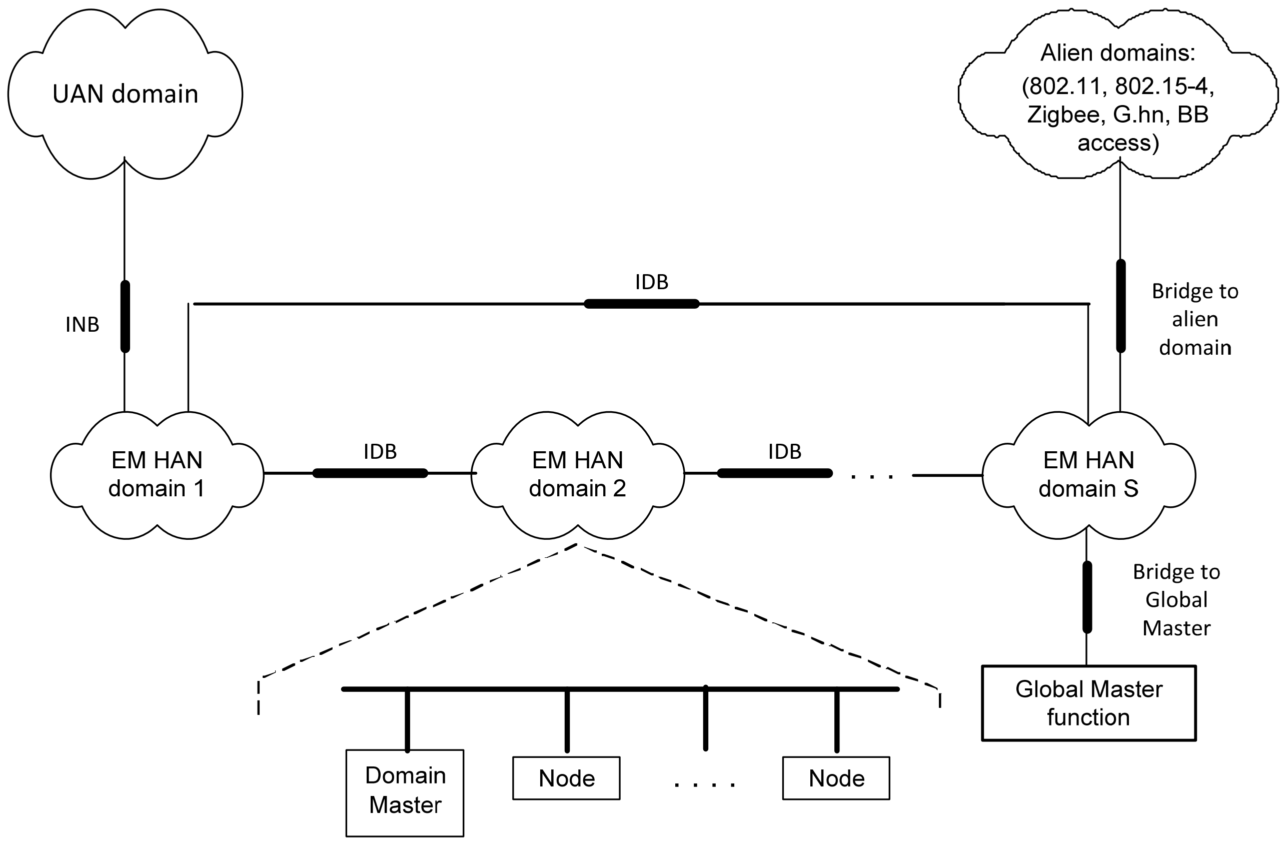


Figure 5-3 – Generic architecture of EM-HAN

NOTE 1 – It is not necessary that all IDBs presented in Figure 5-3 be used. Depending on the application, domains could be daisy-chained, or star-connected, or could use another connection topology. Support of multi-route connections between domains is for further study.

NOTE 2 – The end-nodes of the HAN are also those operating in the residence electric vehicle charging facility (EVCF), both in its stationary part, the electrical vehicle supply equipment (EVSE) and in the plug-in electrical vehicle (PEV).

An example of HAN containing one ITU-T G.9955 domain and one alien domain is presented in Figure 5-4. The nodes of the ITU-T G.9955 domain include one installed in an EVSE and one serving to connect the in-home energy management system (EMS). The alien domain is bridged to the ITU-T G.9955 domain via L3 IDB.

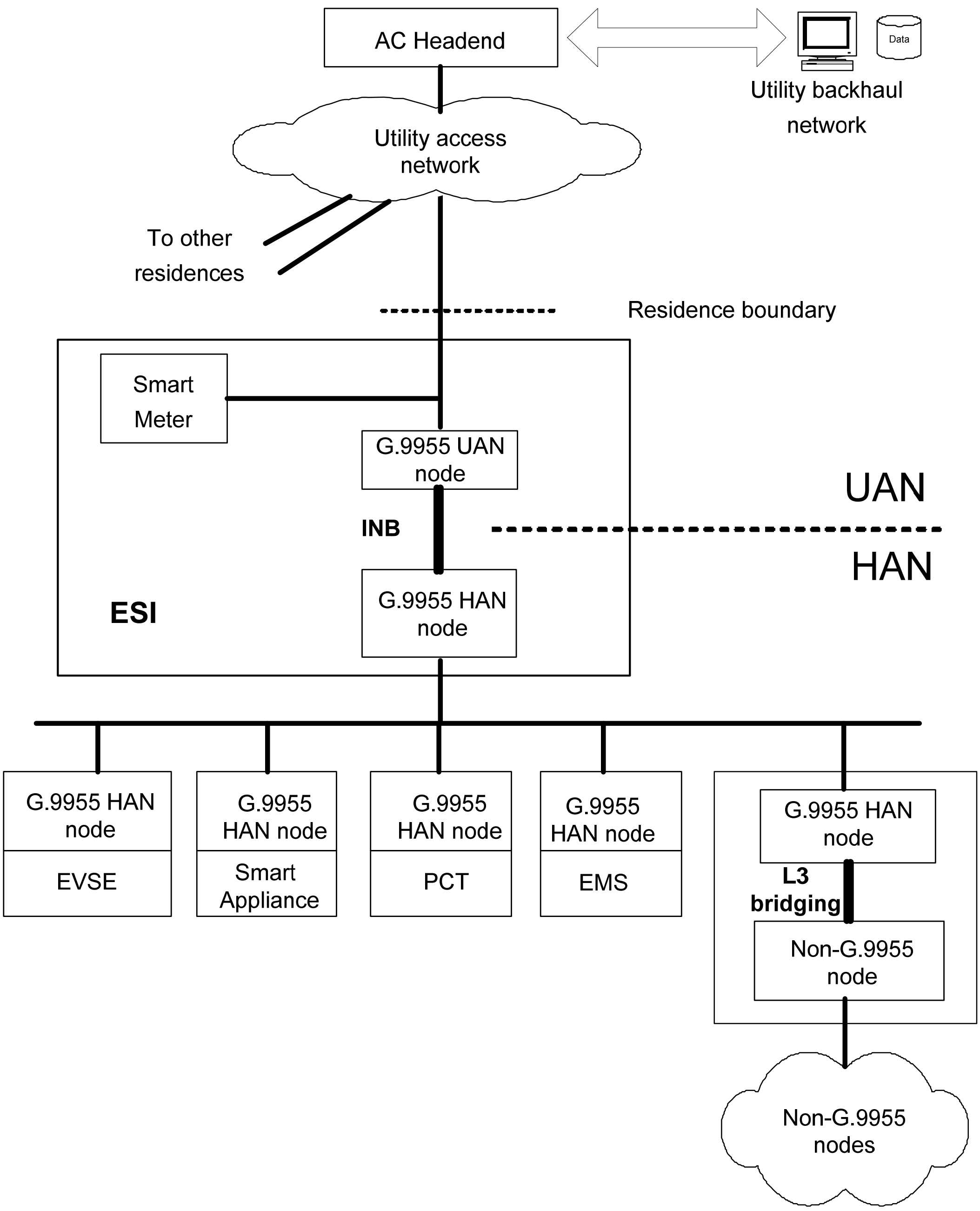


Figure 5-4 – Example of functional diagram of an EM-HAN connected to utility

5.1.2.3 Coexistence with other PLC networks

Two mechanisms are defined to allow coexistence with other PLC operating in the same frequency range:

– Frequency division (FD) coexistence mechanism – allows suppressing interference from ITU-T G.9955 into a particular frequency band or bands by using non-overlapping ITU-T G.9955 bandplans (see clause 7.5). Flexible use of different bandplans provides an opportunity to separate systems operating over the same medium in non-overlapping bandplans. The FD coexistence mechanism can provide coexistence with both the narrowband FSK/PSK PLC systems and wideband PLC systems;

– Frequency notching coexistence mechanism – shall be used to suppress interference from ITU-T G.9955 into a particular (relatively narrow) frequency range by notching out one or more subcarriers (see clause 7.6.1). Frequency notching allows ITU-T G.9955 to coexist with the existing narrowband FSK/PSK systems operating over the same frequency band;

– Preamble-based coexistence mechanism – shall be used by ITU-T G.9955 to fairly share the medium with other types of PLC technologies operating over the same frequency band (and utilizing this coexistence mechanism). The definition of this coexistence mechanism is for further study. This same coexistence mechanism also facilitates coexistence between the ITU-T G.9955 implementations using different overlapping bandplans.

The above coexistence mechanisms can be applied simultaneously, enabling ITU-T G.9955 coexistence with multiple PLC technologies operating over the same medium.

5.2 Reference models

5.2.1 Protocol reference model of transceiver

The protocol reference model of a transceiver is presented in Figure 5-5. It includes three main reference points: application interface (A-interface), physical medium-independent interface (PMI), and medium-dependent interface (MDI). Two intermediate reference points, x1 and x2, are defined in the data link layer, and two other intermediate reference points, α and δ, are defined in PHY layer, Figure 5-5. The shaded part of the reference model is defined in this Recommendation; the non-shaded part is defined in the [ITU-T G.9956].

The MDI is a physical interface defined in the terms of physical signals transmitted over a medium and mechanical connection to the medium (clause 5.2.2.3).

The PMI is both medium independent and application independent. The A-interface is network layer (Layer 3) protocol specific (e.g., Ethernet, IP). Both PMI and A-interface are defined as functional interfaces, in terms of sets of primitives exchanged across the interface.

All intermediate reference points are medium independent and are defined as functional (logical) interfaces in the terms of logical primitives exchanged across these reference points.

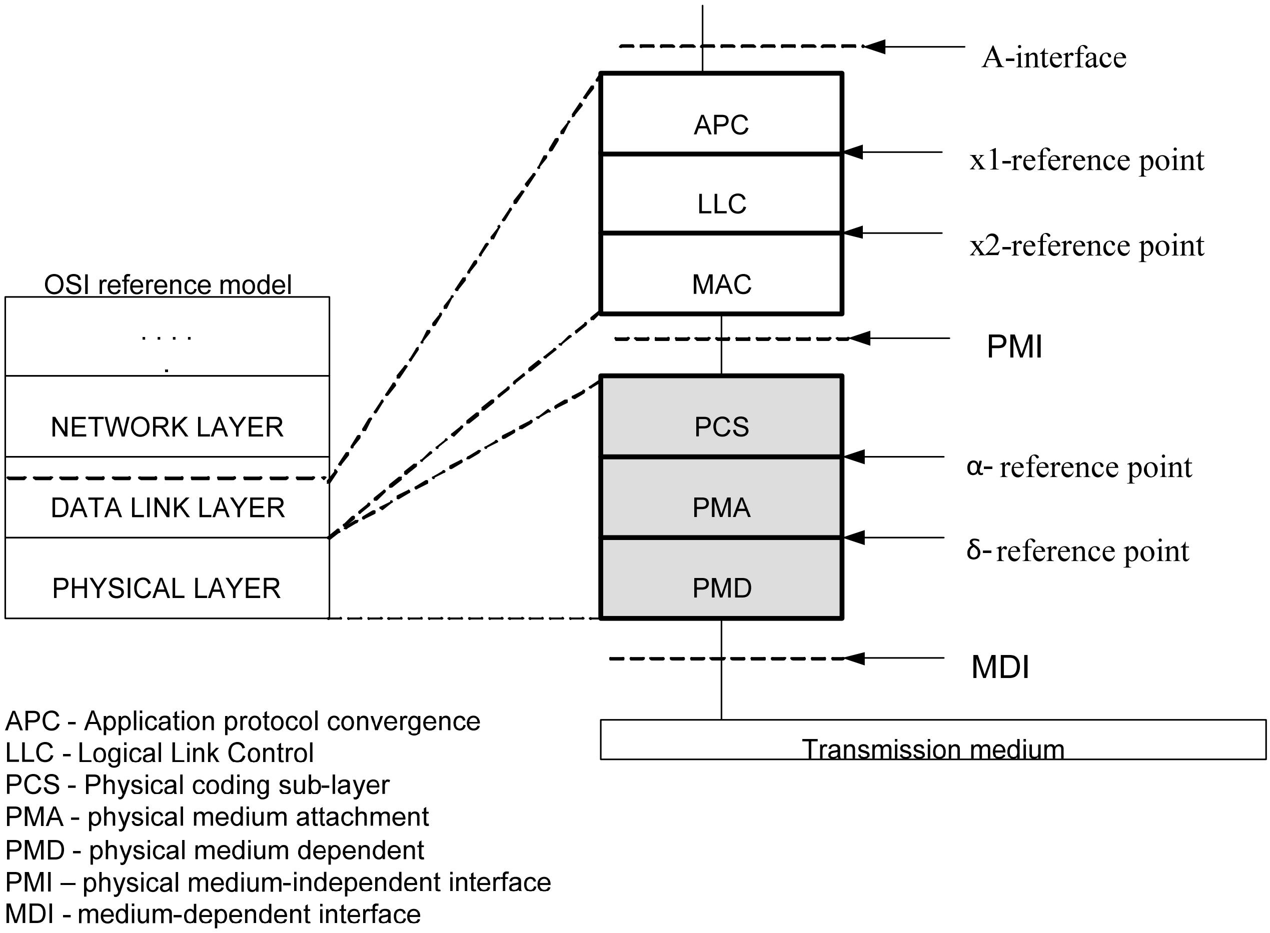


Figure 5-5 – Protocol reference model of ITU-T G.9955 transceiver

The application protocol convergence sub-layer (APC) provides an interface with the network layer (layer 3), also called application entity (AE), which operates with an application-specific protocol, such as IP. The APC also provides the bit rate adaptation between the AE and the transceiver.

The logical link control sub-layer (LLC) coordinates transmission of nodes in accordance with rules of operation in the domain. In particular, it is responsible for establishing, managing, resetting and terminating all connections of the node with other nodes in the domain. The LLC also facilitates Quality of Service (QoS) constraints defined for its established connections.

The medium access control sub-layer (MAC) controls access of the node to the medium using medium access protocols defined in clause 7.4 of the Recommendation.

The physical coding sub-layer (PCS) provides bit rate adaptation (data flow control) between the MAC and PHY and encapsulates transmit MPDUs into the PHY frame and adds PHY-related control and management overhead.

The physical medium attachment sub-layer (PMA) provides forward error correction encoding and interleaving of the PHY frame content (header and payload) for transmission over the medium.

The physical medium dependent sub-layer (PMD) modulates encoded PHY frames for transmission over the medium using orthogonal frequency division modulation (OFDM). In the receive direction, PMD demodulates PHY frames incoming from the medium.

The functionality of the DLL and PHY is the same for any type of medium (e.g., utility access LV and MV wires, in-home power line wires, in-home phone wires, or similar) or any application, although their parameters may be medium-specific or application-specific. With appropriate parameter settings (determined by the transceiver management functions), operation of a single node and all nodes in the domain can be configured to fit the type of the medium or a particular application.

Partitioning into data and management functions are not presented in Figure 5-5 and described in clause 5.2.2.

5.2.2 Functional description of interfaces

This clause contains the functional description of the ITU-T G.9955 transceiver interfaces (reference points) based on the protocol reference model presented in Figure 5-6. The interfaces shown in Figure 5-6 are defined in this Recommendation.

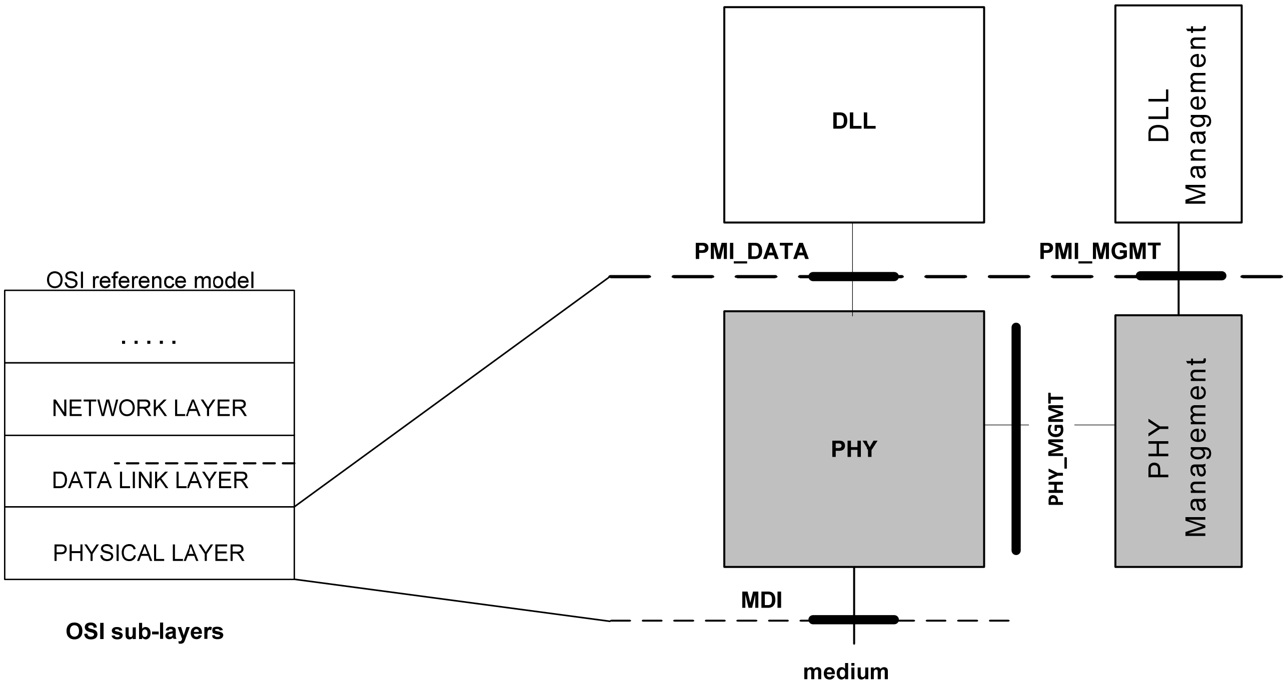


Figure 5-6 – Transceiver reference points related to PHY

The model in Figure 5-6 shows interfaces related to the application data path (PMI_DATA, and MDI), the management data path (PMI_MGMT), and management interfaces between data and management plains of the PHY (PHY_MGMT). All interfaces are specified as reference points in terms of primitive flows exchanged between the corresponding entities. The description does not imply any specific implementation of the transceiver interfaces.

5.2.2.1 Physical medium-independent interface (PMI)

The PMI is described in terms of primitives exchange between the DLL and PHY layer presented in Table 5-1; the direction of each primitive flow indicates the entity originating the primitive. Both transmit and receive data primitives are exchanged by MAC protocol data units (MPDUs). The details of the PMI_DATA and PMI_MGMT primitives are defined in clause 7.8.

Table 5-1 – PMI primitive description

Primitive	Direction	Description
PMI-interface data primitives		
PMI_DATA.REQ	DLL → PHY	DLL requests the PHY to transmit an MPDU or an ACK frame
PMI_DATA.CNF	PHY → DLL	PHY frame transmission status (transmission complete, not complete, failed)
PMI_DATA.IND	PHY → DLL	Received frame passed by the PHY to the DLL
PMI-interface management & control primitives		
PMI_MGMT.REQ	DLL → PHY	Transmission and configuration parameters asserted by the DLL
PMI_MGMT.CNF	PHY → DLL	Confirms transmission and configuration parameters asserted by DLL (accepted or rejected)
PMI_MGMT.IND	PHY → DLL	Transmission parameters of the received frame payload and channel characteristics reported by the PHY
PMI_MGMT.RES	DLL → PHY	Acknowledges transmission parameters of the received frame and channel characteristics reported by the PHY
NOTE – Primitives presented in this table are exclusively for descriptive purposes and do not imply any specific implementation.		

5.2.2.2 Medium-dependent interface (MDI)

Functional characteristics of the MDI are described by two signal flows:

- Transmit signal (TX DATA) is the flow of PHY frames transmitted onto the medium.
- Receive signal (RX DATA) is the flow of PHY frames received from the medium.

Electrical characteristics of the MDI are described in clause 7.7.

5.2.2.3 Peer interfaces between data and management paths

5.2.2.3.1 PHY_MGMT reference point

This reference point defines control and management primitives related to all sub-layers of the PHY (PCS, PMA, PMD), as defined in Figure 5-5. These primitives (PCS_MGMT, PMA_MGMT, and PMD_MGMT) are shown in DLL functional model, clause 7.1, and defined in clause 7.8.

5.2.3 Functional model of transceiver

The functional model of a transceiver is presented in Figure 5-7. It addresses nodes without extended capabilities as well as nodes with extended capabilities such as domain master. This Recommendation addresses only the shaded part of the functional model; the non-shaded part is addressed in [ITU-T G.9956].

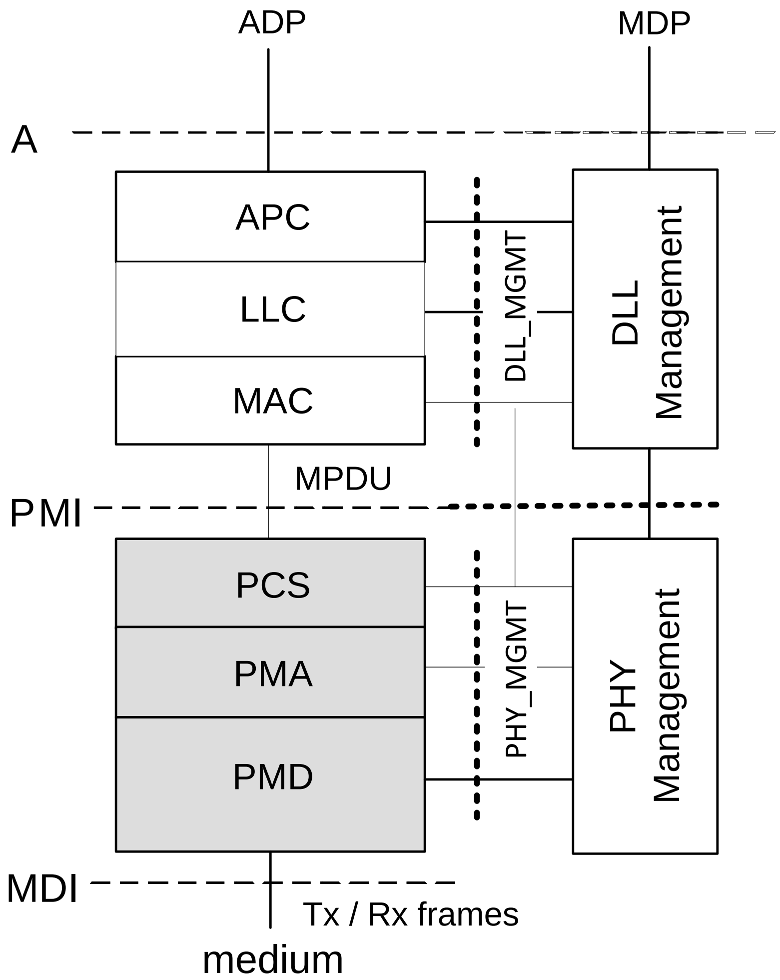


Figure 5-7 – Functional model of ITU-T G.9955 transceiver

The detailed description of the functional model of the PHY layer is presented in clause 7.1.

6 Conventions

6.1 Bit ordering convention

A block of data composed of multiple octets shall be ordered by octet numbers in ascending order: 'octet 0' for the first octet, 'octet 1' for the second octet, and so on. If a block of data is segmented into multiple fields, the size of each field shall be expressed in terms of bits. The field may not be of an integer number of octets. The location of each field within a block of data shall be described as follows:

- The octets of an N-octet data block are ordered with numbers from 0 (first octet) to N–1 (last octet).
- The block is divided into non-overlapping groups of octets. Each group contains an integer number of consecutive octets, numbered from J to J+V–1, where V is the size of the group, and is described as a bit string with 'bit 0', the LSB of the octet with the smallest number (J), and 'bit (8×V–1)', the MSB of the octet with the largest number (J+V–1).
- Each group is divided into one or more fields, where the boundaries of each field are determined by the LSB and the MSB of the bits of the group that contains this field.

Any block of data or part of it shall be passed over the protocol stack with the octet having the smallest number first, i.e., octet 0 shall be the first octet of the block to be passed. Within each group of octets, LSB (bit 0) of each octet shall be passed first.

Table 6-1 shows an example of a field description used throughout this Recommendation. The 'Octet' column represents the octet numbers for a group of octets to which a specific field belong, and 'Bits' column represents the bit location within this group of octets. In the presented example, there are 4 groups of octets:

- Group 1 = Octet 0, fields A, B, C, D
- Group 2 = Octets 1 and 2, fields E, F
- Group 3 = Octet 3, field G
- Group 4 = Octets 4 to 7, field H.

Figure 6-1 illustrates a mapping of these fields onto corresponding octets based on the example given in Table 6-1.

Table 6-1 – Example of field description

Field	Octet	Bits	Description
A	0	[2:0]	…
B	0	[3]	…
C	0	[4]	…
D	0	[7:5]	…
E	1	[1:0]	…
F	1-2	[15:2]	…
G	3	[7:0]	…
H	4-7	[31:0]	…

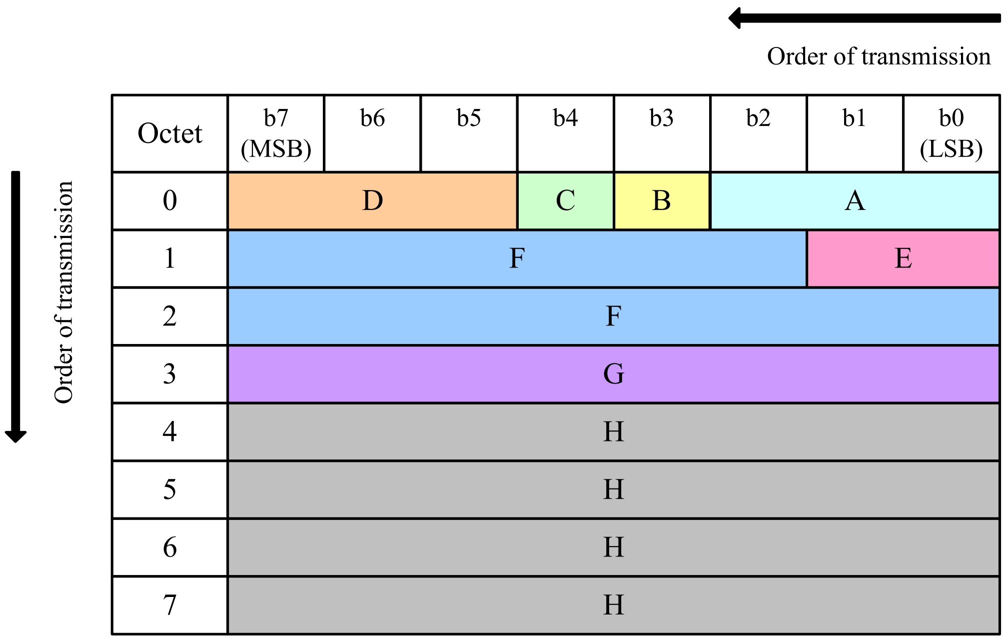


Figure 6-1 – Example of mapping fields onto groups of octets

7 Physical layer (PHY) specification

7.1 Functional model of PHY

The functional model of the PHY is presented in Figure 7-1. The PMI and MDI are, respectively, two demarcation reference points between the PHY and MAC and between the PHY and transmission medium. Internal reference points δ and α show separation between the PMD and PMA, and between the PCS and PMA, respectively. The data primitives and management primitives at the PMI reference point and MDI reference point are defined in clauses 7.8.1 and 7.8.2, respectively. The primitives of MDI reference point are defined in clause 7.7.

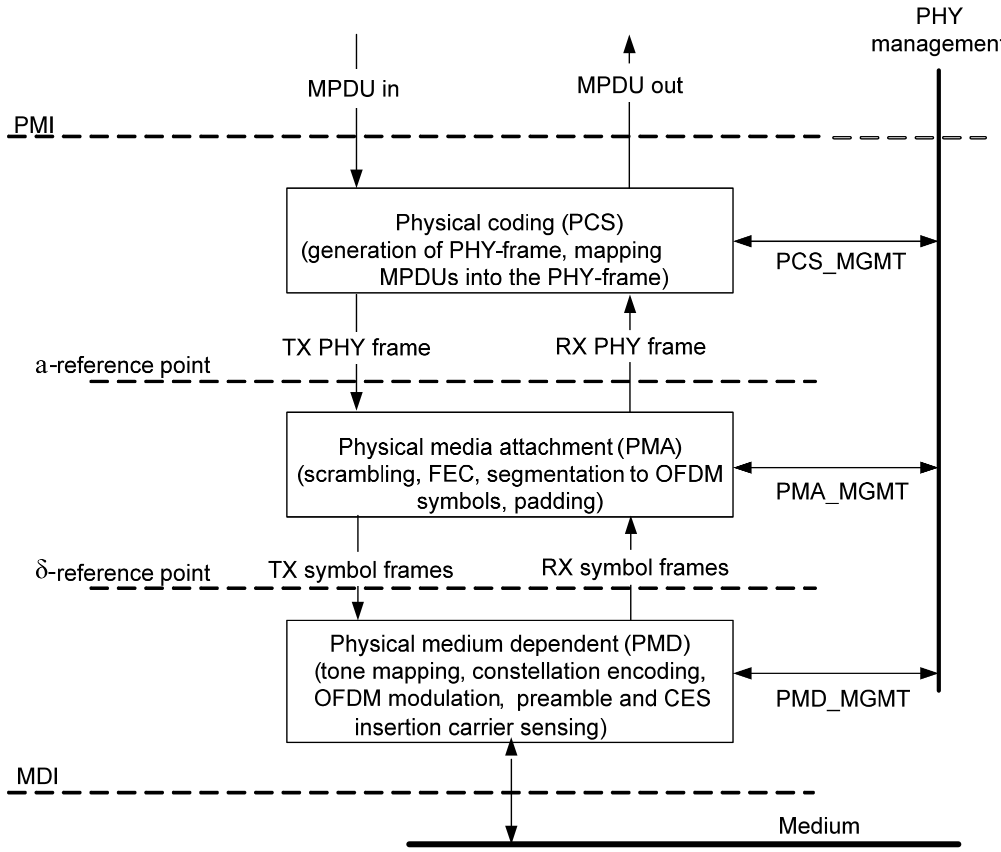


Figure 7-1 – Functional model of PHY

In the transmit direction, data enters the PHY from the MAC via the PMI by blocks of bytes called MAC protocol data units (MPDUs). The incoming MPDU is mapped into the PHY frame originated in the PCS, scrambled and encoded in the PMA, modulated in the PMD, and transmitted over the medium using OFDM modulation with relevant parameters. In the PMD, a preamble and channel estimation symbols (CES) are added to assist synchronization and channel estimation in the receiver.

In the receive direction, a frame entering from the medium via the MDI is demodulated and decoded. The recovered MPDU is forwarded to the MAC via the PMI. The recovered PHY frame header (PFH) is processed in the PHY to extract the relevant frame parameters specified in clause 7.2.3.

7.2 Physical coding sub-layer (PCS)

The functional model of the PCS is presented in Figure 7-2. It is intended to describe in more detail the PCS functional block presented in Figure 7-1.

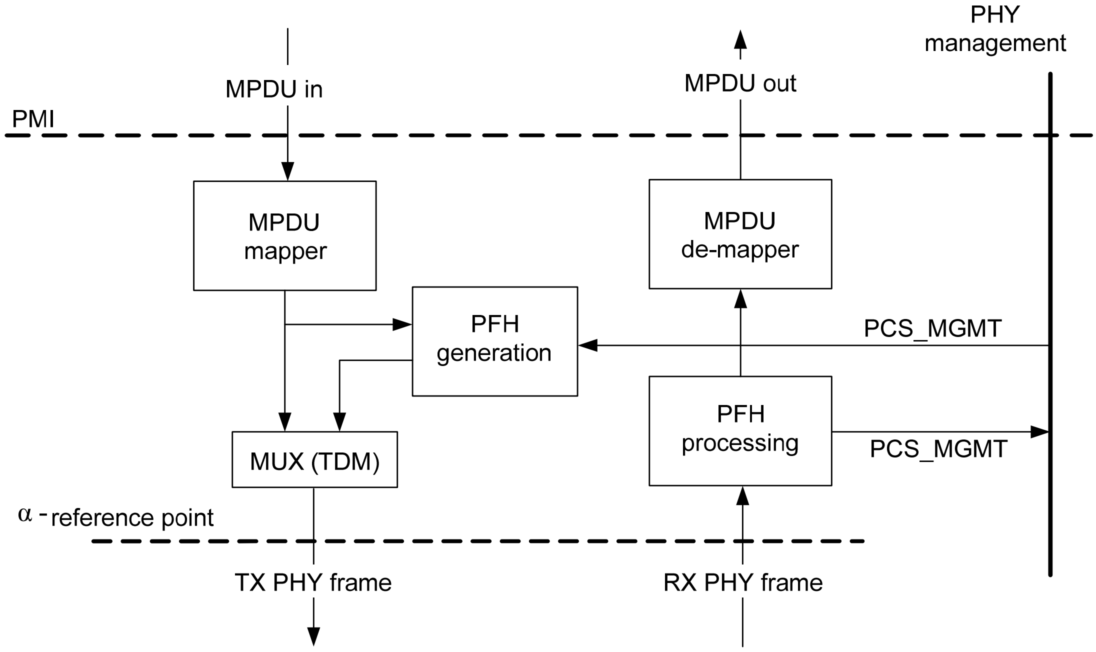


Figure 7-2 – Functional model of PCS

In the transmit direction, the incoming MPDU is mapped into a payload field of a PHY frame (clause 7.2.1) as described in clause 7.2.2. Further, the PFH is generated and added to form a TX PHY frame. The TX PHY frame is passed via the α-reference point for further processing in the PMA.

In the receive direction, the decoded PHY frame payload and header are processed and originally transmitted MPDU is recovered from the payload of the received PHY frame (RX PHY frame) and submitted to the PMI. Relevant control information conveyed in the PFH is processed and submitted to the PHY management entity, Figure 7-2.

The management primitives of the PCS (PCS_MGMT) are defined in clause 7.8.2.

7.2.1 PHY frame format

The format of the PHY frame is presented in Figure 7-3. The PHY frame includes preamble, PFH, channel estimation symbols (CES) and payload. Preamble and CES are added to the PHY frame in the PMD. The PFH and the payload are generated and formatted in the PCS. Preamble and CES do not carry any data and are intended for synchronization and initial channel estimation only. The structure of the preamble and its parameters are specified in clause 7.4.5, and for the CES, the parameters are defined in clause 7.4.6.

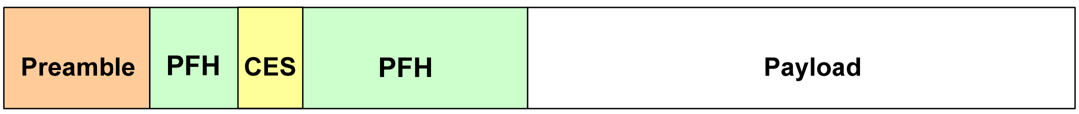


Figure 7-3 – Format of the PHY frame

All components of the PHY frame (preamble, PFH, CES, and the payload) consist of an integer number of OFDM symbols.

The number of symbols of the PFH depends on the applied bandplan, as described in Table 7-16. All symbols in the PFH for a particular bandplan are transmitted using a predefined set of coding and modulation parameters, as defined in clauses 7.3.2.3, 7.4.2.5, 7.4.7).

The length of the payload may vary from frame to frame; payload may also be of zero length. For payload, different coding and modulation parameters (including number of repetitions, tone masking, and bit loading) can be used in different PHY frames, depending on channel and noise characteristics of the medium. The coding and modulation parameters of the payload are defined in the PFH, as described in clause 7.2.3.2.

PHY frames are divided into several types, depending on their purpose. The type of the PHY frame is indicated in the PFH. The types of PHY frames specified in this Recommendation are summarized in Table 7-1. The format of the PHY frame of each type is defined in clause 7.2.3.1.

Table 7-1 – PHY frame types

Frame Type	Payload	Description
Type 1 frame	√	A PHY frame carrying a payload field with user data or management data.
Type 2 frame	√	Reserved by ITU-T (Note)
Type 3 frame	None	A PHY frame containing no payload field.
Type 4 frame	√	Reserved by ITU-T (Note)
NOTE – Upon reception of a frame with type defined as "reserved" (i.e., frame type 2 or 4) for the current revision of the Recommendation, a node shall: – discard the received PHY frame; – apply medium access rules based on the value of the Duration field indicated on the PFH (as specified in clause 7.2.3.2.2).		

7.2.2 MPDU mapping

MPDUs are passed to the PHY as an ordered sequence of bytes, which are processed as an ordered stream of bits from LSB to MSB within each byte. The first bit of the MPDU shall be the first transmitted bit of the payload.

The only valid sizes of MPDU are those that meet the representation presented in Table 7-5. Padding of the MPDUs to match the valid values indicated in Table 7-5 shall be done by the DLL, as defined in clause 8.1.3.1, [ITU-T G.9956]. Incoming MPDUs of invalid values shall be dropped.

7.2.3 PHY frame header (PFH)

The PFH is PHY_H bits long and comprise of a common part and a variable part. The common part contains fields that are common for all PHY frame types. The variable part contains fields according to the PHY frame type. The type of the PHY frame is indicated by the FT field. The content of the PFH is protected by a 12-bit header check sequence (HCS). The PFH format is defined in Table 7-2. The size of the variable field depends on the bandplan as specified in Table 7-2.

Table 7-2 – PFH format

Field	Number of bits	Description	Comment
FT	2	Frame type	Common part
FTSF	Variable	Frame-type specific field	For FCC and FCC-2 bandplans, the FTSP field is 60 bits For CENELEC and FCC-1 bandplans, the FTSP field is 28 bits
HCS	12	Header check sequence (12 bits)	Common part

The ordering of bits and bytes of the PFH is detailed in clause 7.2.3.3.

7.2.3.1 Common part fields

7.2.3.1.1 Frame type (FT)

The Frame type (FT) field is a 2-bit field which indicates the type of the PHY frame as described in Table 7-3.

Table 7-3 – Encoding of the FT field

Frame type	Value
Type 1 frame	00
Type 2 frame	01
Type 3 frame	10
Type 4 frame	11

7.2.3.1.2 Header check sequence (HCS)

The HCS field is intended for PFH verification. The HCS is a 12-bit cyclic redundancy check (CRC) and shall be computed over all the fields of the PFH in the order they are transmitted, starting with the LSB of the first field of the PFH (FT) and ending with the MSB of the last field of the FTSF.

The HCS shall be computed using the following generator polynomial of degree 12:

$$G(x) = x^{12}+x^{11}+x^{3}+x^{2}+x+1.$$

The value of the HCS shall be the remainder after the content of the HCS calculation fields (treated as a polynomial where the first input bit is associated with the highest degree, x^{PHY_H-13}, where PHY_H is the PFH length in bits, and the last input bit is associated with x^0) is multiplied by x^{12}, then XOR-ed with a value of all-ones ($0FFF_{16}$), and then divided by G(x).

The HCS field shall be transmitted starting with the coefficient of the highest order term (i.e., with x^{11}).

7.2.3.2 Variable part fields

The content of the variable part of the PFH depends on the frame type (FT field value) and shall be as shown in Figure 7-4 and further described in Table 7-4.

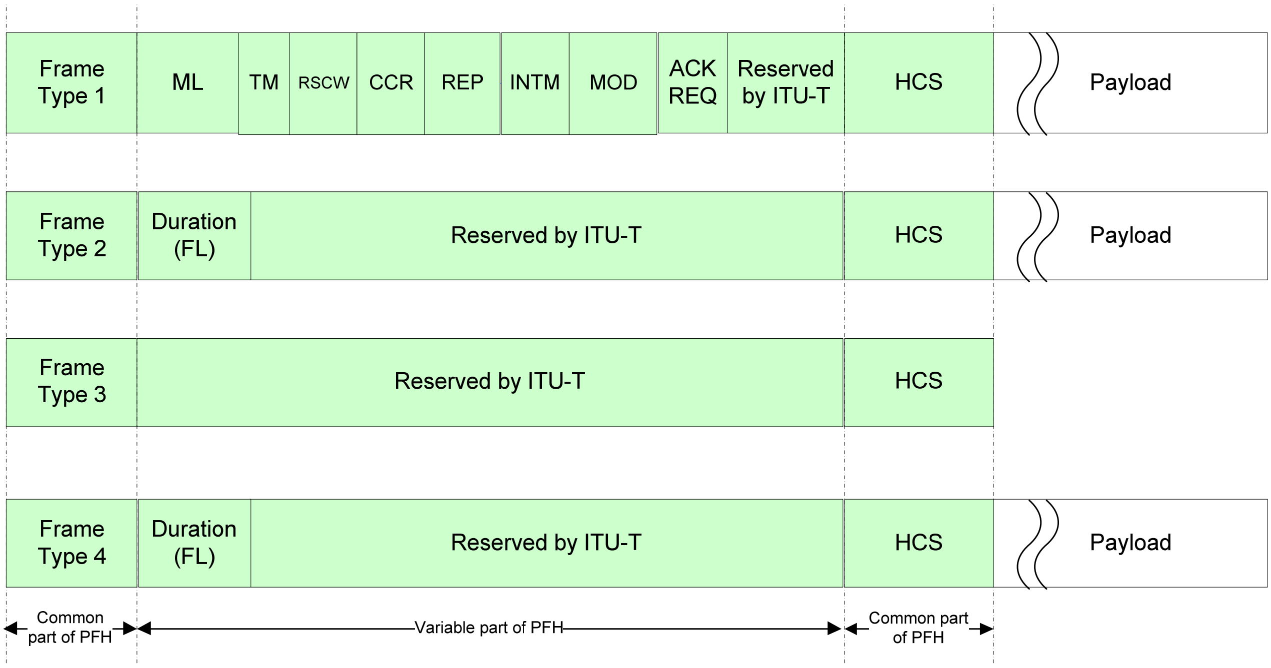


Figure 7-4 – Content of the PFH depending on the Frame Type field

Table 7-4 – Fields comprising the variable part of the PFH

Field	Number of bits		Description	Reference
	CENELEC, FCC-1	FCC, FCC-2		
MPDU Length (ML)	8	8	Indicate the length of the payload in bytes expressed using logarithmic scale	Clause 7.2.3.2.1
Duration (FL)	7	10	Indicates the duration of the PHY frame sequence expressed in OFDM symbols.	Clause 7.2.3.2.2
Tone mask (TM)	8	40	Defines the tone mask used to transmit the payload	Clause 7.2.3.2.3
RS code word size (RSCW)	1	1	Indicates the maximum value of the RS code word size to be used for payload encoding.	Clause 7.2.3.2.4
CC Rate (CCR)	1	1	Indicates the coding rate of the convolutional code used to transmit the payload	Clause 7.2.3.2.5
Repetitions (REP)	3	3	Indicates number of repetitions used to transmit the payload	Clause 7.2.3.2.6
Interleaving Mode (INTM)	1	1	Indicates the interleaving mode used to transmit the payload	Clause 7.2.3.2.7
Modulation (MOD)	2	2	Indicates the modulation used to transmit the payload	Clause 7.2.3.2.8

Table 7-4 – Fields comprising the variable part of the PFH

Field	Number of bits		Description	Reference
	CENELEC, FCC-1	FCC, FCC-2		
Acknowledgement request (ACK REQ)	2	2	Indicates whether the receiver should respond with an ACK to indicate MPDU reception status	Clause 7.2.3.2.9
Reserved by ITU-T	FT dependent	FT dependent	Reserved bits for future use by ITU-T.	Clause 7.2.3.2.10

7.2.3.2.1 MPDU length (ML)

This 8-bit field indicates the number of bytes in the MPDU. The number of bytes is represented based on a mapping between the unsigned integer value in ML field and the MPDU size in bytes as shown in Table 7-5.

Table 7-5 – Mapping of the ML field to MPDU size

From ML_{10} value	To ML_{10} value	Mapped MPDU [bytes]
0	63	$ML_{10} + 1$
64	127	$65 + 2 \times (ML_{10} - 64)$
128	191	$193 + 8 \times (ML_{10} - 128)$
192	255	$697 + 16 \times (ML_{10} - 192)$
NOTE – ML_{10} is a decimal representation of ML field.		

7.2.3.2.2 Duration (FL)

This 7-bit/10-bit unsigned integer field indicates the duration of the PHY frame sequence, excluding the duration of the PFH and the preamble of the transmitted frame, represented in multiples of K_{Dur} OFDM symbols as specified in Table 7-6.

NOTE 1 – The duration of the preamble and the PFH is the same for all frames transmitted by nodes of the same domain (see clause 7.8).

NOTE 2 – The duration indicated in the FL field is counted from the beginning of the first symbol of the transmitted frame to the end of the last symbol of the last frame in the frame sequence (the last symbol of the ACK frame, if requested). More details are described in [ITU-T G.9956], clause 8.3.3.1.

This field is used with Frame Type 2 and Frame Type 4 only.

Table 7-6 – K_{Dur} value per bandplan

Band	K_{Dur}
CENELEC	4
FCC-1	8
FCC, FCC-2	1

7.2.3.2.3 Tone mask (TM)

This 8-bit/40-bit field is a bitmap that indicates whether a particular subcarrier group is active (i.e., is from ASC set) or inactive (i.e., is from ISC set), as defined in clause 7.4.2.1. The actual band is divided into groups of G tones, according to the applied bandplan, as specified in clause 7.4.2.4, and each bit in the TM bitmap shall indicate whether the G consecutive tones are active (the respective bit in the TM field equals 1) or inactive (the respective bit in the TM field equals 0). The LSB of the TM field corresponds to the first group of subcarriers (with the lowest indices).

This TM field size and the value of G for different bandplans shall be as specified in Table 7-4 and in Table 7-7, respectively.

Table 7-7 – Value of G for different bandplans

Bandplan	G
CENELEC A	4 (Note)
CENELEC B	2
CENELEC CD	2
FCC-1	4
FCC, FCC-2	4
NOTE – The tone mask settings of the last tone (#33) shall be the same as the value in bit b7 (i.e., masked if set to 0, and unmasked if set to 1).	

To indicate use of BAT Type 0, BAT Type 1, and BAT Type 5, the TM field shall be set to all zeros, and MOD field value shall be set to 00 to indicate use of BAT Type 0 and to 01 to indicate use of BAT Type 1 and to 10 to indicate use of BAT Type 5 and to 11 to indicate use of BAT Type 7.

7.2.3.2.4 RS code word size (RSCW)

This 1-bit field indicates the value to use as the maximum RS code word size for dividing the MPDU into code words (as specified in clause 7.3.3).

If the maximum RS code word size of 239 bytes is used, the field shall be set to 0.

If the maximum RS code word size of 128 bytes is used, the field shall be set to 1.

7.2.3.2.5 CC Rate (CCR)

This 1-bit field indicates whether CC Rate of 1/2 or 2/3 for convolutional encoding is used in the payload.

If CC Rate of 1/2 is used, the field value shall be set to 0.

If CC rate of 2/3 is used, the field value shall be set to 1.

7.2.3.2.6 Repetitions (REP)

This 3-bit field indicates the number of repetitions used in the payload (value of the R for the payload encoding specified in clause 7.3.3).

The mapping of the field values to the values of R parameter of the FRE is given in Table 7-8.

Table 7-8 – Encoding of the REP field

REP field value	R parameter of the FRE
000	1
001	2
010	4
011	6
100	12
101-111	Reserved by ITU-T

7.2.3.2.7 Interleaving mode (INTM)

This 1-bit field indicates whether IoF or IoAC interleaving mode is used in the payload.

If the IoF mode is used, the field shall be set to 0.

If the IoAC mode is used, the field shall be set to 1.

7.2.3.2.8 Modulation (MOD)

This 2-bit field indicates the modulation used to transmit the payload, as specified in clause 7.4.3.

The mapping of the field values to the modulation used for payload transmission is given in Table 7-9.

Table 7-9 – Encoding of the MOD field

Mod field value	Modulation used
00	1-Bit
01	2-Bit
10	3-Bit
11	4-Bit

7.2.3.2.9 Acknowledgement request (ACK REQ)

This 2-bit field indicates to the receiver whether the transmitter requires it to respond with an ACK frame and indicates the type of the ACK frame as follows:

– 00 – no ACK frame is requested
– 10 – a regular Imm-ACK frame is requested
– 01 – an extended Imm-ACK frame is requested
– 11 – reserved by ITU-T.

The formats of the Imm-ACK frame and the Extended Imm-ACK frame are defined in [ITU-T G.9956], clause 8.3.3.1.1.

7.2.3.2.10 Reserved by ITU-T

The bits reserved by ITU-T are for further study. These bits shall be set to zero by the transmitter and ignored by the receiver.

The field size in bits depends on the frame type.

7.2.3.3 Ordering of the bits and bytes of the PFH

The ordering of the bits and bytes of the PFH (per frame type and bandplan) is shown in Table 7-10 through Table 7-13.

Table 7-10 – Ordering of bits and bytes of the PFH for Frame Type 1

Field	CENELEC, FCC-1	FCC, FCC-2	Description
	Bits	**Bits**	
FT	[1:0]	[1:0]	Clause 7.2.3.1.1
ML	[9:2]	[9:2]	Clause 7.2.3.2.1
TM	[17:10]	[49:10]	Clause 7.2.3.2.3
RSCW	[18]	[50]	Clause 7.2.3.2.4
CCR	[19]	[51]	Clause 7.2.3.2.5
REP	[22:20]	[54:52]	Clause 7.2.3.2.6
INTM	[23]	[55]	Clause 7.2.3.2.7
MOD	[25:24]	[57:56]	Clause 7.2.3.2.8
ACK REQ	[26]	[58]	Clause 7.2.3.2.9
Reserved by ITU-T	[29:27]	[61:59]	Clause 7.2.3.2.10
HCS	[41:30]	[73:62]	Clause 7.2.3.1.2

Table 7-11 – Ordering of bits and bytes of the PFH for Frame Type 2

Field	CENELEC, FCC-1	FCC, FCC-2	Description
	Bits	**Bits**	
FT	[1:0]	[1:0]	Clause 7.2.3.1.1
FL	[8:2]	[11:2]	Clause 7.2.3.2.2
Reserved by ITU-T	[29:9]	[61:12]	Clause 7.2.3.2.10
HCS	[41:30]	[73:62]	Clause 7.2.3.1.2

Table 7-12 – Ordering of bits and bytes of the PFH for Frame Type 3

Field	CENELEC, FCC-1	FCC, FCC-2	Description
	Bits	**Bits**	
FT	[1:0]	[1:0]	Clause 7.2.3.1.1
Reserved by ITU-T	[29:2]	[61:2]	Clause 7.2.3.2.10
HCS	[41:30]	[73:62]	Clause 7.2.3.1.2

Table 7-13 – Ordering of bits and bytes of the PFH for Frame Type 4

Field	CENELEC, FCC-1	FCC, FCC-2	Description
	Bits	**Bits**	
FT	[1:0]	[1:0]	Clause 7.2.3.1.1
FL	[8:2]	[11:2]	Clause 7.2.3.2.2
Reserved by ITU-T	[29:9]	[61:12]	Clause 7.2.3.2.10
HCS	[41:30]	[73:62]	Clause 7.2.3.1.2

7.3 Physical medium attachment sub-layer (PMA)

The functional model of the PMA is presented in Figure 7-5. It is intended to describe in more detail the PMA functional block presented in Figure 7-1.

In the transmit direction, the PFH and payload of the incoming PHY frame at the α-reference point has a format as defined in clause 7.2.1. Both the PFH bits and the payload bits of the incoming frame are scrambled as described in clause 7.3.1. The PFH bits of the incoming frame are further encoded as described in clause 7.3.4. The payload bits are encoded, as described in clause 7.3.3. The parameters of payload encoder are controlled by the PHY management entity (PMA_MGMT primitives). The parameters of the PFH encoder are predefined for each particular bandplan to facilitate interoperability.

After encoding, the PFH and payload are each mapped into an integer number of symbol frames as described in clause 7.3.6. The obtained symbol frames of the PFH and the payload are submitted to the PMD (at the δ-reference point) for modulation and transmission over the medium.

In the receive direction, all necessary inverse operations of decoding, and de-scrambling are performed on the received symbol frames. The recovered PFH and payload are submitted to the α-reference point for further processing in the PCS.

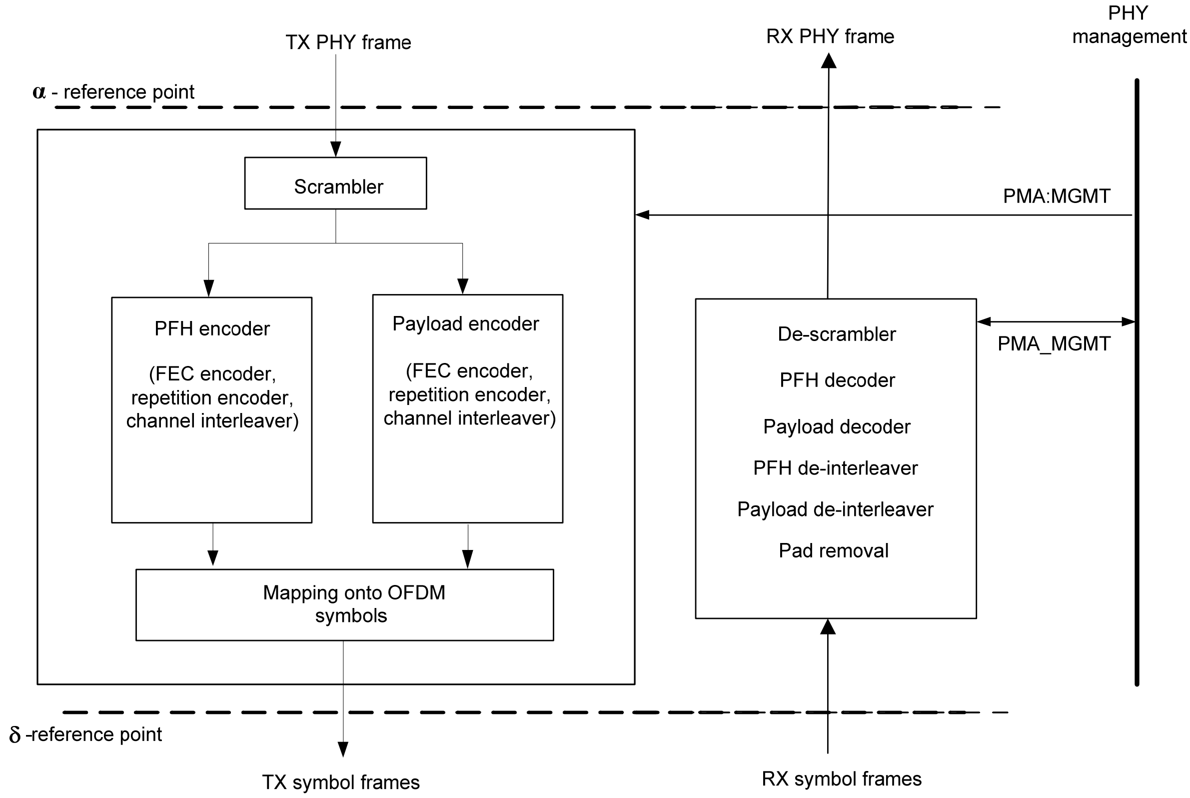


Figure 7-5 – Functional model of PMA

The management primitives of the PMA (PMA_MGMT) are defined in clause 7.8.2.3.

7.3.1 Scrambler

All data bits, starting from the first bit of the PFH and ending by the last bit of the payload, shall be scrambled with a pseudo-random sequence generated by the linear feedback shift register (LFSR) with the polynomial $p(x) = x^7 + x^4 + 1$, as shown in Figure 7-6.

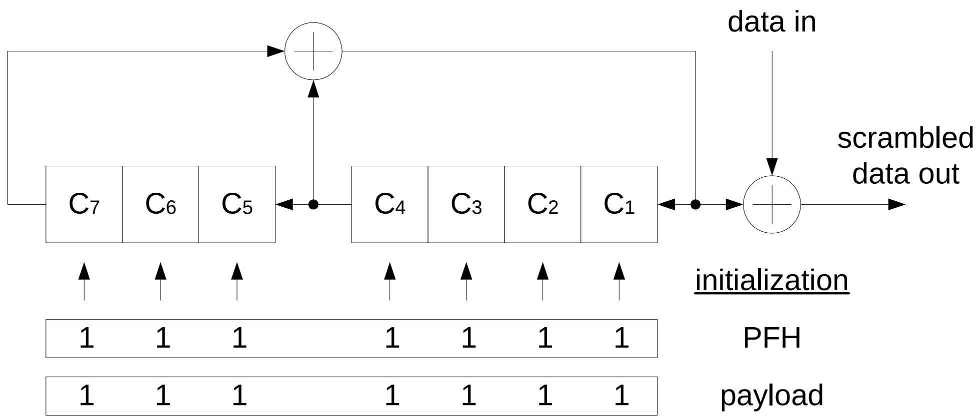


Figure 7-6 – Scrambler

The LFSR shall be initialized at the first bit of the PFH with the initialization vector equal to 0x7F (where the LSB corresponds to C_1); this initialization is used for scrambling of the PFH data. A second initialization shall be performed for payload data, immediately after the last bit of the PFH is read out from the scrambler and before the first bit of the payload is read out from the scrambler. For the second initialization, the initialization vector shall be set to 0x7F.

7.3.2 FEC encoder

The FEC encoder is shown in Figure 7-7. It consists of an inner convolutional encoder and the outer Reed Solomon (RS) encoder. The parameters of the FEC encoder are:

- the number of incoming RS information blocks, $m \geq 1$;
- the number of bytes, K, in the incoming RS information blocks;
- the number of RS parity-check bytes, R;
- the number of bits incoming the inner encoder, k_I;
- the inner code rate, r_I.
- the number of output bits, N_{FEC} (the FEC codeword size depends on the overall code rate).

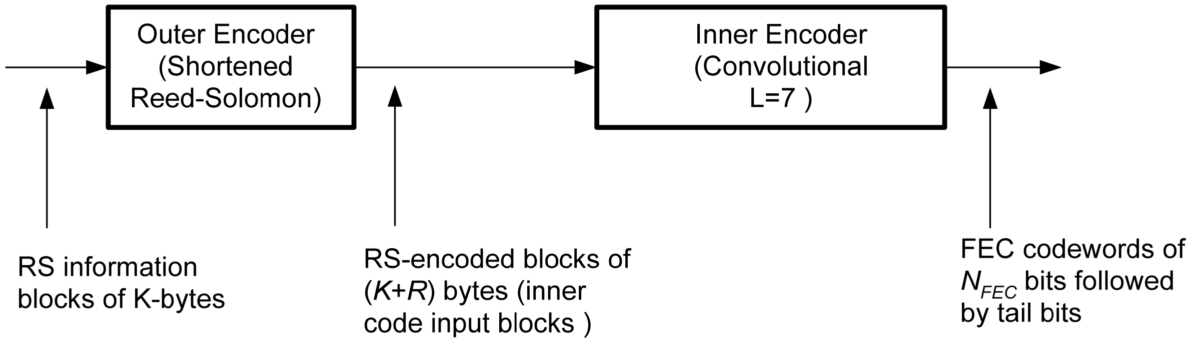


Figure 7-7 – FEC encoder

The incoming MPDU shall be first divided into RS information blocks. The number of RS information blocks, m, depends on the size of the MPDU and is determined by the PMI_DATA_REQ primitive (see clause 7.8.1.1). The size of each information block, K_l, where $l = 1, 2, ...m$, shall be an integer number of bytes and shall be computed for the given value of m as follows:

– The size of the first RS information block shall be 16 bytes (the size of the MPH, see [ITU-T G.9956], clause 8.1.3.1.1);

– The m_1 following RS information blocks shall be of the size $K_L = floor[(N_{MPDU} - 16)/(m - 1)] + 1$ bytes, where $m_1 = mod[(N_{MPDU} - 16)/(K_L - 1)]$ and N_{MPDU} is the size of MPDU in bytes.

– The remaining $m - m_1 - 1$ information blocks shall be of the size $K_S = K_L - 1$ bytes.

The valid values of other parameters of the FEC for the payload and the PFH are specified in Table 7-14 and Table 7-15, respectively. The m output FEC codewords followed by tail bits generated by the inner encoder shall be concatenated into an FEC codeword block. The order of the FEC codewords in the FEC codeword block (at the output of the FEC encoder) shall be the same as the order of the corresponding RS information blocks at the input of the FEC encoder.

The PFH shall be encoded as one single codeword. Encoding of the Extended Imm-ACK frame is for further study.

7.3.2.1 Reed-Solomon encoder

The outer code shall use a standard byte-oriented Reed-Solomon code. The encoded RS block shall contain $N = K+R$ bytes, comprised of R check bytes $c_0, c_1, ..., c_{R-2}, c_{R-1}$ appended to the K bytes $m_0, m_1, ..., m_{K-2}, m_{K-1}$ of the input information block. The check bytes shall be computed from the information bytes using the equation:

$$C(D) = M(D)D^R \bmod G(D)$$

where

$M(D) = m_0 D^{K-1} \oplus m_1 D^{K-2} \oplus ... \oplus m_{K-2} D \oplus m_{K-1}$ is the polynomial representing input block,

$C(D) = c_0 D^{R-1} \oplus c_1 D^{R-2} \oplus ... \oplus c_{R-2} D \oplus c_{R-1}$ is the check polynomial, and

$G(D) = \prod_{i=1}^{R} \left(D \oplus \alpha^i\right)$ is the generator polynomial of the RS code.

The polynomial *C(D)* is the remainder obtained from dividing $M(D)D^R$ by *G(D)*. The arithmetic shall be performed in the Galois Field GF(256), where α is a primitive element that satisfies the primitive binary polynomial $x^8 \oplus x^4 \oplus x^3 \oplus x^2 \oplus 1$. Bits $(d_7, d_6, ..., d_1, d_0)$ of data byte *D* are identified by the Galois field element $d_7\alpha^7 \oplus d_6\alpha^6 \oplus ... \oplus d_1\alpha \oplus d_0$.

With the above definitions, an input block size of (255-*R*) bytes can corrected up to $t = R/2$ erroneous bytes. A *t*-error correcting code for all smaller input block sizes shall be obtained by using the following procedure:

- the input block is substituted by appending zeros to the size 255–2*t*;
- the 2*t* parity bytes are computed as defined above;
- the output block is formed by appending the 2*t* parity bytes to the input block.

The maximum value of *t* shall not exceed 8 and the maximum input block size shall not exceed 239 bytes. The output block size shall be configurable to have any integer value in the range from 25 bytes to 255 bytes, inclusive. For input blocks shorter than 25 bytes, the RS encoder shall be bypassed. The valid values of error-correcting capability, $t = R/2$, for different input block size are defined in Table 7-7.

7.3.2.2 Convolutional encoder

Each RS information block encoded by the outer encoder shall be converted to a bit stream (LSB first) to form the inner input block of $k_I = 8 \times (K + R)$ bits. Inner input blocks shall be concatenated in the same order as the corresponding RS information blocks at the input of the FEC encoder. The last inner block shall be appended by six zeros (tail bits). The concatenated inner blocks shall be input to the inner convolutional encoder shown in Figure 7-8. The inner convolutional encoder shall have mother code rate 1/2 and constraint length $L = 7$, and code generator polynomials $G1=1111001_2 = 171_8$ and $G2 = 1011011_2 = 133_8$. The convolutional encoder state shall be set to zero before the first bit of the first inner block enters the encoder. The six zeroes appended to the last incoming inner block are to flush the encoder.

For the mother code of rate, $r_I = 1/2$, all X and Y bits generated by the encoder (see Figure 7-8) shall be output in the order: $X_0Y_0X_1Y_1..X_kY_k$ …

For a code rate of $r_I = 2/3$, puncturing of the output bits of the convolutional encoder shall be applied according to the pattern [1 1; 0 1], i.e., every alternate X output shall be punctured to yield the output bit stream in the order: $X_0Y_0Y_1$ $X_2Y_2Y_3..X_{2k}Y_{2k}Y_{2k+1}$ …

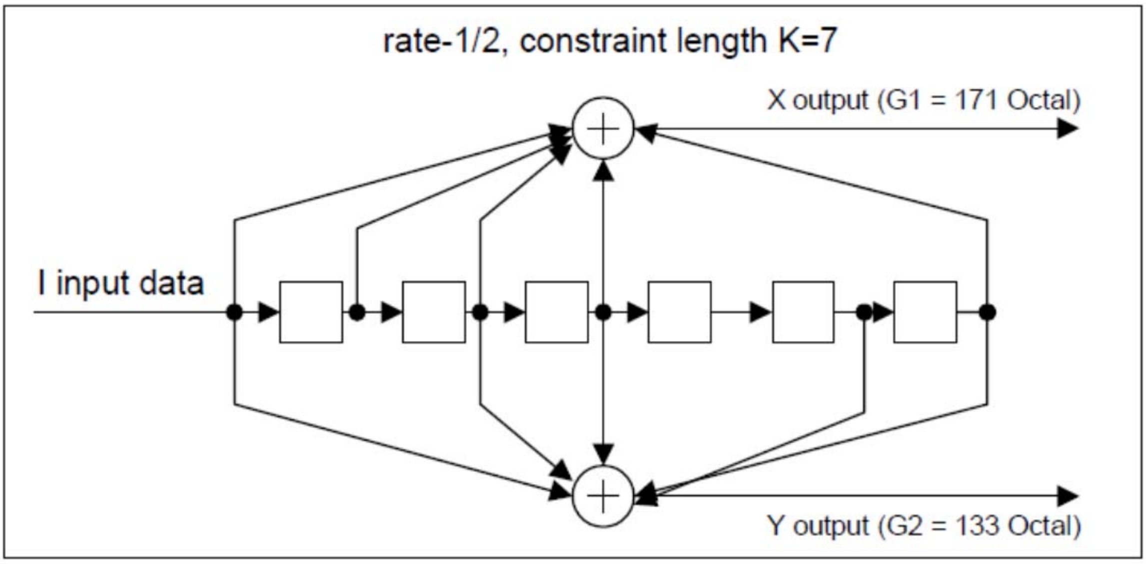


Figure 7-8 – Inner convolutional code encoder

The output bits of the inner encoder corresponding to the same inner input block form the output FEC codeword. The length of the FEC codeword can be computed as: $N_{FEC} = k_I / r_I$ bits.

7.3.2.3 FEC encoding parameters

The summary of valid FEC encoding parameters is specified in Table 7-14.

Table 7-14 – Valid values of payload FEC encoding parameters

RS information block size *K*, bytes	Valid inner code rate, r_I	RS parity check $R = 2_t$, bytes
≤25	1/2, 2/3	0
26-50	1/2, 2/3	4
51-75	1/2, 2/3	8
76-100	1/2, 2/3	12
101-239	1/2, 2/3	16

The output FEC codeword size, N_{FEC}, for the given values of K, r_I, and R presented in Table 7-14 can be computed as: $N_{FEC} = (8\times(K+R)) / r_I$ bits.

For the PFH, the outer encoder shall be bypassed. The inner encoder block size shall be $k_I = \text{PHY}_H$ bits (see clause 7.2.3) and code rate shall be 1/2, as presented in Table 7-15. The output FEC codeword size is $(k_I + 6)/r_I$ bits.

Table 7-15 – Valid values of PFH FEC encoding parameters

Bandplans	Inner encoder input block, k_I, bits	Inner code rate, r_I
CENELEC, FCC-1	42	1/2
FCC, FCC-2	74	1/2

The total number of bits in an FEC codeword block corresponding to m input information blocks can be computed as:

$$N_{FECB} = 6/r_I + \sum_{l=1}^{m} N_{FEC,l} = \left[6 + 8 \times \sum_{l=1}^{m} (K_l + R)\right] / r_I$$

NOTE – The overall coding rate of the FEC encoder can be computed as:

$$r = \left[8 \times \sum_{l=1}^{m} K_l\right] / N_{FECB}$$

7.3.3 Payload encoder

The functional diagram of the payload encoder is presented in Figure 7-9. It contains an FEC encoder, an aggregation and fragmentation block (AF), a fragment repetition encoder (FRE), and an interleaver. The FRE is to support robust communication mode (RCM) and is bypassed in case of normal mode of operation (no repetitions).

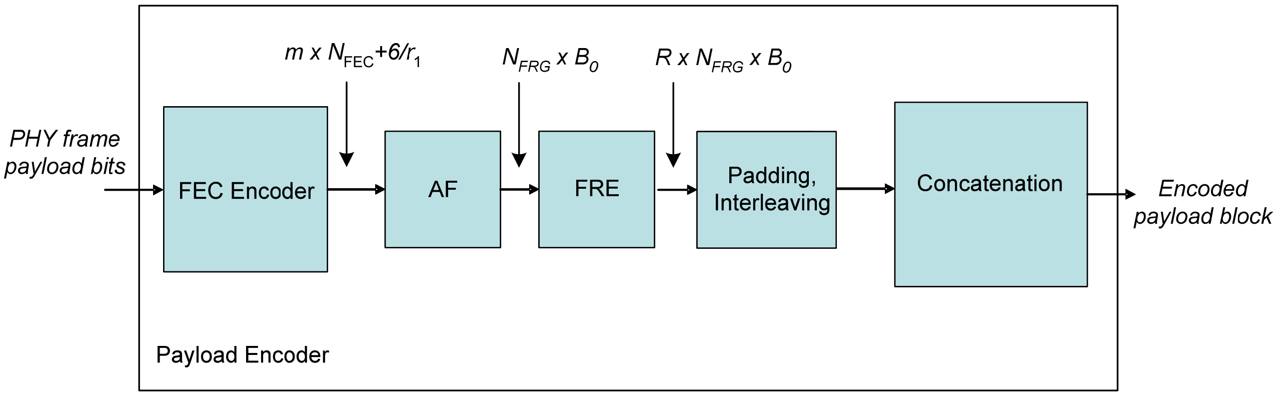


Figure 7-9 – Functional diagram of the payload encoder

The incoming PHY-frame payload bits shall be divided into m sequential information blocks of K_l bytes per block, $l = 1, 2, ...m$, and each information block shall be encoded by the FEC encoder, as described in clause 7.3.2. The valid values of FEC parameters K, R, and r_I, and the coded block size N_{FEC} are presented in clause 7.3.2.3. The bytes in each information block shall be in the same order as they are in the corresponding MPDU.

The AF first collects the FEC codeword block of NFECB bits generated by the FEC for the encoded payload. Further, the FEC codeword block is partitioned into fragments of the same size B_0 bits each (e.g., $B_1 - B_4$ in Figure 7-10). The number of fragments is N_{frg} = ceiling(N_{FECB}/B_0). To obtain integer number of fragments, the FEC codeword block shall be padded with up to $B_P = B_0 \times N_{frg} - N_{FECB}$ bits.

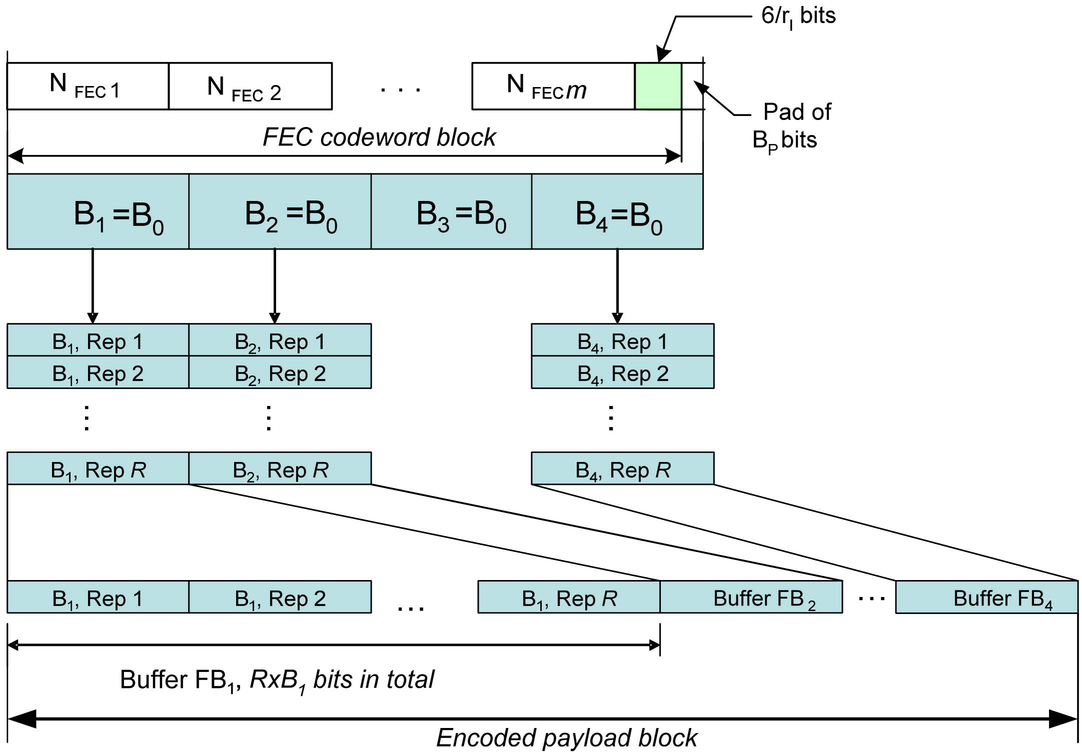


Figure 7-10 – Generation of the encoded payload block (case N_{frg} = 4, cyclic shifting, interleaving and padding of fragments when in IoAC mode is not shown)

The value of B_0 shall be calculated as an integer divisor of the total number of bits in the FEC codeword block and then increased to fit an integer number of symbols. This shall be the maximum divisor which value is less than or equal to the minimum of:

- The total number of input bits, N_{FECB}, in the FEC codeword block;
- The total number of bits, N_{ZC}, loaded on the symbols that span at least 10ms for the case of 50 Hz AC lines, and at least 8.33 ms for the case of 60 Hz AC lines or lines with no AC;
- The maximum fragment size of B_{max} = 3072 bits.

The number of bits used to fit B_0 to integer number of symbols shall not exceed the number of bits loaded onto a symbol (k_p) minus 1.

With the definitions above, the fragment size, B_0, and the number of pad bits, B_P, can be computed using the following steps:

- find the upper limit of the fragment size: $P = min(N_{FECB}, N_{ZC}, B_{max})$;
- find the number of fragments: $N_{frg} = ceiling(N_{FECB}/P)$;
- find the fragment size: $B_0' = ceiling(N_{FECB}/N_{frg})$; $B_0 = k_p \times ceiling\ (B_0'/k_p)$;
- find the number of pad bits $B_P = B_0 \times N_{frg} - N_{FECB}$,

where k_p is the number of bits loaded onto a symbol. The pad bits, B_P, shall be generated by continuously extracting the MSB from the LFSR shown in Figure 7-17 until the pad is filled up. The generation polynomial shall be as defined clause 7.4.2.6. The LFSR initialization shall be all-ones as shown in Figure 7-17 prior to first pad bit is extracted. The number of pad bits shall be less than $N_{frg} \times k_p$.

The FRE provides repetitions of fragments with the repetition rate of R. Each fragment shall be copied R times and all copies shall be concatenated into the fragment buffer, FB, so that the first bit of each copy follows the last bit of previous copy, see Figure 7-10. The total size of the FB is $B_0 \times R$ bits. The FRE shall support the values R = 1, 2, 4, 6, 12 (value of R = 1 corresponds to normal mode of operation). If R = 1, an FB, accordingly, shall contain a single fragment of B_0 bits.

All fragments and their copies of each FB shall be interleaved. The interleaving method and parameters of the interleavers are defined in clause 7.3.5 and are the same for all valid values of R. Two modes of interleaving are defined:

- Interleave-over-fragment (IoF);
- Interleave-over-AC-cycle (IoAC).

The mode of interleaving is indicated in the PFH, as defined in clause 7.2.3.2.7 and shall be selected on discretion of the transmitter. In both modes, for each fragment, prior to interleaving, the bits of each fragment copy starting from the second copy ("Rep 2" in Figure 7-10) shall be cyclically shifted by M = *ceiling* (B_0/R_T) bits relative to the previous copy in the direction from LSB to MSB, i.e., the copy "Rep(d+1)" shall be shifted by $d \times$ M bits relative to copy "Rep 1" so that the LSB of copy "Rep 1" will have bit number ($d \times$ M) in the copy "Rep(d+1)". The value of $R_T \geq R$ is the total number of repetitions, including padding; it depends on the mode of interleaving.

If IoF mode is set, each fragment of the FB shall be interleaved separately. After interleaving of all copies of the fragment, the FB shall be passed for concatenation. The value of R_T shall be set equal to R.

If IoAC mode is set, each FB (containing R copies of the fragment) shall be padded to the closest integer number of symbols that is equal or more than the closest integer number of N_{ZC}, Figure 7-11. The pad shall be generated by cyclical repeating of the bits of this same FB, starting from its first bit: the first bit of the pad shall follow the last bit of the FB and shall be the repetition of the first bit of the same FB.

Further, all copies of the fragment, both original and padded, shall be interleaved as defined in clause 7.3.5 for payload interleaver. The total number of interleaved copies, $R_T = ceiling(ceiling((B_0 \times R)/N_{ZC}) \times N_{ZC}/B_0)$. From the last copy, only the symbols that fill up the padded FB, as shown in Figure 7-11, shall be taken from the interleaver. After interleaving of all copies of the fragment, the padded FB shall be passed for concatenation.

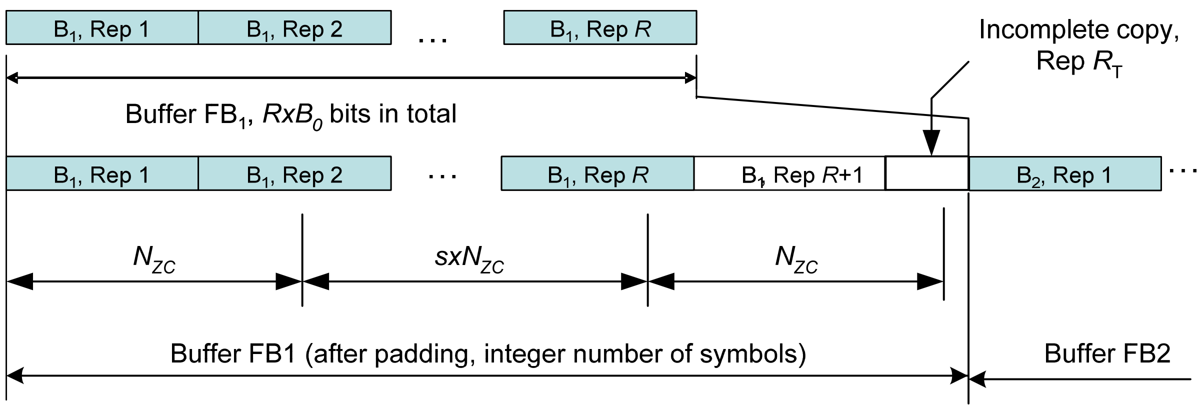


Figure 7-11 – Padding of the FB in IoAC mode

The FBs processed as described above shall be concatenated into an encoded payload block, in the order of the sourcing fragments, as shown in Figure 7-10.

The encoded payload block is passed for mapping into symbol frames (see clause 7.3.6).

7.3.4 PFH encoder

The functional diagram of the PFH encoder is presented in Figure 7-12, where all functional blocks operate as described in clause 7.3.3.

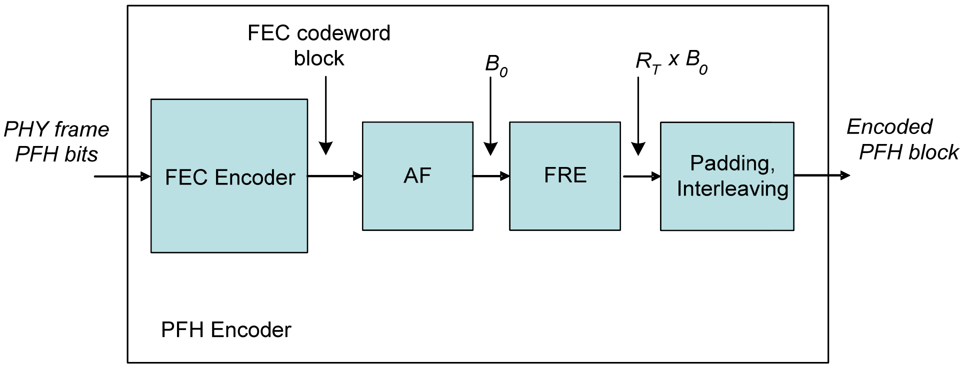


Figure 7-12 – Functional diagram of the PFH encoder

The bits of the PFH shall input the PFH FEC encoder in their original order and encoded as described in clause 7.3.2. The parameters of the PFH FEC encoder shall be as specified in clause 7.3.2.3, Table 7-15. The FEC codeword block at the output of the FEC encoder contains one FEC codeword and is 2 × (PHY_H + 6) bits long, where PHY_H is defined in clause 7.2.3.

Generation of an encoded PFH block is presented in Figure 7-13. The value of B_0 shall be equal to the FEC codeword block. The number of repetitions, R_T, depends on the bandplan used and is determined by the number of symbols to carry the PFH, NS_H, and shall be computed as: $R_T = ceiling((NS_H \times k_H)/B_0)$, where k_H is the number of bits loaded onto a symbol. Two values of NS_H are defined for each bandplan: normal and robust, as presented in Table 7-16. The particular value of NS_H is determined by the PMI_MGMT.REQ primitive (see clause 7.8.2.1).

Table 7-16 – Number of symbols in encoded PFH for 50Hz and 60Hz mains

Bandplan	Number of symbols, NSH		
	Normal	Robust	
	50 Hz, 60 Hz	50 Hz	60 Hz
CENELEC A	15	30	25
CENELEC B	30	45	50
CENELEC CD	45	45	50
FCC	8	30	25
FCC-1	19	30	25
FCC-2	10	30	25

The block of bits B_0 shall be copied R_T times and copies shall be concatenated in numerical order and divided into fragments of NS_I symbols, starting from the first symbol of the first copy, as presented in Figure 7-13. The size of the fragment shall be set as:

$$NS_I = min(\text{floor}(B_{max}/k_H), \text{ceiling}(N_{ZC}/k_H), NS_{H\_Normal}),$$

where values B_{max} and N_{ZC} shall be as defined in clause 7.3.3, and NS_{H_Nornal} is the normal value of NS_H and shall be as defined in Table 7-16. The total number of fragments will be $R_F = \text{ceiling}(NS_H/NS_I)$. If the number of bits in R_T copies is insufficient to complete integer number of fragments, the last fragment shall be completed by adding more copies of the block B_0.

Each fragment, starting from the second one ("Fragment 2" in Figure 7-13) shall be cyclically shifted by M = *ceiling*((NS_I × k_H)/R_F) bits relative to the previous copy, as described in clause 7.3.3. After cyclic shifting, all fragments shall be interleaved as defined in clause 7.3.5, for the PFH interleaver. If the last fragment is incomplete, only bits for the first symbols that are required to fit the size NS_H of the encoded PFH block shall be read out from the interleaver, as shown in Figure 7-13.

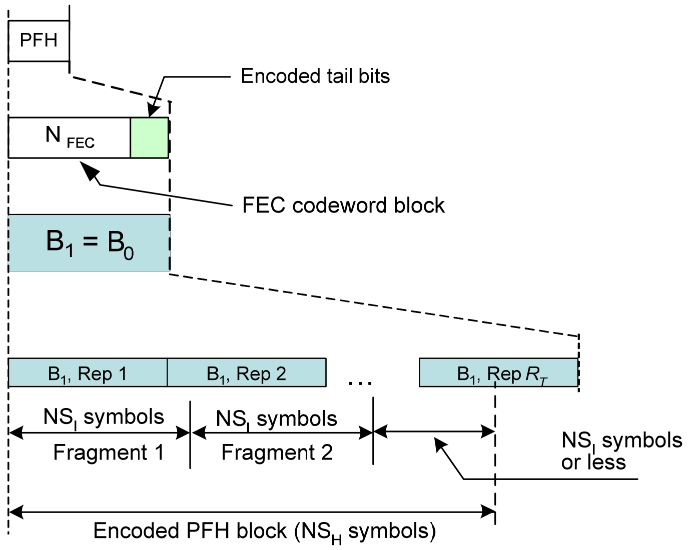


Figure 7-13 – Generation of the encoded PFH block

7.3.5 Channel interleaver

The channel interleaver interleaves a block of B_I bits (see clauses 7.3.3, 7.3.4), based on the number of subcarriers per symbol frame that are loaded bits, denoted in this clause by *m*. For the payload, these subcarriers are those identified in the TM field of the PFH, except the subcarriers from PMSC, RMSC (unless BAT Type 0 is used), and PSC sets. For the PFH, these are all subcarriers from the RMSC set and all subcarriers from the SSC set, except those from the PSC set (see clauses 7.4.2.1, 7.4.2.2, 7.4.2.5).

For the payload encoder $B_I = B_0$, for PFH encoder $B_I = NS_I \times k_H$. The interleaver is only defined for values of B_I that are multiples of *m*, i.e., $n = B_I / m$ is an integer. The B_{0I} input bits shall be written into the permutation matrix with *n* rows and *m* columns. The insertion of the bits into the matrix shall be performed using the equations below:

$q = floor(p/(k \times m))$

$r = mod(p,k \times m)$

$i = floor(r,k)$

$j = k \times q + mod(r,k)$

where: *p* is the sequential number of the bit in the input sequence (input vector), in the range from 0 to B_I-1;

k is the modulation used (*k*=1 for 1-bit modulation, *k*=2 for 2-bit modulation, etc.).

i is the index of the column and *j* is the index of the row in the permutation matrix in the range from 0 to *m*-1 and from 0 to *n*-1, respectively (*m* columns by *n* rows).

Figure 7-14 shows the insertion of the bits into a matrix when the equations are used with k=2. Each box in the Figure 7-14 represents a bit. The number in the box indicates the position of the bit in the input bit sequence (input vector) and in the output bit sequence (output vector), respectively.

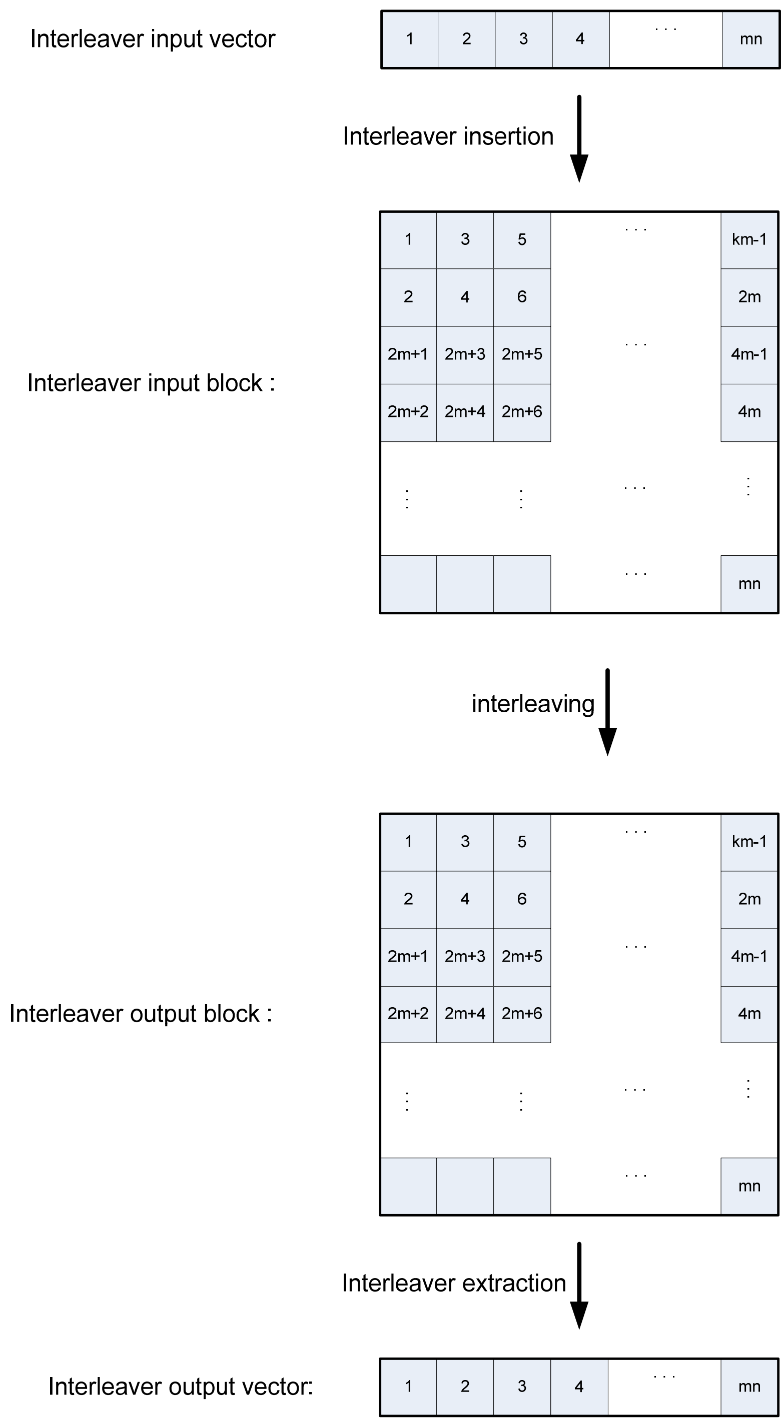


Figure 7-14 – Order of writing in and reading out of the permutation matrix

The entries of the $n \times m$ matrix shall be permuted. The relation between input and output bit indices shall be determined from the following equations: for the bit with original position (i, j), where $i = 0,1,..., m - 1$ and j = 0,1,..., $n - 1$, the interleaved bit position (I, J) shall be:

$$J = (j \times n\_j + i \times n\_i) \bmod n$$

$$I = (i \times m\_i + J \times m\_j) \; mod \; m,$$

where m_i, m_j, n_i, and n_j are selected based the values of m and n, under the constraint that

$$m\_i, m\_j, n\_i, n\_j > 2$$

$$\mathrm{GCD}(m\_i,m) = \mathrm{GCD}(m\_j,m) = \mathrm{GCD}(n\_i,n) = \mathrm{GCD}(n\_j,n) = 1,$$

where GCD stands for the greatest common divisor.

The values of n_i, n_j and m_i, m_j shall be computed as follows: For a given value of n, all the co-prime numbers of n except numbers 1 and 2 shall be sorted in ascending order; then, n_i shall be the first co-prime element above $n/2$ in that co-prime number set, and n_j shall be the next element to n_i. Same steps shall be applied to compute m_i and m_j, for a given value of m.

Following is an example for co-prime selection for $n = 8$, $m = 10$:

- Since $n = 8$, co-prime numbers for 8 except 1 and 2 are: 3,5,7.

  The first co-prime number above $n/2$ is 5, so $n\_i = 5$; and the next co-prime is 7, so $n\_j = 7$;
- Since $m = 10$, co-prime numbers for 10 except 1 and 2 are: 3, 7, 9.

  The first co-prime number above $m/2$ is 7, so m_i = 7; and the next is 9, so $m\_j = 9$;

After permutation, bits shall be extracted from the permutation matrix in the same order that they were written into the matrix. An example for 2-bit modulation (k=2) is given in Figure 7-14.

7.3.6 Mapping onto symbol frames

The encoded payload block from the output of the payload encoder and the encoded PFH block from the output of the PFH encoder shall be mapped onto symbol frames. The number of bits in the symbol frame shall be equal to k_P for payload symbol frames and to k_H for PFH symbol frame. Payload and PFH symbol frames shall be passed to the PMD, as described in Figure 7-5.

7.3.6.1 Payload mapping

The encoded payload block shall be mapped onto one or more symbol frames. The number of symbol frames, M, shall be equal to the minimum number needed to accommodate all bits of the encoded payload block as defined in clause 7.3.3.

NOTE – The number of bits in the encoded payload block is always a multiple of k_P.

The first symbol frame shall contain the first k_P bits of the encoded payload block, the second frame shall contain the second k_P bits of the encoded payload block and so on, until the last symbol frame needed to accommodate the encoded payload block.

The payload mapping procedure is presented in Figure 7-15, showing also the convention for the start of the symbol frame further used for reference purposes (the start of the first frame is the LSB of octet 0 of the payload, the start of the second frame is bit with the number ($k_P + 1$) of the payload block and so on).

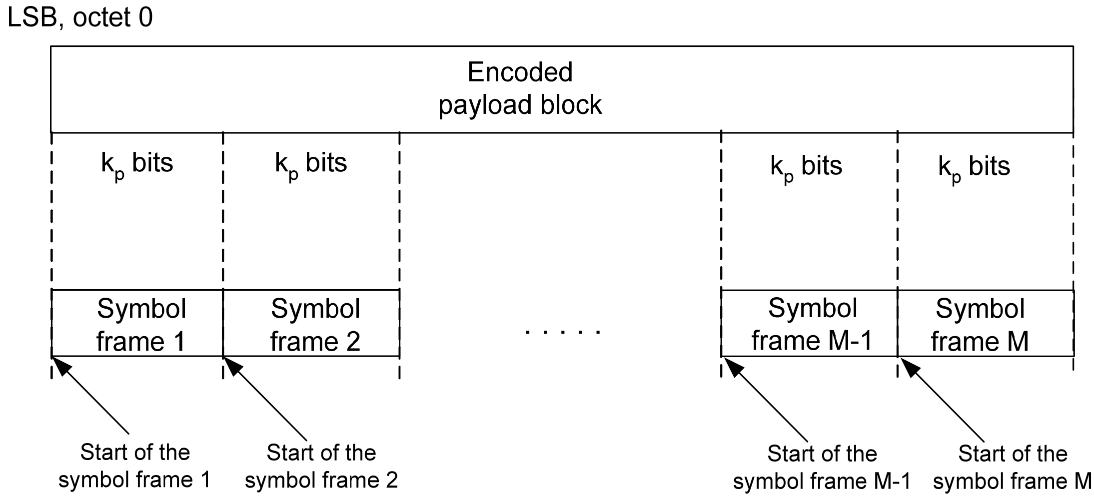


Figure 7-15 – Payload mapping

7.3.6.2 PFH mapping

The encoded PFH block shall be segmented into one or more symbol frames using the same convention as the payload block (the number of bits in the encoded PFH block is integer number of k_H, see clause 7.3.4).

7.4 Physical medium dependent sub-layer (PMD)

The functional model of the PMD is presented in Figure 7-16. In the transmit direction, the Tone mapper divides the incoming symbol frames of the PFH and the payload into groups of bits and associates each group of bits with a specific subcarrier onto which this group shall be loaded, as specified in clause 7.4.2. The constellation encoder converts each group of incoming bits into a complex number that represents the constellation point for this subcarrier. The constellation mapping process is described in clause 7.4.3. The unused subcarriers and pilot subcarriers are modulated by a pseudo-random bit sequences generated as described in clauses 7.4.2.6 and 7.4.2.7, respectively.

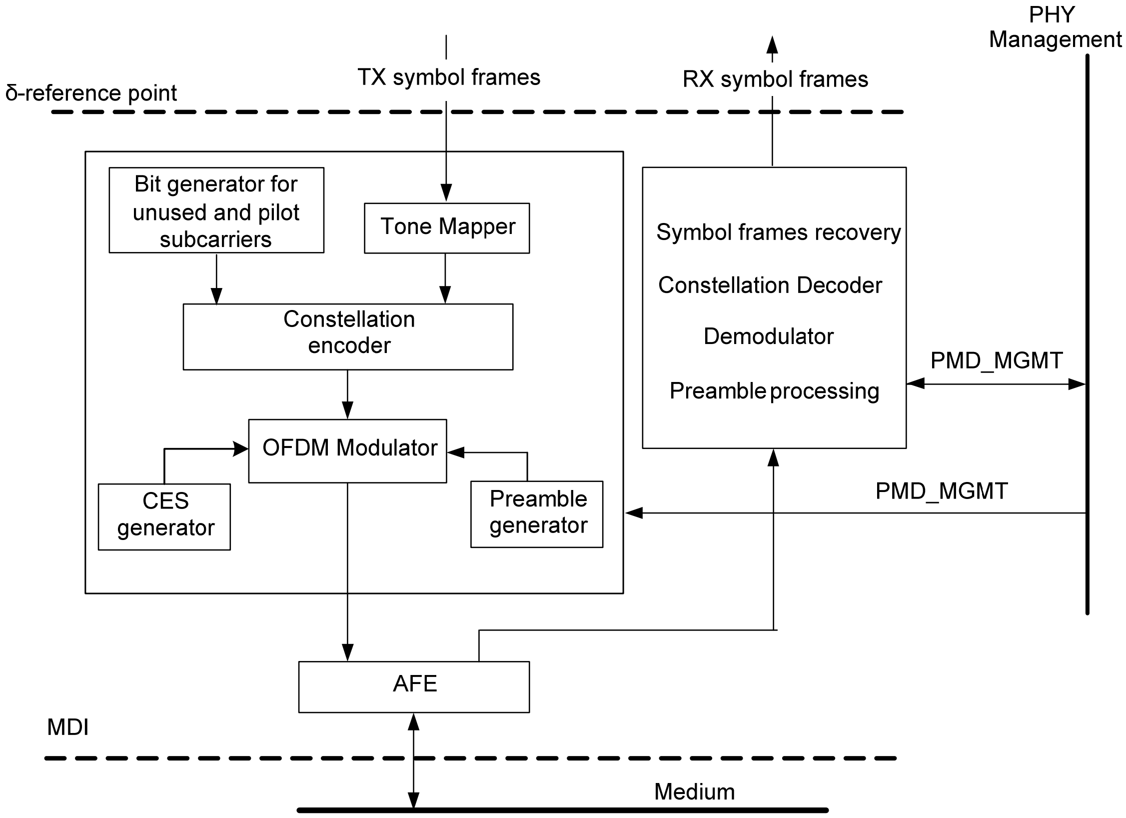


Figure 7-16 – Functional model of PMD

The OFDM modulator (see clause 7.4.4) converts the incoming stream of the N complex numbers into a stream of N complex time-domain samples. After adding the preamble and CES, the transmit signal is sent to the medium via the analog front end (AFE). Parameters of the preamble defined in clause 7.4.5 are determined by the PHY management primitive PMD.MGMT.REQs.

In the receive direction, frames incoming from the medium are demodulated and decoded. The recovered symbol frames are transferred to the PMA via δ-reference point. The preamble and CES are processed and the processing results are passed to the PHY management entity.

The management primitives of the PMD (PMD_MGMT) are defined in clause 7.8.2.4.

7.4.1 Subcarrier spacing and indexing

The subcarrier spacing F_{SC} is the frequency spacing between any two adjacent subcarriers. Valid values of subcarrier spacing are presented in Table 7-6.

The subcarrier index i corresponds to the order of subcarriers in frequency: the subcarrier with index i shall be centered at frequency $f = F_{\mathrm{US}} - (N/2 - i) \times F_{\mathrm{SC}}$. The range of index i is from 0 to N–1. Subcarrier index is also referred to as subcarrier number.

Some subcarriers may not be used for data transmission. Some of these unused subcarriers may be switched off. This function is performed by subcarrier masking (see clause 7.6.1).

NOTE – The particular subcarriers used for data transmission between two particular nodes may depend on channel characteristics, such as loop attenuation and noise, and on the specific spectrum-use requirements, such as notching of specific frequency bands to share the medium with other services.

7.4.2 Tone mapper

The tone mapper divides the incoming symbol frames of the PFH and payload into groups of bits, according to the used bit allocation table (BAT) and associates these groups of bits with specific subcarriers onto which these groups of bits shall be loaded. This information is passed to the constellation encoder.

7.4.2.1 Summary of subcarrier types

For the purpose of tone mapping, the following types of subcarriers are defined.

1) Masked subcarriers (MSC) are those on which transmission is not allowed, i.e., the gain on this subcarrier (see clause 7.4.3.3) shall be set to zero. Two types of MSC are defined:
   - Permanently masked subcarriers (PMSC) – those that are forbidden for transmission in all regions. Data bits shall not be mapped on PMSC.
   - Regionally masked subcarriers (RMSC) – those that are forbidden for transmission in some regions, while may be allowed in other regions, and for some applications. The list of RMSC depends on the region or application or both.

   The number of MSC, #MSC = #PMSC + #RMSC.

2) Supported subcarriers (SSC) are those on which transmission is allowed under restrictions of the relevant PSD mask. Three types of SSC are defined:
   - Active subcarriers (ASC) – those that are loaded bits ($b \geq 1$) for data transmission. ASC are subject to constellation mapping and scaling as described in clause 7.4.3. Data bits shall be mapped on ASC as described in clause 7.4.2.2.
   - Inactive subcarriers (ISC) – those that are loaded pseudo-random bits instead of data bits. ISC can be used for measurement purposes or other auxiliary purposes. The modulation of ISC is defined in clause 7.4.2.6.

     NOTE – Using zero transmit power with ISC provide tone masking capabilities on a per connection basis rather than static masking provided by the MSC set.
   - Pilot subcarriers (PSC) – those that carry pilots instead of data bits. PSC can be used for timing recovery, channel estimation, or other auxiliary purposes. The modulation of PSC is defined in clause 7.4.2.7.

   The number of SSC, #SSC = #ASC + #ISC + #PSC. The SSC are subject to transmit power shaping by using gain scaling (see clause 7.4.3.3).

All subcarriers belong to either MSC or SSC. That is, #MSC + #SSC = N.

7.4.2.2 Bit allocation table (BAT)

Tone mapping is defined by a BAT that associates subcarrier indices with the number of bits to be loaded on the subcarrier. The subcarrier indices in a BAT shall be in ascending order, from the smallest index to the largest index. Bits of the TX symbol frame shall be loaded onto the subcarriers as defined in clause 7.4.3, in the order of subcarrier indices in the BAT.

The BATs used by the node to transmit the particular PHY frame shall be indicated to the receiving node(s) in the PFH, as described in clause 7.2.3.2.2. Up to 16 BATs, with BAT ID values in the range from 0 to 15 can be defined. The assignment of BAT IDs shall be as described in Table 7-17.

Table 7-17 – Assignment of BAT_ID

BAT_ID	Type of BAT	Reference
0	Type 0	Clause 7.4.2.2.1
1	Type 1	
2	Type 2	
3	Type 3	
4	Type 4	
5	Type 5	
6	Type 6	
7	Type 7	
8-15	Reserved by ITU-T for other BATs	

Every node shall support at least BATs of Type 0, Type 1, Type 2, Type 4, Type 5, Type 6 and Type 7.

7.4.2.2.1 Predefined BATs

The following BATs are predefined:

1. BAT Type 0: Uniform 2-bit loading on all subcarriers except the PMSC and PSC sets.
2. BAT Type 1: Uniform 2-bit loading on all subcarriers except the PMSC, PSC, and RMSC sets (i.e., loaded onto all subcarriers of the SSC set except the PSC).
3. BAT Type 2: Uniform 2-bit loading on a particular ASC set.
4. BAT Type 3: Uniform 3-bit loading on a particular ASC set.
5. BAT Type 4: Uniform 4-bit loading on a particular ASC set.
6. BAT Type 5: Uniform 1-bit loading on all subcarriers except the PMSC, PSC, and RMSC sets (i.e., loaded onto all subcarriers of the SSC set except the PSC).
7. BAT Type 6: Uniform 1-bit loading on a particular ASC set.
8. BAT Type 7: Uniform 1-bit loading on all subcarriers except the PMSC and PSC sets

NOTE – BAT Type 0, Type 1, Type 5, and Type 7 may be used when channel characteristics are unknown (i.e., no knowledge is available on whether particular subcarriers could be loaded with bits or not). In case SNR is below the level to provide reliable detection of 1-bit or 2-bit loading, repetition encoding should be used, as defined in clause 7.3.3.

The particular ASC set to be used in conjunction with BATs of Types 2, 4, and 6 shall be defined as a particular subcarrier mask associated with the communication channel by using the TM field of the PFH, while the total number of loaded bits per symbol can also be derived from the PFH fields TM and MOD, as defined in clause 7.2.3.2.2.

7.4.2.3 Transmitter-determined and receiver-determined mapping

Two types of tone mapping are defined: transmitter-determined and receiver-determined. With transmitter-determined mapping, the BAT is defined by the transmitter and shall be either a predefined BAT or it shall be communicated using the BAT communication protocol to all destination nodes prior to transmission. With the receiver-determined mapping, the BAT is determined by the receiver of the destination node and communicated to the transmitter. The type of mapping to use is determined by the transmitter. If a transmitter selects to use receiver-determined mapping, the BAT is communicated from the receiver to the transmitter as a part of the channel estimation protocol defined in [ITU-T G.9956], clause 8.5.4.

7.4.2.4 Subcarrier grouping

With subcarrier grouping, the entire bandplan used is divided into groups of consecutive subcarriers, with G subcarriers in each group. The value of $G = 1$ corresponds to no grouping. If grouping is used ($G > 1$), all subcarriers of the same group shall use the same bit loading and the same gain value. The valid values of G are 2, 4, and 8 subcarriers; the eligible values depend on the bandplan and are defined in clause 7.2.3.2.3.

The first group shall include G subcarriers in ascending order of subcarrier indices starting from the smallest index of the used bandplan, as defined in clause 7.5. The second group includes G subcarriers in ascending order of subcarrier indices starting from the smallest index that is bigger than indices of the first group, and so on. If a group includes subcarriers that are masked (e.g., PMSC or RMSC), or are from the PSC set, or extends beyond the upper subcarrier index of the bandplan, the node shall apply the bit loading and gain assigned for this group only to its active subcarriers. The default group index G for the particular bandplan is defined in Table 7-7. Using of more than one (default) value of G for a particular bandplan is for further study.

7.4.2.5 Special mappings

7.4.2.5.1 Tone mapping for PFH

The PFH shall use a uniform loading of 2 bits per subcarrier on all subcarriers except the PMSC set and PSC set (BAT Type 0).

7.4.2.5.2 Tone mapping for RCM

Payload transmission in robust communication mode (RCM) shall use a uniform loading of 2 bits per subcarrier (BAT Type 0 or BAT Type 1).

7.4.2.5.3 Assignment of pilot subcarriers

The PSCs shall be assigned in all symbols of the PFH and in all symbols of the PHY frame payload. Each symbol of the PFH and of the payload shall be assigned the same number of PSCs.

For PSC assignment, the subcarrier indices of a symbol shall be enumerated sequentially over all the subcarriers of the SSC set excluding those of the ISC set, starting from 0 (subcarrier with lowest frequency) to M-1 (subcarrier with highest frequency), where M is equal to the difference between the number of SSC and the number of ISC.

The number of PSCs in a symbol, p, shall be computed as:

$$p = \begin{cases} floor(M/n), & if \bmod(M,n) \prec k \\ ceiling(M/n), & if \bmod(M,n) \geq k \end{cases}$$

where:

- n is the number of subcarriers between adjacent PSC (PSC spacing); the value of n shall be set to 12 for all bandplans;
- k is an index shift between PSC indices of adjacent symbols and shall be set to 3.

The indices of the PSCs in a symbol with sequential number j, $j = 1, 2, \ldots s$, assigned with p PSCs, shall be equal to:

$$d_x = \mathrm{mod}(\mathrm{mod}(\mathrm{M}, n) + (j-1) \times k + (x-1) \times n, M), \text{ for } x = 1, \ldots, p.$$

where $\{d_x\}$ is the set of indices of the PSC taken from the set of M subcarriers defined above, where the first subcarrier index of the symbol is 0. The value of $j = 1$ corresponds to the first symbol of the PFH, and the value $j = s$ corresponds to the last symbol of the payload.

An example of the values of d_x for the set of parameters: $M = 36$ and $n = 12$ (that correspond to: $\mathrm{mod}(M,n) = 0$ and $p = 3$) for the first 6 OFDM symbols is given in Table 7-18.

Table 7-18 – Values of dx for 6 OFDM symbols, using M = 36 and n = 12

x	Symbol (*j*)	Pilot tone position (d_x)
1	1	0
2	1	12
3	1	24
1	2	3
2	2	15
3	2	27
1	3	6
2	3	18
3	3	30
1	4	9
2	4	21
3	4	33
1	5	12
2	5	24
3	5	0
1	6	15
2	6	27
3	6	3

7.4.2.6 Modulation of inactive subcarriers

Inactive subcarriers (ISC) shall be loaded with a pseudo-random binary sequence (PRBS) defined by the LFSR generator with the polynomial $p(x) = x^7 + x^4 + 1$ shown in Figure 7-17. The LFSR generator shall be initialized at the beginning of the first payload OFDM symbol with a seed 0x7F (bit C_1 in Figure 7-17 is LSB).

The LFSR shall be advanced by two bits for each inactive subcarrier of each symbol of the payload.

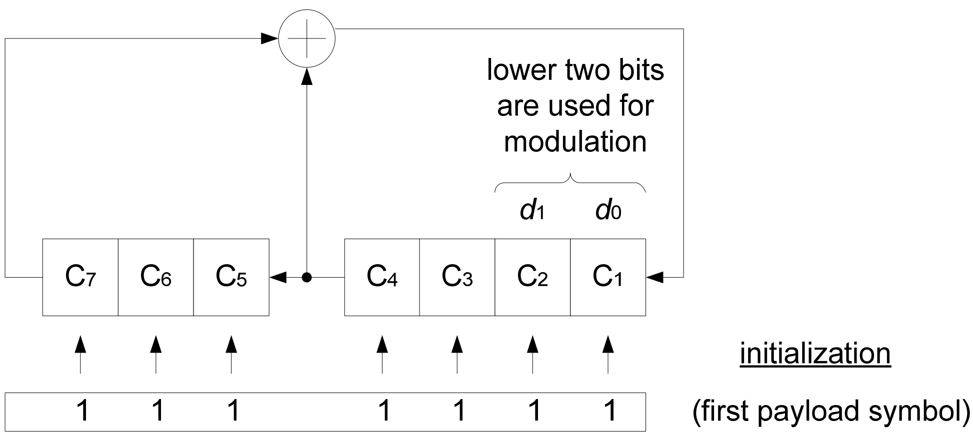


Figure 7-17 – LFSR for modulation of inactive subcarriers

The modulation of ISC shall start from the first payload OFDM symbol, each subcarrier from the ISC set shall be modulated with the two bits which are the LSBs of the LFSR, d_0, and d_1 (as presented in Figure 7-17), using 2-bits constellation mapping defined in clause 7.4.3.

Bits from LFSR shall be loaded on subcarriers from the ISC set in ascending order of subcarrier indices according to subcarrier indexing defined in clause 7.4.1. Modulation of subcarriers shall start from the ISC with the lowest index of the first payload symbol, continue in ascending order of subcarrier indices till the ISC with the highest index of the first payload symbol, continue with the ISC with the lowest index of the second payload symbol, continue in ascending order of indices till the ISC with the highest index of the second payload symbol, and so on till the ISC with the highest index of the last payload symbol.

7.4.2.7 Modulation of pilot subcarriers

Pilot subcarriers shall be modulated with 2-bit modulation where the bits shall be generated using an LFSR initialized with all ones at the beginning of the PFH, prior the first PSC is transmitted. The generation polynomial shall be as defined clause 7.4.2.6.

The modulation of PSC shall start from the first PFH symbol, each subcarrier from the PSC set shall be modulated with the two bits which are the LSBs of the LFSR, d_0, and d_1 (as presented in Figure 7-17), using 2-bits constellation mapping defined in clause 7.4.3.

7.4.3 Constellation encoder

Constellation encoder divides the symbol frame (of the PFH or of the payload, see clause 7.3.6) into sequential groups of bits $\{d_{b-1}, d_{b-2}, \ldots, d_0\}$ and maps each group on the corresponding subcarrier. The number of bits in each group and the order of subcarriers is determined by the BAT, as defined in clause 7.4.2.2.

Groups of bits for encoding shall be taken from the symbol frame in sequential order, starting from the first bit of the symbol frame (as bit d_0 of the first group) and ending with the last bit of the symbol frame (bit d_{b-1} of the last group). Groups shall be loaded on subcarriers in the order they are taken from the symbol frame, in ascending order of subcarrier indices (i.e., starting from the ASC with the lowest index and ending by the ASC with the highest index, running sequentially through all subcarrier indices defined in the BAT). Bit assignment for unloaded subcarriers (ISC and PSC) is defined in clauses 7.4.2.6 and 7.4.2.7.

Constellation mapping associates every group of bits to be loaded onto a subcarrier, with the values of I (in-phase component) and Q (quadrature component) of a constellation point. Each incoming group of b bits $\{d_{b-1}, d_{b-2}, \ldots d_0\}$ shall be associated with specific values of I and Q computed as described in this clause. The output of the constellation encoder for a subcarrier i is represented as a complex number Z_i and passed to the modulator (see clause 7.4.4). Z_i is derived from I_i and Q_i as defined in clause 7.4.3.3.

7.4.3.1 Constellations for even number of bits

If the number of bits, b, loaded onto the subcarrier is even (i.e., 2 or 4), square-shaped constellations with mappings described in this clause shall be used. Support of the 2-bit constellation is mandatory at both the transmitter and the receiver. Support of 4-bit constellation is mandatory at the transmitter and optional at the receiver.

Constellation mapping for b = 2 shall be as presented in Figure 7-18 and described in Table 7-19.

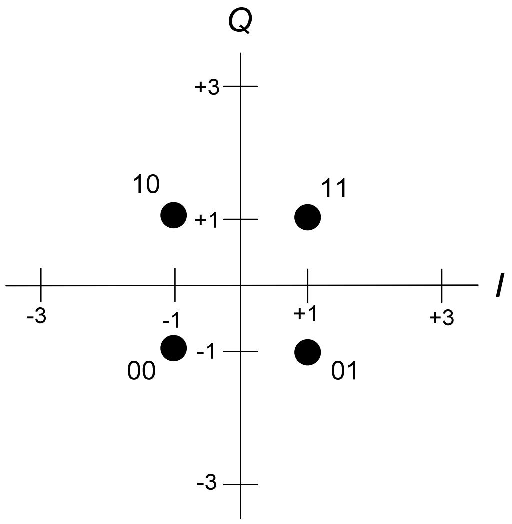


Figure 7-18 – Constellation mapping for b = 2 (d_1d_0)

Table 7-19 – Mapping for b = 2 (QPSK)

Bit d0	I		Bit d1	Q
0	–1		0	–1
1	1		1	1

Constellation mapping for b = 4 shall be as described in Table 7-20. The first quadrant of the mapping is presented in Figure 7-19.

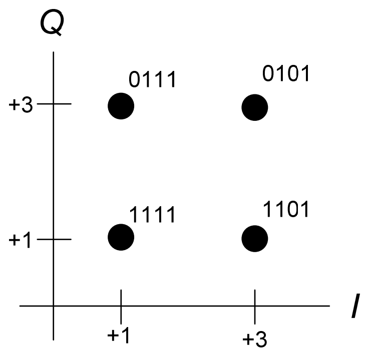


Figure 7-19 – Constellation mapping for b = 4 ($d_3d_2d_1d_0$, first quadrant)

Table 7-20 – Mapping for b = 4 (16-QAM)

Bits [d_1d_0]	*I*		Bit [d_3d_2]	*Q*
00	–3		00	–3
10	–1		10	–1
11	1		11	1
01	3		01	3

7.4.3.2 Constellations for odd number of bits

If the number of bits, *b*, loaded onto the subcarrier is odd (i.e., 1 or 3) constellations with mappings described in this clause shall be used. Support of the 1-bit constellation is mandatory at both the transmitter and the receiver. Support of 3-bit constellation is mandatory at the transmitter and optional at the receiver.

Constellation mapping for $b = 1$ shall be as presented in Figure 7-20 and Table 7-21.

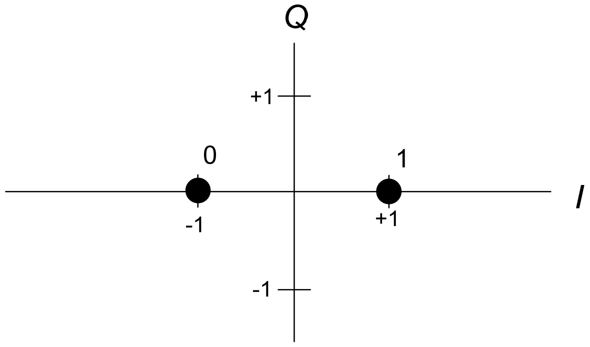


Figure 7-20 – Constellation mapping for $b = 1$ (d_0)

Table 7-21 – Mapping for $b = 1$ (BPSK)

Bit d_0	***I***
0	–1
1	1

Constellation mapping for $b = 3$ is for further study.

7.4.3.3 Constellation scaling

Each constellation point (I_i, Q_i) for a subcarrier *i*, corresponding to the complex value $I_i + jQ_i$ at the output of the constellation encoder, shall be scaled by the gain scaling factor g and power normalization factor $\chi(b)$ where *b* denotes the number of bits loaded onto a subcarrier. The output of the constellation encoder Z_i shall be:

$$Z_i = g \times \chi(b) \times (I_i + jQ_i)$$

7.4.3.3.1 Power normalization

The power normalization scaling provides all constellations, regardless of their size, having the same average transmit power. The required power normalization scaling, $\chi(b)$, for a subcarrier loaded with *b* bits depends only on the value of *b* and shall be set as presented in Table 7-22.

Table 7-22 – Power normalization factor

Number of bits loaded (*b*)	**$\chi(b)$ (linear scale)**
1	1
2	$1/\sqrt{2}$
3	for further study
4	$1/\sqrt{10}$

7.4.3.3.2 Gain scaling

The gain scaling, *g* provides power shaping by applying certain average power on different subcarriers. The average transmitted power of a particular subcarrier is controlled by setting an appropriate gain. The following rules shall apply for any frame:

– subcarriers with same indices of all preamble symbols and all CES symbols shall have the same gain factor;
– subcarriers with same indices of all PFH symbols shall have the same gain factor;
– subcarriers with same indices of all payload symbols shall have the same gain factor.

Further, the gain of subcarriers of the same symbol in the preamble, header, and payload shall comply with the rules defined in Table 7-23.

Table 7-23 – Gain factor of different subcarrier sets

Case	ASC	PSC	ISC	MSC
Preamble and CES	$GN_0 \times GB_P$	N/A	N/A	0
Header	$GN_0 \times GB_H$	$GN_0 \times GB_H$	N/A	0
Payload	GN_0	GN_0	0 to GN_0	0
NOTE 1 – The GN_0 stands for the nominal gain and GB stands for gain boost. NOTE 2 – The selection of the ISC gain in the assigned range is vendor discretionary.				

The nominal gain (payload gain) GN_0 and the gain boosts GB_P (of the preamble) and GB_H (of the PFH) relative to the payload gain GN_0 shall be set so that the transmit power limits defined in clause 7.7 shall not be violated during preamble, PFH, and payload.

The maximum value of either GB_P or GB_H is for further study, but shall not exceed 1.41 (3 dB boost). The default value GB is 1 (no boost for preamble and header).

By default, the nominal gain, GN_0, is the same for all subcarriers. Use of different values of GN_0 for subcarriers with different indices (spectrum shaping) is for further study.

7.4.4 OFDM modulator

The OFDM modulator consists of the following major parts: IDFT, cyclic extension, windowing, overlap and add, and frequency up-shift. The incoming signal to the modulator at the *l*-th OFDM symbol in the present frame for a single subcarrier with index *i*, is a complex value $Z_{i,l}$ generated by the constellation encoder, as described in clause 7.4.3 (for symbols of the PFH and the payload), or by preamble generator, as described in clause 7.4.5 (for symbols of the preamble), or by CES generator, as described in clause 7.4.6 (for CES symbols). Time-domain samples generated by the IDFT, after adding the cyclic prefix and windowing, are frequency up-shifted by F_{US}. The functional diagram of OFDM modulator is presented in Figure 7-21.

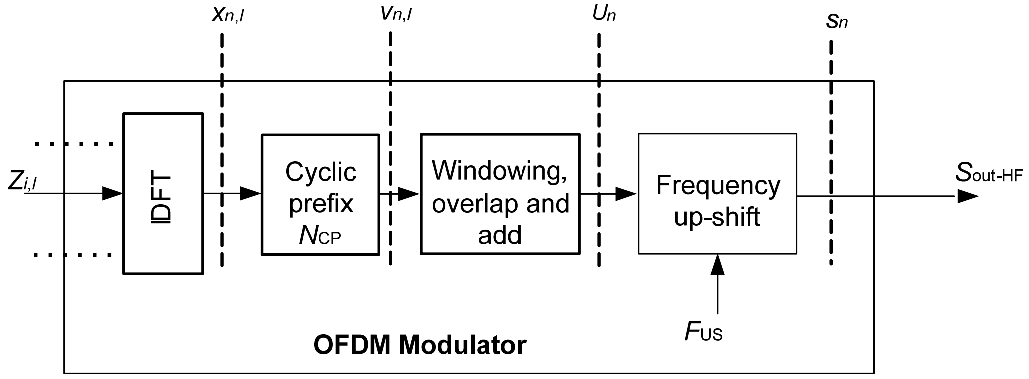


Figure 7-21 – Functional diagram of the OFDM modulator

The presented functional diagram and other figures presented in this clause do not imply any specific implementation. All aspects of signal processing used in the modulator shall comply with equations and textual descriptions.

7.4.4.1 IDFT

The IDFT converts the stream of the N complex numbers $Z_{i,l}$ at its input into the stream of N complex time-domain samples $x_{n,l}$. The input values represent the N mapped blocks of data, where the i-th block of data represents the complex value $Z_{i,l}$ of the i-th modulated subcarrier of the OFDM signal, where $i = 0, 1, \ldots N - 1$ is the subcarrier index and l is the sequential number of the OFDM symbol within the current frame, excluding the preamble. The conversion shall be performed in accordance with the equation:

$$x_{n,l} = \sum_{i=0}^{N-1} \exp\left(j \cdot 2\pi \cdot i \frac{n}{N} \right) \cdot Z_{i,l} \qquad \text{for } n = 0 \text{ to } N-1, \quad l = 0 \text{ to } M_F - 1$$

where M_F denotes the total number of OFDM symbols in the current frame excluding the preamble symbols, and the value of N represents the maximum number of possibly modulated subcarriers in the OFDM spectrum and shall be either 128 or 256 (see Table 7-27). The value of $Z_{i,l}$ for all masked subcarriers shall be set to 0. For non-masked subcarriers with indices $i < N$ that are from the ISC and PSC subcarrier sets), the corresponding values of $Z_{i,l}$ shall be generated as described in clauses 7.4.2.6, 7.4.2.7, respectively.

7.4.4.2 Cyclic extension and OFDM symbol

The cyclic extension provides a guard interval between adjacent OFDM symbols. This guard interval is intended to protect against inter-symbol interference (ISI).

The guard interval of the l-th OFDM symbol in the frame shall be implemented by pre-pending the last $N_{CP}(l)$ samples of the IDFT output (called cyclic prefix) to its output N samples, as presented in Figure 7-22. The order of samples in the symbol shall be as follows:

- The first sample of the symbol is the IDFT output sample $N - N_{CP}(l)$;
- The last sample of the cyclic prefix is the IDFT output sample $N - 1$; the next sample is the IDFT output sample 0.

The l-th OFDM symbol consists of N IDFT samples and $N_{CP}(l)$ cyclic extension, samples, in total:

$$N_W(l) = N + N_{CP}(l) \text{ [samples].}$$

After cyclic extension as described above, time-domain samples at the reference point $\upsilon_{n,l}$ in Figure 7-17 shall comply with the following equations:

$$\upsilon_{n,l} = x_{n-N_{CP}(l),l} = \sum_{i=0}^{N-1} Z_{i,l} \times \exp\left(j \cdot 2\pi \cdot i \frac{n - N_{CP}(l)}{N} \right) \cdot \quad \text{for } n = 0 \text{ to } N_W(l) - 1 = N + N_{CP}(l) - 1$$

.

The number of IDFT samples, N, and the number of windowed samples, β, shall be the same for all symbols of the same PHY frame.

7.4.4.3 Symbol timing

The PHY frame consists of a preamble followed by an integer number, M_F, of OFDM symbols. The first symbol following the preamble (the first symbol of the PFH) shall have symbol count 0, and the last symbol of the frame shall have symbol count $M_F – 1$. The time position of each symbol in the frame is defined by sample count. The first sample of the symbol with symbol count 0 shall have sample count $M(0)=N_{pr}–\beta$, where N_{pr} is the number of samples in the preamble. The count of the first sample of the l-th symbol ($l = 1, 2, \ldots, M_F – 1$) in the frame shall be:

$$M(l) = N_{\text{pr}} - \beta + \sum_{k=0}^{l-1} N_S(k)$$

where $N_S(k) = N + N_{CP}(k) – \beta$ and $N_S(k)$ are different for symbols of the PFH and the, payload, as described in clause 7.4.7.

7.4.4.4 Windowing, overlap and add

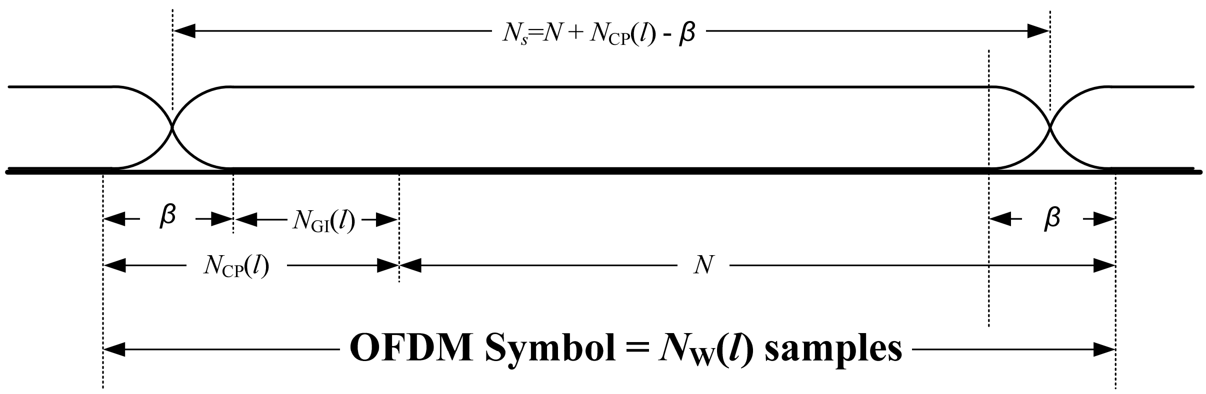


Figure 7-22 – Structure of an OFDM symbol

The first β samples of the cyclic prefix and last β samples of the IDFT output shall be used for shaping the envelope of the transmitted signal (windowing). The window function facilitates PSD shaping: it allows sharp PSD roll-offs used to create deep spectral notches and reduction of the out-of-band PSD. The number of windowed samples, β, shall be the same for all of the payload symbols, PFH symbols, CES, and preamble symbols of the same frame.

The windowed samples of adjacent symbols shall overlap, as shown in Figure 7-22. The value of $N_{CP}(l) – \beta = N_{GI}(l)$ forms the guard interval. The number of samples in the l-th OFDM symbol is thus $N_S(l) = N + N_{CP}(l) – \beta$.

After windowing, overlap and add, the time-domain samples at the reference point u_n in Figure 7-22 shall comply with the following equations:

$$u_n = u_n^{(pr)} + \sum_{l=0}^{M_F-1} w(n-M(l),l) \times \upsilon_{n-M(l),l} \qquad \text{for } n = 0 \text{ to } M(M_F-1) + N_W(M_F-1) - 1$$

where $u_n^{(pr)}$ is the n'th sample of the preamble, as defined in clause 7.4.5 (the signal $u_n^{(pr)}$ already includes windowing), and $w(n,l)$ is the windowing function defined on $N_W(l)$ samples of the OFDM symbol in the following way:

$$w(n,l) = \begin{cases} w_\beta(n) & 0 \le n < \beta \\ 1 & \beta \le n < N_W(l) - \beta \\ w_\beta(N_W(l) - 1 - n) & N_W(l) - \beta \le n < N_W(l) \\ 0 & \text{otherwise} \end{cases},$$

where $w_\beta(n)$ is the function describing the roll-off section of the window. The roll-off function $w_\beta(n)$ shall be vendor discretionary, however, it shall comply with the following rules:

- $w_\beta(n) + w_\beta(\beta - n - 1) = 1$ for $0 \le n < \beta$.
- $0 \le w_\beta(n) \le 1$.

The symbol period T_{OFDM} for the given value of N_{CP} and β shall be computed, respectively, as:

$$T_{OFDM} = \frac{N + N_{CP} - \beta}{N \times F_{SC}}$$

7.4.4.5 Frequency up-shift

The frequency up-shift offsets the spectrum of the transmit signal shifting it up by F_{US}. The value of F_{US} shall be a multiple of the subcarrier frequency F_{SC}:

$$F_{US} = m \times F_{SC}$$

where m is an integer and $m \ge N/2$. The valid values of m are specified in clause 7.4.7, Table 7-27.

The real and imaginary components of the signal after frequency up-shift (reference point s_n in Figure 7-21) shall be as follows:

$$s_n = u_{n/p} \times \exp\left(j\frac{2\pi mn}{Np}\right) = \mathrm{Re}(s_n) + j\,\mathrm{Im}(s_n) \qquad \text{for } n = 0 \text{ to } [M(M_F-1) + N_W(M_F-1)] \times p - 1;$$

$$\mathrm{Re}(s_n) = \mathrm{Re}(u_{n/p})\cos\left(\frac{2\pi mn}{Np}\right) - \mathrm{Im}(u_{n/p})\sin\left(\frac{2\pi mn}{Np}\right)$$

$$\mathrm{Im}(s_n) = \mathrm{Re}(u_{n/p})\sin\left(\frac{2\pi mn}{Np}\right) + \mathrm{Im}(u_{n/p})\cos\left(\frac{2\pi mn}{Np}\right)$$

where $u_{n/p}$ is u_n after interpolation with factor p. The interpolation factor p is vendor discretionary, and shall be equal to or higher than 2.

NOTE 1 – The minimum value of p sufficient to avoid distortions depends on the ratio between the up-shift frequency FUS and the bandwidth of the transmit signal BW = N^*F_{SC}. It is assumed that an appropriate low-pass filter is included to reduce imaging.

NOTE 2 – The phase of the up-shift should be initialized to zero at the first sample of the preamble and be advanced by $\frac{2\pi m}{Np}$ per each sample (after interpolation).

7.4.4.6 Output signal

The output signal of the modulator shall be the real component of sn:

$$S_{out\text{-}HF} = \mathrm{Re}(s_n)$$

7.4.5 Preamble

7.4.5.1 General preamble structure

The preamble shall be pre-pended to every PHY frame as defined in clause 7.2.1. It is intended to assist the receiver in detecting the presence of the frame, synchronizing to the frame boundaries, and acquiring the physical layer parameters such as channel estimation and OFDM symbol alignment. The preamble shall meet the same transmit signal limits as the PFH and the payload symbols of the PHY frame, as defined in clause 7.7.

Table 7-24 presents the general structure of the ITU-T G.9955 preamble. The preamble comprises of two sections. Each section I (I = 1, 2) comprises N_I repetitions of an OFDM symbol S_I employing all subcarriers of the SSC set (with subcarrier spacing F_{SC}). Each preamble section shall be windowed in order to comply with the transmit signal limits using the windowing mechanism defined in clause 7.4.4.4. The general preamble structure is illustrated in Figure 7-26, and the relevant parameters N_1 and N_2 are defined in Table 7-24.

Table 7-24 – Structure of the preamble

Parameter	1st section	2nd section
Number of symbols (N_I)	N_1 (Note 1)	N_2 =1
Subcarrier spacing	F_{SC}	F_{SC}
Type of symbol (S_I)	S_1	$S_2 = -S_1$ (Note 2)
NOTE 1 – The valid values of N_1 are 8 and (8 + *ceiling*[(AC_Cycle/4)/T_{OFDM}], where AC_Cycle = 20 ms for 50 Hz mains and 16.67 ms for 60 Hz mains. Other valid values of N_1 are for further study. The value of N_1 to be used is determined by the PMD_MGMT.REQ primitives (see clause 7.8.2.4). NOTE 2 – The OFDM symbol of the 2nd section shall be an inverted time-domain waveform of the symbol used in the 1st section.		

Figure 7-23 shows the ITU-T G.9955 preamble waveform.

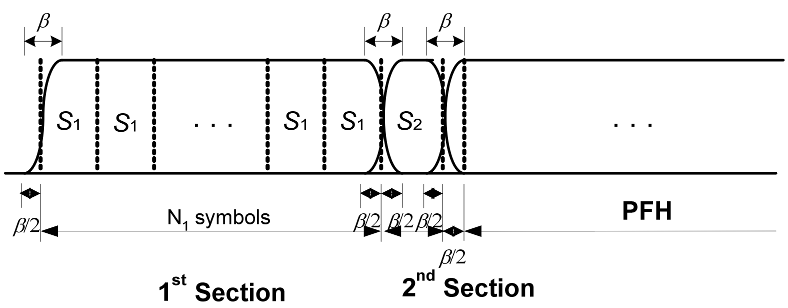


Figure 7-23 − Preamble structure (N_2 = 1)

7.4.5.2 Preamble generation

The preamble generation method described in this clause is applicable to all frequency bands.

7.4.5.2.1 Frequency-domain symbol generation

The preamble generator shall output complex values Z_i for each subcarrier i in the range from $i = 0$ to $i = N - 1$. These values shall be modulated onto corresponding subcarriers of the symbols of the preamble in accordance with the relevant subcarrier mask (i.e., modulated onto all subcarriers except those from PMSC and RMSC shall be masked out), as defined in clause 7.4.4.

The values of Z_i shall be generated by the constellation encoder for 2-bit constellation, as defined in clause 7.4.3.1, fed by the pseudo-random binary sequence (PRBS) generator, as shown in Figure 7-24.

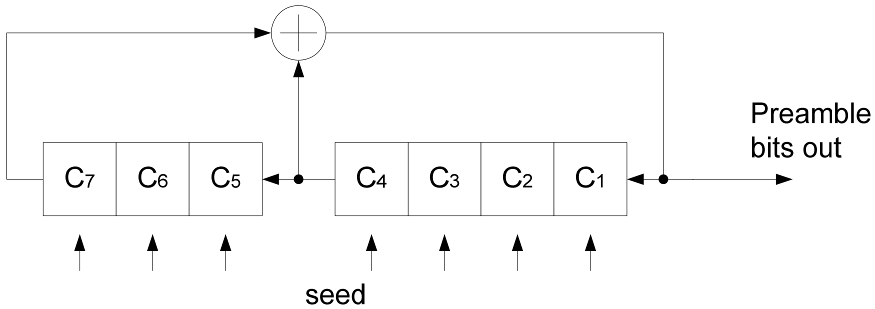


Figure 7-24 – PRBS generator

The PRBS generator shall be initialized at the beginning of each symbol to a seed. The default value of the seed shall be as specified in Table 7-25. In Figure 7-24, C_1 is the LSB of the seed. Other values of the seed are for further study.

Table 7-25 – Default seed value of the PRBS that generates the preamble

Bandplan	Seed value
CENELEC A	29_{16}
CENELEC B	23_{16}
CENELEC CD	50_{16}
FCC	$4C_{16}$
FCC-1	63_{16}
FCC-2	$0E_{16}$

The PRBS generator shall implement the polynomial $g(x) = x^7 + x^4 + 1$. The PRBS shall be advanced by 2 bits for each subcarrier (either masked or not; the shift of the PRBS for subcarrier index k shall be $2k+2$). The output bits of the PRBS generator shall be taken as the input bits of the constellation encoder, $\{d_0, d_1\}$, where d_0 corresponds to C_1 and d_1 corresponds to C_2 of the PRBS generator. Bits shall be assigned to subcarriers in ascending order of their indices, starting from index $i = 0$.

7.4.5.2.2 Time-domain symbol generation

To form a section of a preamble, the output preamble symbol shall be repeated N_I times.

The first and second sections of the preamble shall be windowed, overlapped and added as described below:

1) First section:
   a) The first symbol of the first section is cyclically extended by pre-pending the last β/2 samples of the symbol S_1;
   b) The last symbol of the first section is cyclically extended by appending the first β/2 samples of the symbol S_1;
   c) The first and last β samples of the extended first section are windowed with a window function w_β(n) and $w_\beta(\beta\text{-}n\text{-}1)$ respectively.
2) Second section:
   a) The symbol of the second section is cyclically extended by pre-pending the last β/2 samples of the symbol S_2 and further cyclically extended by appending the first β/2 samples of the symbol S_2;
   b) The first and last β samples of the extended second section are windowed with a window function w_β(n) and $w_\beta(\beta–n–1)$ respectively.
3) Overlap and add:
   a) The β windowed samples at the end of the first section and at the beginning of the second section are overlapped and added.
   b) The β windowed samples at the end of the second section are overlapped and added with the β windowed samples at the beginning of the PFH as described in clause 7.4.4.4.

The window shaping function w_β(n) shall comply with the rules specified in clause 7.4.4.4.

Assembling of the OFDM symbols in the preamble is illustrated in Figure 7-25.

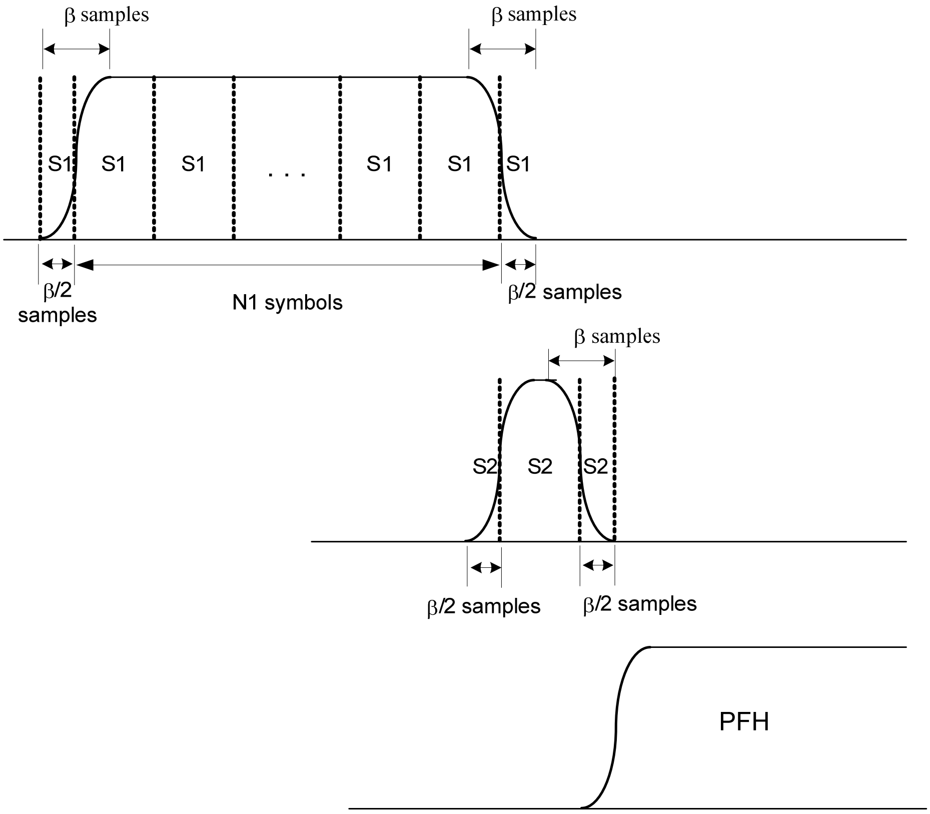


Figure 7-25 – Preamble time-domain generation

The total number N_{pr} of samples in the preamble can be computed as:

$$N_{pr} = \beta + N_1 \times N + N_2 \times N = \beta + N \times (N_1 + 1)$$

7.4.6 Channel estimation symbols

The Channel Estimation Symbols (CES) shall be transmitted using the BAT Type 0. The modulation parameters of the CES shall be the same as for PFH symbols, as defined in clause 7.4.6. The windowing shall be as used for PFH symbols.

The CES shall be transmitted after N_{OCES} PFH symbols, using the same signal levels as symbols of the preamble, and meet transmit signal limits defined in clause 7.7. The value of N_{OCES} depends on the bandplan and shall be as defined in Table 7-26. If the number of symbols in the PFH (see Table 7-16) is less than the value of N_{OCES} shown in Table 7-26, the CES symbols shall follow the PFH.

Table 7-26 – CES offset value for different bandplans

Bandplan	N_{OCES}
CENELEC A, B, CD (50 Hz)	7
CENELEC A, B, CD (60 Hz)	6
FCC, FCC-1, FCC-2 (50 Hz)	15
FCC, FCC-1, FCC-2 (60 Hz)	13
NOTE – 50 Hz and 60 Hz are the frequencies of the mains.	

The bits loaded onto CES shall be generated using the PRBS generator defined in clause 7.4.5.2.1. The PRBS generator shall be initialized at the beginning of each CES with the same seed as for the preamble symbols S1 and S2. The first CES shall be equal S2, while the second CES shall be an inverted copy of the first CES, i.e., –S2 = S1.

7.4.7 PMD control parameters

Table 7-27 summarizes valid values of control parameters of an OFDM modulator described in clause 7.4.4. This list is a superset of all parameters used for different bandplans; a list of valid values of modulation parameters and their valid combinations for each bandplan is presented in clause 7.5.

Table 7-27 –OFDM control parameters

Notation	Parameter	Valid values or range
N	Number of subcarriers	2^k, $k = 7, 8$
F_{SC}	Subcarrier spacing [kHz]	$15.625/n$, $n = 5, 10$
N_{GI-CES}	Guard interval of the CES [samples]	0
N_{GI-HD}	Guard interval of the PFH [samples]	0
N_{GI-PL}	Guard interval of the payload [samples]	$(12/128)*N$, $(24/128)*N$
β	Window size [samples]	Any even integer between 0 and $N/16$
F_{US}	Up-shift frequency, [kHz]	$N/2 \times F_{SC}$
NOTE – Guard interval and window size are expressed in samples at Nyquist rate.		

Secondary parameters of the OFDM modulator are presented in Table 7-28.

Table 7-28 – Secondary parameters of the modulator

Notation	Parameter	Definition
BW	Total bandwidth [Hz]	$BW = N \times F_{SC}$
N_W	Total number of samples in an OFDM symbol	$N_W = N + N_{CP}$
T_{OFDM}	Symbol period [s]	$T_{OFDM} = \frac{N + N_{CP} - \beta}{N \times F_{SC}}$
N_{GI}	Guard interval	$N_{GI} = N_{CP} - \beta$
f_s	Transmit clock	$f_s = N \times F_{SC}$

7.5 Frequency band specification

For compliance to this Recommendation it is mandatory to support at least one of the CENELEC bandplans or at least one of the FCC bandplans.

7.5.1 CENELEC band

When operating on CENELEC band (3 kHz – 148.5 kHz), a node shall use the control parameters specified in Table 7-29 (see clause 7.4.7).

Table 7-29 – OFDM modulator control parameters for CENELEC band

Notation	Value
N	128
F_{SC}	1.5625 kHz
N_{GI-PL}	12 – 1, 2 bit mapping 24 – 3, 4 bit mapping
N_{GI-HD}	0
N_{GI-CES}	0
β	8
F_{US}	$64 \times F_{SC}$

CENELEC band is divided into sub-bands, forming bandplans A, B, and CD described in this section.

7.5.1.1 CENELEC-A bandplan

Parameters for CENELEC-A bandplan are defined in Table 7-30.

Table 7-30 – Parameters for CENELEC-A bandplan

Notation	Value	Note
F_{START}	35.9375 kHz	Lowest frequency of CENELEC-A bandplan (subcarrier number 23)
F_{END}	90.625 kHz	Highest frequency of CENELEC-A bandplan (subcarrier number 58)
PMSC indices	0 to 22, 59 to 127	Clause 7.4.2.1

7.5.1.2 CENELEC-B bandplan

Parameters for CENELEC-B bandplan are defined in Table 7-31.

Table 7-31 – Parameters for CENELEC-B bandplan

Notation	Value	Note
F_{START}	98.4375 kHz	Lowest frequency of CENELEC-B bandplan (subcarrier number 63)
F_{END}	120.3125 kHz	Highest frequency of CENELEC-B bandplan (subcarrier number 77)
PMSC indices	0 to 62, 78 to 127	Clause 7.4.2.1

7.5.1.3 CENELEC-CD bandplan

Parameters for CENELEC-CD bandplan are defined in Table 7-32.

Table 7-32 – Parameters for CENELEC-CD bandplan

Notation	Value	Note
F_{START}	125 kHz	Lowest frequency of CENELEC-CD bandplan (subcarrier number 80)
F_{END}	143.75 kHz	Highest frequency of CENELEC-CD bandplan (subcarrier number 92)
PMSC indices	0 to 79, 93 to 127	Clause 7.4.2.1

7.5.2 FCC band

When operating on FCC band (9 kHz – 490 kHz), a node shall use the control parameters specified in Table 7-33 (see clause 7.4.7).

Table 7-33 – OFDM modulator control parameters for FCC band

Notation	Value
N	256
F_{SC}	3.125 kHz
N_{GI}	24 – 1, 2 bit mapping 48 – 3, 4 bit mapping
$N_{GI\text{-}HD}$	0
$N_{GI\text{-}CES}$	0
β	16
F_{US}	$128 \times F_{SC}$

Bandplans FCC, FCC-1 and FCC-2 defined over the FCC band are described in this clause. Additional bandplans over FCC band are for further study.

7.5.2.1 FCC bandplan

Parameters for FCC bandplan are defined in Table 7-34.

Table 7-34 – Parameters for FCC bandplan

Notation	Value	Note
F_{START}	34.375 kHz	Lowest frequency of FCC bandplan (subcarrier number 11)
F_{END}	478.125 kHz	Highest frequency of FCC bandplan (subcarrier number 153)
PMSC indices	0 to 10, 154 to 255	Clause 7.4.2.1

7.5.2.2 FCC-1 bandplan

Parameters for FCC-1 bandplan are defined in Table 7-35.

Table 7-35 – Parameters for FCC-1 bandplan

Notation	Value	Note
F_{START}	34.375 kHz	Lowest frequency of FCC bandplan (subcarrier number 11)
F_{END}	137.5 kHz	Highest frequency of FCC bandplan (subcarrier number 44)
PMSC indices	0 to 10, 45 to 255	Clause 7.4.2.1

7.5.2.3 FCC-2 bandplan

Parameters for FCC-2 bandplan are defined in Table 7-36.

Table 7-36 – Parameters for FCC-2 bandplan

Notation	Value	Note
F_{START}	150 kHz	Lowest frequency of FCC bandplan (subcarrier number 48)
F_{END}	478.125 kHz	Highest frequency of FCC bandplan (subcarrier number 153)
PMSC indices	0 to 47, 154 to 255	Clause 7.4.2.1

7.6 Transmit PSD mask

7.6.1 Frequency notching

This Recommendation supports frequency notching for regulatory and coexistence purposes. Notching shall apply to all components of a PHY frame (preamble, PFH, CES, and payload) and to all PHY frames transmitted in the domain.

If frequency notching is implemented by masking subcarriers, masked subcarriers shall be determined using the following rules:

- A frequency region between any two consecutive subcarriers (F_{SC}) is divided into 4 equally-spaced sections, which are further grouped into two equal regions: R1 that is around each subcarrier and R2 that is in the middle of two subcarriers, as shown in Figure 7-26.
- If the notched frequency falls in R1 region of a subcarrier, this subcarrier and two adjacent subcarriers shall be masked (i.e., total of three subcarriers, which indices are $n – 1$, n, and $n + 1$ shall be masked if the notched frequency falls in R1 region that contains subcarrier n).
- If the notched frequency falls in R2 region, the two nearest subcarriers in both sides shall be masked (i.e., total of four subcarriers, which indices are $n – 1$, n, $n + 1$, and $n + 2$ shall be masked if the notched frequency falls in R2 region between subcarriers n and $n + 1$).

NOTE – Depending on the relative position of the required to be notched frequency with respect to subcarriers, the number of masked subcarriers can vary, but the notched frequency is at least ($7 \times F_{SC}/4$) kHz away from the nearest subcarrier that is not masked.

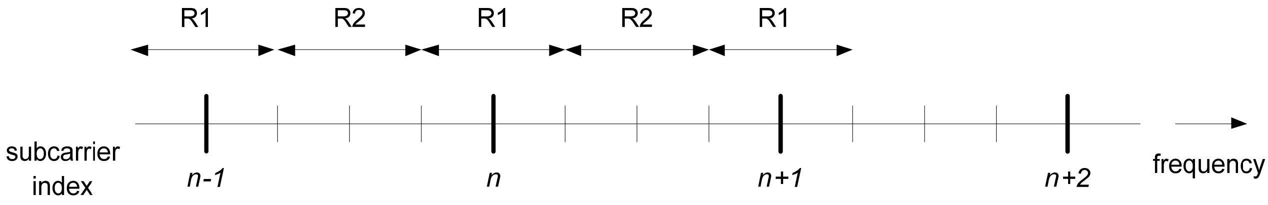


Figure 7-26 – Frequency notching

7.7 Electrical specification

7.7.1 System clock frequency tolerance requirements

The node system clock frequency tolerance shall not exceed ±50 ppm.

The subcarrier frequencies and symbol timing shall be derived from this same system clock oscillator and thus shall have the same tolerance.

7.7.2 Transmit signal limits

The measurement methods and apparatus used for quasi-peak, peak, and average detectors shall be as defined in [CISPR 16-1].

7.7.2.1 CENELEC bandplans

For all CENELEC bandplans specified in clause 7.5.1, ITU-T G.9955 transceivers shall comply in-band and out-of-band transmit signal limits specified in Annex F. These limits shall be met when loaded on the standard Artificial Mains Network (AMN) specified in Annex F, Figure F.2, connected as specified in clause F.1, for single phase and Figure F-4 for 3-phase devices.

7.7.2.2 FCC bandplans

For all FCC bandplans specified in clause 7.5.2, the following limits shall be met:

1) The output signal voltage measured using a peak detector with 200 Hz bandwidth in no part of the frequency band shall exceed 120 dB(μV) when loaded on a standard termination network (TN).
2) The output signal voltage measured using a peak detector over the entire bandplan when loaded on a standard TN shall not exceed 134 dB(μV) for FCC-1 and shall not exceed 137 dB(μV) for FCC and FCC-2. Higher transmit signal limits for medium voltage (MV) lines are for further study.
3) The output signal voltage measured outside the spectral bandwidth of the bandplan shall not exceed:
   - In the frequency range from 9 kHz to 150 kHz, the limit for the output signal voltage measured by a quasi-peak detector with resolution bandwidth 200Hz shall decrease linearly with the logarithm of frequency from 89 dB (μV) at 9 kHz to 66 dB (μV) at 150 kHz.
   - In the frequency range from 150 kHz to 535 kHz, the limit for the output signal voltage measured by a quasi-peak detector with resolution bandwidth 9kHz shall decrease linearly with the logarithm of frequency from 66 dB (μV) at 150kHz to 60 dB (μV) at 535 kHz.

Spectral bandwidth definition shall comply with Figure 7-27.

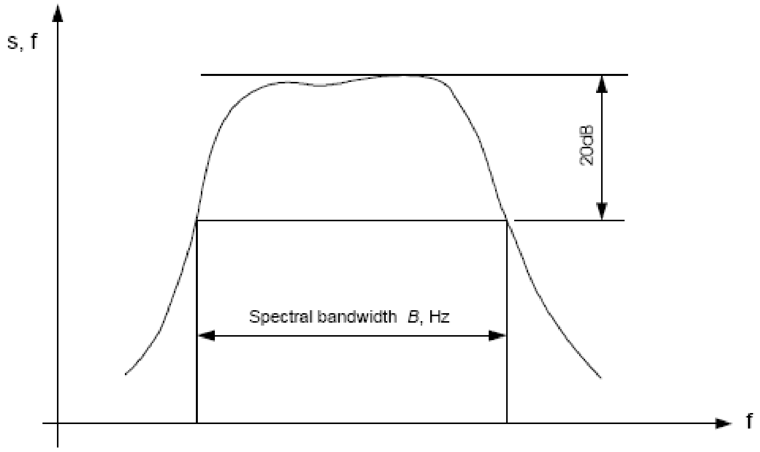


Figure 7-27 – Measurement of spectral bandwidth

Other transmit signal limits are for further study. Connections of the ITU-T G.9955 transceiver to TN for transmit signal limit verification for both single phase and two-phase is for further study.

7.7.2.3 Notched frequency bands

The output signal voltage measured using a quasi-peak detector with 200 Hz bandwidth in no part of the notched frequency band shall exceed 70 dB (µV) when loaded on a standard termination network (TN).

7.7.2.4 FCC standard termination network

The standard termination network, TN, shall be used exclusively for transmit signal limit verification purposes. The TN impedance shall be formed as a 50 Ohm resistive load connected in parallel with a 50µH inductance, FCC line impedance stabilization network (LISN).

Other types of termination networks are for further study.

7.7.3 Error vector magnitude limits

The deviation of the actual transmit signal from the corresponding constellation point shall be estimated by the value of Error Vector Magnitude (EVM) calculated as:

$$EVM = 10\log\left(\frac{error\_vector\_RMS}{reference\_signal}\right)^2$$

The interpretation of EVM components for a constellation point is illustrated in Figure 7-28.

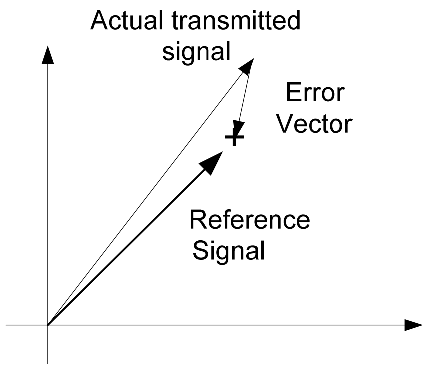


Figure 7-28 – Interpretation of EVM

The EVM shall be determined for the first 12 payload symbols of the transmitted frame using the following procedure:

1) Compute the rms error between the actually transmitted and the ideal constellation points for each symbol as the sum of the squared Euclidean distances between the two mentioned constellation points over all the subcarriers in the symbol (the PPM drift between the transmitter and sampling device should be estimated and corrected):

$$\text{error\_rmsi} = \sum_{c=0}^{K} abs\{A_{ic} \times \exp[j\Phi_{ic}] - B_{ic} \times \exp[j\Theta_{ic}]\}^2$$

where:

K is the number of ASC in the symbol, numbered from c = 0,1, …K;

A_{ic} and Φ_{ic} are the multitude and phase of the actually transmitted constellation point;

B_{ic} and Θ_{ic} are the multitude and phase of the ideal constellation point.

2) Compute the total rms error as the sum of the rms errors of 12 individual payload symbols numbered from 0 to 11:

$$\text{total\_error\_rms} = \sum_{i=0}^{11} error\_rms_i$$

3) Compute the rms of each transmitted symbol as:

$$\text{Tx\_rmsi} = \sum_{c=0}^{K} A_{ic}^{\ 2}$$

and the total rms for 12 transmitted symbols as:

$$\text{total\_Tx\_rms} = \sum_{i=0}^{11} Tx\_rms_i$$

4) Compute EVM, as a ratio between the total error rms and total_Tx_rms, expressed in dB:

$$\text{EVM} = 10 \times \log(\text{total\_error\_rms}/\text{total\_Tx\_rms}).$$

The value of EVM shall not exceed the values in Table 7-37.

Table 7-37 – Maximum allowed EVM values

Modulation	EVM, dB (Note)
1 and 2 bits	–15
3 and 4 bits	–19
NOTE – These EVM requirements shall be met for all applied transmit power levels.	

The EVM values specified in Table 7-37 shall be achieved when the device is loaded on standard termination impedance as defined in clauses 7.7.2.1 and 7.7.2.4 for CENELEC and FCC bandplans, respectively.

For modulation with 3 and 4 bits, the transmit power levels under which these requirements are met may be lower than those for 1 and 2 bit modulation.

7.8 PHY data, management, and control primitives

This clause describes in detail the PHY-related reference points defined in clause 5.2.2 (PMI_DATA, PMI_MGMT, and PHY_MGMT).

7.8.1 PMI-interface data primitives

The following data primitives at the PMI_DATA reference point are defined:

Table 7-38 – PHY data primitives

Category	Primitive	Direction	Description
PMI_DATA	PMI_DATA.REQ	DLL → PHY	DLL requests the PHY to transmit an MPDU
	PMI_DATA.CNF	PHY → DLL	PHY reports to DLL the status of the MPDU transmission (transmission complete, not complete, failed)
	PMI_DATA.IND	PHY → DLL	PHY passes to DLL a received MPDU data

7.8.1.1 PMI_DATA.REQ

This primitive is sent by the DLL to request transmission of the MPDU. The attributes of the primitive are defined in Table 7-39.

Table 7-39 – The attributes of the PMI_DATA.REQ primitive

Name	Type	Valid range	Description
MPDU length	Integer	0x00-0x6A9	The number of bytes contained in the MPDU to be transmitted by the PHY.
MPDU	Array of bytes	Any	An array of bytes forming the MPDU to be transmitted by the PHY
Number of information codewords	Integer	1-32	The number of RS information blocks in the MPDU, *m* (Note).
NOTE – The size of the RS information blocks shall be as defined in clause 7.3.2.			

The PHY should start the transmission no later than $0.1*T_{TS}$ after the PMI_DATA.REQ is issued by the MAC. The T_{TS} is defined in clause 8.1.4 of [ITU-T G.9956].

7.8.1.2 PMI_DATA.CNF

This primitive reports the status of the MPDU transmission to a peer PHY. The attributes of this primitive are defined in Table 7-40.

Table 7-40 – The attributes of the PMI_DATA.CNF primitive

Name	Type	Valid range	Description
MPDU Tx status	Integer	0-3	The status of the MPDU requested for transmission: 0 – Transmitted successfully (PHY is ready to accept the next frame for transmission) 1 – Not transmitted (busy transmitting a frame, Note) 2 – Transmission failed (PHY is receiving a frame or getting ready to receive a frame, Note) 3 – Transmission failed (MPDU of invalid size)
NOTE – If DLL sends a PMI_DATA.REQ when PMI_DATA.CNF = 1, 2, the PHY may ignore the PMI_DATA.REQ primitive and discard the MPDU requested for transmission.			

7.8.1.3 PMI_DATA.IND

This primitive indicates the transfer of a received MPDU from the PHY to the DLL. The attributes of the primitive are defined in Table 7-41.

Table 7-41 – The attributes for the PMI_DATA_MPDU.IND primitive

Name	Type	Valid range	Description
MPDU length	Integer	0x00-0x6A9	The number of bytes contained in the MPDU received by the PHY.
MPDU	Array of bytes	N/A	An array of bytes forming the MPDU received by the PHY
MPDU error	Bit map	32-bit	This primitive indicates errors that were detected in the *m* RS information blocks of the received MPDU: 0 – No error detected in the codeword by the PHY 1 – PHY detected an error in the k-th RS information block of the received MPDU The first bit of the bit map shall correspond to the first RS information block, and the *m*-th bit of the bit map shall correspond to the last RS information block in the received MPDU.

7.8.2 PMI-interface and PHY management and control primitives

The control and management primitives at the PMI_MGMT reference point and PHY_MGMT reference point are defined in Table 7-42:

Table 7-42 – PHY management and control primitives

Category	Primitive	Description
PMI_MGMT	PMI_MGMT.REQ	DLL request PHY to apply particular parameters or perform particular functions
	PMI_MGMT.CNF	PHY confirms parameters and functions requested by the DLL
	PMI_MGMT.IND	PHY indicates to the DLL its status, status of the medium, and particular parameters of the received frame
	PMI_MGMT.RES	DLL acknowledges reception of PHY status, status of the medium, parameters of the received frame
PHY_MGMT.REQ	PCS_MGMT.REQ	PHY management entity requests to apply particular parameters of PCS, PMA, PMD for the transmit frames
	PMA_MGMT.REQ	
	PMD_MGMT.REQ	
PHY_MGMT.CNF	PCS_MGMT.CNF	PHY sub-layers (PCS, PMA, PMD) confirms parameters applied for the transmit frame
	PMA_MGMT.CNF	
	PMD_MGMT.CNF	
PHY_MGMT.IND	PCS_MGMT.IND	PHY sub-layers (PCS, PMA, PMD) report to the PHY management entity particular parameters of the received frame and acquired channel characteristics
	PMA_MGMT.IND	
	PMD_MGMT.IND	
PHY_MGMT.RES	PCS_MGMT.RES	DLL management acknowledges parameters of the received frame and channel characteristics reported by the PHY sub-layers (PSC, PMA, PMD)
	PMA_MGMT.RES	
	PMD_MGMT.RES	

7.8.2.1 PMI_MGMT primitives

7.8.2.1.1 PMI_MGMT.REQ

This primitive requests the PHY to turn into a particular status (enable or disable the receiver), apply particular parameters, and perform particular functions asserted by the DLL. The attributes of the primitive are defined in Table 7-43.

Table 7-43 – The attributes of the PMI_MGMT.REQ primitive

Name	Type	Valid range	Description
RxEnbl	Integer	0, 1	Requests to turn on/off the receiver: 0 – receiver is enabled 1 – receiver is disabled NOTE – Receiver shall be off when node transmits a frame. Node shall not transmit when this primitive is set to 0.

Table 7-43 – The attributes of the PMI_MGMT.REQ primitive

Name	Type	Valid range	Description
Request for physical carrier sense	Integer	0-3	Requests the PHY for the physical carrier sense status: 0 – No request; 1 – Request for ITU-T G.9955 carrier sense; 2 – Request for non-ITU-T G.9955 carrier sense (see clause 5.1.2.3, "Preamble-based coexistence mechanism"); 3 – Request for both ITU-T G.9955 and non-ITU-T G.9955 carrier sense.
ACK request	Integer	0-3	Request for an ACK for the transmitter frame: 0 – No request 1 – Regular ACK requested 2 – Extended ACK requested 3 – Reserved by ITU-T
ACK data type	Integer	0-3	The type of the ACK request to for the transmitted framed (see [ITU-T G.9956], clause 8.3.3.1.1): 0 – Acknowledgement to MS-MPDU 1 – Acknowledgement to SS-MPDU 2 – Extended acknowledgement 3 – Reserved by ITU-T
TP-PR	Array of bits	See [ITU-T G.9956], clause 8.3.3.1.1.1	The content of the TP partial report to be transmitted by the node using format defined in clause 8.3.3.1.1.1
ACK data	Array of bits	See [ITU-T G.9956], clause 8.3.3.1.1	A set of bits forming the ACK related parameters to be transmitted by the PHY in the Imm-ACK frame (see [ITU-T G.9956], clause 8.3.3.1.1)
PHY parameters	See 7.8.2.2	See 7.8.2.2	The attributes of the PHY_MGMT.REQ primitive asserted by the DLL management entity and defined in clause 7.8.2.2.1 (PCS), clause 7.8.2.3.1 (PMA), and clause 7.8.2.4.1 (PMD)

7.8.2.1.2 PMI_MGMT.CNF

This primitive confirms the status, parameters, and functions of the PHY in response to PMI_MGMT.REQ. The attributes of the primitive are defined in Table 7-44.

Table 7-44 – The attributes for the PMI_MGMT.CNF primitive

Name	Type	Valid range	Description
Receiver status	Integer	0-2	Confirms the status of the receiver: 0 – receiver is enabled 1 – receiver is disabled 2 – receiver is busy NOTE – The "busy" status indicates that the receiver is in the middle of receiving a frame and cannot perform the request to be disabled.
ACK TX status	Integer	0, 1	0 – Transmitted (PHY is ready to accept the next frame for transmission) 1 – Not transmitted (busy transmitting the ACK frame)
PHY parameters status	Array of integers	0, 1	The attributes of PHY_MGMT.CNF primitive, indicates whether the PHY parameters asserted by the DLL management entity and defined in clause 7.8.2.2.2 (PCS), clause 7.8.2.3.2 (PMA), and clause 7.8.2.4.2 (PMD) was accepted or denied: 0: success 1: request is denied

7.8.2.1.3 PMI_MGMT.IND

This primitive indicates to the DLL management entity the status of the PHY and the medium, and the parameters of the received frame. The attributes of the primitive are defined in Table 7-45.

Table 7-45 – The attributes of the PMI_MGMT.IND primitive

Name	Type	Valid range	Description
Physical carrier sense	Integer	0-3	See Physical Carrier Sense attribute of PMD_MGMT.IND primitive , Table 7-54
ACK request	Integer	0-3	See ACK Request attribute of the PCS_MGMT.IND primitive, Table 7-48
ACK data type	Integer	0-3	See ACK Data Type attribute of the PCS_MGMT.IND primitive, Table 7-48
ACK data	Array of bits	See [ITU-T G.9956], clause 8.3.3.1.1	See ACK Data attribute of the PCS_MGMT.IND primitive, Table 7-48
TP-PR	Array of bits	See [ITU-T G.9956], clause 8.3.3.1.1.1	See TP-PR attribute of the PCS_MGMT.IND primitive, Table 7-48
PHY parameters	See clause 7.8.2.2	See 7.8.2.2	The attributes of PHY_MGMT.IND primitive delivered by the received frame to be passed to the DLL management entity and defined in clause 7.8.2.2.3 (PCS), clause 7.8.2.3.3 (PMA), and clause 7.8.2.4.3 (PMD)

7.8.2.1.4 PMI_MGMT.RES

This primitive is for further study.

7.8.2.2 PCS_MGMT primitives

7.8.2.2.1 PCS_MGMT.REQ

This primitive requests the PCS to use particular parameters for frame transmission. The attributes of the primitive are defined in Table 7-46.

Table 7-46 – The attributes of the PCS_MGMT.REQ primitive

Name	Type	Valid range	Description
Type of the frame	Integer	1-4	Type of the transmitted PHY frame
PFH data	See clause 7.2.1 and [ITU-T G.9956] clause 8.3.3.1.1	See clause 7.2.1 and [ITU-T G.9956] clause 8.3.3.1.1	The PFH parameters of the transmitted frame are defined: – clause 7.8.1 – Imm-ACK frame related – clause 7.8.3 – PMA-related – clause 7.8.4 – PMD related

7.8.2.2.2 PCS_MGMT.CNF

This primitive confirms the particular parameters used by the PCS for frame transmission. The attributes of the primitive are as defined in Table 7-47.

If the PHY is unable to comply with a particular attribute in the PCS_MGMT.REQ, it shall set this primitive to one, which means that the request is denied (and the frame is not be transmitted). Otherwise the value of the PCS_MGMT.CNF primitive shall be set to zero.

Table 7-47 – The attributes of the PCS_MGMT.CNF primitive

Name	Type	Valid range	Description
Status	Integer	0,1	0: success 1: request is denied

7.8.2.2.3 PCS_MGMT.IND

This primitive provides the PHY management with particular parameters of the received frame derived from the received PFH. The attributes of the primitive are defined in Table 7-48.

Table 7-48 – The attributes of the PCS_MGMT.IND primitive

Name	Type	Valid range	Description
Virtual carrier sense	Integer	0-1024	Indicates the number of symbols in the payload of the frame sequence during which the medium will be busy (valid for ITU-T G.9955 frame types 2, 4 only)
Type of the frame (Note)	Integer	1-4	Type of the received PHY frame
RX PFH status	Integer	0-2	Status of PFH of the received frame: 0 – correct 1 – HCS error 2 – Invalid content
MPDU size	Integer	0-255	Number of bytes in the MPDU of the received frame

Table 7-48 – The attributes of the PCS_MGMT.IND primitive

Name	Type	Valid range	Description
Payload modulation	Integer	2-4	Number of bits per subcarrier used for payload modulation in the received frame
Payload repetitions	Integer	1-12	Number of repetitions in the payload of the received frame
Payload interleaving mode	Integer	0, 1	Payload interleaving mode of the received frame: 0 – IoAC 1 – IoF
RS codeword size	Integer	0, 1	Maximum number of bytes in RS codeword in the payload of the received frame 0 – 239 1 – 128
Inner code rate	Integer	0, 1	Indicates the code rate of the convolutional encoder: 0 – 1/2 1 – 2/3
Tone mask	Array of bits	1_{16}-FF_{16} (CENELEC, FCC-1) 1_{16}-$FFFFFFFFFF_{16}$ (FCC, FCC-2)	Indicates the tone mask used to transmit the payload of the received frame.
ACK request	Integer	0, 3	Indicates whether acknowledgement for the received frame is required: 0 – ACK not required 1 – a regular Imm-ACK required 2 – an extended Imm-ACK required 3 – reserved by ITU-T
ACK data type	Integer	0-3	The type of the ACK data in received Imm-ACK frame (see [ITU-T G.9956], clause 8.3.3.1.1): 0 – Acknowledgement to MS-MPDU 1 – Acknowledgement to SS-MPDU 2 – Extended ACK 3 – Reserved by ITU-T
ACK data	Array of bits	See [ITU-T G.9956], clause 8.3.3.1.1	The ACK data delivered by the received Imm-ACK frame (see [ITU-T G.9956], clause 8.3.3.1.1)
TP-PR	Array of bits	See [ITU-T G.9956], clause 8.3.3.1.1.1	The TP partial report delivered by the received Imm-ACK frame (as defined in clause 8.3.3.1.1.1)
LQI	1-bit integer	0, 1	The LQI value delivered by the received Imm-ACK frame (see [ITU-T G.9956], clause 8.3.3.1.1)

Table 7-48 – The attributes of the PCS_MGMT.IND primitive

Name	Type	Valid range	Description
BAT Type used	Integer	0-15	Indicates the BAT that was used in the received frame: 0 – BAT Type 0 1 – BAT Type 1 2 – BAT Type 2 3 – BAT Type 3 4 – BAT Type 4 5 – BAT Type 5 6 – BAT Type 6 7 – BAT Type 7 Other values are reserved by ITU-T
NOTE – The primitives that are irrelevant for the indicated frame type shall be set to a default value of 0.			

7.8.2.2.4 PCS_MGMT.RES

This primitive is for further study.

7.8.2.3 PMA_MGMT primitives

7.8.2.3.1 PMA_MGMT.REQ

This primitive requests the PMA to use particular parameters for frame transmission. The attributes of the primitive are defined in Table 7-49.

Table 7-49 – The attributes of the PMA_MGMT.REQ primitive

Name	Type	Valid range	Description
Payload repetitions	Integer	1-12	Number of repetitions in the payload of the transmit frame; valid values are 1, 2, 4, 6,12
Payload interleaving mode	Integer	0, 1	Payload interleaving mode of the transmit frame: 0 – IoAC 1 – IoF
Number of information codewords	Integer	1-32	The number of RS information blocks in the MPDU, *m* (Note).
Number of PFH symbols	Integer	0, 1	0 – Number of symbols used by the PFH shall comply Normal mode 1 – Number of symbols used by the PFH shall comply Robust mode
Inner code rate	Integer	0, 1	Indicates the code rate of the convolutional encoder: 0 – 1/2 1 – 2/3
NOTE – The size of the RS codeword shall be as defined in clause 7.3.2.			

7.8.2.3.2 PMA_MGMT.CNF

This primitive confirms the particular parameters used by the PMA for frame transmission. The attributes of the primitive are as defined in Table 7-50.

If the PMA is unable to comply with a particular attribute in the PMA_MGMT.REQ, it shall set this primitive to one, which means that the request is denied (and the frame is not be transmitted). Otherwise the value of the PMA_MGMT.CNF primitive shall be set to zero.

Table 7-50 – The attributes of the PMA_MGMT.CNF primitive

Name	Type	Valid range	Description
Status	Integer	0,1	0: success 1: request is denied

7.8.2.3.3 PMA_MGMT.IND

This primitive indicates to the PHY management the particular parameters of the received frame. The attributes of the primitive are defined in Table 7-51.

Table 7-51 – The attributes of the PMA_MGMT.IND primitive

Name	Type	Valid range	Description
RS codeword error	Bit map	32-bit	This primitive indicates errors that were detected in the *m* RS information blocks of the received MPDU: 0 – No error detected in the codeword by the PHY 1 – PHY detected an error in the k-th RS information block of the received MPDU The first bit of the bit map shall correspond to the first RS information block, and the *m*-th bit of the bit map shall correspond to the last RS information block in the received MPDU.

7.8.2.3.4 PMA _MGMT.RES

This primitive is for further study.

7.8.2.4 PMD_MGMT primitives

7.8.2.4.1 PMD_MGMT.REQ

This primitive requests the PMD to use the particular parameters for frame transmission. The attributes of the primitive are defined in Table 7-52.

Table 7-52 – The attributes of the PMD_MGMT.REQ primitive

Name	Type	Valid range	Description
Bandplan	Integer	0-16	The bandplan to be used for transmission: 0 – CENELEC A 1 – CENELEC B 2 – CENELEC CD 4 – FCC 5 – FCC-1 6 – FCC-2 Other values are reserved by ITU-T
TX Power	Integer	0-255	The power setting PHY has to use for the transmit frame. The value represents the required transmit power in dB microvolt.
Payload modulation	Integer	2-4	The number of bits per subcarrier to be used by the PHY for payload modulation in the transmit frame
Tone mask	Array	0-1	The tone mask that the PHY has to use for transmission of the frame: 0 – indicates subcarriers that are not loaded bits (RMSC, ISC, and PSC); 1 – indicates subcarriers that are loaded bits (ASC).
Number of preamble symbols	Integer	0, 1	The value of N_1 symbols that shall be used for the preamble: 0 – 8 symbols 1 – 8 + *ceiling*(T_0/T_{OFDM}) symbols, where T_0 = 5 ms for 50 Hz mains and T_0 = 4.167 ms for 60 Hz mains
TX Power of inactive subcarriers	Integer	0, 1	The transmit power setting for inactive subcarriers (ISC set): 0 – zero power on all inactive subcarriers 1 – same power on all active and inactive subcarriers
NOTE – The primitives that are irrelevant for the indicated frame type shall be sent to a default value of 0.			

7.8.2.4.2 PMD_MGMT.CNF

This primitive confirms the particular parameters used by the PMD for frame transmission. The attributes of the primitive are as defined in Table 7-53.

If the PHY is unable to comply with a particular attribute in the PMD_MGMT.REQ, it shall set this primitive to one, which means that the request is denied (and the frame is not be transmitted). Otherwise the value of the PMD_MGMT.CNF primitive shall be set to zero.

Table 7-53 – The attributes of the PMD_MGMT.CNF primitive

Name	Type	Valid range	Description
Status	Integer	0,1	0: success 1: request is denied

7.8.2.4.3 PMD_MGMT.IND

This primitive provides to the PHY management particular parameters of the received frame. The attributes of the primitive are defined in Table 7-54.

Table 7-54 – The attributes of the PMD_MGMT.IND primitive

Name	Type	Valid range	Description
Physical carrier sense	Integer	0, 1	Indicates the status of the medium: (physical carrier sense based on preamble detection) 0 – IDLE; 1 – BUSY due to ITU-T G.9955 transmission; 2 – BUSY due to non-ITU-T G.9955 transmission (Note); 3 – BUSY due to both ITU-T G.9955 and non-ITU-T G.9955 transmission (Note).
Reception quality	Integer	For further study	A vendor-discretionary parameter that characterizes the quality of the link (e.g., to generate channel estimation response and LQI)
NOTE – Values of 2 and 3 are only valid if a preamble based coexistence mechanism is enabled (see clause 5.1.2.3); otherwise the valid values of the primitive are 0 and 1 only.			

The Physical Carrier Sense parameter should be changed to BUSY no later than T_{TS}*0.8 after the actual transmission is started on the line (first sample of the first symbol in the preamble is transmitted). The T_{TS} is defined in clause 8.1.4 of [ITU-T G.9956].

7.8.2.4.4 PMD_MGMT.RES

This primitive is for further study.

Annex A

G3-PLC PHY Specification for CENELEC A Band

(This annex forms an integral part of this Recommendation.)

NOTE – This is a stand-alone annex which can be implemented independently from the main body of this Recommendation.

A.1 Scope

This annex specifies the physical layer entity for an orthogonal frequency division multiplexing (OFDM) power line communications (PLC) system operating in the CENELEC A band.

A.2 Acronyms

ACK	Acknowledge
AFE	Analog Front End
AGC	Automatic Gain Control
AMM	Automated Meter Management
CC	Convolutional Code
CENELEC	European Committee for Electrotechnical Standardization
CP	Cyclic Prefix
CRC	Cyclic Redundancy Check
D8PSK	Differential Eight Phase Shift Keying
DBPSK	Differential Binary Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
FCH	Frame Control Header
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FL	Frame Length
GF	Galois Field
GI	Guard Interval
ICI	Inter Carrier Interference
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IS	Information System
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
NACK	Negative Acknowledge
OFDM	Orthogonal Frequency Division Multiplexing
PAR	Peak to Average Ratio
PDC	Phase Detection Counter
PHY	Physical Layer
PLC	Power Line Communication
PPDU	PHY Protocol Data Unit
PPM	parts per million
PSDU	PHY Service Data Unit
RC	Repetition Code
RES	Reserved (bit fields)
RMS	Root Mean Square
RS	Reed-Solomon
RX	Receiver
SC	Segment Count
SDO	Standards Development Organization
S-FSK	Spread Frequency Shift Keying
SN	Sequence Number
SNR	Signal to Noise Ratio
SYNCP, SYNCM	Synchronization Symbols
TMI	Tone Map Index
TX	Transmitter

A.3 Introduction

Power line communication has been used for many decades, but a variety of new services and applications require more 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, it is subject to impulsive noise, and narrowband interference and group delays up to several hundred microseconds.

OFDM is a modulation technique that efficiently utilizes the allowed bandwidth within the CENELEC band 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 G3-PLC 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. Ability of notching selected frequencies, allowing the cohabitation with S-FSK narrow band communication.

4.	Dynamic tone adoption capability to varying power line channel to ensure a robust communication.

## A.4	General description

The following diagram illustrates an example of an AMM system.

The system provides a reliable two-way communication using OFDM-PLC between the meters installed at the customer premise and the concentrator, communicating in a master and slave configuration.

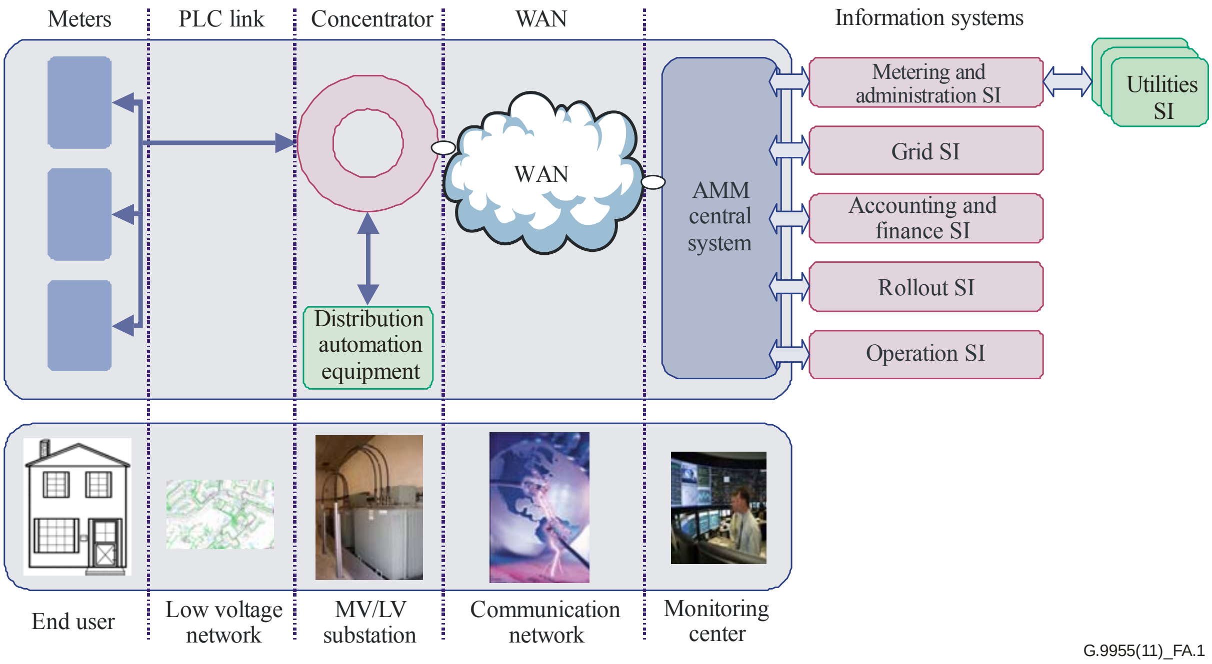


Figure A.1 – Network architecture

The AMM architecture consists of the 5 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 and the meters. Complementary equipment supplied by the electrical network that can be connected downstream of the hub;
- The PLC (LAN) technology, allowing the use of a low voltage electrical network to exchange data and commands between meters and hubs;
- Remote connection (WAN) allowing 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.

A.5 Physical layer specification

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

A.5.1 Overview of the system

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 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 power line channel.

Figure A.2 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 PSK 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 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 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 receive signal, the receiver (if requested by the transmitter) shall feedback 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.

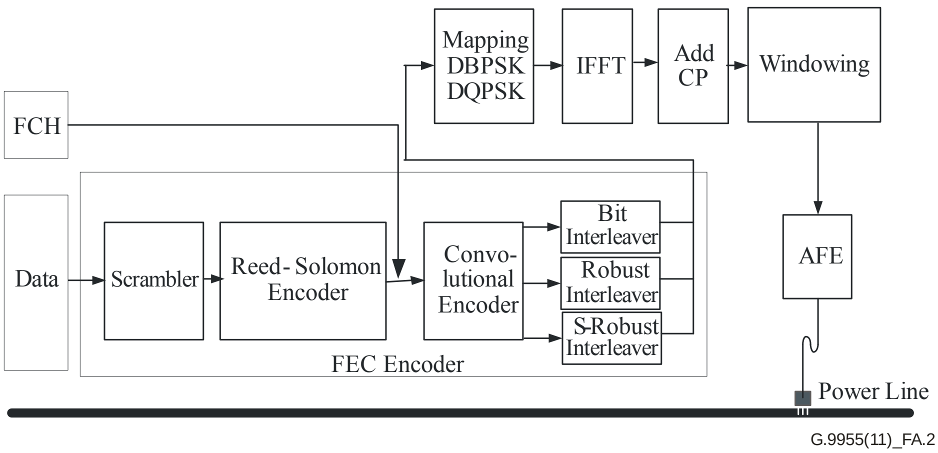


Figure A.2 – Block diagram of OFDM transceiver

A.5.2 Fundamental system parameters

The G3-PLC supports the portion between 35.9 kHz to 90.6 kHz of the CENELEC-A band. An OFDM with DBPSK and DQPSK modulation schemes per subcarrier is selected to support up to 33.4 kbit/s data rate in normal mode of operation. The DBPSK, DQPSK, and D8PSK modulation for each subcarrier makes the receiver design significantly simpler since no tracking circuitry is required at the receiver for coherently 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.

There is potential to use this standard to support communication in frequencies up to 180 kHz. As a result, the sampling frequency at the transmitter and receiver is selected to be 0.4 MHz in order to provide some margin above the Nyquist frequency for signal filtering in the transmitter (for PSD shaping to remove the signal images) and at the receiver (for band selection and signal enhancement).

The maximum number of subcarriers that can be used is selected to be 128, resulting in an IFFT size of 256. This results in a frequency spacing between the OFDM subcarriers equal to 1.5625 kHz (Fs / N), where Fs 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 word, 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 obtained as given in Table A.1.

Table A.1 – Number of subcarriers for various bands

	Number of subcarriers	First subcarrier (kHz)	Last subcarrier (kHz)
CENELEC A	36	35.938	90.625

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 parity of 8 and 16 bytes.

In robust mode the FEC is composed of Reed Solomon and convolutional encoders followed by a repetition code (RC). The RC code, repeats each bit four times making system more robust to channel impairments. This of course will reduce the throughput by about factor of 4.

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 A.2 and A.3.

Table A.4 shows the rate including the data transmitted in FCH. To calculate the data rate, it is assumed that the packets are continuously transmitted with no inter frame time gap.

Table A.2 – 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 A.3 – Data rate for various modulations (excluding FCH)

CENELEC A	Data rate per modulation type, bps			
Number of symbols	D8PSK, P16 [1)]	DQPSK, P16 [1)]	DBPSK, P16 [1)]	Robust, P8 [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
[1)] P16 is Reed-Solomon with 16 bit parity [2)] P8 is Reed-Solomon with 8 bit parity NOTE – N/A means not applicable and the reason is that the corresponding number of symbols specified results in RS encoder block length that exceeds the maximum allowable limit of 255.				

Table A.4 – Data rate for various modulations (including FCH)

CENELEC A	Data rate per modulation type, bps			
Number of symbols	D8PSK, P16 [1)]	DQPSK, P16 [1)]	DBPSK, P16 [1)]	Robust, P8 [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

[1)] P16 is Reed-Solomon with 16 bit parity.

[2)] P8 is Reed-Solomon with 8 bit parity.

NOTE – N/A means not applicable and the reason is that the corresponding number of symbols specified results in RS encoder block length that exceeds the maximum allowable limit of 255.

The data rate is calculated based on the number of symbols per PHY frame (N_S), number of subcarrier per symbol (N_{car}) and number of parity bits added by FEC blocks. As an example, consider the system in the CENELEC A band working in Robust mode. Total number of bits carried by the whole PHY frame is equal to:

$$\text{Total\_No\_Bits} = N_S \times N_{car} = 40 \times 36 = 1440 \text{ bits}$$

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

$$\text{No\_Bits\_Robust} = 1440 \times \text{Robust}_{\text{Rate}} = 1440 \times 1/4 = 360 \text{ bits}$$

Considering the fact that convolutional encoder has a rate equal to 1/2 ($CC_{Rate} = 1/2$) and also consider adding CCZerotail = 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 Reed Solomon encoder ($MAXRS_{bytes}$) shall be equal to:

$$MAXRS_{bytes} = \text{floor}((\text{No\_Bits\_Robust} \times CC_{Rate} - \text{CCZeroTail})/8) = \text{floor}((360 \times 1/2 - 6)/8) = 21$$

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:

$$\text{TFrame} = (((N_S + N_{FCH}) \times (N_{CP} + N - N_O) + (Npre \times N)))/Fs$$

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. Typical values for all these parameters for various frequency bands are given in Table A.5.

Table A.5 – System Specifications

Number of FFT points	$N = 256$
Number of overlapped samples	$N_O = 8$
Number of cyclic Prefix samples	$N_{CP} = 30$
Number of FCH symbols	$N_{FCH} = 13$
Sampling frequency	$F_s = 0.4$ MHz
Number of symbols in Preamble	$N_{pre} = 9.5$

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

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

Therefore the data rate is calculated by:

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

A.5.3 Frame structure

The PHY supports two types of frames. A typical data frame for the OFDM PHY is shown in Figure A.3. 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 first symbol includes raised cosine shaping on the leading points. The last half symbol also includes raised cosine shaping on the trailing points. The preamble is followed by 13 data symbols allocated to frame control header (FCH). FCH has the important control information required to demodulate the data frame. Data symbols are transmitted next. The first FCH symbol uses phase from the last preamble P symbol and the first data symbol uses the phase from last FCH symbol. In the figures, "GI" stands for guard interval, which is the interval containing the cyclic prefix.

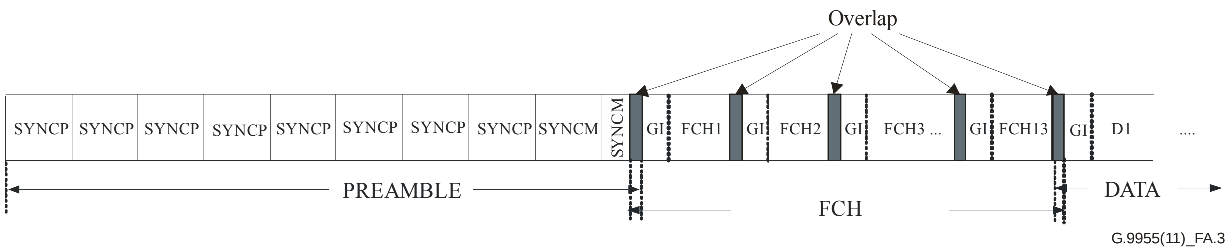


Figure A.3 – Typical data frame structure

The PHY also supports an ACK/NACK frame, which only consists of preamble and the FCH. The frame structure of the ACK frame is shown in Figure A.4. The bit fields in the FCH, explained in clause A.5.5 will perform the ACK/NACK signalling.

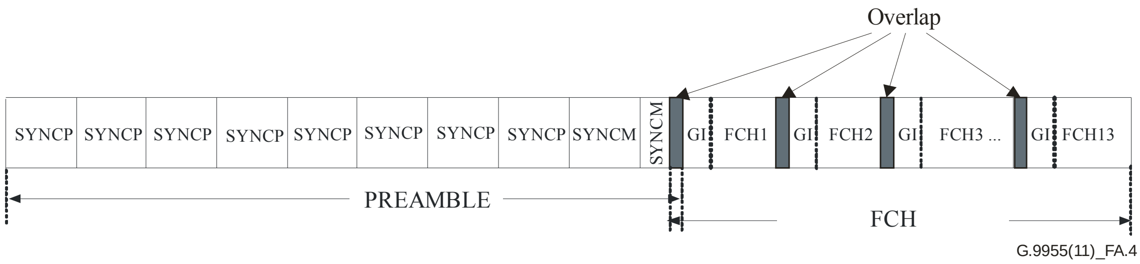


Figure A.4 – ACK/NACK frame structure

A.5.4 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 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 36 equally spaced subcarriers with the phase of each subcarrier given by ϕ_c as shown in Table A.6. One way to generate this signal is to start in the frequency domain and create 36 complex subcarriers with the initial phases ϕ_c, as shown in Table A.6. Figure A.15 shows how the 36 subcarriers are mapped to the IFFT input where the first modulated subcarrier is subcarrier 23 and the last modulated subcarrier is subcarrier 58.

Table A.6 – Phase vector definition

c	ϕ_c	c	ϕ_c	c	ϕ_c
0	2(π/8)	12	1(π/8)	24	13(π/8)
1	1(π/8)	13	11(π/8)	25	2(π/8)
2	0(π/8)	14	5(π/8)	26	6(π/8)
3	15(π/8)	15	14(π/8)	27	10(π/8)
4	14(π/8)	16	7(π/8)	28	13(π/8)
5	12(π/8)	17	15(π/8)	29	0
6	10(π/8)	18	7(π/8)	30	2(π/8)
7	7(π/8)	19	15(π/8)	31	3(π/8)
8	3(π/8)	20	6(π/8)	32	5(π/8)
9	15(π/8)	21	13(π/8)	33	6(π/8)
10	11(π/8)	22	2(π/8)	34	7(π/8)
11	6(π/8)	23	8(π/8)	35	7(π/8)

A.5.5 Frame control header

The thirteen data symbols immediately after preamble are reserved for frame control header (FCH). The FCH is a data structure transmitted at the beginning of each data frame and contains information regarding the current frame. It has information about type of the frame, tone map index of the frame, length of the frame, etc. The FCH data is protected with CRC5. Table A.7 defines the structure of FCH. The FCH shall use the default tone map (all allowed subcarriers).

The Tone Map (see clause A.3.3.3.2.2 of [ITU-T G.9956]) field of the FCH is made of 9 bits, numbered from TM[0] to TM[8], where: TM[7] is the Most Significant Bit (MSB) of one byte while TM[0] is the Least Significant Bit of that byte; TM[8] is the MSB of 2nd byte. Those 9 bits are mapped to frequency bands as in the following:

– TM[8]: Unused in CENELEC A band
– TM[7]: Unused in CENELEC A band
– TM[6]: Unused CENELEC A band
– TM[5] is 82.8125 to 90.625 kHz.
– TM[4] is 73.4375 to 81.25 kHz.
– TM[3] is 64.0625 to 71.875 kHz.
– TM[2] is 54.6875 to 62.5 kHz.
– TM[1] is 45.3125 to 53.125 kHz.
– TM[0] is 35.9375 to 43.75 kHz.

Table A.7 – FCH bit fields

Field	Byte	Bit number	Bits	Definition
PDC	0	7-0	8	Phase detection counter
MOD	1	7-6	2	Modulation type: 00: Robust Mode (clause A.5.7.3) 01: DBPSK 10: DQPSK 11: D8PSK
FL	1	5-0	6	PHY frame length in PHY symbols
TM[7:0]	2	7-0	8	TM[7:0] – Tone map
TM[8]	3	7	1	TM[8] – Tone map
DT	3	6-4	3	Delimiter type: 000: Start of frame with no response expected 001: Start of frame with response expected 010: Positive acknowledgement (ACK) 011: Negative acknowledgement (NACK) 100-111: Reserved by ITU-T
FCCS	3	3-0	4	Frame control check sequence (CRC5)
	4	7	1	
ConvZeros	4	6-1	6	6 zeros for convolutional encoder
NOTE – Robust Mode uses DBPSK with 4 repetitions.				

The frame length bit field gives the number of symbols in the frame based on the formula:

$$\text{Number of symbols} = FL \times 4$$

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

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

A.5.5.1 Data

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 Appendix A-1).

A.5.6 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 A.5. The bits in the scrambler are initialized to all ones at the start of processing each PHY frame.

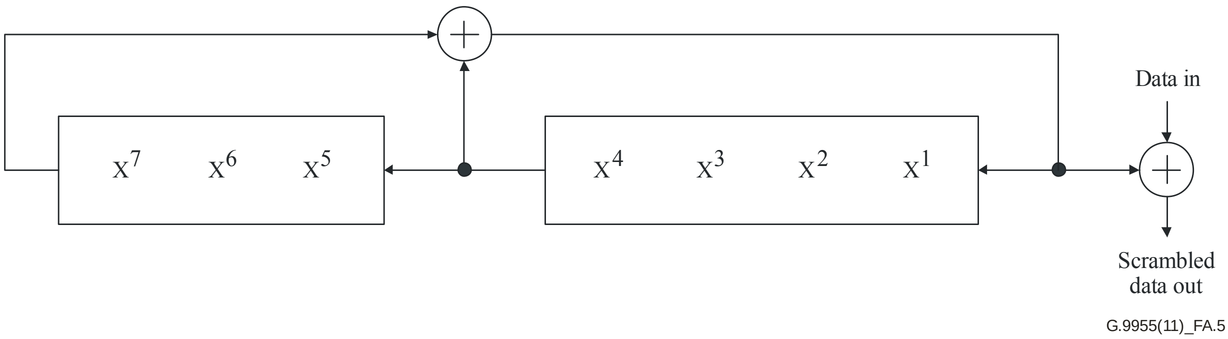


Figure A.5 – Data scrambler

A.5.7 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 (RC4), 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 (RC6), is used after the convolutional encoder in order to repeat the bits at the output of convolutional encoder six times.

A.5.7.1 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 Robust mode, the code with T=4 is used. The number of parity words in a RS-block is 2T bytes.

Code Generator Polynomial $\qquad g(x) = \prod_{i=1}^{2T} \left(x - a^i\right)$

Field Generator Polynomial: $\qquad p(x) = x^8 + x^4 + x^3 + x^2 + 1$ (435 octal)

The representation of α0 is "00000001", where the left most bit of this RS symbol is the MSB and is 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 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, ..., d^1, d^0) is identified with the Galois field element $d^7\alpha^7 + d^6\alpha^6 ... + d^1\alpha + d^0$.

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 first message symbol to last message symbol followed by parity symbols, with each symbol shifted out most significant bit first.

A.5.7.2 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 A.6.

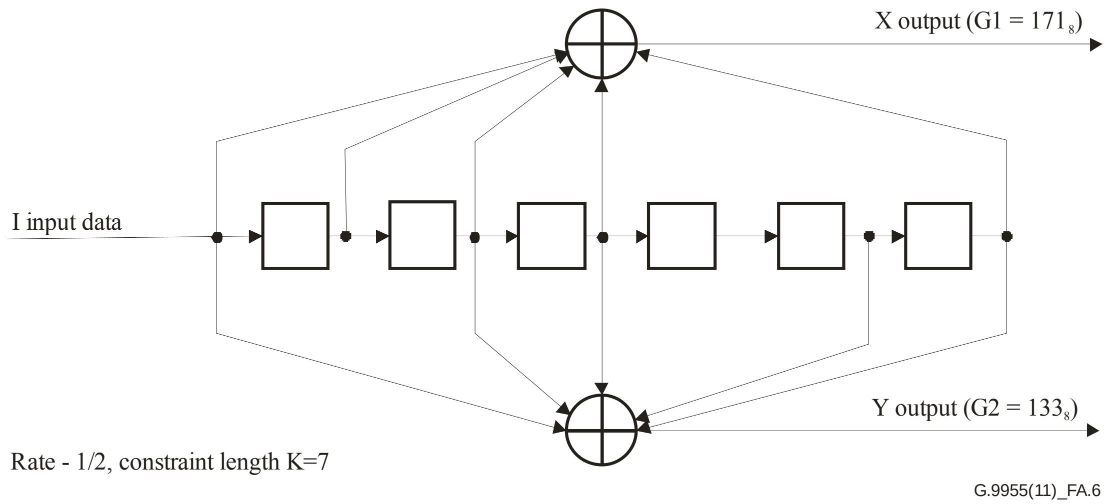


Figure A.6 – Convolutional encoder

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.

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.

A.5.7.3 Robust and super robust modes

When Robust or Super Robust modes are used, the underlying modulation is always DBPSK.

A.5.7.3.1 Repetition coding by 4 (RC4)

In Robust mode, every bit at the output of the convolutional encoder is repeated 4 times and then passed as input to the interleaver as described in clause A.5.8. This encoder (RC4) is only activated in Robust mode.

A.5.7.3.2 Repetition coding by 6 (RC6)

In the Super Robust mode, every bit at the output of the convolutional encoder is repeated 6 times and then passed as input to the interleaver as described in clause A.5.8. Only the FCH uses Super Robust mode but without Reed-Solomon encoding.

A.5.8 Interleaver

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

- 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.

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 including the padding bits.

$$n = ceil\left(\frac{Total\_number\_of\_bits}{4 * m * mod_{size}}\right) * 4$$

with mod_size=1, 2, 3, 4 is the modulation size i.e., the number of bits per constellation symbol.

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 to these conditions :

- GCD(m_i, m) = GCD(m_j, m) = 1.
- m_i < m_j
- GCD(n_i, n) = GCD(n_j, n) = 1
- n_j < n_i.

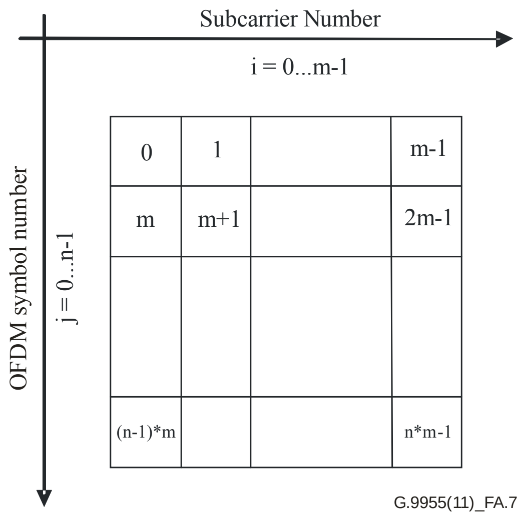


Figure A.7 – Bit order input into the Interleaver buffer

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:

$$J = (j \times n\_j + i \times n\_i) \% n$$

$$I = (i \times m\_i + J \times m\_j) \% m$$

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

The DBPSK modulation permutation matrix corresponds to the elementary permutation matrix while DQPSK and D8PSK modulations use respectively two and three times the elementary permutation matrix. Thus, the dimension of the permutation matrix for DQPSK and D8PSK modulations are m columns and n*mod_size.

The data to be interleaved are stored in the input buffer which dimensions are m columns and n*mod_size rows.

The data bits are put in the input buffer row by row as shown in Figure A.8. Zero padding will be used to match permutation matrix dimensions.

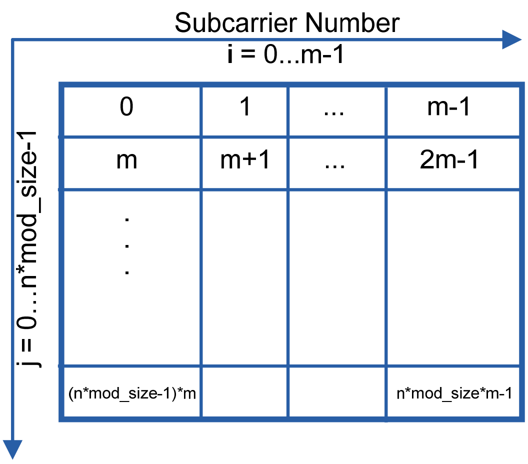


Figure A.8 – Bit order input into the input buffer

Once interleaved each bit is stored in an output buffer as shown in Figure A.9.

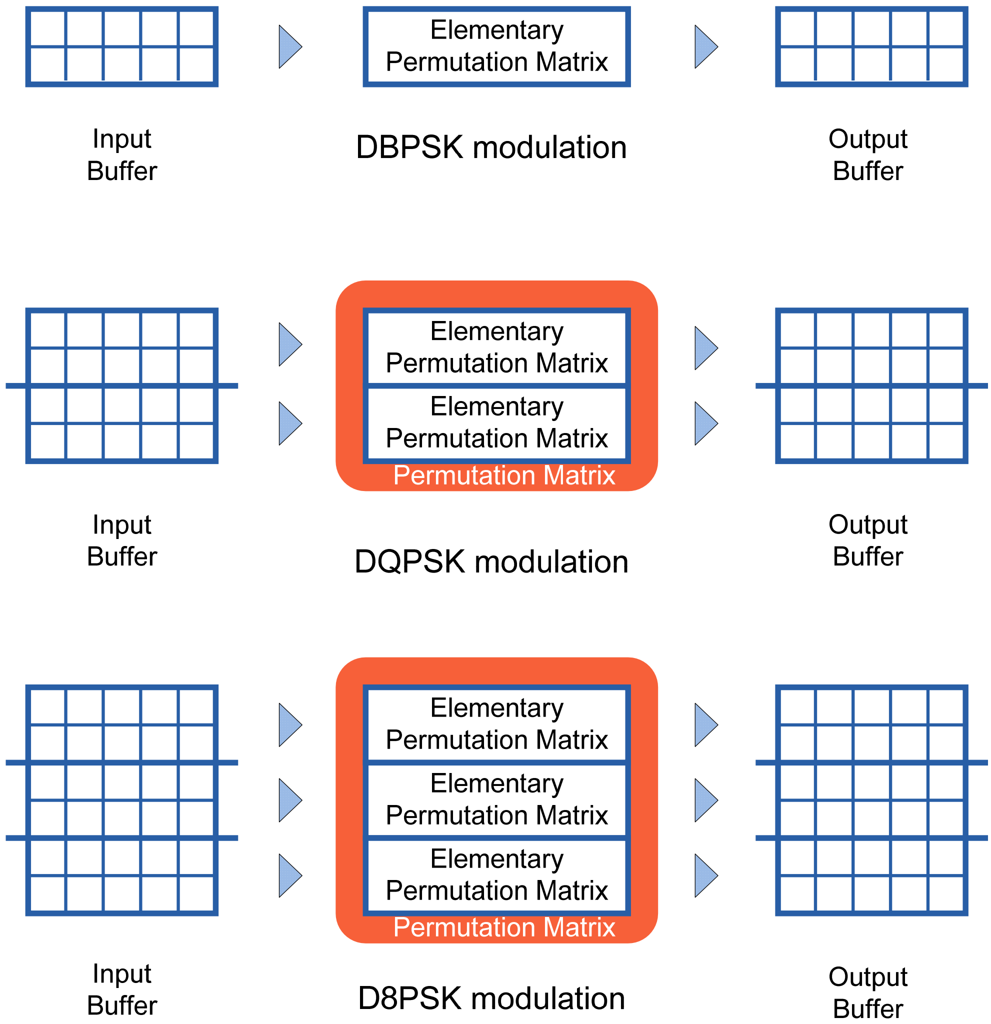


Figure A.9 – Permutation matrix used with different modulations

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 for information here.

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. 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. Figure A.10 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.

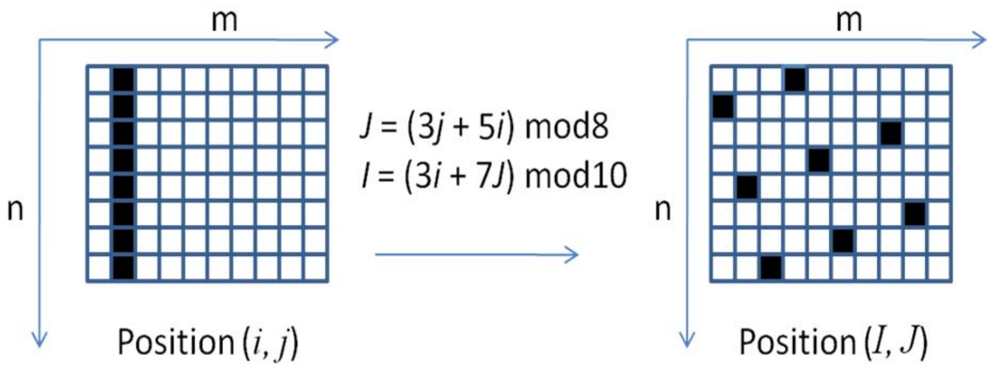


Figure A.10 – Example of spreading behaviour

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 A.11(a). The vertical dimension of the matrix is n*mod_size (i.e., 2*1=2). After that, interleaving is done with interleaving block size n*m (i.e., 2*3). After all the bits are processed, the bits 1'2'3'…6' are mapped to the modulator as shown in Figure A.11(c).

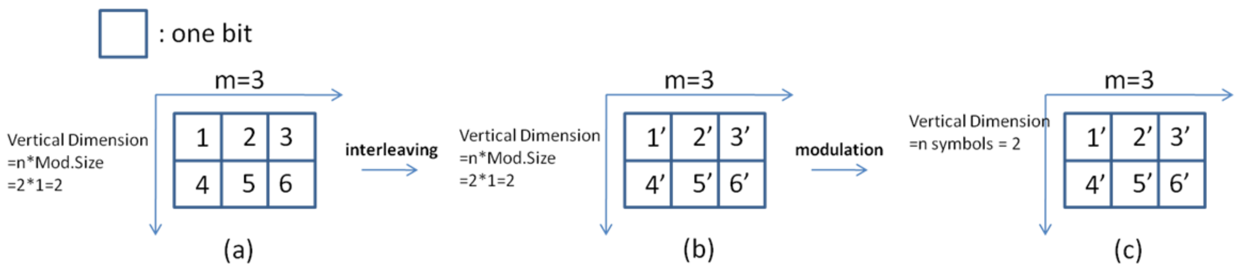


Figure A.11 – Example of interleaving with DBPSK

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 A.12(a). The vertical dimension of the matrix is n* mod_size (i.e., 2*2=4). After that, interleaving is done with interleaving block size n*m (i.e., 2*3). After all the bits are processed, the bits 1' 2' 3'…11' 12' are mapped to the modulator as shown in Figure A.12(c).

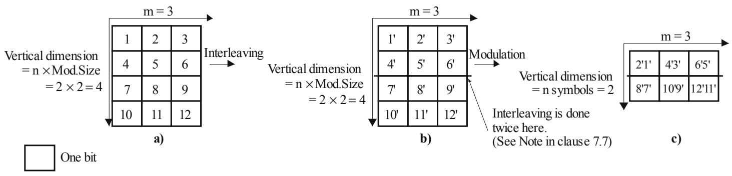


Figure A.12 – Example of interleaving with DQPSK

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

```
for ( i = 0; i < size; i += ILV_SIZE ) //See Note 1 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 follow:

```
ILV_SIZE = m * n

    for ( j = 0; j < n; j++ )
    {
        for ( i = 0; i < m; i++ )
        {
            J = ( j * n_j + i * n_i ) % n;
            I = ( i * m_i + J * m_j ) % m;
            ILV_TBL[ i + j * m ] = I + J * m;
        }
    }
```

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

A.5.9 DBPSK/DQPSK/D8PSK mapping

Each subcarrier is modulated with differential binary or differential quadrature phase shift keying (DBPSK or DQPSK or D8PSK) or Robust. Robust modulation is a robust form of DBPSK that provides extensive time and frequency diversity to improve the ability of the system to operate under adverse conditions. 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 concepts of the MAC layer. 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 subcarriers that are to be used for a particular communication between two modems. For example, subcarriers that suffer deep fades can be avoided, and no information is transmitted on those subcarriers.

A.5.9.1 Mapping for DBPSK, DQPSK, D8PSK modulations

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 phase from the last preamble P symbol and the first data symbol uses the phase from the last FCH symbol. The data encoding for DBPSK and DQPSK is defined in Table A.8 and Table A.9, where Ψk 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 A.8 – DBPSK encoding table of k-th subcarrier

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

Table A.9 – 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 A.10 – D8PSK encoding table of k-th subcarrier

Input bit pattern (X,Y), Y 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 A.8, A.9 and A.10 can be represented in a constellation diagram (with reference phase assumed equal to 0 degrees), as shown in Figure A.13.

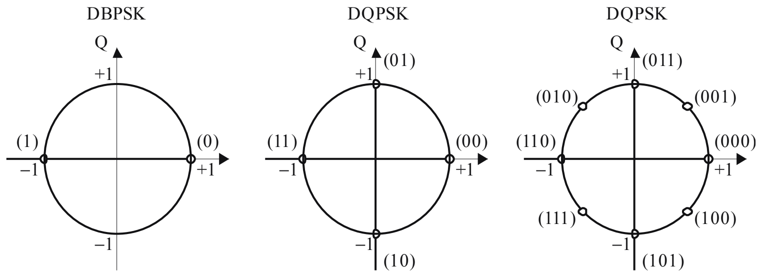


Figure A.13 – Constellation encoding

A.5.10 Frequency domain pre-emphasis

The purpose of this block is to provide frequency shaping to the transmit signal in order to compensate for attenuation introduced to the signal as it goes through the power line.

The frequency-domain pre-emphasis filter shall consist of a multiplier that multiplies the complex frequency domain samples of an OFDM symbol with 128 real filter coefficients. If the optional TXCOEFF parameters are not implemented, the frequency domain pre-emphasis filter should use values to satisfy the spectrum flatness criterion stated in clause A.6.6. Otherwise, the filter coefficients are 4 bits representing signed values from –8 to +7. Their values are computed from the TXRES and TXCOEFF parameters that are part of the tone map response message that the destination station sends to the source station as described in clause A.5.13. The filter multiplies the first 128 frequency-domain complex samples of an OFDM symbol with the 128 real coefficients of the filter. The rest of the 128 frequency-domain samples of the OFDM symbol shall be set to zero and shall not be multiplied by the filter coefficients. Figure A.14 below shows a block diagram of the pre-emphasis filter. The output of the filter shall be the input to the IFFT.

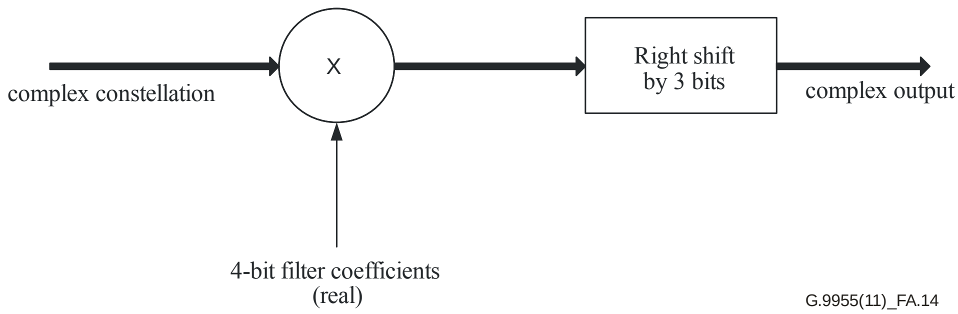


Figure A.14 – Block diagram of the pre-emphasis filter

A.5.11 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 A.15.

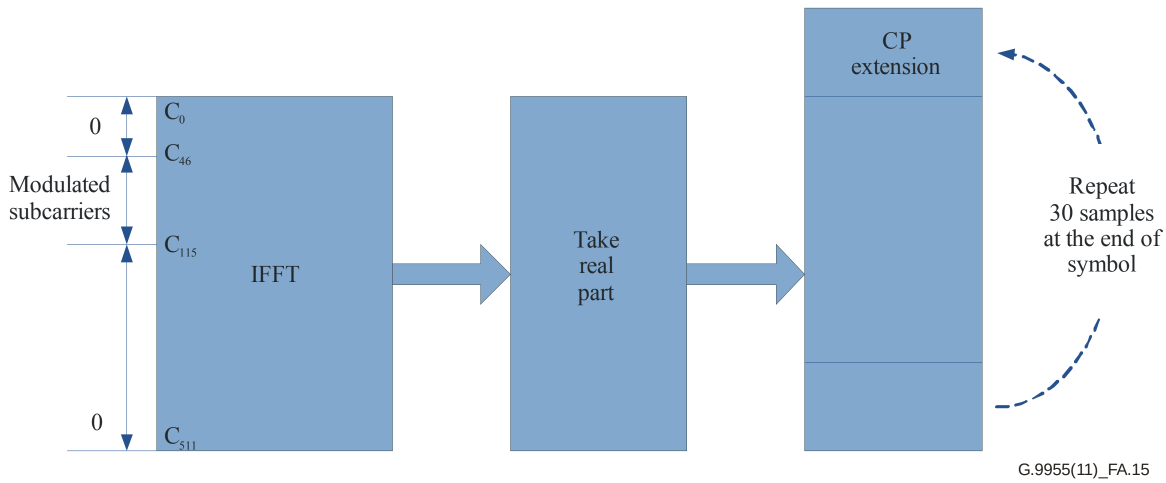


Figure A.15 – IFFT input/output and CP addition

A.5.12 Windowing

In order to reduce the out of band emission and to reduce the spectral side lobe, the raised cosine shaping is applied to all the data 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 by a raised cosine function as shown in Figure A.16.

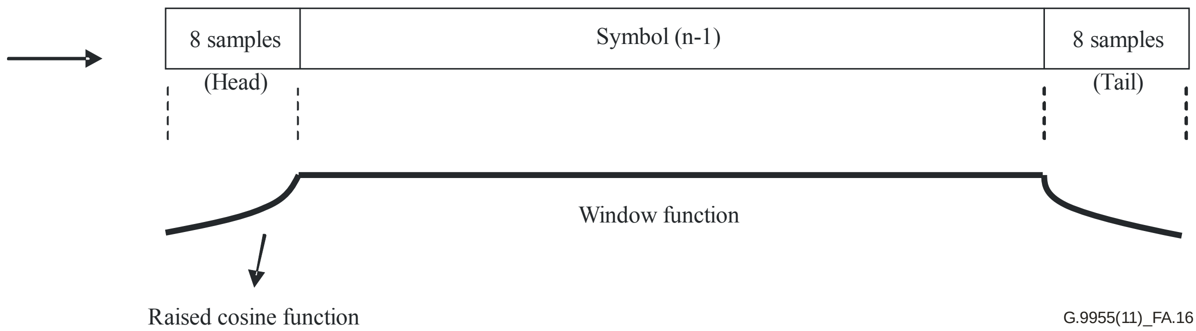


Figure A.16 – Raised cosine windowing

The windowing function at each 8-sample boundary is a raised cosine function and its values are given in Table A.11. 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 symbol are overlapped with the tail and head samples of adjacent symbols as shown in Figure A.17.

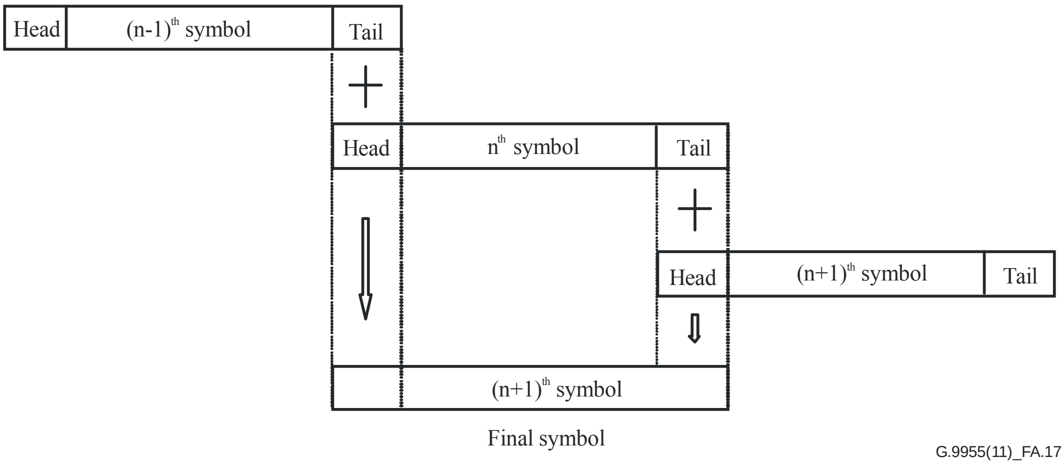


Figure A.17 – Overlap/add

Figure A.13 – In other words, in order 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 is 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 preamble. And the tail of last symbol is sent out with no overlapping applied.

Table A.11 – The raised cosine samples

	Head samples	Tail samples
1	0	0.9619
2	0.0381	0.8536
3	0.1464	0.6913
4	0.3087	0.5000
5	0.5000	0.3087
6	0.6913	0.1464
7	0.8536	0.0381
8	0.9619	0

A.5.13 Adaptive tone mapping & transmit power control

G3-PLC shall estimate the SNR of the received signal subcarriers and adaptively select the usable tones and optimum modulation and code rate (including DBPSK, DQPSK, D8PSK) to ensure reliable communication over the power line channel. It shall also specify what power level the remote transmitter shall use and what 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. However, at least one group of subcarriers (as indicated by the TM field of the FCH – see clause A.5.5) shall carry data.

The goal of the adaptive tone mapping is to allow the G3-PLC 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 may request a destination station to estimate a channel condition by setting TMR bit of FCH as described in clause A.5.5.

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 A.9 of [ITU-T G.9956].

A.5.13.1 PN modulating unused subcarriers

For the data part of the frame, the mapping function for DBPSK, DQPSK, D8PSK and Robust shall obey the tone map; thus subcarriers that are masked are not assigned phase symbols, and the amplitude is zero. When the modulation type is DBPSK or DQPSK or D8PSK the mapping function also obeys the tone map. When a subcarrier is encountered on which no information is to be transmitted, the mapping function substitutes a binary value from a pseudo noise (PN) sequence. The one bit output of the PN sequence should be duplicated for all modulated bits (1 for BPSK, 1x2 for QPSK, 1x3 for 8PSK etc.).

The PN sequence shall be generated using the same generator polynomial introduced in clause A.5.6. The bits in the PN sequence generator shall all be initialized to ones at the start of processing each frame and sequenced to the next value after every mapped, unmapped or masked carrier. The first value of the PN sequence (the output when all bits are initialized to ones) corresponds to carrier number 0 of the first OFDM symbol of each frame and the 35th value corresponds to carrier number 0 of the second OFDM symbol.

A.5.14 Crossing MV/LV transformer

The G3-PLC operates over both low voltage power lines as well as medium voltage power lines. When operating over medium voltage power line it can communicate with G3-PLC operating over low-voltage power lines. This means that the receiver on the LV side can detect the transmitted signal after it has been severely attenuated as a result of going through a MV/LV transformer. As the signal goes through the transformer, it is expected to experience overall severe attenuation in its power level as well as frequency-dependent attenuation. Both transmitter and receiver have mechanisms to compensate for this attenuation. The transmitter can adjust its overall signal level as well as shape its power spectrum, while the receiver has an automatic gain control in order to achieve enough gain to compensate for the overall attenuation.

The G3-PLC system, in addition to being able to operate in normal mode, can operate as a repeater. When configured in "repeater" mode, the G3-PLC system can decode received frames and then re-transmit them at a higher signal level in order to partially compensate for the attenuation introduced by the transformer. The repeater, when needed, can be placed on the LV side of the MV/LV transformer.

A.5.15 MV coupler (informative)

The G3-PLC modem interfaces with the MV power line through a PLC coupling device, which is basically a high-pass filter whose purpose is to permit the PLC signal to pass, but reject the power system frequency and protect the communications equipment from the power system voltage and transient voltages caused by switching operations.

The basic circuit diagram is shown in figure below. A complete coupling comprises a line trap to prevent the PLC signal from being short-circuited by the substation, and a coupling filter formed by the coupling capacitor and the coupling device.

For the G3-PLC modem, resolving impedance mismatching is very important in the sense of transferring maximum power to the signal input terminal of the MV power distribution lines. It is recommended that any transformer being used should be verified by measuring transmission and reflection characteristics through vector network analyser.

The proposed coupling interface, shown in Figure A.18, should interface between the PLC device and the MV medium (with 24 kV and impedance of 75 Ω to 175 Ω).

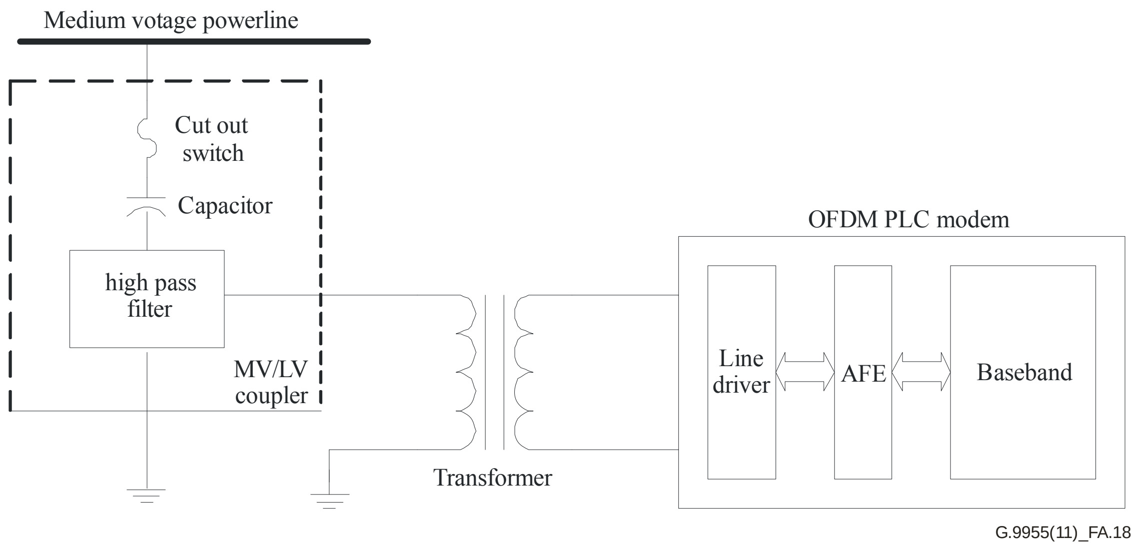


Figure A.18 – Proposed coupling circuit

A.5.15.1 Coupler technical characteristics

Table A.12 – Coupler technical characteristics

Parameter	Measurement conditions	Value
	Medium voltage circuit parameters	
Primary test voltage U_N	Voltage between the device input and grounding output	$24/\sqrt{3}$ kV_{RMS}
Test short-term alternating voltage U_{TH}	Voltage between the device input and grounding output during 1 min.	50 kVrms
Maximum short-term working voltage U_{MAX}	Medium Voltage during 9 hours	26 kV_{RMS} 9 hours
Test lightning impulse voltage U_L	Impulse with duration of 1.2/50 us between the device input and the grounding output	125 kV
Partial discharge level		≤ 20 pC
Ambient temperature during operation		–40-+65°
Coupling capacitor capacity Cc	–40°C < Ta < +70°C	1.5-13 nF
Fuse operate time max	at I ≥ 30A at I ≥ 45A	t ≤ 100 ms t ≤ 10 ms

Table A.12 – Coupler technical characteristics

Parameter	Measurement conditions	Value
	Low voltage circuit parameters	
Nominal line side impedance R_{LINE}		75Ω ≤ R ≤ 170Ω
Nominal equipment side impedance R_{LOAD}		75 Ω
Maximum operating attenuation in receive and transmit direction at R_{LOAD} = 75 Ω, R_{LINE} = 170 Ω	35 kHz ≤ f ≤ 170 kHz	3 dB

A.5.16 AC phase detection

It is necessary to know which phase each meter is placed on in an AMM application. This information is mainly useful at system level in order to check for unexpected losses on the distribution line and shall be stored in the MIB.

Three phases on the mains are sinusoidal waveforms with a phase shift of 120° from each other where each half cycle is equal to 10 ms at 50 Hz and 8.3 ms at 60 Hz. A zero-crossing detector delivers an output pulse based on the transition through zero volt of a 50 Hz sinusoidal on power line shall be used to synchronizes a Tx-meter and a Rx-meter. The Tx-meter generates a time stamp based on internal counter at the instant a packet shall be transmitted. The receiver provides its own time stamp and delay between the Tx-meter and the Rx-meter provides the phase difference. The procedure to achieve the phase difference between transmitter and receiver is as follows:

1. All devices including meter and data concentrator shall have internal timer, which are synchronized to zero-crossing detector.
2. All devices shall have a zero-crossing detector delivers an output pulse so that the pulse width is 5% of total period. The characteristic of the zero crossing detector is shown in Figure A.19.

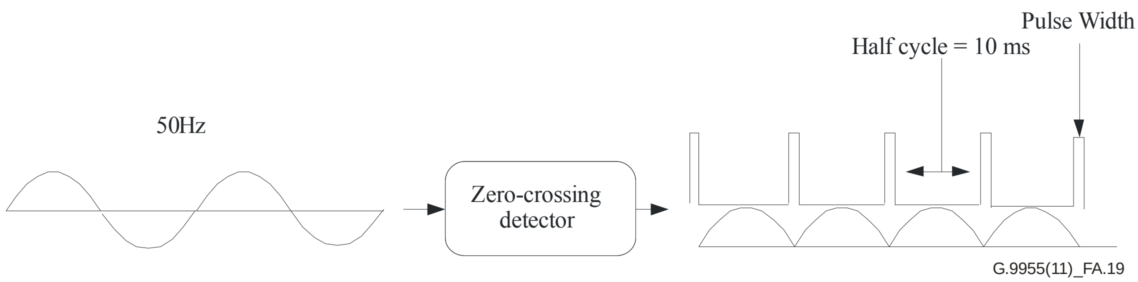


Figure A.19 – Zero crossing detector

3. An eight bits counter provides a time stamp placed on the FCH frame upon transmission of payload. This counter counts from zero to 255 in one period of the mains, and is reinitialized each time a zero crossing event is detected.
4. Upon detection of FCH frame, receiver shall compute the delay, which is the difference between transmit counter and received counter. The phase differential shall be computed as shown below.

Phase differential = (Rx_counter – Tx_Counter) /3

Electromagnetic propagation time and additional delay for packet processing and detection shall be considered measuring delay. Electromagnetic propagation delay is 5.775 us/km, which can be neglected; however, processing delay shall be factored into equation above as follows.

New_Phase differential = (Rx_counter – detection_delay) – (Tx_Counter – trasmission_delay)/3

A.6 Transmitter electrical specifications

A.6.1 Output level measurement

G3-PLC transmitter output level shall be compliant with Annex F.

A.6.2 Transmit spectrum mask

G3-PLC PHY is provisioned to have programmable notches at certain frequencies in order to:

13. Avoid certain frequencies that are reserved by power line regulatory bodies for other applications.
14. Allow cohabitation with S-FSK systems defined by official SDOs.
15. Allow inter-operability with other potential systems operating on power line.

The transmitter shall use an appropriate scheme to insert deep notches in the spectrum. In particular, two frequencies referred to in IEC 61334-5-1 standard as mark and space frequencies f_M and f_S, shall be notched in order to cohabitate with S-FSK systems.

Depending on the relative position of required notch frequency with respect to subcarriers, a few subcarriers are masked. No data is sent over the masked subcarriers. According to the figure below, if the notch frequency is in R1 region, SC(n-1), SC(n) and SC(n+1) are masked (total three subcarriers). If the notch frequency is in R2 region the two nearest subcarriers in either side (i.e., SC(n-1), SC(n), SC(n+1) and SC(n+2)) are masked (a total of four subcarriers).

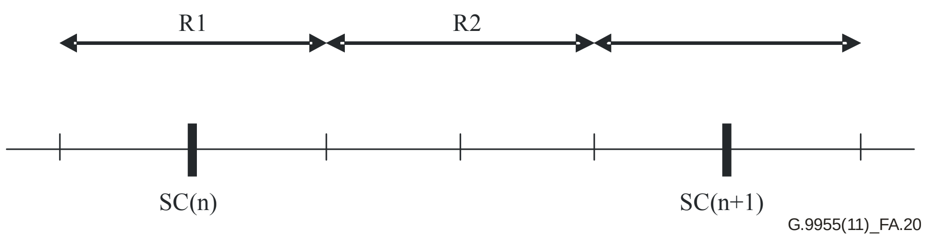


Figure A.20 – Frequency notching

Notching map should be a global parameter that is set in the initialization step of the devices. As described above, to provide sufficiently deep notches for a particular frequency band, it is required to zero one (or sometimes two) extra subcarriers before and after that band, depending on the position of the notch with respect to the subcarriers. The following pseudo code can be used for the decision between one/two extra subcarriers.

```
if NotchFreq / SamplingFreq × FFTSize is in R1
    Sc(n-1) = Sc(n) = Sc(n+1) = 0;

if NotchFreq / SamplingFreq × FFTSize is in R2
    Sc(n-1) = Sc(n) = Sc(n+1) = Sc(n+2) = 0;
```

SamplingFreq and FFTSize are 400 kHz and 256 respectively.

Sc is an array that determines which subcarriers are used to transmit data (if Sc(i) is zero, no data is sent using that subcarrier).

Frequency notching reduces the number of active tones that are used for transmitting information. Since notching is done for all the transmit signals, including FCH, the number of symbols in FC depends on the number of active tones.

The following piece of code can determine the number of OFDM symbols that are used for transmitting the 33-bit FC:

```
fcSize = 33; // Size of FC
rxFCSymNum = ceil(((fcSize + 6) × 2 × 6) / freqNum);
```

where freqNum is the number of available subcarriers after frequency notching and *ceil* is the ceiling function.

In order to have minimum effect on S-FSK, the OFDM modem shall not transmit any signal in between S-FSK frequencies i.e., in 63 kHz to 74 kHz band. The notched subcarriers in this mode are shown in Table A.13.

Table A.13 – Notched subcarriers in cohabitation mode

Subcarrier number	Frequency of the subcarrier
39	60.9375
40	62.5000
41	64.0625
42	65.6250
43	67.1875
44	68.7500
45	70.3125
46	71.8750
47	73.4375
48	75.0000
49	76.5625

Therefore 11 subcarriers cannot transmit data. Considering the fact that there are a total of 36 subcarriers available, 25 subcarriers remain for data transmission, resulting in FC with 19 OFDM symbols because *ceil*((33 + 6) × 2 × 6 / 25) = 19.

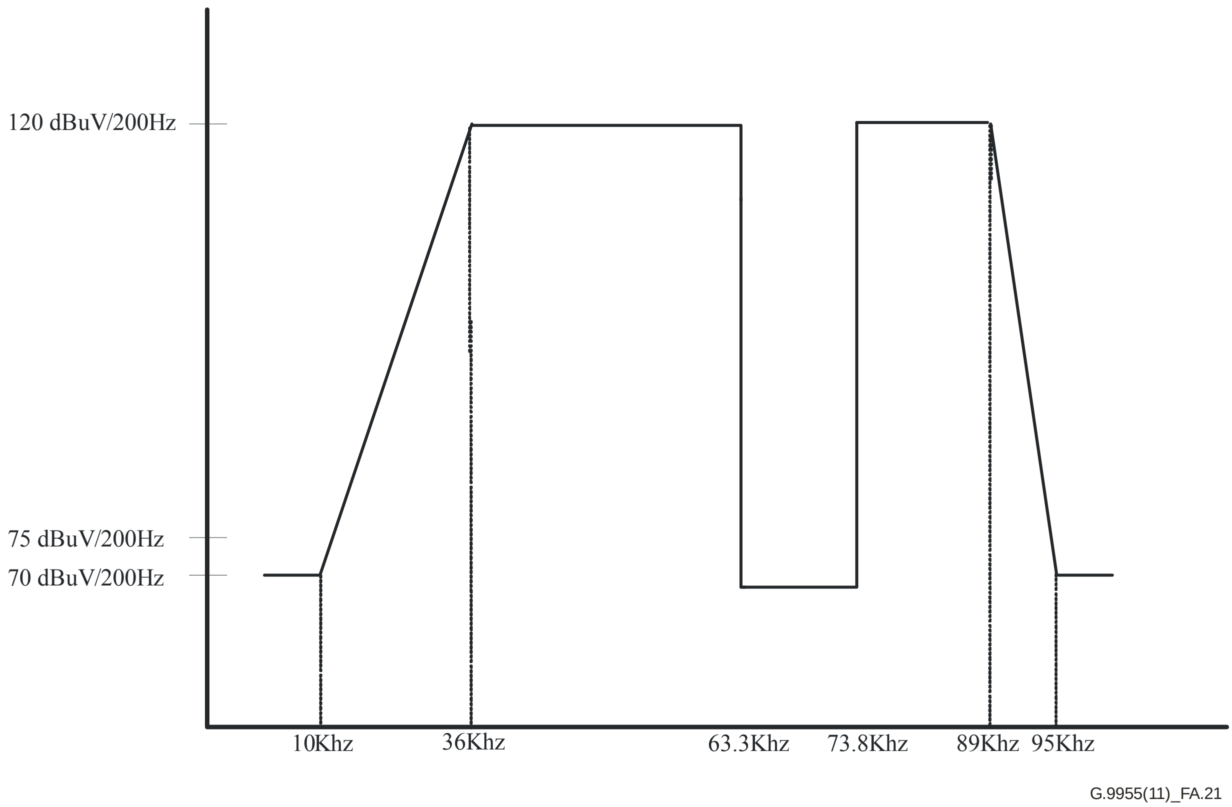


Figure A.21 – Spectrum with two notches inserted to cohabitate with S-FSK PLC modem

All stations shall use tone masking on the subcarriers specified in each substation in order to be compliant with the transmit spectrum mask. The transmitted power spectral density of notched frequency shall be 25 dB below the limits specified for rest of the subcarriers.

Measurements are made using spectrum analyser with a resolution bandwidth of 200 Hz and a quasi-peak detector. The transmitter shall be configured to repeatedly transmit maximum length rolling data pattern packets.

A.6.3 Spurious transmission

It is the obligation of the manufacturer to ensure that spurious transmissions conform to regulations in effect for the country in which this station is used.

A.6.4 System clock frequency tolerance

The system clock tolerance shall be ±25 ppm maximum. The transmit frequency and symbol timing shall be derived from the same system clock oscillator.

A.6.5 Transmit constellation accuracy

A.6.5.1 Transmit constellation error

The relative constellation rms error, averaged over all subcarriers in a symbol, and averaged over several OFDM symbols, shall not exceed –15 dB from the ideal signal rms level.

A.6.5.2 Transmit modulation accuracy test

The transmit modulation accuracy test shall be performed by instrumentation capable of converting the transmitted signal into a stream of samples at 400 K samples per second or more, with sufficient accuracy in terms of amplitude, DC offsets, and phase noise. The sampled signal shall be processed in a manner similar to an actual receiver, according to the following steps, or an equivalent procedure:

1. Pass a sequence of 37 bytes all ones, representing a 12-symbol QPSK frame, through an ideal floating-point transmitter and save the complex input to the IFFT block for each of the 12 data symbols as $A_{i,c}e^{j\Phi_{i,c}}$, where $A_{i,c}e^{j\Phi_{i,c}}$ is the reference constellation point corresponding to the -th OFDM symbol carried over the c-th sub-carrier. Index'*i*' shall have values between 0 and 11 while index '*c*' shall be between 0 and 35. The ideal transmitter should include all the transmitter blocks specified in this standard, including scrambler, forward error correction, interleaver, and mapper.
2. Next, use the transmitter under test to generate the same frame using the bits specified in step 1.
3. Connect the test equipment that will simulate the receiver directly to the transmitter to detect start of frame.
4. Save all time sample of the 12 OFDM symbols of the frame.
5. Offline, apply a floating point FFT on each OFDM symbol and store the complex values as $B_{i,c}e^{j\Theta_{i,c}}$ where '' is the OFDM symbol number and 'c' is the carrier number corresponding to that symbol. $B_{i,c}e^{j\Theta_{i,c}}$ represents the actually transmitted constellation point and, ideally, $A_{i,c}e^{j\Phi_{i,c}} = B_{i,c}e^{j\Theta_{i,c}}$.
6. Compute the Mean Square Error (MSE) between the ideal constellation points and the actually transmitted ones obtained at the end of Step 5 for each symbol as the sum of the squared Euclidean distance between the two points over all the subcarriers in the symbol. The MSE of the i-th symbol is defined as

$$MSE_i = \frac{1}{36}\sum_{c=0}^{35}\left|A_{i,c}e^{j\Phi_{i,c}} - B_{i,c}e^{j\Theta_{i,c}}\right|^2$$

   Next, compute the total MSE as the sum of the MSEs of the each OFDM symbols:

$$Total\_MSE = \sum_{i=0}^{11} MSE_i$$

7. Compute the average energy of the reference constellation points carried by the i-th OFDM symbol:

$$\text{Avg\_En}_i^{(ref)} = \frac{1}{36}\sum_{c=0}^{35}\left|A_{i,c}\right|^2$$

   and the total average energy for all transmitted OFDM symbols as:

$$\text{Tot\_En}^{(ref)} = \sum_{i=0}^{11}\text{Avg\_En}_i^{(ref)}$$

8. The normalized total MSE in dB should satisfy the following equation:

$$10\log_{10}\left(\frac{Total\_MSE}{Tot\_En^{(ref)}}\right) < -15\text{ dB}$$

A.6.6 Transmitter spectral flatness

No individual carrier shall have average power outside of the range ±2 dB with respect to the average power in all of the subcarriers as measured into a 50 Ω impedance.

A.7 PHY primitives

A.7.1 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 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, nor 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 processing or transmission of PHY is not possible due to invalid parameters or any other reasons, 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 processing or transmission of PHY is not possible due to invalid parameters or any other reasons, the PHY entity shall discard the constructed ACK/NACK frame and issue the PD-ACK.confirm primitive with a FAILED status.

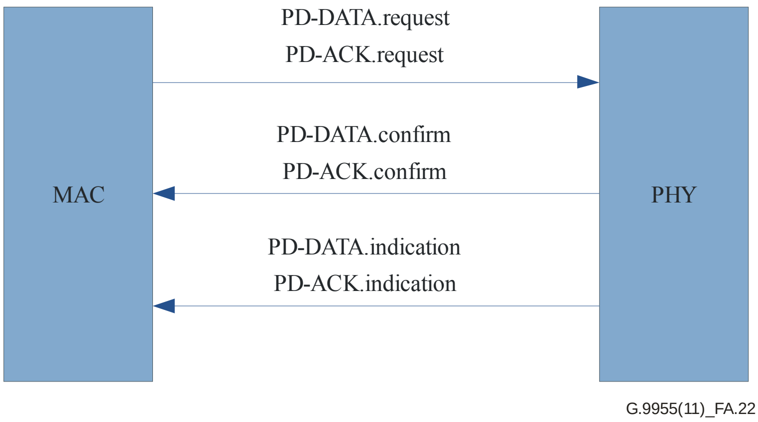


Figure A.22 – Data or ACK primitive flow

A.7.1.1 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 A.14 specifies the parameters for the PD-DATA.request primitive.

Table A.14 – The parameters for the PD-DATA.request primitive

Name	Type	Valid range	Description
psduLength	Integer	0x00-0xEF	The number of bytes contained in the PSDU to be transmitted by the PHY entity.
psdu	Integer Array	Any	The set of bytes forming the PSDU request to transmit by the PHY entity.

The PHY should start the transmission no later than 0.1*aSlotTime after the PD-DATA.request is issued by the MAC. The aSlotTime is defined in Table A.13 of [ITU-T G.9956].

A.7.1.2 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 A.15 specifies the parameters for the PD-DATA.confirm primitive.

Table A.15 – 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.

A.7.1.3 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
)

Table A.16 specifies the parameters for the PD-DATA.indication primitive.

Table A.16 – The parameters for the PD-DATA.indication primitive

Name	Type	Valid range	Description
psduLength	Integer	0x00-0xEF	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 (LQI) value measured during reception of the PPDU

The LQI shall be measured for each received packet and is a characterization of the quality of the underlying powerline channel.

The LQI is an integer ranging from 0x00 to 0xFF and LQI values in-between shall be uniformly distributed between these two limits. The LQI value is the average SNR (where averaging is done over all Active Tones and Pilot Tones, if present, in the bandplan and overall OFDM symbols in the received packet) normalized to the range from –10 dB or lower (0x00) to 53 dB or higher (0xFF), where the value of –9.75 dB is represented as 0x01 and the value of 52.75 dB is represented as 0xFE. Active tones are defined as tones which carry data (pilot tones and dummy bit tones are not included).

The LQI value is computed in the PHY and passed to the MAC with the PD-DATA.indication primitive through the ppduLinkQuality parameter – see Table A.16. The LQI shall be measured and reported and it may be used to determine the transmission parameters, such as modulation modes.

A.7.1.4 PD-ACK.request

The PD-ACK.request primitive requests to send ACK frame to the PHY from the local MAC sublayer entity. The semantics of the PD-ACK.request primitive is as follows:

```
PD-ACK.request (
        FCH
)
```

Table A.17 specifies the parameter for the PD-ACK.request primitive.

Table A.17 – The parameters for the PD-ACK.request primitive

Name	Type	Valid range	Description
FCH	Structure	Clause A.5.5 PHY	MAC layer provides all Frame Control Header parameters described in clause A.5.5 to construct FCH frame for ACK.

A.7.1.5 PD-ACK.confirm

The PD-ACK.confirm confirms the end of the transmission of an ACK packet. The semantics of the PD-ACK.confirm primitive is as follows:

```
PD-ACK.confirm (
        Status
)
```

Table A.18 specifies the parameter for the PD-ACK.confirm primitive.

Table A.18 – The parameters for the PD-ACK.confirm primitive

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS BUSY_RX, BUSY_TX, FAILED	Confirm transmission of ACK frame.

A.7.1.6 PD-ACK.indication

The PD-ACK.indication primitive indicates reception of ACK frame from the PHY to the local MAC sublayer entity. The semantics of the PD-ACK.indication primitive is as follows:

PD-DATA.indication (
FCH
)

Table A.19 specifies the parameter for the PD-ACK.indication primitive.

Table A.19 – The parameters for the PD-ACK.indication primitive

Name	Type	Valid range	Description
FCH	Structure	Clause A.5.5 PHY	MAC layer receives all Frame Control Header parameters described in clause A.5.5 from PHY layer.

A.7.2 Management primitive

There are three types of management primitive, which are Get, Set and Confirm, are used to initiate commends or retrieve data from PHY. PLME_SET.request function configures PHY to initial specific function. PLME_GET.request to retrieve specific parameters from PHY And PLME_GET.confirm reports the result of an action initiated by MAC.

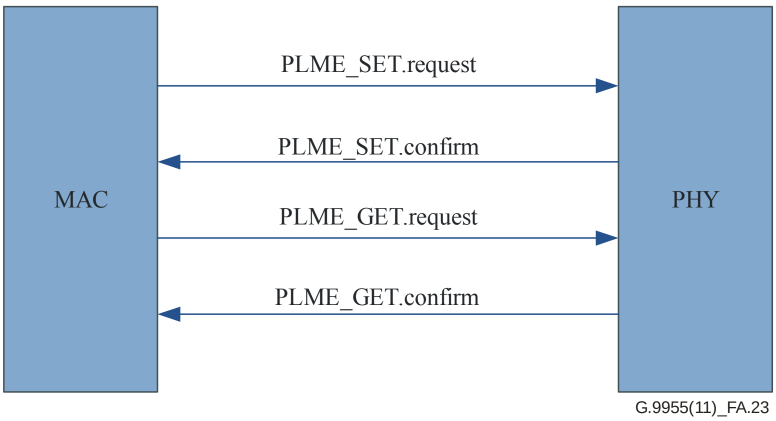


Figure A.23 – Management primitive flow

A.7.2.1 PLME_SET.request

The semantics of the PLME_SET.request primitive is as follows:

PLME_SET.request (
TXPower
ModulationType
ToneMap
PreEmphasis
ToneMask

DT
)

Table A.20 specifies the parameters for the PLME_SET.request primitive.

Table A.20 – The parameters for the PLME_SET.request primitive

Name	Type	Valid range	Description
TXPower	Integer	0x00-0x20	MAC layer uses this primitive to notify PHY about the gain/power setting PHY has to use to transmit the next packet.
AGCGain	Integer	0x0-0x3F	MAC changes the AGC gain to a desired Energy level.
ModulationType	Integer	0x0-0x3	Set the TX modulation scheme for the next frame.
ToneMap	Array	0x0-0x1	Tone map parameter. The value of 0 indicates to the remote transmitter that dummy data should be transmitted on the corresponding sub carrier while a value of 1 indicates that valid data should be transmitted on the corresponding subcarrier.
PreEmphasis	Integer	0x00-0x1F	Specify transmit gain for each 10 kHz section of the available spectrum.
ToneMask	Array	0x0-0x1	Tone Mask parameter. The value of 0 indicates tone is notched 1 indicates that tone is enabled.
DT	Integer	0x00-0x07	Delimiter Type as specified in Table A.7.

A.7.2.2 PLME_SET.confirm

PHY stores new parameters and returns new stored value back to MAC layer. The semantics of the PLME_SET.confirm primitive is as follows:

PLME_SET.confirm (
TXPower
ModulationType
ToneMap
PreEmphasis
ToneMask
DT
)

Table A.21 specifies the parameters for the PLME_SET.confirm primitive.

Table A.21 – The parameters for the PLME_SET.confirm primitive

Name	Type	Valid range	Description
TXPower	Integer	0x00-0x20	Returns new stored value back to MAC
ModulationType	Integer	0x0-0x3	Returns new stored value back to MAC
ToneMap	Array	0x0-0x1	Returns new stored value back to MAC
PreEmphasis	Integer	0x00-0x1F	Returns new stored value back to MAC
ToneMask	Array	0x0-0x1	Returns new stored value back to MAC
DT	Integer	0x00-0x07	Delimiter Type as specified in Table A.7.

A.7.2.3 PLME_GET.request

The PLME_GET.request primitive requests PHY to get the parameters described in Table A.22. The semantics of the PLME_GET.request primitive is as follows:

PLME_GET.request (
)

A.7.2.4 PLME_GET.confirm

The semantics of the PLME_GET.confirm primitive is as follows:

PLME_GET.confirm (
SNR
CarrierSNR
RXSensitivity
ZCTDifferential
TXPower,AGCGain,
ModulationType,
ToneMap,
PreEmphasis,
ToneMask,
DT
)

Table A.22 specifies the parameters for the PLME_GET.confirm primitive.

Table A.22 – The parameters for the PLME_GET.confirm primitive

Name	Type	Valid range	Description
SNR	Integer	0x00-0xFF	MAC layer requests to get channel SNR value in dB.
CarrierSNR	Integer	0x00-0x3F	PHY provides SNR value per each carrier.
RX Sensitivity	Integer	0x0-0x1F	PHY provides receiver sensitivity to MAC layer.
ZCTDifferential	Integer	0x00-0xFF	PHY computes and provide time difference between local 50 Hz phase and remote end to MAC layer.
TXPower	Integer	0x00-0x20	MAC layer uses this primitive to notify PHY about the gain/power setting PHY has to use to transmit the next packet.
ModulationType	Integer	0x0-0x3	Set the TX modulation scheme for the next frame.

Table A.22 – The parameters for the PLME_GET.confirm primitive

Name	Type	Valid range	Description
ToneMap	Array	0x0-0x1	Tone map parameter. The value of 0 indicates to the remote transmitter that dummy data should be transmitted on the corresponding sub carrier while a value of 1 indicates that valid data should be transmitted on the corresponding sub carrier.
PreEmphasis	Integer	0x00-0x1F	Specify transmit gain for each 10 kHz section of the available spectrum.
ToneMask	Array	0x0-0x1	Tone Mask parameter. The value of 0 indicates tone is notched 1 indicates that tone is enabled.
DT	Integer	0x00-0x07	Delimiter Type as specified in Table A.7.

SNR is an integer ranging from 0x00 to 0xFF, where values in-between shall be uniformly distributed between these two limits. The SNR values are normalized to the range from –10 dB or lower (0x00) to 53 dB or higher (0xFF), where the value of –9.75 dB is represented as 0x01 and the value of 52.75 dB is represented as 0xFE.

CarrierSNR is an integer ranging from 0x00 to 0x3F, where values in-between shall be uniformly distributed between these two limits. The CarrierSNR values are normalized to the range from –10 dB or lower (0x00) to 53 dB or higher (0x3F), where the value of –9 dB is represented as 0x01 and the value of 52 dB is represented as 0x3E.

A.7.2.5 PLME_SET_TRX_STATE.request

The PLME_SET_TRX_STATE.request primitive requests PHY to change the state. The semantics of the PLME_SET_TRX_STATE.request primitive is as follows:

```
PLME_SET_TRX_STATE.request (
        State
)
```

Table A.23 specifies the parameters for the PLME_SET_TRX_STATE.request primitive.

Table A.23 – The parameters for the PLME_SET_TRX_STATE.request primitive

Name	Type	Valid range	Description
State	Enumeration	TXON_RXOFF TXOFF_RXON	Turns off the RX PHY when transmitting packet. Turns off the transmitter and enable RX when PHY is not transmitting.

A.7.2.6 PLME_SET_TRX_STATE.confirm

The PLME_SET_TRX_STATE.confirm primitive confirms the changing PHY state. The semantics of the PLME_SET_TRX_STATE.confirm primitive is as follows:

```
PLME_SET_TRX_STATE.confirm (
        Status
)
```

Table A.24 specifies the parameters for PLME_SET_TRX_STATE.confirm primitive.

Table A.24 – The parameters for the PLME_SET_TRX_STATE.confirm primitive

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS BUSY_TX BUSY_RX	Confirm RX and TX are set or provide error message if TX or RX are busy.

A.7.2.7 PLME_CS.request

The PLME_CS.request primitive requests PHY to get media status using carrier sense. The semantics of the PLME_CS.request primitive is as follows:

PLME_CS.request (
)

A.7.2.8 PLME_CS.confirm

The PLME_CS.confirm primitive reports media status. The semantics of the PLME_CS.confirm primitive is as follows:

PLME_CS.confirm (
    Status
)

Table A.25 specifies the parameters for the PLME_CS.confirm primitive.

Table A.25 – The parameters for the PLME_CS.confirm primitive

Name	Type	Valid range	Description
Status	Enumeration	IDLE BUSY	Power line media status

Appendix A-I

G3-PLC: Examples on encoding and decoding

(This appendix does not form an integral part of this Recommendation.)

A-I.1 Example for data encoding

Suppose we have a 40 bytes MAC packet to send in DQPSK mode (2 bits per symbol) with 25 carriers available (due to notching and/or tone-mapping).

The size of the data at the interleaver input is equal to inter_input_size = (((40*8) + (16*8)) + 6) * 2 = 908 bits (Reed-Solomon adds 16 bytes, the convolutional encoder adds 6 bits and multiplies the size by 2)

The minimal interleaver buffer size:

– We have 25 carriers so m = 25.

– We have n = FL*4*bits_per_symbol, so

FL = ceiling(inter_input_size / (m * 4 * bits_per_symbols))

= ceiling(908 / (25*4*2)) = ceiling(4,54) = 5 and n = 40.

As m = 25 and n = 40, the matrix can "store" 1000 bits and the data is 908 bits long, so 92 bits of padding must be added. Those 92 bits of padding are split between Byte Padding and Bit Padding, the Byte Padding being maximized (with the constraint that the input is in bytes). So the upper layer shall add floor(92 / 2 / 8) = 5 bytes of padding before the data enters the Scrambler, and 12 remaining bits of Bit Padding shall be added by the PHY layer at the interleaver input.

A-I.2 Example for data decoding

When decoding a frame, we need to compute the amount of Bit Padding to process the frame. The FCH contains the following information (decoding the example in above paragraph):

– FL = 5

– DQPSK modulation (2 bits per symbol)

– 25 carriers used (tone-map + notching information)

So, the interleaver buffer can hold 25 * (4 * FL * 2) = 1000 bits.

In these 1000 bits:

– 16*8*2 bits were added by Reed-Solomon.

– 12 bits were added by the convolutional encoder.

– The remaining 732 bits are a mix of data and padding:
  - The data part is equal to floor(732 / 2 / 8) bytes = 45 bytes.
  - The Bit Padding is equal to 732 – (data_size * 8 * 2) bits = 12 bits.

In the 45 bytes of data, 5 bytes of Byte Padding are removed by the MAC layer using the "Segment length" header information.

Annex B

PRIME power line communications PHY

(This annex forms an integral part of this Recommendation.)

NOTE – This is a stand-alone annex which can be implemented independently from the main body of this Recommendation.

B.1 Introduction

This annex is the technical specification for PRIME technology.

B.1.1 Scope

This annex specifies a physical layer for narrowband data transmission over electrical power lines that could be part of a Smart Grid system.

B.1.2 Overview

The purpose of this annex is to specify a PHY for narrowband data transmission system for the power line environment based on orthogonal frequency division multiplexing (OFDM) for providing mainly core utility services.

The description is written from the transmitter perspective to ensure interoperability between devices and allow different implementations.

B.1.3 Normative 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.

[IEC 61334-4-1] IEC 61334-4-1 Ed.1996, *Distribution automation using distribution line carrier systems – Part 4: Data communication protocols – Section 1: Reference model of the communication system*.

[IEC 61334-4-32] IEC 61334-4-32 Ed.1996, *Distribution automation using distribution line carrier systems – Part 4: Data communication protocols – Section 32: Data link layer – Logical link control (LLC)*.

[IEC 61334-4-511] IEC 61334-4-511 Ed. 2000, *Distribution automation using distribution line carrier systems – Part 4-511: Data communication protocols – Systems management – CIASE protocol*.

[IEC 61334-4-512] IEC 61334-4-512, Ed. 1.0:2001, *Distribution automation using distribution line carrier systems – Part 4-512: Data communication protocols – System management using profile 61334-5-1 – Management*.

B.1.4 Document conventions

This document is divided into clauses.

Binary numbers are indicated by the prefix '0b' followed by the binary digits, e.g., '0b0101'. Hexadecimal numbers are indicated by the prefix '0x', e.g., '0x0F'.

Mandatory requirements are indicated with 'shall' in the main body of this document.

Optional requirements are clearly indicated. If an option is incorporated in an implementation, it shall be applied as specified in this document.

floor(x) denotes to the largest integer that is lower than or equal to x.

B.1.5 Definitions

This annex defines the following terms:

B.1.5.1 base node: Master node which controls and manages the resources of a subnetwork.

B.1.5.2 beacon slot: Location of the beacon PDU within a frame.

B.1.5.3 destination node: A node that receives a frame.

B.1.5.4 downlink: Data travelling in direction from Base Node towards Service Nodes.

B.1.5.5 level (PHY layer): When used in physical layer (PHY) context, it implies the transmit power level.

B.1.5.6 level (MAC layer): When used in medium access control (MAC) context, it implies the position of the reference device in switching hierarchy.

B.1.5.7 MAC frame: Composite unit of abstraction of time for channel usage. A MAC frame is comprised of one or more beacons, one SCP, and zero or one CFP. The transmission of the beacon by the base node acts as a delimiter for the MAC frame.

B.1.5.8 neighbour node: Node A is neighbour node of node B if A can directly transmit to and receive from B.

B.1.5.9 node: Any one element of a subnetwork which is able to transmit to and receive from other subnetwork elements.

B.1.5.10 PHY frame: The set of OFDM symbols and preamble which constitute a single PHY layer protocol data unit (PPDU).

B.1.5.11 preamble: The initial part of a PHY Frame, used for synchronizations purposes.

B.1.5.12 registration: Process by which a service node is accepted as member of a subnetwork and allocated an LNID.

B.1.5.13 service node: Any one node of a subnetwork which is not a base node.

B.1.5.14 source node: A node that sends a frame.

B.1.5.15 subnetwork: A set of elements that can communicate by complying with this annex and share a single base node.

B.1.5.16 subnetwork address: Property that universally identifies a subnetwork. It is its base node EUI-48 address.

B.1.5.17 switching: Providing connectivity between nodes that are not neighbour nodes.

B.1.5.18 unregistration: Process by which a Service Node leaves a Subnetwork.

B.1.5.19 uplink: Data travelling in direction from Service Node towards Base Node

B.1.6 Abbreviations and acronyms

This annex uses the following abbrevations and acronyms

AC	Alternating Current
AES	Advanced Encryption Standard
AMM	Advanced Meter Management
ARQ	Automatic Repeat Request

ATM	Asynchronous Transfer Mode
BER	Bit Error Rate
BPDU	Beacon PDU
BPSK	Binary Phase Shift Keying
CENELEC	European Committee for Electrotechnical Standardization
CFP	Contention Free Period
CID	Connection Identifier
CL	Convergence layer
ClMTUSize	Convergence layer Maximum Transmit Unit Size.
CPCS	Common Part Convergence Sublayer
CRC	Cyclic Redundancy Check
CSMA-CA	Carrier Sense Multiple Access-Collision Avoidance
D8PSK	Differential Eight-Phase Shift Keying
DBPSK	Differential Binary Phase Shift Keying
DHCP	Dynamic Host Configuration Protocol
DPSK	Differential Phase Shift Keying (general)
DQPSK	Differential Quaternary Phase Shift Keying
DSK	Device Secret Key
ECB	Electronic Code Book
EMA	Exponential Moving Average
ENOB	Effective Number Of Bits
EUI-48	48-bit Extended Unique Identifier
EVM	Error Vector Magnitude
FCS	Frame Check Sequence
FEC	Forward Error Correction
FFT	Fast Fourier Transform
GK	Generation Key
GPDU	Generic MAC PDU
HCS	Header Check Sum
IEC	International Electrotechnical Committee
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IGMP	Internet Group Management Protocol
IPv4	Internet Protocol, Version 4
kbit/s	kilobit per second
KDIV	Key Diversifier
LCID	Local Connection Identifier

LFSR	Linear Feedback Shift Register
LLC	Logical Link Control
LNID	Local Node Identifier
LSID	Local Switch Identifier
LWK	Local Working Key
MAC	Medium Access Control
MK	Master Key
MLME	MAC Layer Management Entity
MPDU	MAC Protocol Data Unit
MSB	Most Significant Bit
MSDU	MAC Service Data Unit
MSPS	Million Samples Per Second
MTU	Maximum Transmission Unit
NAT	Network Address Translation
NID	Node Identifier
NSK	Network Secret Key
OFDM	Orthogonal Frequency Division Multiplexing
PDU	Protocol Data Unit
PHY	Physical Layer
PIB	PLC Information Base
PLC	Power Line Communications
PLME	PHY Layer Management Entity
PNPDU	Promotion Needed PDU
PPDU	PHY Protocol Data Unit
ppm	parts per million
PSD	Power Spectral Density
PSDU	PHY Service Data Unit
QoS	Quality of Service
SAP	Service Access Point
SAR	Segmentation and Reassembly
SCP	Shared Contention Period
SCRC	Secure CRC
SDU	Service Data Unit
SEC	Security
SID	Switch Identifier
SNA	Subnetwork Address
SNK	Subnetwork Key (corresponds to either REG.SNK or SEC.SNK)

SNR	Signal to Noise Ratio
SP	Security Profile
SSCS	Service Specific Convergence Sublayer
SWK	Subnetwork Working Key
TCP	Transmission Control Protocol
TOS	Type Of Service
UI	Unique Identifier
USK	Unique Secret Key
VJ	Van Jacobson
WK	Working Key

B.2 General description

This annex is the first part of the specification for a solution for powerline communications in the CENELEC A-Band using OFDM modulation. This solution focuses on providing a very robust communication channel in applications such as automated meter management (AMM). The target transmission rate is in the order of tens of kilobits per second.

B.2.1 General description of the architecture

Figure B.1 depicts the communication layers and the scope of this specification.

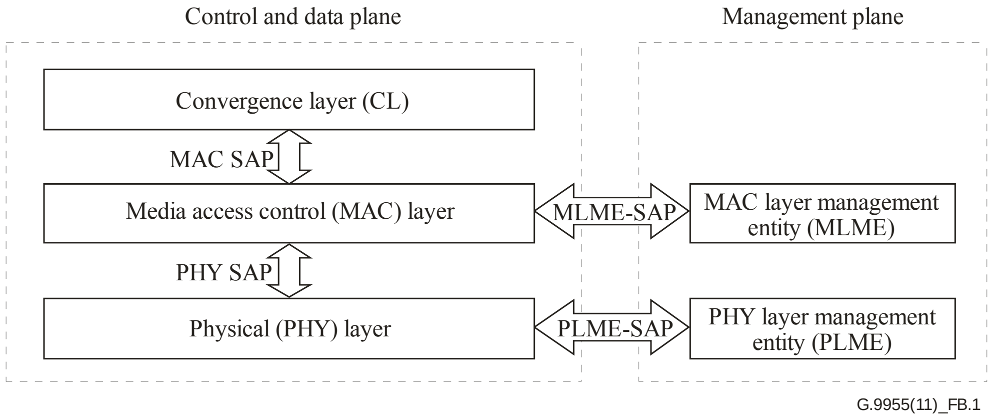


Figure B.1 – Reference model of PRIME protocol layers

The service-specific convergence layer (CL) classifies traffic associating it with its proper MAC connection. This layer performs the mapping of any kind of traffic to be properly included in MAC service data units (MSDUs). It may also include compression functions. Several SSCSs are defined to accommodate different kinds of traffic into MSDUs.

The MAC layer provides core MAC functionalities of system access, bandwidth allocation, connection establishment/maintenance, and topology resolution.

The PHY layer transmits and receives MPDUs between neighbour nodes using orthogonal frequency division multiplexing (OFDM). OFDM is chosen as the modulation technique mainly because of the following:

- its inherent adaptability in the presence of frequency selective channels (which are quite common but unpredictable, due to narrowband interference or unintentional jamming);
- its robustness to impulsive noise , resulting from extended symbol duration and use of FEC, its capacity for achieving high spectral with simple transceiver implementations.

B.3 Physical layer

B.3.1 Introduction

This clause specifies the Physical Layer (PHY) Entity for an OFDM based PLC communications scheme in the CENELEC A band as defined in Annex F. The PHY entity uses frequencies in the 3 kHz up to 95 kHz band and is restricted to electricity distributors and their licensees. However, it is well known that frequencies below 40 kHz show several problems in typical LV power lines. For example:

- Load impedance modulus seen by transmitters is sometimes below 1 Ω, especially for base nodes located at transformers;
- Coloured background noise, which is always present in power lines and caused by the summation of numerous noise sources with relatively low power, exponentially increases its amplitude towards lower frequencies;
- Meter rooms pose an additional problem, as consumer behaviour is known to have a deeper impact on channel properties at low frequencies, i.e., operation of all kinds of household appliances leads to significant and unpredictable time-variance of both the transfer function characteristics and the noise scenario.

Consequently, the OFDM signal will use a frequency bandwidth of 47.363 kHz located on the high frequencies of CENELEC A band.

The OFDM signal itself will use 97 (96 data plus one pilot) equally spaced subcarriers with a short cyclic prefix.

Differential modulation is used with three possible constellations: DBPSK, DQPSK or D8PSK. Thus, theoretical uncoded speeds of around 47 kbit/s, 94 kbit/s, and 141 kbit/s (without cyclic prefix overhead) could be obtained.

An additive scrambler is used to avoid the occurrence of long sequences of identical bits.

Finally, rate ½ convolutional coding will be used along with bit interleaving. This can be disabled by higher layers if the channel is good enough and higher throughputs are needed.

B.3.2 Overview

Figure B.2 shows the PHY layer transmitter block diagram.

On the transmitter side, the PHY layer receives an MPDU from the MAC layer, and generates a PHY Frame. If decided by higher layers, the PPDU after the CRC block is convolutionally encoded and then interleaved (however, it will always be scrambled). The output is differentially modulated using a DBPSK, DQPSK or D8PSK scheme. The next step is OFDM, which comprises the IFFT (inverse fast Fourier transform) block and the cyclic prefix generator.

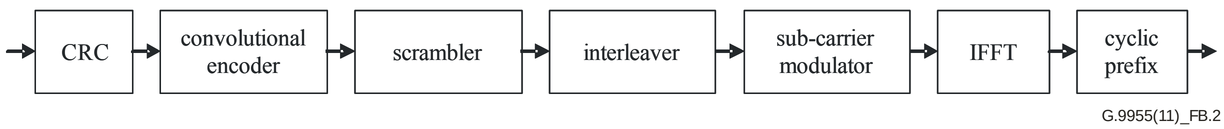


Figure B.2 – PHY layer transmitter

The structure of the PHY Frame is shown in Figure B.3. Each PHY Frame starts with a preamble lasting 2.048 ms, followed by a number of OFDM symbols, each lasting 2.24 ms. The first two OFDM symbols carry the PHY Frame header. The PHY header is also generated as described in clause B.3.4. The remaining M OFDM symbols carry payload, generated as described in clause B.3.4. The value of M is signalled in the PHY header, and is at most equal to 63.

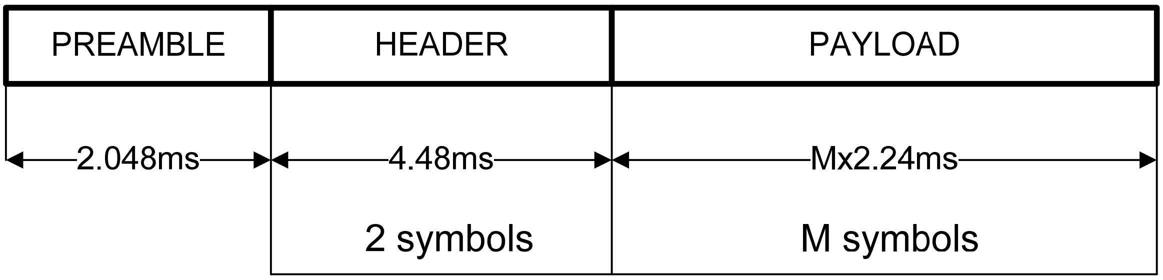


Figure B.3 – PHY frame format

B.3.3 PHY parameters

Table B.1 lists frequency and timing parameters.

Table B.1 – Frequency and timing parameters of the PRIME PHY

Baseband clock (Hz)	250000	
Subcarrier spacing (Hz)	488.28125	
Number of data subcarriers	84 (header)	96 (payload)
Number of pilot subcarriers	13 (header)	1 (payload)
FFT interval (samples)	512	
FFT interval (μs)	2048	
Cyclic prefix (samples)	48	
Cyclic prefix (μs)	192	
Symbol interval (samples)	560	
Symbol interval (μs)	2240	
Preamble period (μs)	2048	

There are parameters which depend on the modulation of each OFDM subcarrier.

Table B.2 shows the PHY data rate during payload transmission, and maximum MSDU length for various modulation and coding combinations.

Table B.2 – PHY data rates for each modulation with FEC on and off

	DBPSK		**DQPSK**		**D8PSK**	
Convolutional code (1/2)	On	Off	On	Off	On	Off
Information bits per subcarrier, N_{BPSC}	0.5	1	1	2	1.5	3
Information bits per OFDM symbol, N_{BPS}	48	96	96	192	144	288
Raw data rate (kbit/s approx.)	21.4	42.9	42.9	85.7	64.3	128.6
Maximum MSDU length (in bits) with 63 symbols	3016	6048	6040	12096	9064	18144
Maximum MSDU length (in bytes) with 63 symbols	377	756	755	1512	1133	2268

Table B.3 shows the modulation and coding scheme and the size of the header portion of the PHY Frame

Table B.3 – Header parameters

	DBPSK
Convolutional code (1/2)	On
Information bits per subcarrier, N_{BPSC}	0.5
Information bits per OFDM symbol, N_{BPS}	42

It is strongly recommended that all frequencies used to generate the OFDM transmit signal come from one single frequency reference. The system clock shall have a maximum tolerance of ±50 ppm, including ageing.

B.3.4 Preamble. header, and payload structure

B.3.4.1 Preamble

The preamble is used at the beginning of every PPDU for synchronization purposes. In order to provide a maximum of energy, a constant envelope signal is used instead of OFDM symbols. There is also a need for the preamble to have frequency agility that will allow synchronization in the presence of frequency selective attenuation and, of course, excellent aperiodic autocorrelation properties are mandatory. A linear chirp signal meets all the above requirements. The waveform of the Preamble is defined as:

$$S_{CH}(t) = A \cdot rect(t/T) \cdot \cos\left[2\pi\left(f_o t + 1/2\mu t^2\right)\right]$$

where T=2048 µs, f_0=41992 Hz (start frequency), f_f =88867 Hz (final frequency), and $\mu=(f_f - f_0) / T$.

$rect(\cdot)$ function is defined as:

$$rect(t) = 1, \quad 0 < t < 1$$
$$rect(t) = 0, \quad otherwise$$

B.3.4.2 Pilot structure

The two OFDM symbols comprising the PHY header. shall contain 13 pilot subcarriers which can be used to estimate the sampling start error and the sampling frequency offset.

For subsequent OFDM symbols, one pilot subcarrier is used to provide a phase reference for frequency domain DPSK demodulation.

Pilot subcarrier frequency allocation is shown in Figures B.4 and B.5, where P_i is the i-th pilot subcarrier and D_i is the j-th data subcarrier.

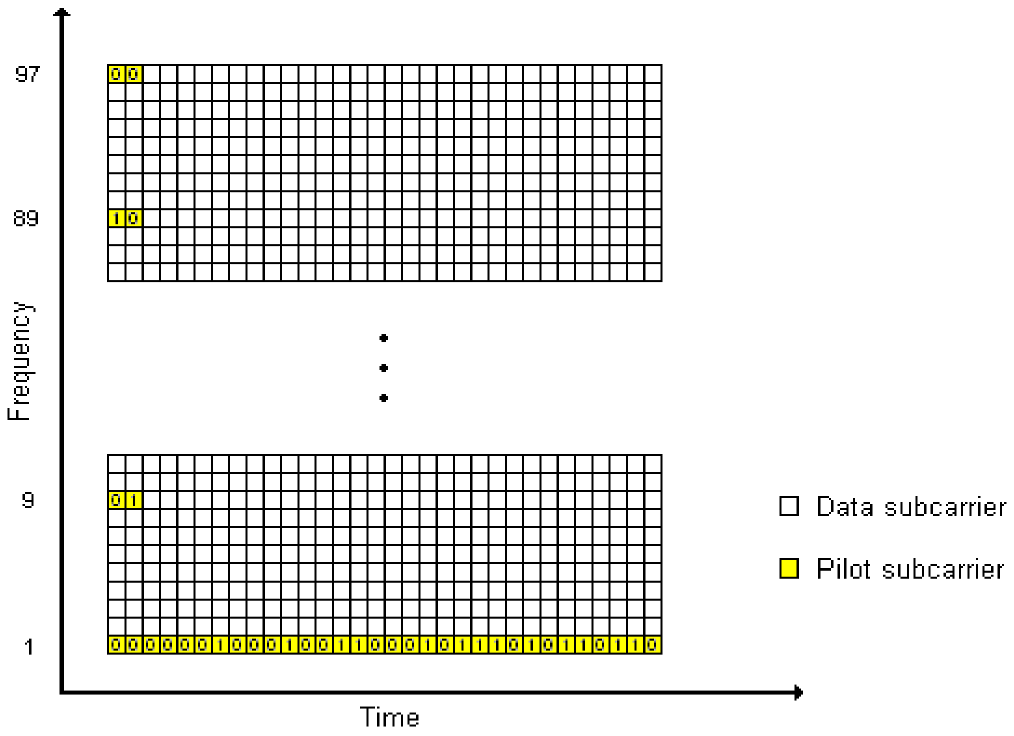


Figure B.4 – Pilot and data subcarrier allocation (OFDM symbols vs subcarriers)

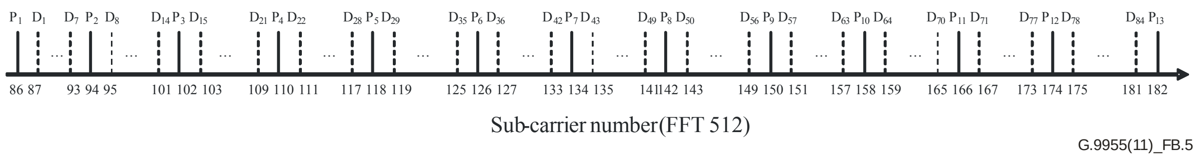


Figure B.5 – Pilot and data subcarrier frequency allocation inside the header

Pilot subcarriers shall be BPSK modulated by a pseudo-random binary sequence (PRBS) to prevent the generation of spectral lines. The phase of the pilot subcarriers is controlled by the PRBS sequence, which is a cyclic extension of the 127 bit sequence given by:

$Pref_{0..126} =$

{0,0,0,0,1,1,1,0,1,1,1,1,0,0,1,0,1,1,0,0,1,0,0,1,0,0,0,0,0,0,1,0,0,0,1,0,0,1,1,0,0,0,1,0,1,1,1,0,1,0,1,1, 0,1,1,0,0,0,0,0,1,1,0,0,1,1,0,1,0,1,0,0,1,1,1,0,0,1,1,1,1,0,1,1,0,1,0,0,0,0,1,0,1,0,1,0,1,1,1,1,1,0,1,0,0, 1,0,1,0,0,0,1,1,0,1,1,1,0,0,0,1,1,1,1,1,1,1}

Where '1' means 180º phase shift and '0' means 0º phase shift. One bit of the sequence will be used per pilot subcarrier, starting with the first pilot subcarrier in the first OFDM symbol, then the next pilot subcarrier, and so on. The same process is used for the second OFDM symbol. For subsequent OFDM symbols, one element of the sequence is used for the pilot subcarrier (see Figure B.4).

The PRBS sequence can be generated by the scrambler defined in Figure B.6 when the "all ones" initial state is used.

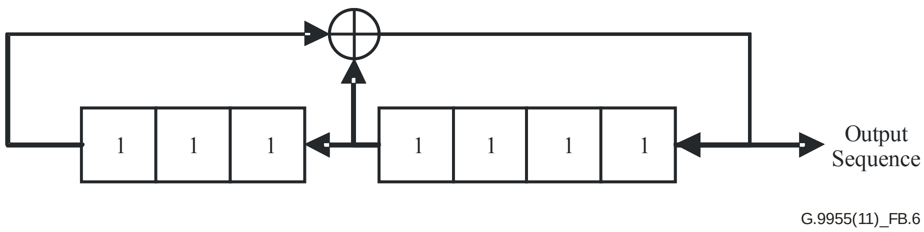


Figure B.6 – LFSR for use in Pilot sequence generation

Loading of the PRBS sequence shall be initiated at the start of every PPDU, just after the preamble.

B.3.4.3 PHY header and payload

The PHY header is composed of 2 OFDM symbols, which are always sent using DBPSK modulation and FEC (convolutional coding) 'On'. However the payload is DBPSK, DQPSK or D8PSKmodulated, depending on the configuration by the MAC layer. The MAC layer selects the modulation scheme, e.g., using information from errors inprevious transmissions to the same receiver(s), or by using the SNR feedback. Thus, the system will then configure itself dynamically to provide the best compromise between throughput and efficiency in the communication. This includes deciding whether or not FEC (convolutional coding) is used.

The first two OFDM symbols in the PPDU corresponding to the PHY header are composed of 84 data subcarriers and 13 pilot subcarriers. After the PHY header, each OFDM symbol in the payload carries 96 data subcarriers and one pilot subcarrier. Each data subcarrier carries 1, 2 or 3 bits.

The bit stream from each field shall be sent MSB first. See Figure B.7.

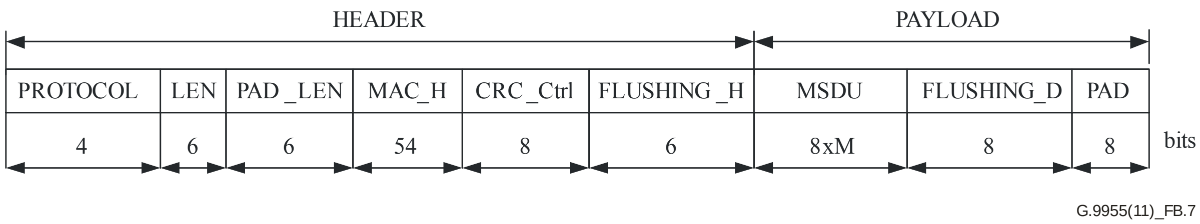


Figure B.7 – PPDU: PHY header and payload (bits transmitted before encoding)

PHY HEADER: Each PPDU contains both PHY and MAC header information. It is composed of the following fields:

- PROTOCOL: contains the transmission scheme of the payload. Added by the PHY layer.

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
DBPSK	DQPSK	D8PSK	RES	DBPSK_F	DQPSK_F	D8PSK_F	RES	RES	RES	RES	RES	RES	RES	RES	RES

Figure B.8 – "PROTOCOL" field of the PPDU

- Where RES means "reserved" and the suffix "_F" means FEC is 'On'.
- LEN: defines the length of the payload (after coding) in OFDM symbols. Added by the PHY layer.
- PAD_LEN: defines the length of the PAD field (before coding) in bytes. Added by the PHY layer.
- MAC_H: MAC layer header. It is included inside the header symbols to protect the information contained. The MAC header is generated by the MAC layer, and only the first 54 bits of the MAC header are embedded in the PHY header.

- CRC_Ctrl: the CRC_Ctrl(m), m = 0..7, contains the CRC checksum over PROTOCOL, LEN, PAD_LEN and MAC_H field (PD_Ctrl). The polynomial form of PD_Ctrl is expressed as follows:

  $$\sum_{m=0}^{69} PD_{Ctrl}(m)x^m$$

  The checksum is calculated as follows: the remainder of the division of PD_Ctrl by the polynomial $x^8 + x^2 + x + 1$ forms CRC_Ctrl(m), where CRC_Ctrl(0) is the LSB. The generator polynomial is the well-known CRC-8-ATM. Some examples are shown in Appendix B-I. Added by the PHY layer.
- FLUSHING_H: flushing bits needed for convolutional decoding. All bits in this field are set to zero to reset the convolutional encoder. Added by the PHY layer.

PAYLOAD:

- MSDU: uncoded MAC layer service data unit.
- FLUSHING_P: flushing bits needed for convolutional decoding. All bits in this field are set to zero to reset the convolutional encoder. This field only exists when FEC is 'On'.
- PAD: In order to ensure that the number of (coded) bits generated in the payload fills an integer number of OFDM symbols, pad bits shall be added to the payload before encoding. All pad bits shall be set to zero.

B.3.5 Convolutional encoder

The uncoded PHY stream can be convolutionally encoded to form the encoded PHY stream. The encoder is a rate 1/2 convolutional encoder with constraint length K = 7 and code generator "polynomials" 1111001 and 1011011. At the beginning, the encoder state is set to zero. At the end of transmission of either the header or the payload, zeroes shall be inserted to flush the encoder (8 zeros for the PHY header and 6 zeros for the payload). The bit generated by the first code generator is first output. The block diagram of the encoder is shown in Figure B.9.

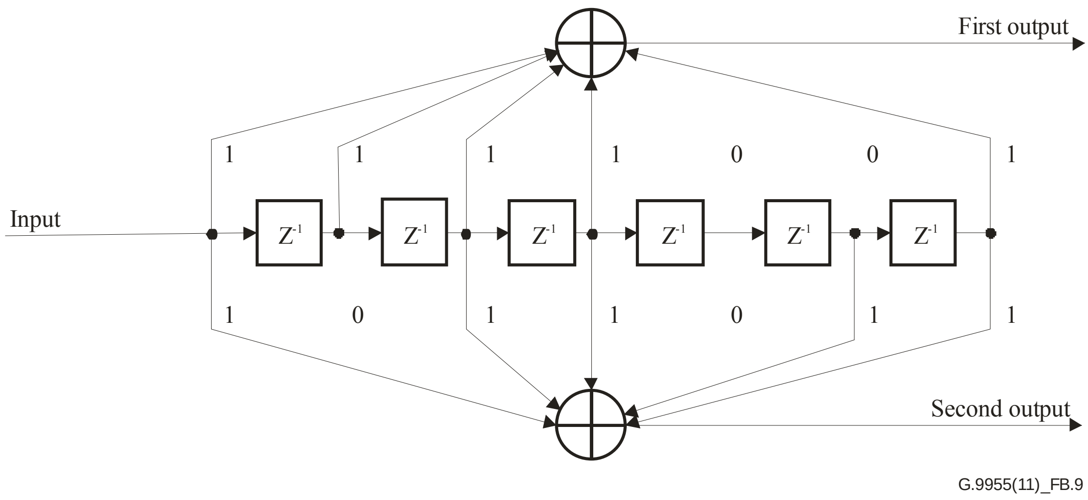


Figure B.9 – Convolutional encoder

B.3.6 Scrambler

The scrambler block randomizes the bit stream, so it reduces the crest factor at the output of the IFFT. Scrambling shall always be performed.

The scrambler block performs an xor of the input bit stream using a pseudo noise sequence pn obtained by a cyclic extension of the 127 element sequence given by:

$Pref_{0..126}$ =

{0,0,0,0,1,1,1,0,1,1,1,1,0,0,1,0,1,1,0,0,1,0,0,1,0,0,0,0,0,0,1,0,0,0,1,0,0,1,1,0,0,0,1,0,1,1,1,0,1,0,1,1,0,1,1,0,0,0,0,0,1,1,0,0,1,1,0,1,0,1,0,0,1,1,1,0,0,1,1,1,1,0,1,1,0,1,0,0,0,0,1,0,1,0,1,0,1,1,1,1,1,0,1,0,0,1,0,1,0,0,0,1,1,0,1,1,1,0,0,0,1,1,1,1,1,1,1}

The PRBS sequence can be generated by the scrambler defined in Figure B.10 when the "all ones" initial state is used.

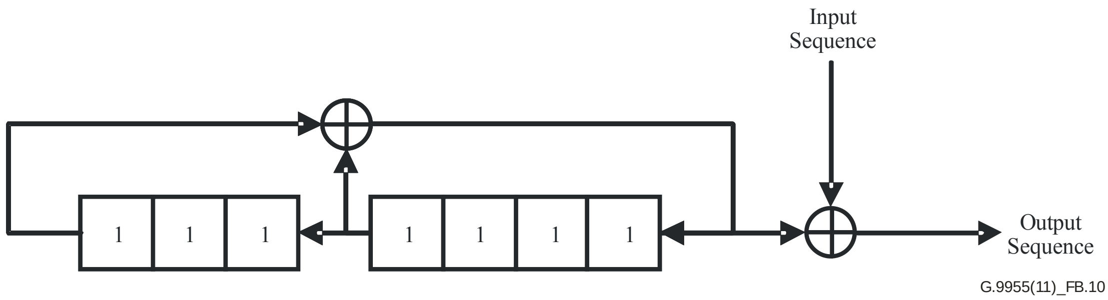


Figure B.10 – LFSR for use in the scrambler block

Loading of the sequence pn shall be initiated at the start of every PPDU, just after the preamble.

B.3.7 Interleaver

Because of the frequency fading (narrowband interference) of typical power line channels, OFDM subcarriers are generally received at different amplitudes. Deep fades in the spectrum may cause groups of subcarriers to be less reliable than others, thereby causing bit errors to occur in bursts rather than be randomly scattered. If (and only if) coding is used as described in clause B.3.4, interleaving is applied to randomize the occurrence of bit errors prior to decoding. At the transmitter, the coded bits are permuted in a certain way, which makes sure that adjacent bits are separated by several bits after interleaving.

Let $N_{CBPS} = 2 \times N_{BPS}$ be the number of coded bits per OFDM symbol in the cases convolutional coding is used All coded bits shall be interleaved by a block interleaver with a block size corresponding to NCBPS. The interleaver ensures that adjacent coded bits are mapped onto non-adjacent data subcarriers. Let $v(k)$, with $k = 0,1,\ldots, N_{CBPS} - 1$, be the coded bits vector at the interleaver input. $v(k)$ is transformed into an interleaved vector $w(i)$, with $i = 0,1,\ldots, N_{CBPS} - 1$, by the block interleaver as follows:

$$w((N_{CBPS} / s) \times (k \bmod s) + \text{floor}(k / s)) = v(k) \qquad k = 0,1,\ldots,N_{CBPS} - 1.$$

The value of s is determined by the number of coded bits per subcarrier, $N_{CBPSC} = 2 \times N_{BPSC}$. N_{CBPSC} is related to N_{CBPS} such that $N_{CBPS} = 96 \times N_{CBPSC}$ (payload) and $N_{CBPS} = 84 \times N_{CBPSC}$ (header)

$s = 8 \times (1 + \text{floor}(N_{CBPSC} / 2))$ for the payload and

$s = 7$ for the header.

The de-interleaver performs the inverse operation.. Hence, if $w'(i)$, with $i = 0,1,\ldots, N_{CBPS} - 1$, is the de-interleaver vector input, the vector $w'(i)$ is transformed into a de-interleaved vector $v'(k)$, with $k = 0,1,\ldots,N_{CBPS} - 1$, by the block de-interleaver as follows:

$$v'(s \times i - (N_{CBPS} - 1) \times \text{floor}(s \times i / N_{CBPS})) = w'(i) \qquad i = 0,1,\ldots,N_{CBPS} - 1.$$

Descriptive tables showing index permutations can be found in Appendix C-I for reference.

B.3.8 Modulation

The PPDU payload is modulated as a multicarrier differential phase shift keying signal with one pilot subcarrier and 96 data subcarriers that comprise 96, 192 or 288 bits per symbol. The header is modulated DBPSK with 13 pilot subcarriers and 84 data subcarriers that comprise 84 bits per symbol.

The bit stream coming from the interleaver is divided into groups of *M* bits where the first bit of the group of *M* is the most significant bit (MSB).

Frequency domain differential modulation is performed. Figure B.11 shows the DBPSK, DQPSK and D8PSK mapping:

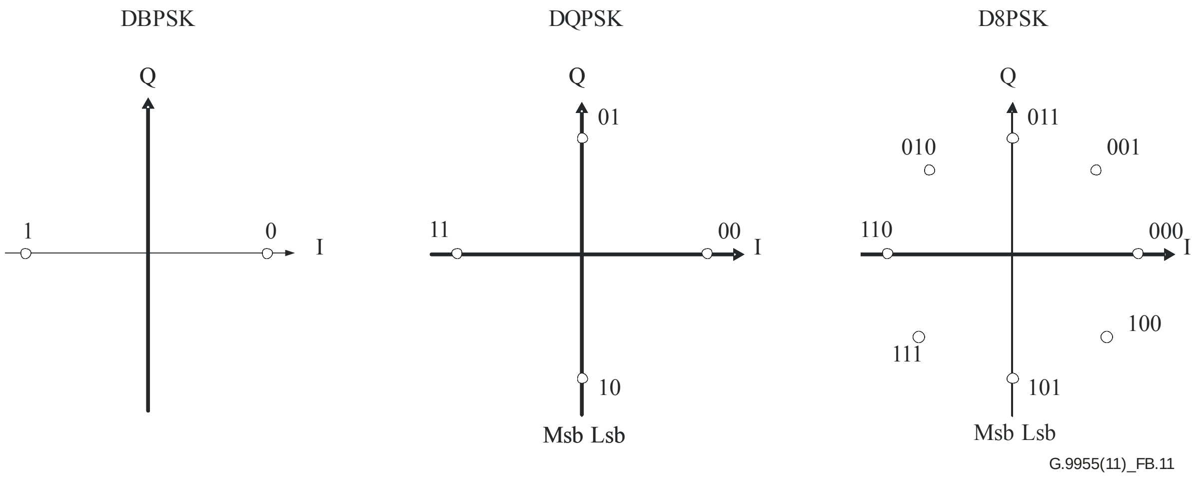


Figure B.11 – DBPSK, DQPSK and D8PSK mapping

The next equation defines the *M*-ary DPSK constellation of *M* phases:

$$s_k = Ae^{j\theta_k}$$

where:

k is the frequency index representing the k-th subcarrier in an OFDM symbol. $k = 1$ corresponds to the phase reference pilot subcarrier.

s^k is the modulator output (a complex number) for the kth given subcarrier.

θ_k stands for the absolute phase of the modulated signal obtained as follows:

$$\theta_k = \left(\theta_{k-1} + (2\pi / M)\Delta b_k\right) \bmod 2\pi$$

This equation applies for $k > 1$ in the payload, the $k = 1$ subcarrier being the phase reference pilot. When the header is transmitted, the pilot allocated in the k-th subcarrier is used as a phase reference for the data allocated in the k+1-th subcarrier.

$\Delta b_k \in \{0,1,..,M-1\}$ represents the information coded in the phase increment, as supplied by the constellation encoder.

$M = 2, 4$, or 8 in the case of DBPSK, DQPSK or D8PSK, respectively.

A represents the ring radius from the centre of the constellation.

The OFDM symbol can be expressed in mathematical form:

$$c_i(n) = \left\{ \sum_{k=86}^{182} s(k-85, i)\exp\left(\frac{j2\pi k}{512}(n - N_{CP})\right) + \sum_{k=330}^{426} s(427-k, i)\exp\left(\frac{j2\pi k}{512}(n - N_{CP})\right) \right\}$$

i is the time index representing the i-th OFDM symbol; $i = 0,1,\ldots M+1$

n is the sample index; $48 \le n \le 559$ $s(k,i)$ is the complex value from the subcarrier modulation block and the symbol * denotes complex conjugate.

If a complex 512-point IFFT is used, the 96 subcarriers shall be mapped as shown in Figure B.12. The symbol '*' represents complex conjugate.

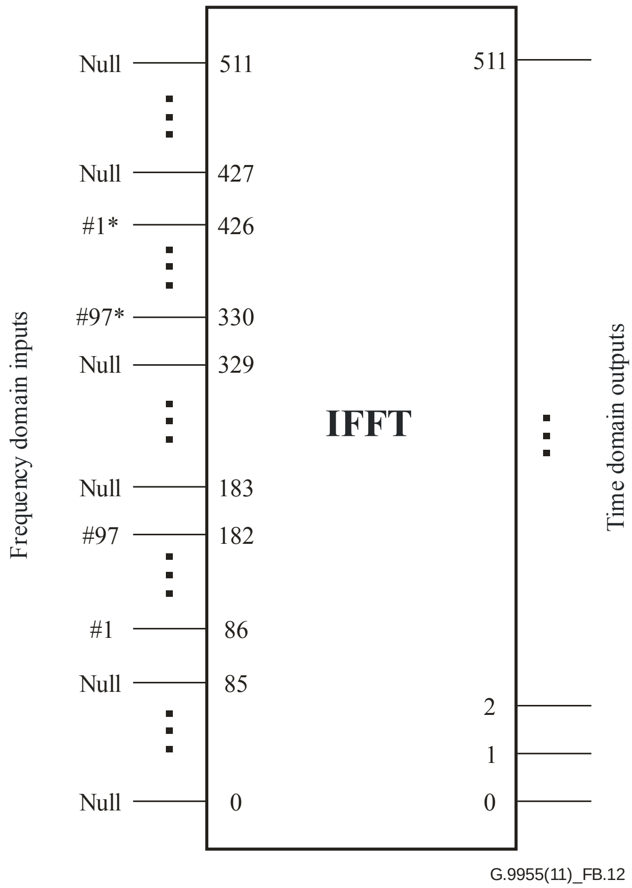


Figure B.12 – Subcarrier mapping

After the inverse Fourier transform, the symbol is cyclically extended by 48 samples to create the cyclic prefix (N_{CP}).

B.3.9 Electrical specification of the transmitter

B.3.9.1 General

The following requirements establish the minimum technical transmitter requirements for interoperability, and adequate transmitter performance.

B.3.9.2 Transmit PSD

Transmitter specifications will be measured according to the following conditions and set-up.

For single-phase devices, the measurement shall be taken on either the phase or neutral connection according to Figure F.2 in Annex F.

For three-phase devices which transmit on all three phases simultaneously, measurements shall be taken in all three phases as per Figure F.4 in Annex F. No measurement is required on the neutral conductor.

The artificial mains network in Figures F.2 and F.4 is shown in Figure B.13. It is based on Annex F, Figure F.3. The 33 uF capacitor and 1 Ω resistor have been introduced so that the network has an impedance of 2 Ω in the frequency band of interest.

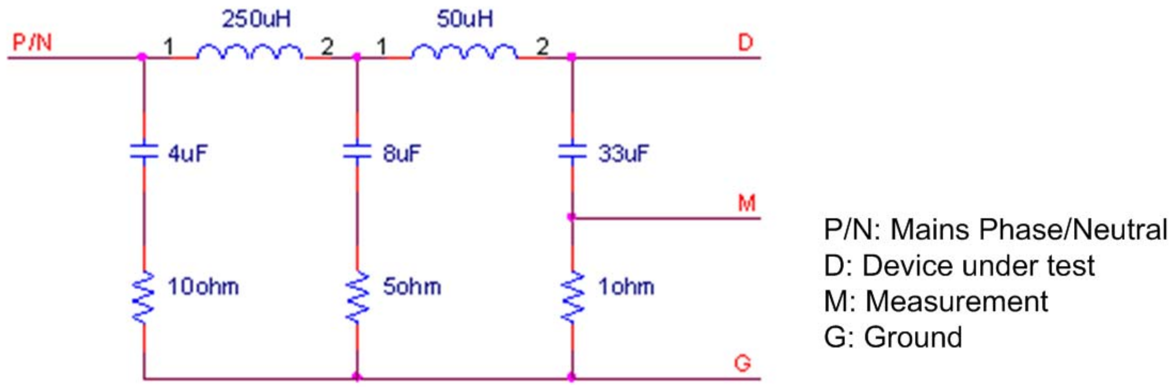


Figure B.13 – Artificial mains network

All transmitter output voltages are specified as the voltage measured at the line terminal with respect to the neutral terminal. Accordingly, values obtained from the measuring device shall be increased by 6 dB (voltage divider of ratio 1/2).

All devices will be tested to comply with PSD requirements over the full range of temperatures, which depend on the type of node:

- base nodes in the range –40ºC to +70ºC
- service nodes in the range –25ºC to +55ºC

All tests shall be carried out under normal traffic load conditions.

In all cases, the PSD shall be compliant with the regulations in force in the country where the system is used.

The power amplifier shall be capable of injecting a final signal level in the transmission node (S1 parameter) of 120 dBμVrms (1 Vrms) when connected to the artificial network of Figure B.13 as described in Figure F.2 for single-phase devices and in Figure F.4 for three-phase devices injecting into one phase at a time. For three-phase devices injecting simultaneously into all three phases, the final signal level shall be 114 dBμVrms (0.5 Vrms). As specified previously, the measurements taken by the measurement instrument shall be increased by 6 dB to compensate the artificial network insertion loss.

B.3.9.3 Error vector magnitude (EVM)

The quality of the injected signal with regard to the artificial mains network impedance shall be measured in order to validate the transmitter device. Accordingly, a vector analyser that provides EVM measurements (EVM meter) shall be used, see clause C.1 for EVM definition. The test set-up described in Figures F.2 and F.4 shall be used in the case of single-phase devices and three-phase devices transmitting simultaneously on all phases, respectively.

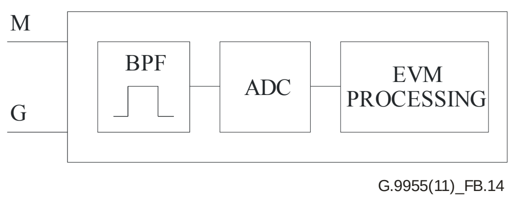


Figure B.14 – EVM meter (block diagram)

The EVM meter shall include a Band Pass Filter with an attenuation of 40 dB at 50 Hz that ensures anti-aliasing for the analog-to-digital converter (ADC).

The minimum performance of the ADC is 1 MSPS, 14-bit effective number of bits (ENOB). The ripple and the group delay of the band pass filter must be accounted for in EVM calculations.

B.3.9.4 Conducted disturbance limits

Regional regulations may apply. For example, in Europe, transmitters shall comply with the maximum emission levels and spurious emissions defined in Annex F for conducted emissions in AC mains in the bands 3 kHz to 9 kHz and 95 kHz to 30 MHz. European regulations also require that transmitters and receivers shall comply with impedance limits defined in Annex F in the range 3 kHz to 148.5 kHz.

B.3.10 PHY service specification

B.3.10.1 General

The PHY shall have a single 20-bit free-running clock incremented in steps of 10 µs. The clock counts from 0 to 1048575, then overflows back to 0. As a result the period of this clock is 10.48576 seconds. The clock is never stopped nor restarted. Time measured by this clock is the one to be used in some PHY primitives to indicate a specific instant in time.

B.3.10.2 PHY Data plane primitives

B.3.10.2.1 General

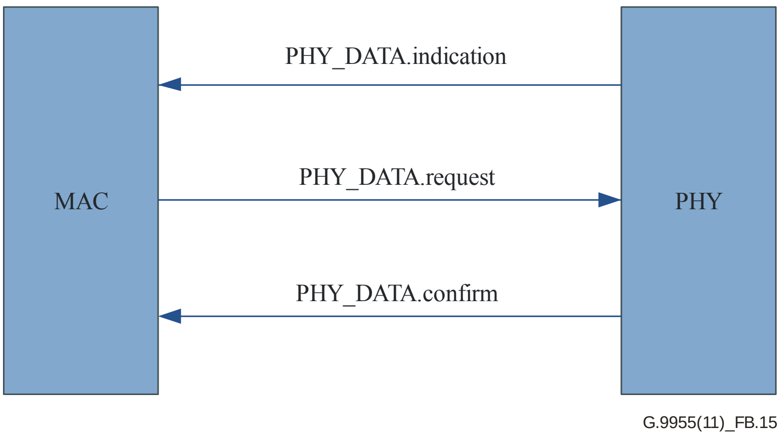


Figure B.15 – Overview of PHY primitives

The request primitive is passed from MAC to PHY to request the initiation of a service.

The indication and confirm primitives are passed from PHY to MAC to indicate an internal PHY event that is significant to MAC. This event may be logically related to a remote service request or may be caused by an event internal to PHY.

B.3.10.2.2 PHY_DATA.request

B.3.10.2.2.1 Function

The PHY_DATA.request primitive is passed to the PHY layer entity to request the sending of a PPDU to one or more remote PHY entities using the PHY transmission procedures. It also allows setting the time at which the transmission shall be started.

B.3.10.2.2.2 Structure

The semantics of this primitive are as follows:

PHY_DATA.request{MPDU, *Length*, *Level*, *Scheme*, *Time*}.

The *MPDU* parameter specifies the MAC protocol data unit to be transmitted by the PHY layer entity. It is mandatory for implementations to byte-align the MPDU across the PHY-SAP. This implies 2 extra bits (due to the non-byte-aligned nature of the MAC layer Header) to be located at the beginning of the header.

The *Length* parameter specifies the length of MPDU in bytes. Length shall be 2 bytes long.

The *Level* parameter specifies the output signal level according to which the PHY layer transmits MPDU. It may take one of eight values:

0: Maximal output level (MOL)

1: MOL –3 dB

2: MOL –6 dB

…

7: MOL –21 dB

The *Scheme* parameter specifies the transmission scheme to be used for MPDU. It may have any of the following values:

0: DBPSK

1: DQPSK

2: D8PSK

3: Not used

4: DBPSK + convolutional code

5: DQPSK + convolutional code

6: D8PSK + convolutional code

7: Not used

The *Time* parameter specifies the instant in time in which the MPDU has to be transmitted. It is expressed in tens of μsec and may take values from 0 to $2^{20} - 1$.

The *Time* parameter shall be calculated by the MAC, taking into account the current PHY time obtained by PHY_timer.get primitive. The MAC shall account for the fact that no part of the PPDU can be transmitted during beacon slots and CFP periods granted to other devices in the network. If the *Time* parameter is set such that these rules are violated, the PHY will return a fail in PHY_Data.confirm.

B.3.10.2.2.3 Use

The primitive is generated by the MAC layer entity whenever data is to be transmitted to a peer MAC entity or entities.

The reception of this primitive will cause the PHY entity to perform all the PHY-specific actions and pass the properly formed PPDU for transfer to the peer PHY layer entity or entities. The next transmission shall start when *Time* = Timer.

B.3.10.2.3 PHY_DATA.confirm

B.3.10.2.3.1 Function

The PHY_DATA.confirm primitive has only local significance and provides an appropriate response to a PHY_DATA.request primitive. The PHY_DATA.confirm primitive tells the MAC layer entity whether or not the MPDU of the previous PHY_DATA.request has been successfully transmitted.

B.3.10.2.3.2 Structure

The semantics of this primitive are as follows:

PHY_DATA.confirm{*Result*}.

The *Result* parameter is used to pass status information back to the local requesting entity. It is used to indicate the success or failure of the previous associated PHY_DATA.request. Some results will be standard for all implementations:

0: Success.

1: Too late. Time for transmission is past.

2: Invalid length.

3: Invalid scheme.

4: Invalid level.

5: Buffer overrun.

6: Busy channel.

7-255: Proprietary.

B.3.10.2.3.3 Use

The primitive is generated in response to a PHY_DATA.request.

It is assumed that the MAC layer has sufficient information to associate the confirm primitive with the corresponding request primitive.

B.3.10.2.4 PHY_DATA.indication

B.3.10.2.4.1 Function

This primitive defines the transfer of data from the PHY layer entity to the MAC layer entity.

B.3.10.2.4.2 Structure

The semantics of this primitive are as follows:

PHY_DATA.indication{*PSDU*, *Length*, *Level*, *Scheme*, *Time*}.

The *PSDU* parameter specifies the PHY service data unit as received by the local PHY layer entity. It is mandatory for implementations to byte-align MPDU across the PHY-SAP. This implies 2 extra bits (due to the non-byte-aligned nature of the MAC layer Header) to be located at the beginning of the header.

The *Length* parameter specifies the length of received PSDU in bytes. Length shall be 2 bytes long.

The *Level* parameter specifies the signal level on which the PHY layer received the PSDU. It may take one of sixteen values:

0: ≤ 70 dBuV

1: ≤ 72 dBuV

2: ≤ 74 dBuV

…

15: > 98 dBuV

The *Scheme* parameter specifies the scheme with which PSDU is received. It may have any of the following values:

0: DBPSK

1: DQPSK

2: D8PSK

3: Not used

4: DBPSK + convolutional code

5: DQPSK + convolutional code

6: D8PSK + convolutional code

7: Not used

The *Time* parameter is the time of receipt of the Preamble associated with the PSDU.

B.3.10.2.4.3 Use

The PHY_DATA.indication is passed from the PHY layer entity to the MAC layer entity to indicate the arrival of a valid PPDU.

B.3.10.3 PHY control plane primitives

Figure B.16 shows the general structure of PHY control plane primitives. Each primitive may have "set", "get" or "confirm" fields. Table B-4 lists the control plane primitives and the fields associated with each of them. Each row lists a control plane primitive. An "X" in a column indicates that the associated field is used in the primitive described in that row.

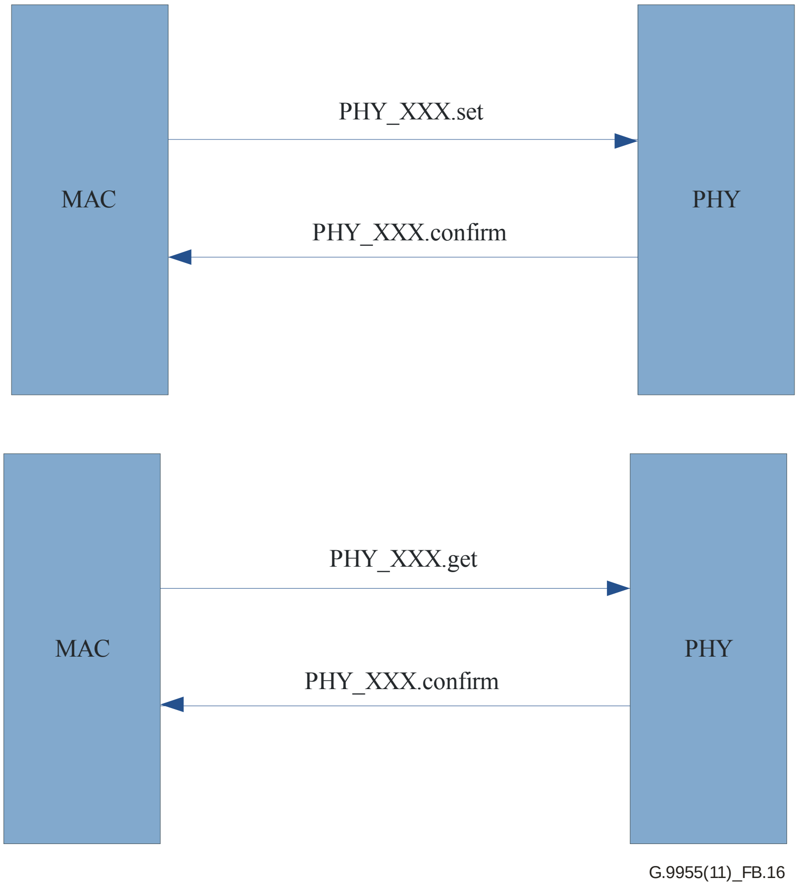


Figure B.16 – Overview of PHY control plane primitives

Table B.4 – Fields associated with PHY control plane primitives

	set	get	confirm
PHY_AGC	X	X	X
PHY_Timer		X	X
PHY_CD		X	X
PHY_NL		X	X
PHY_SNR		X	X
PHY_ZCT		X	X

B.3.10.3.1 PHY_AGC.set

B.3.10.3.1.1 Function

The PHY_AGC.set primitive is passed to the PHY layer entity by the MAC layer entity to set the Automatic Gain Mode of the PHY layer.

B.3.10.3.1.2 Structure

The semantics of this primitive are as follows:

PHY_AGC.set {*Mode*, *Gain*}.

The Mode parameter specifies whether or not the PHY layer operates in automatic gain mode. It may take one of two values:

0: Auto

1: Manual

The *Gain* parameter specifies the initial receiving gain in auto mode. It may take one of N values:

0: min_gain dB

1: min_ gain + step dB

2: min_ gain + 2 × step dB

…

N–1: min_ gain + (N – 1) × step dB

where min_ gain and *N* depend on the specific implementation. step is also an implementation issue but it shall not be more than 6 dB. The maximum Gain value min_ gain + (*N* – 1) × step shall be at least 21 dB.

B.3.10.3.1.3 Use

The primitive is generated by the MAC layer when the receiving gain mode has to be changed.

B.3.10.3.2 PHY_AGC.get

B.3.10.3.2.1 Function

The PHY_AGC.get primitive is passed to the PHY layer entity by the MAC layer entity to get the automatic gain mode of the PHY layer.

B.3.10.3.2.2 Structure

The semantics of this primitive are as follows:

PHY_AGC.get{}.

B.3.10.3.2.3 Use

The primitive is generated by the MAC layer when it needs to know the receiving gain mode that has been configured.

B.3.10.3.3 PHY_AGC.confirm

B.3.10.3.3.1 Function

The PHY_AGC.confirm primitive is passed to the MAC layer entity by the PHY layer entity in response to a PHY_AGC.set or PHY_AGC.get command.

B.3.10.3.3.2 Structure

The semantics of this primitive are as follows:

PHY_AGC.confirm {*Mode*, *Gain*}.

The *Mode* parameter specifies whether or not the PHY layer is configured to operate in automatic gain mode. It may take one of two values:

0: Auto

1: Manual

The *Gain* parameter specifies the current receiving gain. It may take one of N values:

0: min_gain dB

1: min_gain + step dB

2: min_gain + 2 × step dB

…

N-1: min_gain + (N – 1) × step dB

where min_gain and N depend on the specific implementation. The parameter step shall not be more than 6 dB. The maximum gain value min_gain + (N – 1) × step will be at least 21 dB.

B.3.10.3.4 PHY_Timer.get

B.3.10.3.4.1 Function

The PHY_Timer.get primitive is passed to the PHY layer entity by the MAC layer entity to get the time at which the transmission has to be started.

B.3.10.3.4.2 Structure

The semantics of this primitive are as follows:

PHY_Timer.get {}.

B.3.10.3.4.3 Use

The primitive is generated by the MAC layer to know the transmission start.

B.3.10.3.5 PHY_Timer.confirm

B.3.10.3.5.1 Function

The PHY_Timer.confirm primitive is passed to the MAC layer entity by the PHY layer entity in response to a PHY_Timer.get command.

B.3.10.3.5.2 Structure

The semantics of this primitive are as follows:

PHY_Timer.confirm {*Time*}.

The Time parameter is specified in tens of microseconds. It may take values of between 0 and 220-1.

B.3.10.3.6 PHY_CD.get

B.3.10.3.6.1 Function

The PHY_CD.get primitive is passed to the PHY layer entity by the MAC layer entity to look for the carrier detect signal. The carrier detection algorithm shall be based on preamble detection and header recognition (see clause B.3.4).

B.3.10.3.6.2 Structure

The semantics of this primitive are as follows:

PHY_CD.get {}.

B.3.10.3.6.3 Use

The primitive is generated by the MAC layer when it needs to know whether or not the physical medium is free.

B.3.10.3.7 PHY_CD.confirm

B.3.10.3.7.1 Function

The PHY_CD.confirm primitive is passed to the MAC layer entity by the PHY layer entity in response to a PHY_CD.get command.

B.3.10.3.7.2 Structure

The semantics of this primitive are as follows:

PHY_CD.confirm {*cd*, *rssi*, *Time*, *header*}.

The *cd* parameter may take one of two values:

0: no carrier detected

1: carrier detected

The *rssi* parameter is the received signal strength indication and refers to the preamble. It is only relevant when *cd* equals 1. It may take one of sixteen values:

0: ≤ 70 dBuV

1: ≤ 72 dBuV

2: ≤ 74 dBuV

…

15: > 98 dBuV

The *Time* parameter indicates the instant at which the present PPDU will finish. It is only relevant when *cd* equals 1. When cd equals 0, Time parameter will take a value of 0. If *cd* equals 1 but the duration of the whole PPDU is still not known (i.e., the header has not yet been processed), header parameter will take a value of 1 and time parameter will indicate the instant at which the header will finish, specified in tens of microseconds. In any other case the value of Time parameter is the instant at which the present PPDU will finish, and it is specified in tens of microseconds. Time parameter refers to an absolute point in time so it is referred to the system clock.

The *header* parameter may take one of two values:

1: if a preamble has been detected but the duration of the whole PPDU is not yet known from decoding the header.

0: in any other case.

B.3.10.3.8 PHY_NL.get

B.3.10.3.8.1 Function

The PHY_NL.get primitive is passed to the PHY layer entity by the MAC layer entity to get the floor noise level value.

B.3.10.3.8.2 Structure

The semantics of this primitive are as follows:

PHY_NL.get {}.

B.3.10.3.8.3 Use

The primitive is generated by the MAC layer when it needs to know the noise level present in the powerline.

B.3.10.3.9 PHY_NL.confirm

B.3.10.3.9.1 Function

The PHY_NL.confirm primitive is passed to the MAC layer entity by the PHY layer entity in response to a PHY_NL.get command.

B.3.10.3.9.2 Structure

The semantics of this primitive are as follows:

PHY_NL.confirm {*noise*}.

The *noise* parameter may take one of sixteen values:

0: ≤ 50 dBuV

1: ≤ 53 dBuV

2: ≤ 56 dBuV

…

15: > 92 dBuV

B.3.10.3.10 PHY_SNR.get

B.3.10.3.10.1 Function

The PHY_SNR.get primitive is passed to the PHY layer entity by the MAC layer entity to get the value of the signal-to-noise ratio, defined as the ratio of measured received signal level to noise level of last received PPDU. The calculation of the SNR is described in B.4.2.

B.3.10.3.10.2 Structure

The semantics of this primitive are as follows:

PHY_SNR.get {}.

B.3.10.3.10.3 Use

The primitive is generated by the MAC layer when it needs to know the SNR in order to analyse channel characteristics and invoke robustness management procedures, if required.

B.3.10.3.11 PHY_SNR.confirm

B.3.10.3.11.1 Function

The PHY_SNR.confirm primitive is passed to the MAC layer entity by the PHY layer entity in response to a PHY_SNR.get command.

B.3.10.3.11.2 Structure

The semantics of this primitive are as follows:

PHY_SNR.confirm{*SNR*}.

The *SNR* parameter refers to the signal-to-noise ratio, defined as the ratio of measured received signal level to noise level of last received PPDU. It may take one of eight values. The mapping of the 3-bit index to the actual SNR value, as calculated in Annex C is given below:

0: ≤ 0 dB

1: ≤ 3 dB

2: ≤ 6 dB

…

7: > 18 dB

B.3.10.3.12 PHY_ZCT.get

B.3.10.3.12.1 Function

The PHY_ZCT.get primitive is passed to the PHY layer entity by the MAC layer entity to get the zero cross time of the mains and the time between the last transmission or reception and the zero cross of the mains.

B.3.10.3.12.2 Structure

The semantics of this primitive are as follows:

PHY_ZCT.get {}.

B.3.10.3.12.3 Use

The primitive is generated by the MAC layer when it needs to know the zero cross time of the mains, e.g., in order to calculate the phase to which the node is connected.

B.3.10.3.13 PHY_ZCT.confirm

B.3.10.3.13.1 Function

The PHY_ZCT.confirm primitive is passed to the MAC layer entity by the PHY layer entity in response to a PHY_ZCT.get command.

B.3.10.3.13.2 Structure

The semantics of this primitive are as follows:

PHY_ZCT.confirm {*Time*}.

The *Time* parameter is the instant in time at which the last zero-cross event took place.

B.3.10.4 PHY management primitives

PHY layer management primitives enable the PHY layer to interface to the MAC layer. Implementation of these primitives is optional. Refer to Figure B.16 for the general structure of the PHY layer management primitives.

Table B.5 – PHY layer management primitives

Primitive	set	get	confirm
PLME_RESET	X		X
PLME_SLEEP	X		X
PLME_RESUME	X		X
PLME_TESTMODE	X		X
PLME_GET		X	X

B.3.10.4.1 PLME_RESET.request

B.3.10.4.1.1 Function

The PLME_RESET.request primitive is invoked to request the PHY layer to reset its present functional state. As a result of this primitive, the PHY should reset all internal states and flush all buffers to clear any queued receive or transmit data. All the SET primitives are invoked by the PLME, and addressed to the PHY to set parameters in the PHY. The GET primitive is also sourced by the PLME, but is used only to read PHY parameters.

B.3.10.4.1.2 Structure

The semantics of this primitive are as follows:

PLME_RESET.request{}.

B.3.10.4.1.3 Use

The upper layer management entities will invoke this primitive to tackle any system level anomalies that require aborting any queued transmissions and restart all operations from initialization state.

B.3.10.4.2 PLME_RESET.confirm

B.3.10.4.2.1 Function

The PLME_RESET.confirm is generated in response to a corresponding PLME_RESET.request primitive. It provides indication if the requested reset was performed successfully or not.

B.3.10.4.2.2 Structure

The semantics of this primitive are as follows:

PLME_RESET.confirm{*Result*}.

The *Result* parameter shall have one of the following values:

0: Success

1: Failure. The requested reset failed due to internal implementation issues.

B.3.10.4.2.3 Use

The primitive is generated in response to a PLME_RESET.request.

B.3.10.4.3 PLME_SLEEP.request

B.3.10.4.3.1 Function

The PLME_SLEEP.request primitive is invoked to request the PHY layer to suspend its present activities including all reception functions. The PHY layer should complete any pending transmission before entering into a sleep state.

B.3.10.4.3.2 Structure

The semantics of this primitive are as follows:

PLME_SLEEP.request{}.

B.3.10.4.3.3 Use

This primitive is designed to help optimizing power consumption.

B.3.10.4.4 PLME_SLEEP.confirm

B.3.10.4.4.1 Function

The PLME_SLEEP.confirm is generated in response to a corresponding PLME_SLEEP.request primitive and provides information if the requested sleep state has been entered successfully or not.

B.3.10.4.4.2 Structure

The semantics of this primitive are as follows:

PLME_SLEEP.confirm{*Result*}.

The *Result* parameter shall have one of the following values:

0: Success

1: Failure. The requested sleep failed due to internal implementation issues.

2: PHY layer is already in sleep state

B.3.10.4.4.3 Use

The primitive is generated in response to a PLME_SLEEP.request

B.3.10.4.5 PLME_RESUME.request

B.3.10.4.5.1 Function

The PLME_RESUME.request primitive is invoked to request the PHY layer to resume its suspended activities. As a result of this primitive, the PHY layer shall start its normal transmission and reception functions.

B.3.10.4.5.2 Structure

The semantics of this primitive are as follows:

PLME_RESUME.request{}.

B.3.10.4.5.3 Use

This primitive is invoked by upper layer management entities to resume normal PHY layer operations, assuming that the PHY layer is presently in a suspended state as a result of previous PLME_SLEEP.request primitive.

B.3.10.4.6 PLME_RESUME.confirm

B.3.10.4.6.1 Function

The PLME_RESUME.confirm is generated in response to a corresponding PLME_RESUME.request primitive and provides information about the requested resumption status.

B.3.10.4.6.2 Structure

The semantics of this primitive are as follows:

PLME_RESUME.confirm{*Result*}.

The *Result* parameter shall have one of the following values:

0: Success

1: Failure. The requested resume failed due to internal implementation issues.

2: PHY layer is already in fully functional state

B.3.10.4.6.3 Use

The primitive is generated in response to a PLME_RESUME.request

B.3.10.4.7 PLME_TESTMODE.request

B.3.10.4.7.1 Function

The PLME_TESTMODE.request primitive is invoked to enter the PHY layer into test mode (specified by the mode parameter). Specific functional mode out of the various possible modes is provided as an input parameter. Following receipt of this primitive, the PHY layer should complete any pending transmissions in its buffer before entering the requested test mode.

B.3.10.4.7.2 Structure

The semantics of this primitive are as follows:

PLME_TESTMODE.request{*enable*, *mode*, *modulation*, *pwr_level*}.

The *enable* parameter starts or stops the test mode and may take one of two values:

0: stop test mode and return to normal functional state

1: transit from present functional state to test mode

The *mode* parameter enumerates specific functional behaviour to be exhibited while the PHY is in test mode. It may have either of the two values.

0: continuous transmit

1: transmit with 50% duty cycle

The *modulation* parameter specifies which modulation scheme is used during transmissions. It may take any of the following 8 values:

0: DBPSK

1: DQPSK

2: D8PSK

3: Not used

4: DBPSK + convolutional code

5: DQPSK + convolutional code

6: D8PSK + convolutional code

7: Not used

The *pwr_level* parameter specifies the relative level at which the test signal is transmitted. It may take either of the following values:

0: Maximal output level (MOL)

1: MOL –3 dB

2: MOL –6 dB

…

7: MOL –21 dB

B.3.10.4.7.3 Use

This primitive is invoked by management entity when specific tests are required to be performed.

B.3.10.4.8 PLME_TESTMODE.confirm

B.3.10.4.8.1 Function

The PLME_TESTMODE.confirm is generated in response to a corresponding PLME_TESTMODE.request primitive to indicate if transition to Testmode was successful or not.

B.3.10.4.8.2 Structure

The semantics of this primitive are as follows:

PLME_TESTMODE.confirm{*Result*}.

The *Result* parameter shall have one of the following values:

0: Success

1: Failure. Transition to Testmode failed due to internal implementation issues.

2: PHY layer is already in Testmode

B.3.10.4.8.3 Use

The primitive is generated in response to a PLME_TESTMODE.request

B.3.10.4.9 PLME_GET.request

B.3.10.4.9.1 Function

The PLME_GET.request queries information about a given PIB attribute.

B.3.10.4.9.2 Structure

The semantics of this primitive is as follows:

PLME_GET.request{*PIBAttribute*}

The *PIBAttribute* parameter identifies specific attribute as enumerated in Id fields of tables that enumerate PIB attributes.

B.3.10.4.9.3 Use

This primitive is invoked by the management entity to query one of the available PIB attributes.

B.3.10.4.10 PLME_GET.confirm

B.3.10.4.10.1 Function

The PLME_GET.confirm primitive is generated in response to the corresponding PLME_GET.request primitive.

B.3.10.4.10.2 Structure

The semantics of this primitive is as follows:

PLME_GET.confirm{*status*, *PIBAttribute*, *PIBAttributeValue*}

The *status* parameter reports the result of requested information and can have one of the values in Table B.6.

Table B.6 – Values of the status parameter in PLME_GET.confirm primitive

Result	Description
Done = 0	Parameter read successfully
Failed = 1	Parameter read failed due to internal implementation reasons.
BadAttr = 2	Specified PIBAttribute is not supported

The *PIBAttribute* parameter identifies specific attribute as enumerated in Id fields of tables that enumerate PIB attributes.

The *PIBAttributeValue* parameter specifies the value associated with given *PIBAttribute*.

B.3.10.4.10.3 Use

This primitive is generated by PHY layer in response to a PLME_GET.request primitive.

Appendix B-I

PRIME: Examples of CRC

(This appendix does not form an integral part of this Recommendation.)

The table below gives the CRCs calculated for several specified strings.

Table B-I.1 – Examples of CRC calculated for various ASCII strings

String	CRC-8
'T'	0xab
"THE"	0xa0
0x03, 0x73	0x61
0x01, 0x3f	0xa8
"123456789"	0xf4

Annex C

PRIME: EVM calculation

(This annex forms an integral part of this Recommendation.)

C.1 EVM and SNR definition

This PRIME annex describes calculation of the EVM by a reference receiver, assuming accurate synchronization and FFT window placement.

Let

$\{r_k^i; k = 1,2,..,97\}$ denotes the FFT output for symbol i and k are the frequency tones.

$\Delta b_k \in \{0,1,\ldots,M-1\}$ represents the decision on the received information symbol coded in the phase increment.

M = 2, 4, or 8 in the case of DBPSK, DQPSK or D8PSK, respectively.

The EVM definition is then given by;

$$EVM = \frac{\sum_{i=1}^{L} \sum_{k=2}^{97} \left[abs\left(r_k^i - r_{k-1^e}^i - \left(\frac{j2\pi}{M} \right) \Delta b_{\ k} - \right) \right]^2}{\sum_{i=1}^{L} \sum_{k=2}^{97} \left[abs\left(r_k^i \right) \right]^2}$$

In the above, abs(.) refers to the magnitude of a complex number. L is the number of OFDM symbols in the Payload of the most recently received PPDU, over which the EVM is calculated.

The SNR is then defined as the reciprocal of the EVM above.

Appendix C-I

PRIME: Interleaving matrices

(This appendix does not form an integral part of this Recommendation.)

Header interleaving matrix:

12	11	10	9	8	7	6	5	4	3	2	1
24	23	22	21	20	19	18	17	16	15	14	13
36	35	34	33	32	31	30	29	28	27	26	25
48	47	46	45	44	43	42	41	40	39	38	37
60	59	58	57	56	55	54	53	52	51	50	49
72	71	70	69	68	67	66	65	64	63	62	61
84	83	82	81	80	79	78	77	76	75	74	73

DBPSK (FEC ON) interleaving matrix:

12	11	10	9	8	7	6	5	4	3	2	1
24	23	22	21	20	19	18	17	16	15	14	13
36	35	34	33	32	31	30	29	28	27	26	25
48	47	46	45	44	43	42	41	40	39	38	37
60	59	58	57	56	55	54	53	52	51	50	49
72	71	70	69	68	67	66	65	64	63	62	61
84	83	82	81	80	79	78	77	76	75	74	73
96	95	94	93	92	91	90	89	88	87	86	85

DQPSK (FEC ON) interleaving matrix:

12	11	10	9	8	7	6	5	4	3	2	1
24	23	22	21	20	19	18	17	16	15	14	13
36	35	34	33	32	31	30	29	28	27	26	25
48	47	46	45	44	43	42	41	40	39	38	37
60	59	58	57	56	55	54	53	52	51	50	49
72	71	70	69	68	67	66	65	64	63	62	61
84	83	82	81	80	79	78	77	76	75	74	73
96	95	94	93	92	91	90	89	88	87	86	85
108	107	106	105	104	103	102	101	100	99	98	97

120	119	118	117	116	115	114	113	112	111	110	109
132	131	130	129	128	127	126	125	124	123	122	121
144	143	142	141	140	139	138	137	136	135	134	133
156	155	154	153	152	151	150	149	148	147	146	145
168	167	166	165	164	163	162	161	160	159	158	157
180	179	178	177	176	175	174	173	172	171	170	169
192	191	190	189	188	187	186	185	184	183	182	181

D8PSK (FEC ON) interleaving matrix:

18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
36	35	34	33	32	31	30	29	28	27	26	25	24	23	22	21	20	19
54	53	52	51	50	49	48	47	46	45	44	43	42	41	40	39	38	37
72	71	70	69	68	67	66	65	64	63	62	61	60	59	58	57	56	55
90	89	88	87	86	85	84	83	82	81	80	79	78	77	76	75	74	73
108	107	106	105	104	103	102	101	100	99	98	97	96	95	94	93	92	91
126	125	124	123	122	121	120	119	118	117	116	115	114	113	112	111	110	109
144	143	142	141	140	139	138	137	136	135	134	133	132	131	130	129	128	127
162	161	160	159	158	157	156	155	154	153	152	151	150	149	148	147	146	145
180	179	178	177	176	175	174	173	172	171	170	169	168	167	166	165	164	163
198	197	196	195	194	193	192	191	190	189	188	187	186	185	184	183	182	181
216	215	214	213	212	211	210	209	208	207	206	205	204	203	202	201	200	199
234	233	232	231	230	229	228	227	226	225	224	223	222	221	220	219	218	217
252	251	250	249	248	247	246	245	244	243	242	241	240	239	238	237	236	235
270	269	268	267	266	265	264	263	262	261	260	259	258	257	256	255	254	253
288	287	286	285	284	283	282	281	280	279	278	277	276	275	274	273	272	271

Annex D

Mode of operation charging electrical vehicles

(This annex forms an integral part of this Recommendation.)

D.1 General

This annex defines a mode of operation that is intended to provide communications between plug-in electrical vehicles (PEV) and the electrical vehicle supply equipment (EVSE). It defines, in particular, communications over the AC wire and over the pilot wire between the PEV and EVSE. To comply with this annex, the following requirements and characteristics shall be met:

- Capable to operate over the CENELEC or FCC bands;
- Requires mandatory support for the main body of this Recommendation;
- When operating over the pilot wire, it shall be only in point-to-point mode, i.e., two transceivers only are connected to the wire;
- The ITU-T G.9955 device that supports this annex shall be capable of falling back into G3-PLC FCC mode subject to the note below. The method for falling back to G3-PLC FCC is defined in the Fallback Protocol of clause D.2.

NOTE – The inclusion of the fallback to Annex E mode described in this clause is contingent on ISO/IEC 15118 choosing G3-PLC FCC as the solution for V2G (Vehicle to Grid) applications. If ISO/IEC chooses another solution, or specifies multiple solutions, support of the fallback protocol may not be necessary for compliance with this annex. Further, depending on the decision of ISO/IEC 15118, this protocol may be adjusted accordingly.

D.2 Fallback protocol

The fallback protocol defined in this clause is required exclusively for compliance of this annex.

To comply with the fallback mode, the ITU-T G.9955 device shall initialize in G3-PLC FCC mode, as defined in Annex E of this Recommendation. Further, after connection between devices using Annex E is established, a handshake protocol shall be performed between PEV and EVSE nodes to indicate their capabilities of supporting the ITU-T G.9955 main body. If both sides support ITU-T G.9955 main body, both sides may switch to operate as per ITU-T G.9955 main body by request of the EVSE node (which is in control of the fallback protocol). If at least one of the nodes indicates no support of ITU-T G.9955 main body, both nodes shall proceed in G3-PLC FCC mode till the end of the communication session.

Other details of the handshake protocol are for further study.

Annex E

FCC extension to G3-PLC of Annex A

(This annex forms an integral part of this Recommendation.)

E.1 FCC extension to G3-PLC Annex A

E.1.1 System fundamental parameters

E.1.1.1 General description

The G3-PLC original specification supports the portion of CENELEC A band between 35.9 kHz and 90.6 kHz. It specifies an OFDM physical layer with DBPSK and DQPSK modulation schemes. In the original specification, the sampling frequency was chosen to be 400 kHz so it could potentially support the CENELEC B, C and D bands as well. This supplement is intended for FCC band, however, so a sampling rate of 1.2 MHz is chosen.

The data rate is calculated based on the number of symbols per physical layer (PHY) frame (NS); number of subcarrier per symbol (N_{CAR}); and number of parity bits added by FEC blocks. As an example, consider the system in the CENELEC A band working in Robust mode with 40 symbols of data. The total number of bits carried by the whole PHY frame is equal to:

$$\text{Total\_No\_Bits} = N_S \times N_{CAR} = 40 \times 36 = 1440 \text{ bits}$$

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

$$\text{No\_Bits\_Robust} = 1440 \times \text{Robust}_{RATE} = 1440 \times 1/4 = 360 \text{ bits}$$

Considering that a convolutional encoder has a rate equal to 1/2 (CC_{RATE} = 1/2) and that adding CCZerotail = 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 Reed Solomon encoder ($MAXRS_{BYTES}$) must be equal to:

$$MAXRS_{BYTES} = \text{floor}\left((\text{No\_Bits\_Robust} \times CC_{RATE} - \text{CCZerotail})/8\right) = \text{floor}\left((360 \times 1/2 - 6)/8\right) = 21$$

Accounting for eight symbols 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:

$$T_{FRAME} = ((N_S+N_{FCH}) \text{ x } (N_{CP} + N - N_O) + (N_{PRE} \times N))/F_S$$

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 FS is the sampling frequency. Typical values for all these parameters for the Cenelec A band are given in Table E.1.

Table E.1 – System specifications

Number of FFT points	N = 256
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 MHz
Number of symbols in Preamble	N_{pre} = 9.5

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

$$T_{FRAME} = ((40+13) \times (256 + 22) + (9.5 \times 256))/400000 = 0.043 \text{ seconds}$$

Therefore, the data rate is calculated by:

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

E.1.1.2 FCC bandplan

The FCC band supports 10 kHz to 490 kHz. This annex defines operation over a subset of frequencies in the FCC band (154.6875 kHz to 487.5 kHz). DBPSK, DQPSK, and D8PSK modulation schemes are supported, resulting in up to 300 kbit/s data rate in Normal mode of operation. Considering these selections and a subcarrier spacing of 4.6875 kHz, the number of usable subcarriers in the 154.6875 kHz to 487.5 kHz range is 72 and given in Table E.2. This bandplan is referred to as the FCC1 Bandplan.

Table E.2 – Number of subcarriers for the FCC1 bandplan.

Bandplans	Number of subcarriers	First subcarrier (kHz)	Last subcarrier (kHz)
FCC1	72	154.6875	487.5

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 E.3 and E.4.

Table E.3 – 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 16 bytes parity. NOTE 2 – Reed Solomon with 8 bytes parity.				

Table E.4 – Data rate for various modulations (excluding FCH)

FCC Number of symbols	Data rate (bps) D8PSK (Note 1)	Data rate (bps) DQPSK (Note 1)	Data rate (bps) DBPSK (Note 1)	Data rate (bps) 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 16 bytes parity. NOTE 2 – Reed Solomon with 8 bytes parity.				

The data rate can be calculated similar to the CENELEC A case. The frame control header uses 72 bits, resulting in 12 FCH symbols. This can be calculated using:

Number of FCH Symbols = ceiling ((72 × 2 × 6)/72) = 12

Typical values for the parameters for FCC are given in Table E.5.

Table E.5 – System specifications

Number of FFT points	$N = 256$
Number of overlapped samples	$N_O = 8$
Number of cyclic Prefix samples	$N_{CP} = 30$
Number of FCH symbols	$N_{FCH} = 12$
Sampling frequency	$F_s = 1.2$ MHz
Cyclic prefix	30
Number of symbols in Preamble	$N_{pre} = 9.5$

The initial phase values that should be used to generate the preamble and modulate the first symbol of FCH are provided in Table E.6. The bit fields for the frame control header FCH are shown in Table E.7.

Table E.6 – Phase vector definition for FCC1 bandplan

c	ϕ_c	c	ϕ_c	C	ϕ_c	c	ϕ_c
				52	10(π/8)	77	8(π/8)
				53	5(π/8)	78	14(π/8)
				54	0	79	3(π/8)
				55	12(π/8)	80	9(π/8)
				56	6(π/8)	81	15(π/8)
				57	1(π/8)	82	3(π/8)
		33	2(π/8)	58	12(π/8)	83	8(π/8)
		34	(π/8)	59	6(π/8)	84	13(π/8)
		35	(π/8)	60	0	85	π/8
		36	0	61	10(π/8)	86	5(π/8)
		37	0	62	3(π/8)	87	9(π/8)

Table E.6 – Phase vector definition for FCC1 bandplan

c	ϕ_c	c	ϕ_c	C	ϕ_c	c	ϕ_c
		38	15(π/8)	63	13(π/8)	88	13(π/8)
		39	14(π/8)	64	6(π/8)	89	π/8
		40	12(π/8)	65	15(π/8)	90	4(π/8)
		41	11(π/8)	66	7(π/8)	91	7(π/8)
		42	9(π/8)	67	0	92	10(π/8)
		43	7(π/8)	68	8(π/8)	93	13(π/8)
		44	4(π/8)	69	0	94	15(π/8)
		45	π/8	70	8(π/8)	95	π/8
		46	15(π/8)	71	15(π/8)	96	3(π/8)
		47	12(π/8)	72	6(π/8)	97	4(π/8)
		48	9(π/8)	73	14(π/8)	98	5(π/8)
		49	5(π/8)	74	4(π/8)	99	7(π/8)
		50	(π/8)	75	11(π/8)	100	7(π/8)
		51	14(π/8)	76	2(π/8)	101	8(π/8)
						102	9(π/8)
						103	10(π/8)
						104	10(π/8)

Table E.7 – FCH bit fields for FCC1 bandplan

<table>
<tr><th>Field</th><th>Byte</th><th>Bit Number</th><th>Bits</th><th>Definition</th></tr>
<tr><td>PDC</td><td>0</td><td>7 to 0</td><td>8</td><td>Phase detection counter</td></tr>
<tr><td rowspan="5">MOD</td><td rowspan="12">1</td><td rowspan="5">7 to 5</td><td rowspan="5">3</td><td>Modulation type</td></tr>
<tr><td>0: ROBO</td></tr>
<tr><td>1: DBPSK</td></tr>
<tr><td>2: DQPSK</td></tr>
<tr><td>3: D8PSK
4: 16-QAM
5-7: Reserved</td></tr>
<tr><td>Coherent Mode</td><td>4</td><td>1</td><td>0: differential;
1: coherent mode</td></tr>
<tr><td rowspan="6">DT</td><td rowspan="6">3 to 1</td><td rowspan="6">3</td><td>Delimiter type:</td></tr>
<tr><td>000: Start of frame with no response expected</td></tr>
<tr><td>001: Start of frame with response expected</td></tr>
<tr><td>010: Positive acknowledgment (ACK)</td></tr>
<tr><td>011: Negative acknowledgment (NACK)</td></tr>
<tr><td>100-111: Reserved</td></tr>
</table>

Table E.7 – FCH bit fields for FCC1 bandplan

Field	Byte	Bit Number	Bits	Definition
FL		0	1	PHY frame length in PHY symbols
	2	7 to 0	8	
TM[7:0]	3	7 to 0	8	TM[7:0]: Tone map
TM[15:8]	4	7 to 0	8	TM[15:8]: Tone Map
TM[23:16]	5	7 to 0	8	TM[23:16]: Tone Map
Reserved	6	7 to 0	8	Reserved
Reserved	7	7 to 6	2	Reserved
FCCS	7-8 8	5 to 0 7 to 6	6 2	Frame control check sequence (CRC8)
ConvZeros	8	5 to 0	6	Zeros for convolutional encoder
NOTE – All reserved bits in the above table are set to 0.				

E.1.1.2.1 Optional FCC bandplans

In addition to the main FCC band from 154.687 kHz to 487.5 kHz, a node can optionally support the following bandplans:

Table E.8 – Optional FCC bandplans.

	Number of subcarriers	First subcarrier (kHz)	Last subcarrier (kHz)
FCC1.a	24	154.687	262.5
FCC 1.b	40	304.687	487.5

The number of FCH symbols for the above bandplans shall be computed according to the procedure described for the main band. For example, for FCC-1 Bandplan, the number of FCH symbol shall be ceiling((72 × 2 × 6)/24) = 36.

The initial phase values that shall be used to generate the preamble and modulate the first symbol of FCH for the above 4 bandplans are provided in Tables E.9 to E.10.

Table E.9 – Phase vector definition for FCC-1 bandplan

C	ϕ_c	C	ϕ_c	c	ϕ_c
33	2(π/8)	41	12(π/8)	49	9(π/8)
34	1(π/8)	42	6(π/8)	50	14(π/8)
35	0(π/8)	43	15(π/8)	51	1(π/8)
36	14(π/8)	44	8(π/8)	52	4(π/8)
37	12(π/8)	45	0(π/8)	53	6(π/8)
38	10(π/8)	46	7(π/8)	54	8(π/8)
39	6(π/8)	47	14(π/8)	55	9(π/8)
40	1(π/8)	48	4(π/8)	56	10(π/8)

Table E.10 – Phase vector definition for FCC-1.b

c	ϕ_c	c	ϕ_c	c	ϕ_c
65	2(π/8)	79	10(π/8)	93	1(π/8)
66	1(π/8)	80	4(π/8)	94	5(π/8)
67	1(π/8)	81	14(π/8)	95	9(π/8)
68	0(π/8)	82	7(π/8)	96	13(π/8)
69	14(π/8)	83	0(π/8)	97	0(π/8)
70	13(π/8)	84	8(π/8)	98	3(π/8)
71	11(π/8)	85	0(π/8)	99	5(π/8)
72	8(π/8)	86	7(π/8)	100	6(π/8)
73	5(π/8)	87	15(π/8)	101	7(π/8)
74	1(π/8)	88	5(π/8)	102	9(π/8)
75	14(π/8)	89	12(π/8)	103	9(π/8)
76	9(π/8)	90	2(π/8)	104	10(π/8)
77	4(π/8)	91	7(π/8)		
78	15(π/8)	92	13(π/8)		

E.1.1.3 Optional coherent mode

This clause describes the operation of the FCC extension of G3-PLC when operating in the optional Coherent mode. This clause only describes the portions of the standard that are different from the main differential mode described in this annex. Portions of the coherent transmitter that are not described here shall operate exactly as described in this annex where it addresses the differential mode.

E.1.1.3.1 Frame structure

Similar to differential mode, 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 P symbol. The only difference from a P symbol is that the S2 symbol consists of a P 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 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 E.1.1.3.14 on pilot tones.

c) The FCH shall be coherently modulated.

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

E.1.1.3.2 Preamble

The preamble for coherent mode is composed of 8 or (8+4=12) identical P symbols followed by an M symbol that is followed by a half M symbol. The P and M symbols for coherent mode are identical to the ones generated in differential mode. Hence, the only difference between the preamble sequence for coherent and differential is that for coherent mode one S1 followed by one S2 symbols are inserted between the last FCH symbol and the first data symbol. The initial phases used for both modes are shown in Table E.6.

All Coherent mode preamble symbols (P and M and the additional symbols between the last FCH symbol and the first data symbol) shall have the same gain factor compared to data symbols. The gain is defined to be 3 dB.

E.1.1.3.3 Frame control header

The twelve symbols immediately after preamble are reserved for a frame control header (FCH) whose format is identical to the one generated in differential mode. The "Coherent Mode" bit in FCH shall be used to indicate whether the payload is modulated differentially or coherently. The frame control header itself shall be modulated coherently.

E.1.1.3.4 CRC8

An 8-bit cyclic redundancy check (CRC) is used for error detection in 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 FCH. The CRC8 is the remainder of the division of the FCH polynomial by the generator polynomial. The ones complement of the remainder is transmitted starting with the highest-order bits and ending with the lowest order bit.

E.1.1.3.5 Data scrambler

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

E.1.1.3.6 FEC coding

The FEC encoder is composed of a Reed-Solomon encoder followed by a convolutional encoder. In Robust mode, an extra encoder, namely, Repetition Code (RC), is used after the convolutional encoder in order to repeat the bits at the output of convolutional encoder four times.

The FEC encoder for coherent mode shall be identical to the one used for differential mode. In particular, Reed-Solomon encoding, convolutional encoding, and Repetition Coding by 4 and 6 shall all be identical to differential mode.

E.1.1.3.7 Payload padding

The encoded output (both FCH and payload) shall be padded to fit the encoded bits to an integer number of OFDM symbols. The padding is done by appending "0"'s at the end to fit the encoded bits into an integer number of OFDM symbols.

E.1.1.3.8 Interleaver

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).

E.1.1.3.9 Coherent mapping for BPSK, QPSK, 8PSK, 16QAM, and robust modes

The mapping block is responsible for assuring that the transmitted signal conforms to the given Tone Map and Tone Mask. The Tone Map and Mask are concepts of the MAC layer. 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, 8PSK, 16QAM, or Robust) as follows: For a given symbol, instead of using the same carrier, 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 E.6. Both FCH symbols and data symbols use the same phase reference vector.

E.1.1.3.10 Mapping for BPSK and robust modulations

In BPSK (and Robust) modulation a phase shift of 0° represents a binary "0" and a phase shift of 180° represent a binary "1" as illustrated in Table E.11.

Table E.11 – 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.

E.1.1.3.11 Mapping for QPSK modulation

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 E.12.

Table E.12 – 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.

E.1.1.3.12 Mapping for 8PSK modulation

In 8PSK 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 E.13.

Table E.13 – 8PSK encoding table of kth 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.

E.1.1.3.13 Mapping for 16QAM modulation

In 16-QAM modulation, 4 bits are mapped to one of sixteen different constellation points. The mapping is shown in Figure E.1 and Table E.14.

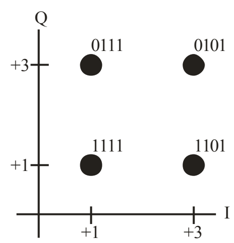


Figure E.1 – 16-QAM constellation diagram

The complete constellation description is given in Table E.14.

Table E.14 – Mapping for 16-QAM

Bits [d_1d_0]	I		Bit [d_3d_2]	Q
00	–3		00	–3
10	–1		10	–1
11	1		11	1
01	3		01	3

E.1.1.3.14 Pilot tones

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.

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

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

Where:

P(i,j) is the relative position of pilot i in symbol j within the set of active sub-carriers. The set of active sub-carriers is enumerated as 0, 1, 2….., M_{ACTIVE}-1

M is the number of sub-carriers per symbol in given band [FCC-1: M=72; FCC-1.a: M=24; FCC-1.b: M=40]

M_{ACTIVE} is the number of active subcarriers ($M_{ACTIVE} \le M$)

FreqSpacing = Frequency spacing between pilots in same symbol [12 for all FCC bands]

i = pilot index = 0,1,2,…,ceil(M_{ACTIVE} /FreqSpacing)-1

j = symbol number = 0,1,2,3,…, N-1

N = total number of data symbols per frame.

OFFSET = X [FCC-1:X = 36; FCC-1.a: X = 0; FCC-1.b: X = 0]

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

$$Pabs(i,j) = STARTINDEX + Q_{ACTIVE}(P(i,j)) \quad \text{(D-2)}$$

Where:

Q= [0, 1, 2,..., M-1] is a vector of the relative indices of the subcarriers of a given band. 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 removing the non-active (i.e., masked) subcarriers. Length(Q_{ACTIVE}) = M_{ACTIVE}

STARTINDEX corresponds to the first subcarrier in the band plan:

STARTINDEX = Y [FCC-1 Y= 33;
FCC-1.a Y=33;
FCC-1.b Y=65]

The pilot tones shall consist of sine waves at the specified tone frequencies modulated in QPSK using the constellation specified. The bits that get mapped to the constellation points shall be generated from a pseudo-random sequence using a linear feedback shift register (LFSR) with the following polynomial:

$$p(x) = x^7 + x^4 + 1$$

as shown in Figure E.2.

The bits in the LFSR shall be initialized to all ones at the start of each PHY frame.

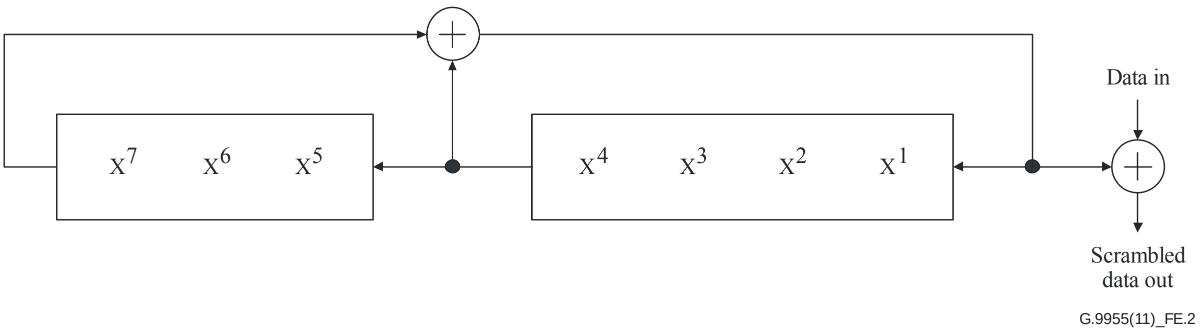


Figure E.2 – LFSR used to generate the data bits that are used to modulate the pilot tones

The LFSR shall only generate bits used for modulating pilots. For every two consecutive output bits from the LFSR, 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.

E.1.1.3.15 Frequency domain pre-emphasis

For further study.

E.1.1.3.16 OFDM generation (IFFT and CP addition)

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

E.1.1.3.17 Windowing

Windowing for coherent mode shall follow the identical procedure used for differential mode.

E.1.1.4 Error vector magnitude limits

For the EVM calculation, the procedure given in clause A.6.5.2 can be used here with the following changes:

1) The number of subcarriers is 72 instead of 36.
2) For the preamble EVM calculation the 6 symbols should be used starting from the third symbol:

   a) $\text{Tot\_En}^{(ref)} = \sum_{i=2}^{7} \text{Avg\_En}_i^{(ref)}$

   b) $Total\_MSE = \sum_{i=2}^{7} MSE_i$

The values of EVM calculated for both data and preamble symbols shall not exceed the values given in Table E.15.

Table E.15 – Maximum allowed EVM values

Modulation	EVM, dB (Note)
1,2, 3 bits	–15
4 bits	–19
NOTE – These EVM requirements shall be met for all applied transmit power levels; however, for 3 and 4 bit modulations, the transmit power levels under which these requirements are met may be lower than those for 1 and 2 bit modulation.	

Annex F

Requirements for frequency bands and electromagnetic disturbances

(This annex forms an integral part of this Recommendation.)

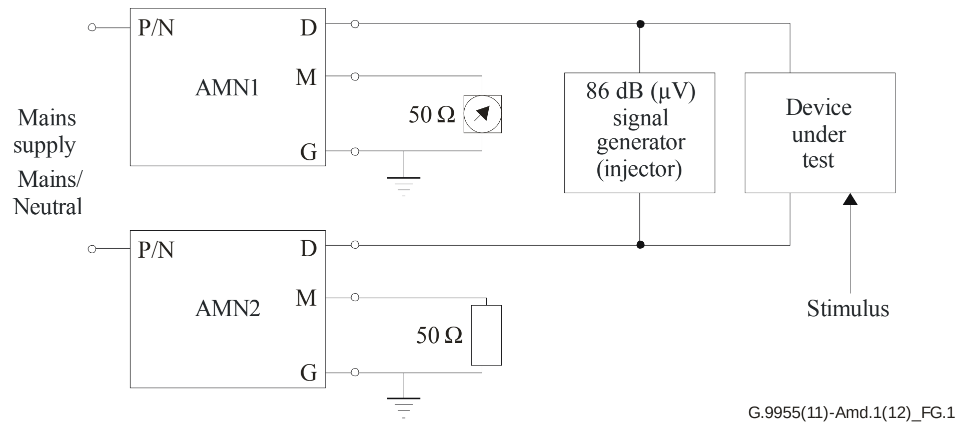
Clauses 6, 7, 8 and 9 of [EN50065-1] shall apply.

Annex G

Method of measurement of the frequency range over which a transmitter device detects a signal from another device in the frequency range 125 kHz to 140 kHz

(This annex forms an integral part of this Recommendation.)

G.1 The layout of the test apparatus is shown in Figure G.1. The artificial mains network shown conforms to clause 11.2 of [CISPR 16-1]. The transmitting device is to be tested at its rated mains supply voltage.



NOTE – AMN1 to AMN2 are artifical mains networks conforming to subclause 11.2 of [CISPR 16-1] (example Figure 5 / 9-148.5 kHz)

Figure G.1 – Measuring arrangements for testing the frequency range of the signal detector

G.2 Tune the measuring receiver to a convenient frequency above 132.5 kHz so that when the transmitting device is activated, transmission is indicated by the measuring receiver, and the measuring receiver does not respond to outputs from the signal generator below 132.5 kHz.

G.3 Set the output voltage of the signal generator so that the signal voltage across the mains terminals of the transmitter is 86 dB (μV), and set the frequency to 132.4 kHz. Attempt to initiate a transmission by the transmitting device in the normal manner. Record whether the measuring receiver is detecting a transmission. There should be no transmission except as allowed by clause 5.3.

G.4 Repeat G.3 while decreasing the signal generator frequency in steps of 200 Hz until transmission is detected. The frequency at which this first occurs shall be less than 131.5 kHz.

G.5 Tune the measuring receiver to a convenient frequency below 132.5 kHz so that when the transmitter is activated, transmission is indicated by the receiver, and the measuring receiver does not respond to outputs from the signal generator above 132.5 kHz.

G.6 Repeat G.3 at 132.6 kHz. Repeat G.4 with increasing frequency steps, recording the first frequency at which transmission resumes. This frequency shall be greater than 133.5 kHz.

Annex H

Method of measurement of the spectral distribution of a transmitting device's signal in the frequency range 125 kHz to 140 kHz

(This annex forms an integral part of this Recommendation.)

Operating conditions are specified in clause 8. For this test:

a) a measuring receiver in accordance with [CISPR 16-1] section 1 and with 200 Hz bandwidth shall be used; and

b) an artificial mains network as described in clause 11.2 of [CISPR 16-1] shall be used.

The measuring receiver output shall be recorded at 200 Hz intervals throughout the range 125 kHz to 140 kHz. It may be necessary to use an accurate frequency source to set up each new frequency. The frequency source should be accurate to ±50 Hz.

For this test, voltages which have a magnitude less than –40 dB relative to the maximum may be ignored.

The weighted sum of the measured voltages across the sub-band shall be at least 30% of the total, according to the following formula:

$$\frac{\sum_{i=125,0}^{140} V_i \, x \, H_i}{\sum_{i=125,0}^{140} V_i} \rangle 0.3$$

where:

V_i is the voltage measured at frequency i kHz and converted to linear units,

$i =$ 125,0, 125,2, …, 140,0, and the values of H_i are given by Table H.1.

Table H.1 – Values of H_i

Frequency (kHz)	H_i (dB)
125.0 to 131.5	Increasing linearly (in dB) with the logarithm of the frequency from –36 to 0
131.5 to 133.5	0
133.5 to 140.0	Decreasing linearly (in dB) with the logarithm of the frequency from 0 to –36

A spectrum analyser may be used for this measurement if it can be shown to give the same result.

Annex J

Methods of measurement (3 kHz to 30 MHz)

(This annex forms an integral part of this Recommendation.)

This annex gives information about the artificial mains network for the measurement of terminal voltages produced by apparatus. All other requirements are given in [CISPR 16-1], section 2.

J.1 Artificial mains network

J.1.1 General

An artificial mains V-network is required to provide a defined impedance at high frequencies across the terminals of the appliance under test. Additional inductors are required to isolate the test circuit from unwanted radio-frequency signals on the supply mains.

J.1.2 Impedances

J.1.2.1 Frequency range 3 kHz to 9 kHz

For the sub-band 3 kHz to 9 kHz an amendment to the network of Figure 23 of [CISPR 16-1] shall be used as shown in Figure F.3.

NOTE – The 0.47 µF capacitor (see Figure F.3) does not have a negligible impedance. Unless otherwise specified it will be necessary to correct the reading of the measuring set for the voltage division caused by this impedance.

J.1.2.2 Frequency range 9 kHz to 30 MHz

The artificial mains V-network shall have an impedance corresponding to a network of (50 Ω//50 µH + 5Ω) or 50 Ω//50 µH as defined in [CISPR 16-1], Figures 7a and 7b.

Attention is drawn to the possible need of a correction factor as detailed in [CISPR 16-1], clause F.2 and Table F.1.

Annex K

Methods of measurement of disturbance power (30 MHz to 1 GHz)

(This annex forms an integral part of this Recommendation.)

NOTE – The application of this method may be limited by physical considerations in some cases.

K.1 General

It is generally considered that for frequencies above 30 MHz the disturbing energy produced by devices is propagated by radiation to the disturbed receiver.

Experience has shown that the disturbing energy is mostly radiated by the portion of the mains lead and other connected leads near the device. It is therefore agreed to define the disturbing capability of a device as the power it could supply to its mains lead and other connected leads. This power is nearly equal to that supplied by the device to a suitable absorbing device placed around any of these leads at the position where the absorbed power is at its maximum.

K.2 Measurement procedure

Measurement is made using an absorbing clamp (consisting of a r.f. transformer followed by absorbing ferrite rings) according to [CISPR 16-2], clause 2.5 with the measuring instrument connected to it. The absorbing clamp is applied successively to all leads whose length is 25 cm or longer, unscreened or screened, which may be connected to the individual unit(s) of the devices under test (e.g., the lead to the mains or to a power supply, signal leads, control leads etc.). On each lead the absorbing clamp is moved a distance of a half wavelength for each frequency of measurement, starting with the clamp positioned so that its transformer is close to the case of the unit. On interconnecting leads between units belonging to the same devices under test two measurements shall be made, the transformer of the clamp facing first one, then the other of the two units at the ends of the lead.

NOTE – An initial measurement could be made with the clamp in a fixed position to find frequencies where the disturbance might be particularly strong.

All leads being 25 cm or longer connected shall during measurement have a length of at least half wavelength at 30 MHz (i.e., 5 m) plus twice the length of the absorbing clamp. The leads should be extended if necessary to fulfil this requirement. However, on an interconnecting lead of original length shorter than a half wavelength at the lower frequencies which at its end is connected to a unit having no other external lead, the movement of the absorbing clamp from this same unit is further restricted to a distance equal to the original length of the lead.

For each lead the maximum measured value which is obtained when the absorbing clamp is moved along the lead the distance specified is to be registered at each frequency. The highest of the maximum values registered for all leads at each frequency, properly calibrated, is taken as the radiated disturbance power of the devices under test.

During measurement the device under test shall be placed at least 0.8 m above the floor on a non-metallic table with the lead having the absorbing clamp attached stretched horizontally straight out from the unit connected to the lead. No metallic object, including a possible other unit of the devices under test, or any person shall be closer to the lead or unit than 0.8 m. Any other lead than that just being measured shall either be disconnected, if mechanically and functionally possible, or fitted with ferrite rings for attenuation of r.f. currents which may affect the measurement results.

Such a lead shall be stretched away from the unit connected in a direction at least 90 ° from the direction of the lead being measured. All connectors not used shall be left unterminated. All connectors having connected leads shall be terminated in a manner representative of use. If the leads are screened and normally terminated in a screened unit, then the termination should be screened.

K.3 Devices having auxiliary apparatus connected at the end of a lead other than the mains Lead

Measurement arrangement

Auxiliary leads normally extendable by the user, for instance leads with a loose end, or leads fitted with a plug or socket on one or both ends shall be extended to a length of about 6 m, this being equal to half a wavelength at 30 MHz plus twice the length of the absorbing clamp; one clamp for measurement and a possible second clamp for additional isolation.

Any plug or socket which will not pass through the absorbing clamp due to its size shall be removed.

Annex L

Attenuation characteristics of measuring instrument above 150 kHz

(This annex forms an integral part of this Recommendation.)

For the measurement of out-of-band signals above 150 kHz a measuring instrument complying with [CISPR 16-1], clause 3 with the following attenuation characteristics shall be used.

Table L.1 – Attenuation of measuring instrument above 150 kHz

Deviation from mid band (kHz)	Attenuation
0	0
4	≤ 6
5	≥ 6
10	≥ 34
20	≥ 81

Annex M

Extremely robust mode

(This annex forms an integral part of this Recommendation.)

This annex specifies procedures and extensions to the main body of this Recommendation required for operation with the extremely robust mode (ERM).

NOTE 1 – The implementation of this annex requires mandatory support for the main body of this Recommendation.

NOTE 2 – This annex may be used in companion to the main body of this Recommendation to support highly robust communication under harsh conditions.

NOTE 3 – implementation of this annex allows operation at the SNR without any need for any special MAC management protocols for synchronizing time or frequency bands between the transmitter and the receiver.

NOTE 4 – One potential application scenario is a channel that includes MV/LV transformer(s), although this annex does not preclude other methods that provide a solution for same or similar application scenarios.

NOTE 5 – This annex specifies a default set of parameters to support ERM. Management procedures required to change the ERM default parameters are for further study.

NOTE 6 – Additional management functions related to the ERM are for further study.

M.1 Use of PFH fields in ERM

The representation of the PFH fields in ERM shall be the same as the main body of this Recommendation, except for the following fields:

1) The value of the duration (FL) field (see clause 7.2.3.2.2) shall be in units of 10 times K_{Dur} OFDM symbols.
2) An extended set of valid values of the Repetitions (REP) field (see clause 7.2.3.2.6) shall be used, as described in Table M.1.

Table M.1 – Extensions to the REP field

REP field value	R parameter of the FRE
101	32
110	64
111	128

M.2 ERM extensions to PMA functionality

1) An extended set of valid values of R defined in Table M.1 shall be supported by FRE. Other values are for further study.
2) The default number of symbols in PFH used in ERM shall be as specified in Table M.2. Other values are for further study.

Table M.2 – Default number of symbols in encoded PFH

Bandplan	Number of symbols, NS_H
CENELEC A	200
CENELEC B	400
CENELEC CD	600
FCC	160
FCC-1	200
FCC-2	210

M.3 ERM extensions of PMD functionality

1) A predefined BAT Type 7 shall be specified for uniform 1-bit loading on all subcarriers except the PMSC and PSC sets.
2) The tone mapping for PFH shall use a uniform loading of 1 bit per subcarrier on all subcarriers except the PMSC set and PSC set (BAT Type 7).
3) The tone mapping for RCM payload transmission in ERM shall use a uniform bit loading of 1 bit per subcarrier (BAT Type 5 or BAT Type 7).

M.3.1 ERM preamble

In ERM a node shall use the ERM preamble defined in this clause.

M.3.1.1 General preamble structure

Table M.3 describes the general preamble structure for ERM.

Table M.3 – Structure of the ERM preamble

Parameter	1st section	2nd section
Number of symbols (N_I)	N_1 (Note 1)	N_2 (Note 3)
Subcarrier spacing	F_{SC}	F_{SC}
Type of symbol (S_I)	S_1 (Note 2)	S_2 (Note 4)
NOTE 1 – The upper and lower limit to the value of N_1 depends on the bandplan. Default upper and lower limit values for N_1 are specified in Table M.4. Other valid upper and lower limit values of N_1 are for further study. The value of N_1 (from its lower limit and up to its upper limit) to be used is determined by the PMD_MGMT.REQ primitive. NOTE 2 – The same symbol S_1 as specified in the main body of this Recommendation is used for ERM. NOTE 3 – The default value of N_2 is 30. Other values of N_2 are for further study. The value of N_2 to be used is determined by the PMD_MGMT.REQ primitive. NOTE 4 – The n-th OFDM S_2 symbol of the 2nd section, in frequency domain shall be: $e^{2\pi j \cdot \varphi_n} \cdot S_3$ where S_3 is a frequency domain QPSK modulated OFDM symbol. S_3 is generated in frequency domain as specified in clause M.3.1.2, and the default phase values of φ_n shall be $\{\varphi_n, n=1,2,...,30\}$=[0, 0, 2, 3, 2, 1, 26, 25, 2, 4, 13, 18, 20, 11, 6, 28, 24, 6, 26, 16, 6, 13, 0, 23, 8, 21, 31, 13, 27, 6] / 32. Other phase values of φ_n are for further study. The φ_n to be used is determined by the PMD_MGMT.REQ primitive.		

Table M.4 – The default upper and lower limit values of N_1 per bandplan

Bandplan	Default lower limit values of N_1	Default upper limit values of N_1
CENELEC A	100	200
CENELEC B	200	400
CENELEC CD	300	600
FCC	50	100
FCC-1	100	200
FCC-2	65	130

M.3.1.2 Frequency-domain preamble symbol generation

The signal S_3 is generated using the same procedure as the signal S_1 (see clause 7.4.5.2.1), where the difference is in the value of the PRBS seed as specified in Table M.5.

Table M.5 – Default seed value of S_3

Bandplan	Default seed value of S_3
CENELEC A	25_{16}
CENELEC B	19_{16}
CENELEC CD	05_{16}
FCC	$4A_{16}$
FCC-1	$6C_{16}$
FCC-2	63_{16}

Other values of the seed are for further study.

M.3.1.3 Time-domain preamble symbol generation

To form a section of a preamble, the output preamble symbol shall be repeated N_I times.

The first and second sections of the preamble shall be windowed, overlapped and added as described below:

First section:

d. The first symbol of the first section is cyclically extended by pre-pending the last β/2 samples of the symbol S_1;

e. The last symbol of the first section is cyclically extended by appending the first β/2 samples of the symbol S_1;

f. The first and last β samples of the extended first section are windowed with a window function $w_\beta(n)$ and $w_\beta(\beta\text{-}n\text{-}1)$ respectively.

Second section:

c. Each $S_2(i)$ symbol of the second section is cyclically extended by pre-pending the last β/2 samples of the symbol $S_2(i)$ and further cyclically extended by appending the first β/2 samples of the symbol $S_2(i)$;

d. The first and last β samples of each $S_2(i)$ symbol of the second section are windowed with a window function $w_\beta(n)$ and $w_\beta(\beta\text{-}n\text{-}1)$ respectively.

Overlap and add:

c. The β windowed samples at the end of the first section and at the beginning of the second section are overlapped and added.

d. The β windowed samples at the end of the first N_2-1 $S_2(i)$ symbols of the second section are overlapped and added with the β windowed samples at the beginning of the next $S_2(i+1)$ symbol of the second section.

e. The β windowed samples at the end of the second section are overlapped and added with the β windowed samples at the beginning of the PFH as described in clause 7.4.4.4.

The window shaping function $w_\beta(n)$ shall comply with the rules specified in clause 7.4.4.4.

Assembling of the OFDM symbols in the ERM preamble is illustrated in Figure M.1.

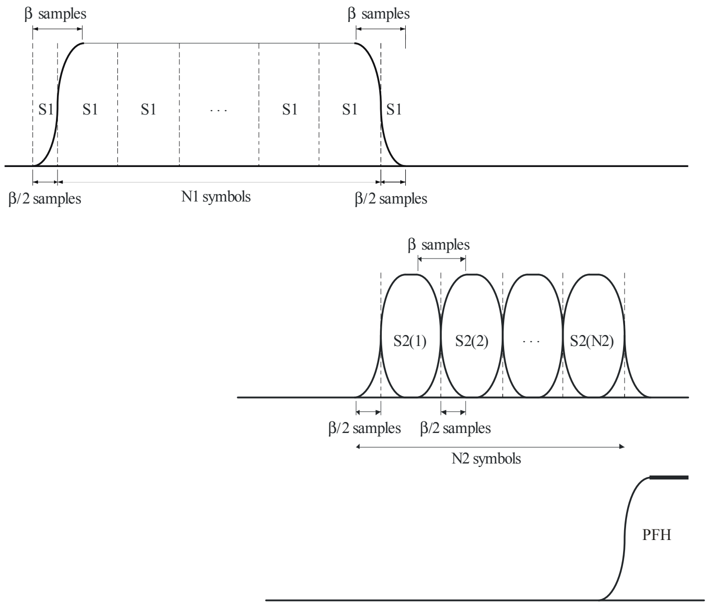


Figure M.1 – Time-domain preamble symbol generation for ERM

The total number N_{pr} of samples in the ERM preamble can be computed as:

$$N_{pr} = \beta + N_1 \times N + N_2 \times N = \beta + N \times (N_1 + N_2)\,.$$

M.3.1.4 CES symbols

In ERM, no CES symbols shall be transmitted.

Appendix I

Design for a single artificial network intended to show the performance of a signalling system

(This appendix does not form an integral part of this Recommendation.)

Measurements on real networks have shown that the two separate artificial mains networks required to be used for compliance testing do not truly represent practical network impedances.

To determine what levels more realistically occur on networks the adaptive network shown in Figure I.1 may be used in conjunction with artificial networks conforming to clause 11.2 of [CISPR 16-1] (example Figure 5).

NOTE – The adaptive network is not for use when testing to the mandatory parts of this standard.

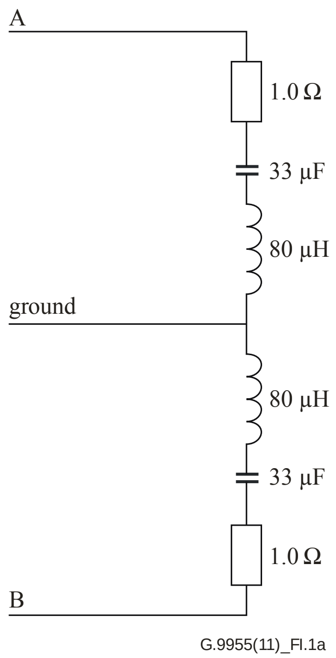
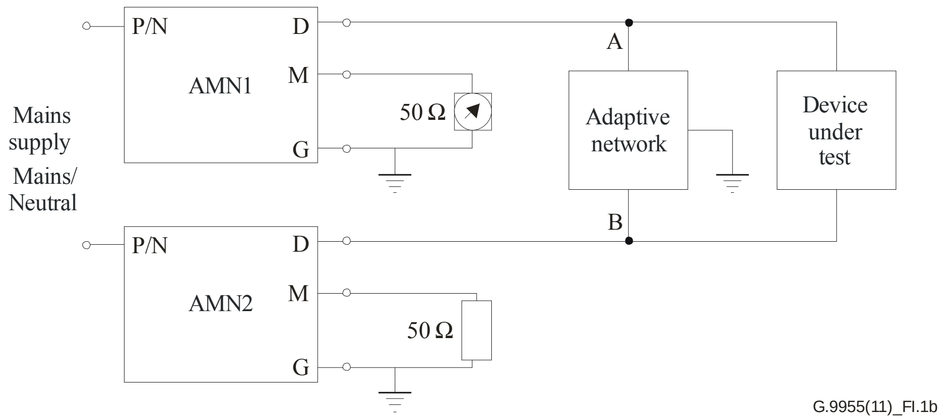


Figure I.1a – The adaptative network for the frequency range 3 kHz-148.5 kHz



NOTE – AMN1 to AMN2 are artifical mains networks conforming to subclause 11.2 of [CISPR 16-1] (example Figure 5 / 9-148.5 kHz)

Figure I.1b – The adaptative network connection with the CISPR 16-1 network

This allows investigative measurement over the complete frequency range 3 kHz-148.5 kHz and presents impedances closer to those found in practice.

Theoretical analysis of impedance is shown in Figure I.2.

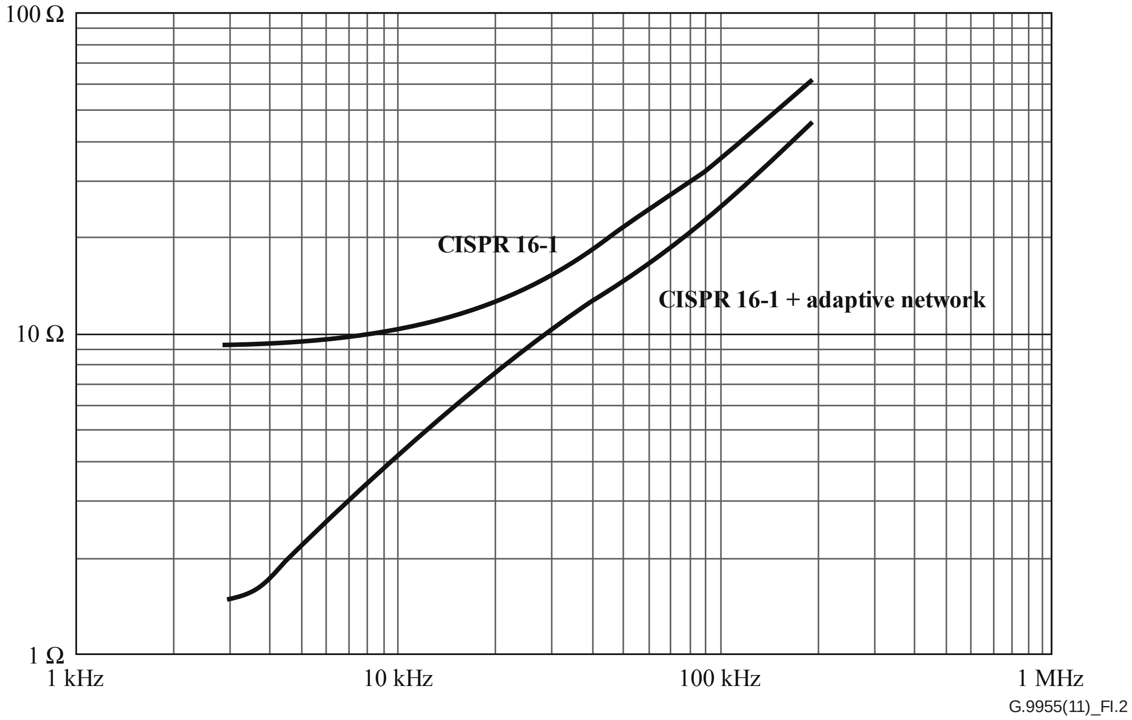


Figure I.2 – The nominal CISPR 16-1 impedance (doubled) and the calculated impedance between points A and B (Figure I.1b) when the adaptative network is added to the CISPR 16-1 network

NOTE 1 – Care shall be taken due to the increased current through the ground wire caused by the connected adaptive network.

NOTE 2 – At the lowest frequencies of the range 3 kHz-148.5 kHz the 0.25 μF capacitor does not have a negligible impedance. It may be necessary to correct the reading of the measuring set for the voltage division caused by this impedance.

Appendix II

Examples and use cases of ITU-T G.9955 network topologies

(This appendix does not form an integral part of this Recommendation.)

II.1 Examples of UAN topologies and deployments scenarios

II.1.1 EM-UAN network deployment examples

The UAN domains addressed by this Recommendation may be established over low voltage (LV) and medium voltage (MV) legs of a power line distribution. The domains established over LV-legs are often associated with a transformer between MV and LV lines (MV-LV transformer). The head-end (domain master) is typically residing at MV-LV transformer and end-nodes are at CPs, connected to the LV line. One example of a service area associated with this type of UAN domain is presented in Figure II.1 and shows a sample of AMI/AMM installation within a neighbourhood. Each black square represents a residence meter, and each residence may potentially also include an EM-HAN.

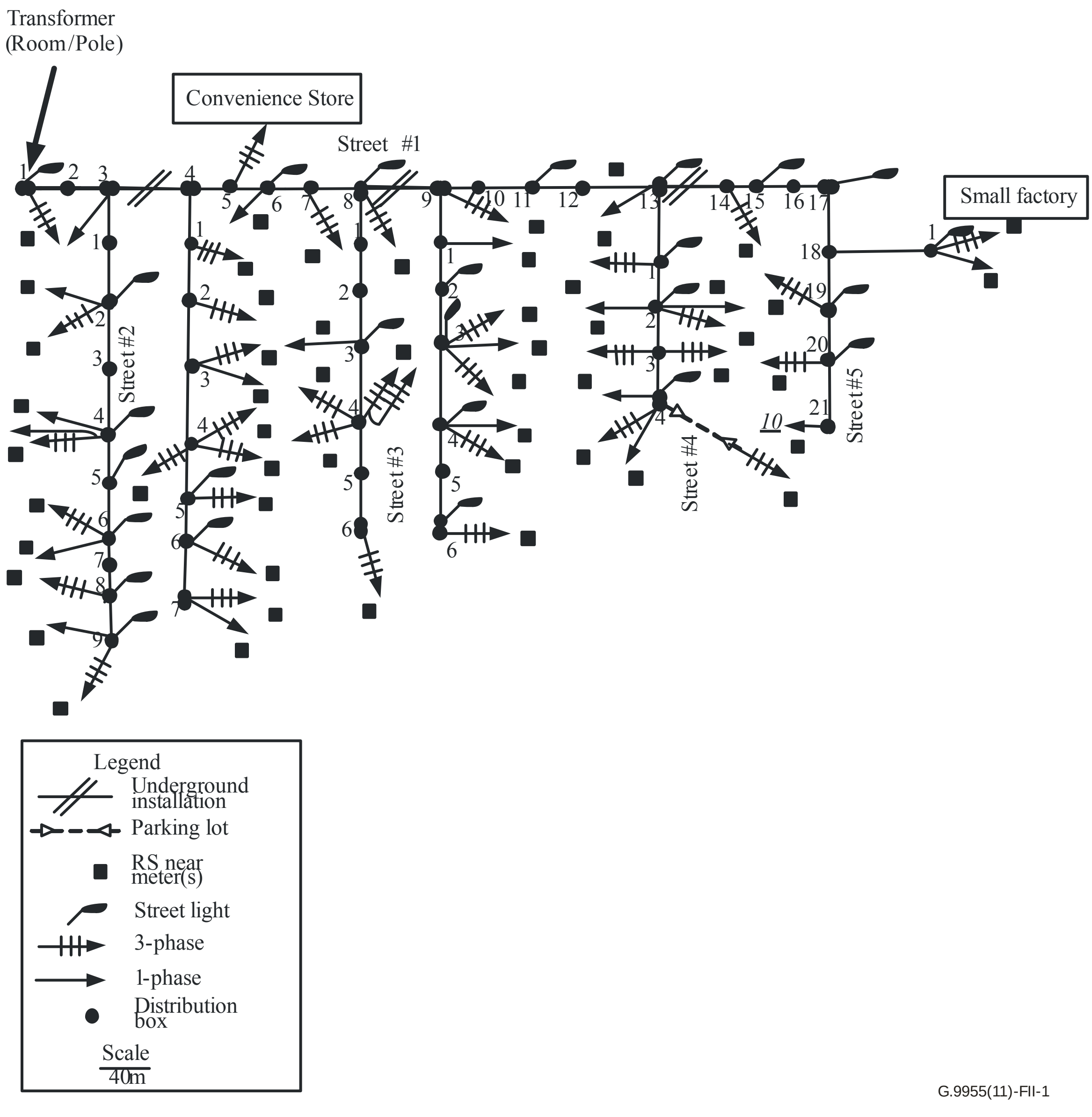
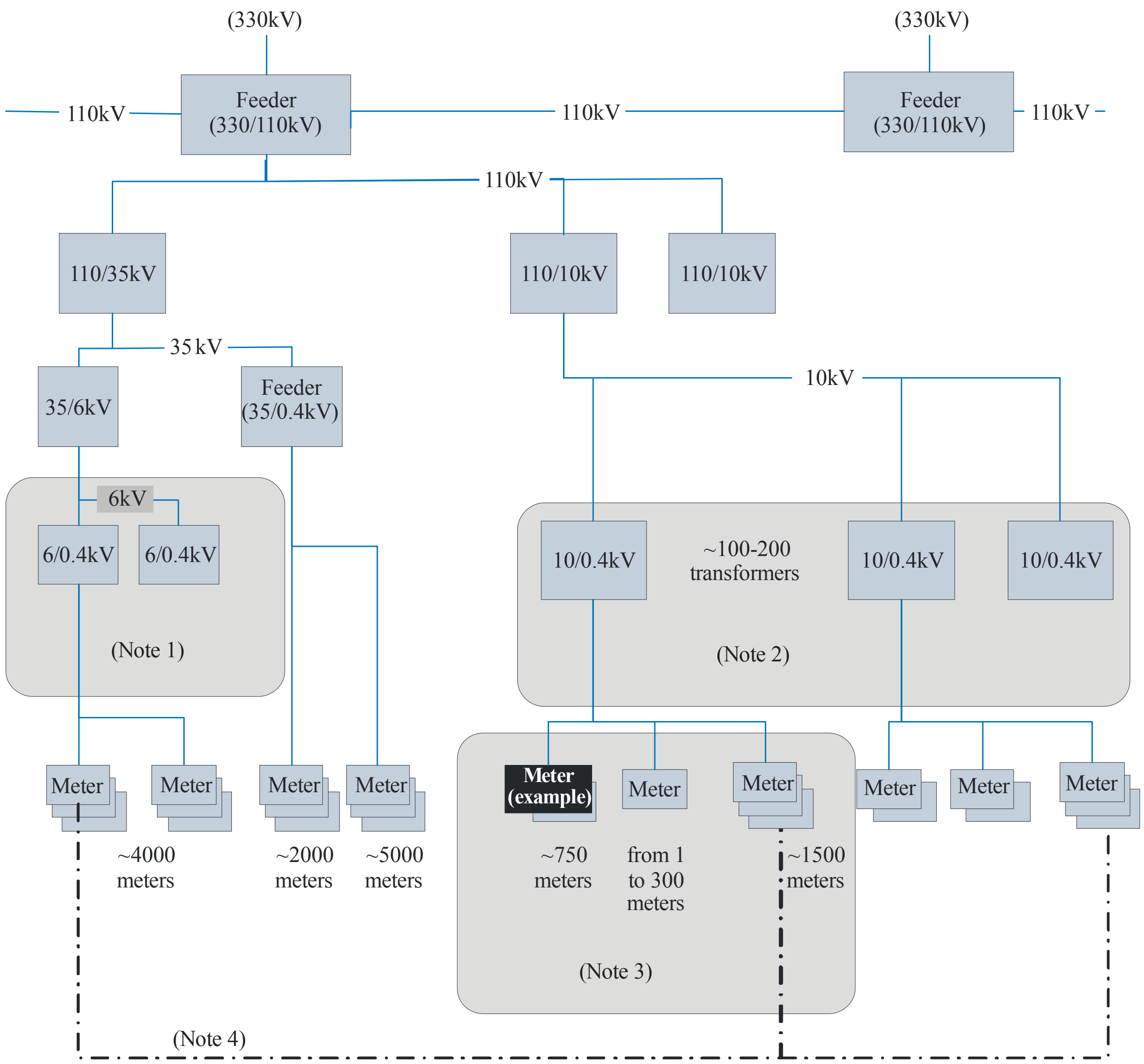


Figure II.1 – Example of neighbourhood AMI/AMM installation diagram

In other network topologies, communications between nodes of the same domain or between different domains may pass through MV-LV transformers (the 35/6 kV, 35/0.4 kV, 10/0.4kV). Communications over high-voltage (HV) lines (110kV) are not expected to be used due to safety reasons, although signals may pass even through MV-HV transformers, though with much lower probability. Overlapping between different parts of the UAN network is expected as shown in Figure II.2.



Note 1 – 80% to 100% of the communication between modems located at the LV-MV 6kV transformer rooms /poles are under the same HV branch.

Note 2 – 80% to 100% of the communication between modems located at the LV-MV 10kV transformer room s/poles are under the same HV branch.

Note 3 – Communication between a selected meter with other meters in physical network is 30%-50% at different times.

Note 4 – 1% of communication between modems is separated by 110kV feeders.

G.9955(11)_FII.2

Figure II.2 – Example of AMI/AMM installation

Another type of UAN domain can be established over MV lines, with its end-nodes residing at MV-LV transformers and bridging this MV domain to the corresponding LV domains. An example model of a UAN network that includes LV domains is presented in Figure II.3. The model includes UAN domains associated with LV lines (called branch domains, in Figure II.3) and UAN domains connecting branch domains to the utility head-end (called core domains in Figure II.3).

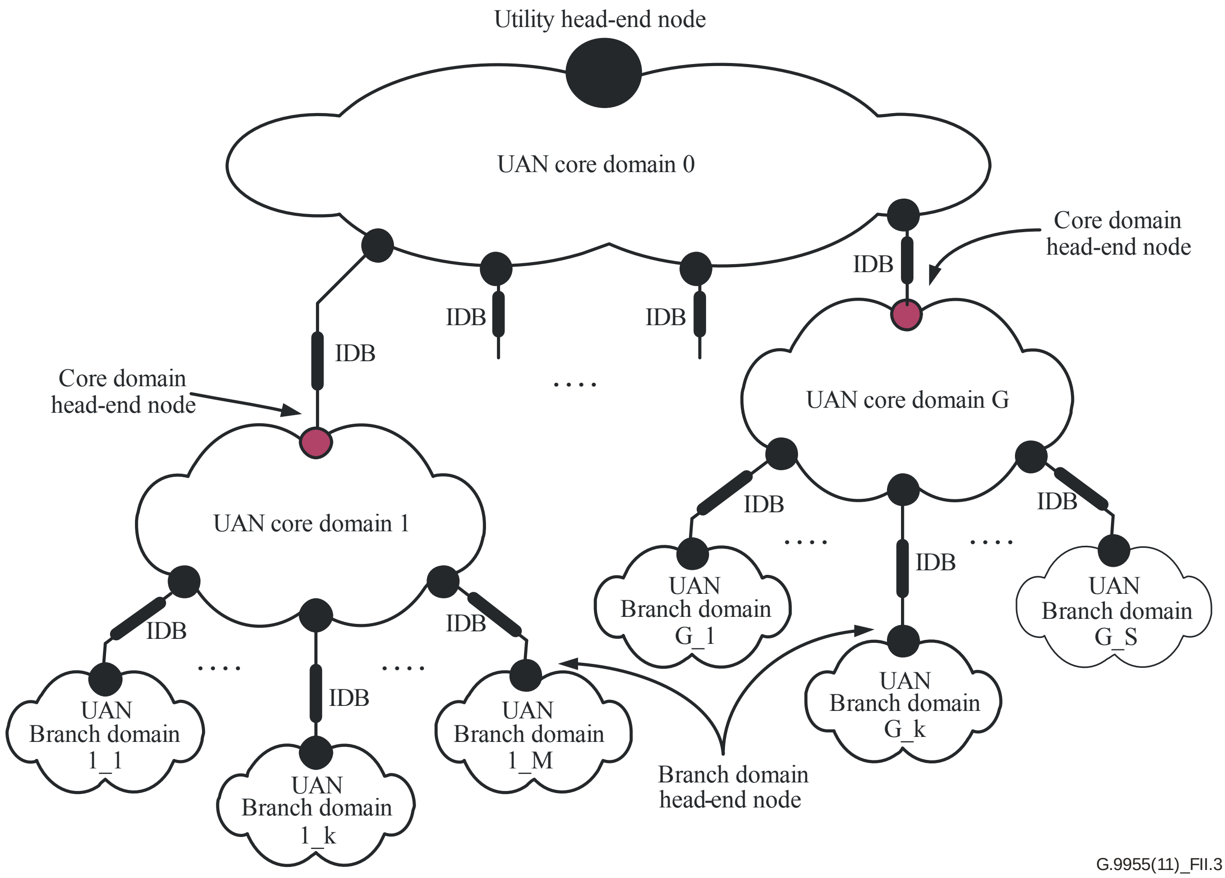


Figure II.3 – Example of UAN with multiple domains

SERIES OF ITU-T RECOMMENDATIONS

Series A	Organization of the work of ITU-T
Series D	General tariff principles
Series E	Overall network operation, telephone service, service operation and human factors
Series F	Non-telephone telecommunication services
Series G	**Transmission systems and media, digital systems and networks**
Series H	Audiovisual and multimedia systems
Series I	Integrated services digital network
Series J	Cable networks and transmission of television, sound programme and other multimedia signals
Series K	Protection against interference
Series L	Construction, installation and protection of cables and other elements of outside plant
Series M	Telecommunication management, including TMN and network maintenance
Series N	Maintenance: international sound programme and television transmission circuits
Series O	Specifications of measuring equipment
Series P	Terminals and subjective and objective assessment methods
Series Q	Switching and signalling
Series R	Telegraph transmission
Series S	Telegraph services terminal equipment
Series T	Terminals for telematic services
Series U	Telegraph switching
Series V	Data communication over the telephone network
Series X	Data networks, open system communications and security
Series Y	Global information infrastructure, Internet protocol aspects and next-generation networks
Series Z	Languages and general software aspects for telecommunication systems

Printed in Switzerland
Geneva, 2014