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Access networks – In premises networks

Unified high-speed wire-line based home networking transceivers - Foundation

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ITU-T Recommendation G.9960

Unified high-speed wire-line based home networking transceivers - Foundation

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ITU-T Draft Recommendation G.9960

Unified high-speed wire-line based home networking transceivers – Foundation[1]

Summary

This Foundation Recommendation specifies basic characteristics of unified high-speed home networking transceivers capable of operating over premises wiring including inside telephone wiring, coaxial cable, and power-line wiring, and combinations of these, with modulation parameters for data rates up to 1 gigabit/second. The specification includes a description of the home network architecture and reference models along with major aspects of the transceiver physical layer specification. A future version of this Recommendation will include the data link layer and regional Annexes to complete the transceiver specification.

Keywords

<Optional>

1 France Telecom Orange is concerned that the migration from existing powerline implementations has not yet been adequately addressed and proposes that the industry delays implementation until this is included. In fact, this Recommendation will deeply fragment the industry for many years and create significant interference problems for service providers
and users since devices based on this Recommendation could be deployed on the same medium where others solutions have been already deployed.

SPiDCOM Technologies is concerned that the migration from existing powerline implementations has not yet been adequately addressed and proposes that the industry delays implementation until this is included.
In fact, this Recommendation will deeply fragment the industry for many years and create significant interference problems for service providers and users since devices based on this Recommendation could be deployed on the same medium where others solutions have been already deployed.

Intellon Corporation has serious concerns about the performance of the specification and lack of interoperability with widely deployed technologies. The specification also does not address the migration from existing powerline implementations that would result in deep industry fragmentation for many years. Inferior performance compared to the deployed technologies would also risk the success of specification.

STMicroelectronics is concerned that this Recommendation can cause interoperability problems to system integrators and service providers that will have to share media contents with already installed appliances based on existing solutions. Moreover, the presence of devices based on this Recommendation on the same medium with already deployed devices could cause interference problems and reduce the overall network performance.

Entropic Communications is concerned that this Recommendation unnecessarily specifies transmissions at ~15dB higher average power levels than state-of-the art home network services already widely deployed over coax. By imposing protocols derived from powerline environments, unnecessarily requiring that each node must receive every transmission regardless of whether the transmission is destined for that node or not, this Recommendation fails to adequately optimize for the coax medium. These unnecessarily high transmission levels will interfere, and thus fail to coexist, with other services on the widely-shared medium.

Furthermore, this Recommendation fails to specify any compatibility with incumbent wireline home networks. By deliberately specifying such incompatibility, this Recommendation:

a) disadvantages pioneering home network companies that have developed advanced non-proprietary high-speed home networking solutions;
b) disadvantages network operator/service providers that have invested hundreds of millions of dollars on widespread commercial deployments; and,
c) disadvantages tens of millions of consumers that already have these home network solutions deployed in their homes.

Consequently, this Recommendation does not offer any benefit for consumers or network operator/service providers over already widely-deployed (and over soon-to-be-deployed next-generation) home networks.

Introduction

This Foundation Recommendation specifies basic characteristics of home networking transceivers capable of operating over premises wiring including inside telephone wiring, coaxial cable, and power-line wiring, and combinations of these. A future version of this Recommendation may specify characteristics of transceivers operating over category 5 cables. The transceivers defined by this specification provide the data rate and quality of service necessary for triple-play residential services as well as business-type services delivered over xDSL, PON, or other access technology. The transceivers use OFDM type modulation and are designed to provide EMC and spectral compatibility between home networking transmission and VDSL2 or other types of DSL used to access the home.

1 Scope

This Foundation Recommendation specifies basic characteristics of home network transceivers designed for the transmission of data over premises wiring including inside telephone wiring, coaxial cable, and power-line wiring, and combinations of these.

Specifically, this Recommendation defines:

- the home network architecture and reference models;
- major aspects of the physical layer specification (PCS, PMA and PMD), including PSD limit masks;

These devices are intended to be compatible with other devices sharing the in-premises wiring.

Additionally, the Recommendation provides for spectrum notching for compatibility with Amateur radio services.

A future version of this Recommendation will specify the data link layer, including APC, LLC and MAC.

A future version of this Recommendation may specify characteristics of transceivers operating over category 5 cables.

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.

[1] ITU-T Recommendation X.1035 (2007), *Password-authenticated key exchange (PAK) protocol*
[2] 802.1D-2004, *IEEE Standard for Local and metropolitan area networks: Media Access Control (MAC) Bridges*

[3] FIPS PUB 197 (2001), *Advanced encryption standard (AES)*

[4] NIST-SP800-38C (2004), *Recommendation for block cipher modes of operation: the CCM mode for authentication and confidentiality*

3 Definitions

This Recommendation defines the following terms:

Address association Table (AAT): a table that associates MAC addresses of the application entities with the DEVICE_ID of the nodes through which these application entities can be reached.

Alien domain: any group of non-G.9960 nodes connected to the same medium or operating in a close proximity. The bridging function to an alien domain, as well as coordination with an alien domain to avoid mutual interference is beyond the scope of G.9960.

Bandplan: a specific range of the frequency spectrum that is associated with only one domain. Multiple bandplans may be used in the same domain provided that any bandplan is either a subset or a superset of all other bandplans in the same domain. The bandplan is defined by a lower frequency and upper frequency except for RF, which is defined by a bandwidth and center frequency. A description of the procedures allowing nodes using different but overlapping bandplans to join the same domain and communicate is for further study.

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 7-29).

Bridge to alien domain/network: an application device implementing an L2 or L3 bridging function to interconnect a G.9960 domain to an alien domain (or alien network). Bridging to alien domains/networks is beyond the scope of G.9960.

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.

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 analyzing 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).

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.

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

Crosstalk: disturbance (including frame collision) introduced by or due to operation of alien networks or other (independent) G.9960 home networks.

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 or preamble.

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.

DEVICE_ID: a unique identifier allocated to a node operating in the home network by the domain master during registration.

Domain: a part of a G.9960 home network comprising the domain master and all those nodes that are registered with the same domain master. In the context of this Recommendation, use of the term 'domain' without a qualifier means 'G.9960 domain', and use of the term 'alien domain' means 'non-G.9960 domain'. Additional qualifiers (e.g., 'power-line') may be added to either 'domain' or 'alien domain'.

Domain access point (DAP): The unique node in centralized mode (CM) that supports relay functionality through which all nodes communicate.

Domain ID: a unique identifier of a domain.

Domain master (DM): a node supporting the domain master functionality thatmanages (coordinates) all other nodes of the same domain (i.e., assign bandwidth resources and manage priorities). Only one active domain master is allowed in a domain, and all nodes within a domain are managed (coordinated) by a single domain master. If a domain master fails, another node of the same domain, capable of operating as a domain master, should pick up the function of the domain master.

Flow: a uni-directional stream of data between two nodes related to a specific application and/or characterized by a set of QoS requirements.

Flow ID: an identifier allocated to a flow for which parameterized QoS is used for traffic delivery. Flow IDs are assigned by and are unique to nodes that originate flows.

Global master (GM): a function that provides coordination between different domains (such as communication resources, priority setting, policies of domain masters, and crosstalk mitigation). A GM may also convey management functions initiated by the remote management system (e.g. TR-69) to support broadband access. Detailed specification and use of this function is for further study.

Guard interval: 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.

Hidden node: a node that can't communicate directly with some other nodes within a domain.

NOTE – A hidden node may be able to communicate with another node or with a domain master using a relay node. A node that is hidden from a domain master uses a relay node as a proxy to communicate with the domain master.

Home 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. A home network consists of one or more domains. In the context of this Recommendation, use of the term 'home network' means 'G.9960 home network'. Use of the term 'alien home network' means 'non-G.9960 home network'. Use of the term 'network' without a qualifier means any combination of 'G.9960 home network', 'non-G.9960 home network' and 'access network'. Use of the term 'alien network' means any combination of 'non-G.9960 home network' and 'access network'.

Inter-domain bridge: a bridging function above the physical layer to interconnect nodes of two different domains.

Jitter: a measure of the latency variation above and below of the mean latency value. The maximum jitter is defined as the maximum latency variation above and below the mean latency value.

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 set for a specific flow, retransmission time is a part of latency for the protocol reference points above MAC.

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.

Management overhead: a part of the overhead used for management purposes (such as home network discovery, channel estimation, acknowledge, establishing and tearing down the flow).

Medium: a wire-line facility, of a single wire class, 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).

Multicast: a type of communication when a node sends the same frame simultaneously to one or more other nodes in the home network.

Net data rate: the data rate available at the A-interface of the transceiver reference model.

Node: any network device that contains a G.9960 transceiver. In the context of this Recommendation, use of the term 'node' without a qualifier means 'G.9960 node', and use of the term 'alien node' means 'non-G.9960 node'. Additional qualifiers (e.g., 'relay') may be added to either 'node' or 'alien node'.

Operational modes of a domain:

- peer-to-peer mode (PM): a mode of domain operation in which all nodes use only P2P with other nodes (without relay nodes). In peer-to-peer mode, no relay nodes are allowed.

- centralized mode (CM): a mode of domain operation in which all nodes use REL with a single relay node. In centralized mode, only one relay node is allowed and it is known as the domain access point (DAP).

NOTE – A DAP is likely to serve also as a domain master

- unified mode (UM): a mode of domain operation in which all nodes within a domain communicate using P2P or REL, as necessary, while some of the relay nodes may have additional functionalities. Unified mode can be used to support hidden nodes. In unified mode, more than one relay node is allowed.

NOTE – In UM, there is no domain access point defined.

Passband: 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 7-29).

Peer-to-peer communication (P2P): a type of communication within a domain in which direct signal traffic is established between nodes with no relay nodes.

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.

Primitives: basic measures of quantities obtained locally or reported by other nodes of the domain. Performance primitives are basic measurements of performance-related quantities, categorized as events, anomalies and defects. Primitives may also be basic measures of other quantities (e.g., ac or battery power).

Priority: a value assigned to the specific frame(s) that determines the relative importance of transmitting frame(s) during the upcoming opportunity to use the medium.

Quality of service (QoS): a set of quality requirements on the communications in the home network. Support of QoS refers to mechanisms that can provide different priority to different flows, or can guarantee a measurable level of performance to a flow based on a set of QoS parameters.

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.

Registration: the process used by a node to join the domain. Specification of the process is for further study.

Relayed communication (REL): a type of communication within a domain in which a node can communicate with other nodes through a relay node. The relay node receives a signal from a node and forwards it to the addressee nodes.

Relay node: a node supporting relay functionality that acts as an intermediary node, through which other nodes of the same domain can pass their signal traffic (data, control, or management).

Residential Gateway: a device providing, among other functions, bridging between the access network and the home network. Residential gateways are beyond the scope of G.9960.

RF: a frequency band defined by an up-convert frequency $F_{UC} > 0$ and a center frequency $F_C = F_{UC} + F_{US} >> F_{SC}\times N/2$ (see Tables 7-28, 7-29).

Stopband: the portion of the frequency spectrum that is not allowed for transmission.

Sub-carrier (OFDM sub-carrier): the center frequency of each OFDM sub-channel onto which bits may be modulated for transmission over the sub-channel.

Sub-carrier spacing: the difference between frequencies of any two adjacent OFDM sub-carriers.

Sub-channel (OFDM sub-channel): a fundamental element of OFDM modulation technology. The OFDM modulator partitions the channel bandwidth into a set of parallel sub-channels.

Symbol (OFDM symbol): a fixed time-unit of an OFDM signal carrying one or more bits of data. An OFDM symbol consists of multiple sine-wave signals or sub-carriers, each modulated by certain number of data bits and transmitted during the fixed time called symbol period.

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.

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.

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.

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).

Unicast: a type of communication when a node sends the frame to another single node.

Wire class: one of the classes of wire, having the same general characteristics: coaxial cable, home electrical-power wire, phone-line wire and Category 5 cable.

4 Abbreviations

This Recommendation uses the following abbreviations:

ADP	application data primitives
AE	application entity
APC	application protocol convergence
BAT	bit allocation table
CB	coax baseband
CM	centralized mode
CRF	coax radio frequency
DAP	domain access point
DLL	data link layer
DM	domain master
DSL	digital subscriber line
GM	global master
IDB	inter-domain bridge
ISI	inter-symbol interference
LDPC-BC	low-density parity-check block-codes
LLC	logical link control
MAC	medium access control
MAP	medium access plan
MDI	medium-dependent interface
OFDM	orthogonal frequency division multiplexing
P2P	peer-to-peer communication
PB	power-line baseband
PCS	physical coding sub-layer
PM	peer-to-peer mode
PMI	physical medium-independent interface
PMA	physical medium attachment
PMD	physical medium dependent
PON	passive optical network
PP	power-line passband
PSD	power spectral density
QC-LDPC-BC	Quasi-cyclic low-density parity-check block-code

QoS	quality of service
REL	Relayed communication
RG	residential gateway
UM	unified mode

5 Home network architecture and reference models

5.1 Home network architecture and topology

An architectural model of the home network is presented in Figure 5-1. The model includes one or more domains, inter-domain bridges, and bridges to alien domains such as a WiFi or Ethernet home network, or a DSL or PON access network. The global master function coordinates resources such as bandwidth reservations, flow priorities, and operational characteristics between domains, and may convey the relevant functions initiated by a remote management system (e.g., Broadband Forum TR-069 [V.1]) to support broadband access. Detailed specification and use of the global master function is for further study. The specification of bridges to alien domains and to the access network is beyond the scope of G.9960.

NOTE 1 − It is not necessary that all inter-domain bridges presented in Figure 5-1 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 – It is possible to install multiple G.9960 home networks (i.e., not connected by inter-domain bridges) per dwelling.

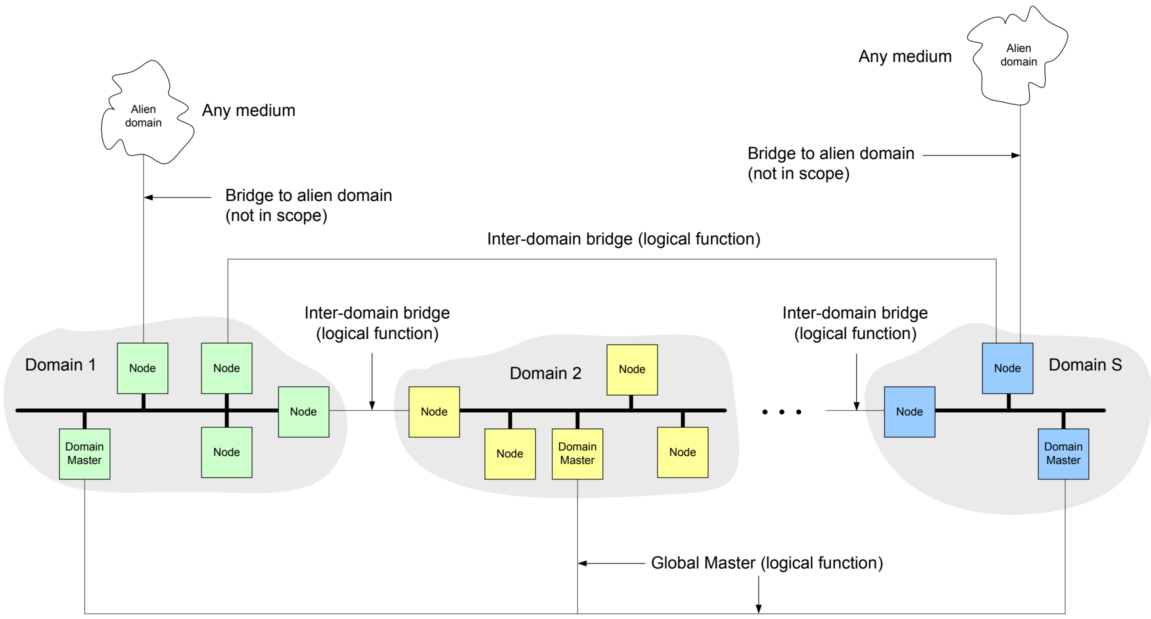

Figure 5-1/G.9960 – Home network architecture reference model

A domain contains nodes connected to the same medium, where one node is acting as a domain master. Nodes of the same domain communicate via the medium over which the domain is established. Nodes connected to different domains communicate via inter-domain bridges (e.g. L2 or L3 bridging, see §5.1.6).

A domain shall be capable of supporting at least 32 registered nodes and may optionally support up to 250 registered nodes. Each node shall be capable of supporting simultaneous communication sessions with at least 8 other nodes using dedicated sets of transmission parameters (e.g., runtime BATs), different from the pre-defined BATs described in §7.1.4.2.2.1.

The scope of G.9960 is limited to transceivers of all nodes capable of operating either with extended capabilities (e.g., domain master, domain access point (DAP), relay node, or combinations thereof) or without extended capabilities in any domain. Other parts of G.9960, including inter-domain bridges, RG (as a bridge to the access network), and bridges to alien domains, are beyond the scope of G.9960; however G.9960 defines all necessary means to support their functionality and the exchange of relevant information.

The domain master considers bridges to alien domains as AEs of a node with certain requirements, while it considers inter-domain bridges as AEs of nodes whose interfaces (see §5.1.6) comply with this Recommendation.

5.1.1 Domains

5.1.1.1 General rules of operation

A domain as depicted in Figure 5-1 may include nodes with a range of capabilities including extended capabilities such as relay, domain master, and DAP functionality.

The function of the domain master is to assign and coordinate resources (bandwidth and priorities) of all nodes in its domain. The following rules apply for any domain:

1. There shall be one and only one active domain master per domain. In case an active domain master is not assigned, fails, or is switched off, a domain master selection procedure is initiated to assign a new active domain master. This procedure is for further study.
2. Nodes of the same home network that can communicate with each other directly at the physical layer (except crosstalk between closely routed wires) shall be assigned to the same domain.
3. All nodes within a domain shall support P2P and REL (REL is considered as a subset of P2P, where the first destination address for the node is a relay node). For both P2P and REL , bandwidth resources and priorities of all nodes within the domain are managed by the domain master.
4. More than one domain may be established over the same medium, for example, by using orthogonal signals over different frequency bands.
5. A home network may include one or more domains.
6. Domains from independent home networks established over the same medium may interfere with each other (e.g., if they use the same frequency band). Coordination between domains of independent home networks sharing a common medium is for further study.
7. Nodes are not required to be domain master capable. That is, some nodes may not support the functionality necessary to become a domain master.
8. All nodes in a domain shall be managed by a single domain master.
9. The home network shall have a unique name. All domains of the same home network shall use this name.
10. The domain master shall assign a DEVICE_ID to a node during the node's registration process.
11. All nodes within the same domain shall use the same domain ID.
12. A node shall keep track of the domain where it associates and shall discard frames received in MSG type PHY frames from domains other than its own. These frames can be distinguished by

examination of the DOD field in the PHY frame headers that are transmitted for these types of frames.

13. A node is required to report the existing of neighboring domains to its domain master when it receives one or more PHY frame headers containing a DOD value other than the one used in its domain.
14. The domain ID shall be used to identify a specific domain.

NOTE – The method of determining a domain ID for assignment is for further study.

5.1.1.2 Modes of operation

A domain can operate in one of 3 modes: peer-to-peer mode (PM), centralized mode (CM), or unified mode (UM). Different domains within the home network can use different modes of operation, i.e., PM, CM, or UM. Examples of domains in different operational modes are presented in Appendix I.

Broadcast and multicast shall be supported in any domain, independent of its operational mode (PM, CM or UM).

In PM, only P2P shall be used in the domain. Thus, direct signal traffic is established between two communicating nodes. Figure 5-2 shows the use of P2P between nodes A and B. Frames addressed to nodes outside the domain are sent to the node associated with the inter-domain bridge (node C in Figure 5-2).

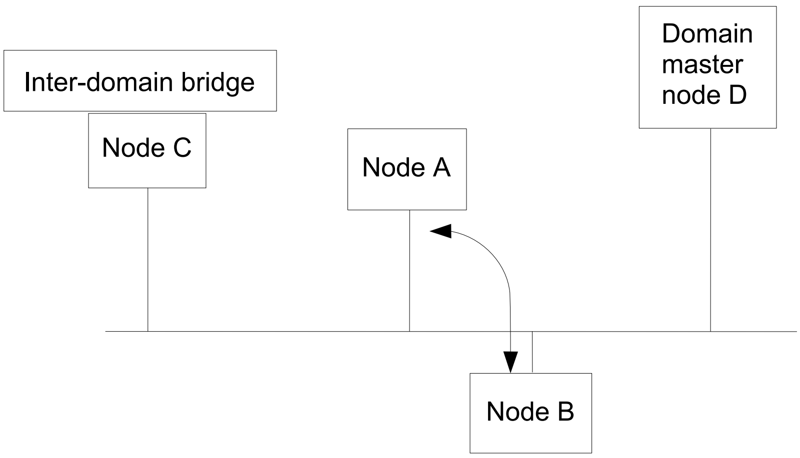

Figure 5-2/G.9960 – Domain operating in peer-to-peer mode (PM)

In CM, only REL shall be used. Thus, any node of the domain can communicate with another node only through the DAP. The DAP receives signals from all nodes of the domain and further forwards them to the corresponding addressee nodes. Frames addressed to nodes outside the domain are forwarded by the DAP to the node associated with the inter-domain bridge (node C in Figure 5-3). Usually, but not necessarily, the DAP also serves as a domain master (Figure 5-3).

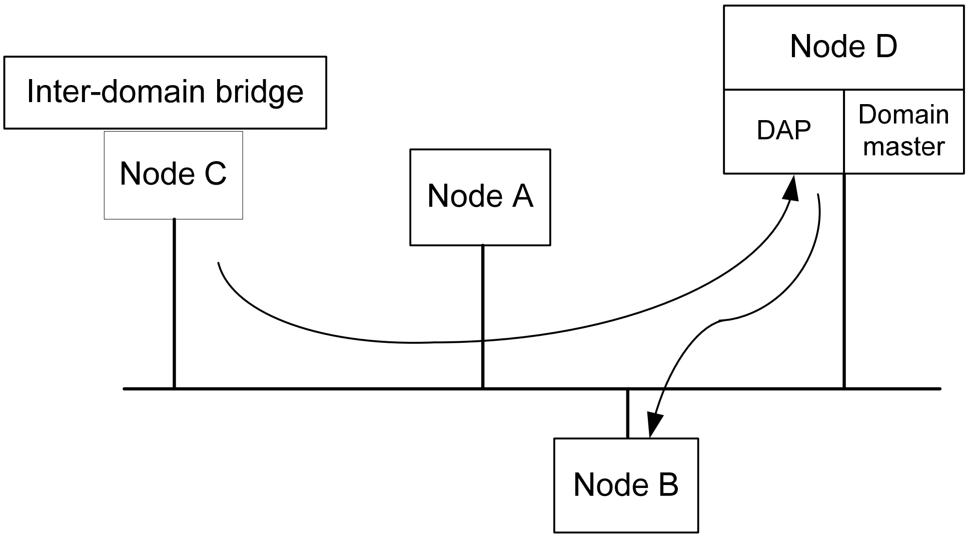

Figure 5-3/G.9960 − Domain operating in centralized mode (CM)

In case of DAP failure, no communication between nodes in the domain is allowed.

In UM, a hidden node in a domain can communicate with another node through a relay node as shown in Figure 5-4. In the example, two nodes within the same domain (node C and node H) that are hidden from each other communicate with each other via the relay node (node A). Both nodes are managed by the domain master (node D) and can communicate directly with all other nodes. Frames addressed to nodes outside the domain are sent to the node associated with the inter-domain bridge (node C in Figure 5-4).

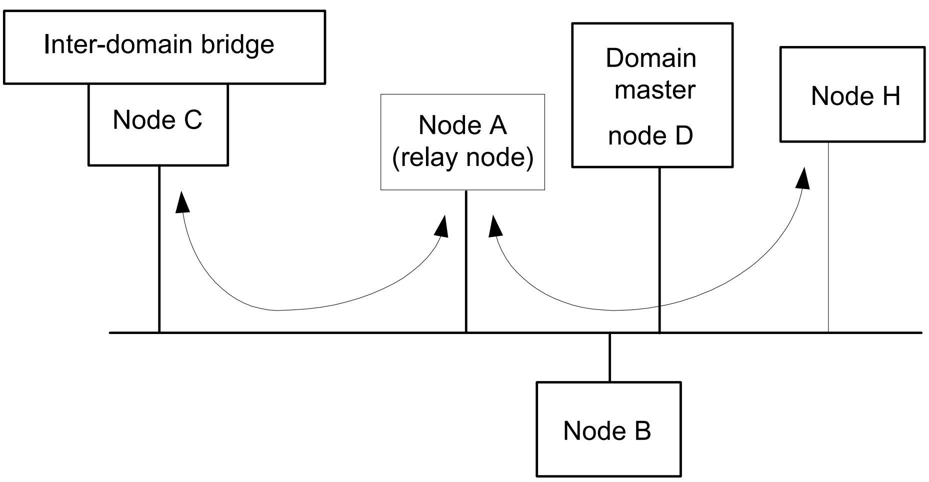

Figure 5-4/G.9960 − A domain operating in unified mode (UM) containing hidden nodes

5.1.1.3 Relationship between domain and medium

Figure 5-5 shows several examples of the relationships between domain, medium and wire class. Note that in Figure 5-5, each of the domains is shown to be associated with a single medium. This represents the focus of G.9960; domains optimized to operate on a single wire class with multiple domains interconnected via inter-domain bridges. Figure 5-5 (A) shows an example segment of a home network comprising three different media: coax, phone line and power line. A single domain exists on each medium and the domains are separated by inter-domain bridges. Figure 5-5 (B) shows another example segment of a home network comprising phone-line and power-line mediums. In this case, the phone-line medium comprises two segments of phone wire that are joined by splicing or at a connector. These two phone-line segments are of a single wire class and therefore are a single medium. As shown in Figure 5-5 (A), there is a single domain on each medium and the domains are separated by inter-domain bridges. Figure 5-5 (C) shows the example segment of a home network from Figure 5-5 (A), but also demonstrates the potential for having multiple domains on a medium. In Figure 5-5 (C), the phone-line medium carries three domains and the power-line medium carries two domains. The multiple domains on each individual medium within a single network shall have orthogonal signaling to avoid interference. For example, on the power line, domain C5 must have signaling that is orthogonal to signaling on domain C6. These domains communicate via the same inter-domain bridges shown that connect the different media. These inter-domain bridges have multiple internal bridge ports to connect the domains operating on the same medium. Refer to Figure I-3 for an alternative representation of multiple domains on a single medium.

NOTE – It is possible to passively couple wire classes and operate them under a single domain. However, it is expected that such scenarios would occur very infrequently and such practices will be avoided if possible.

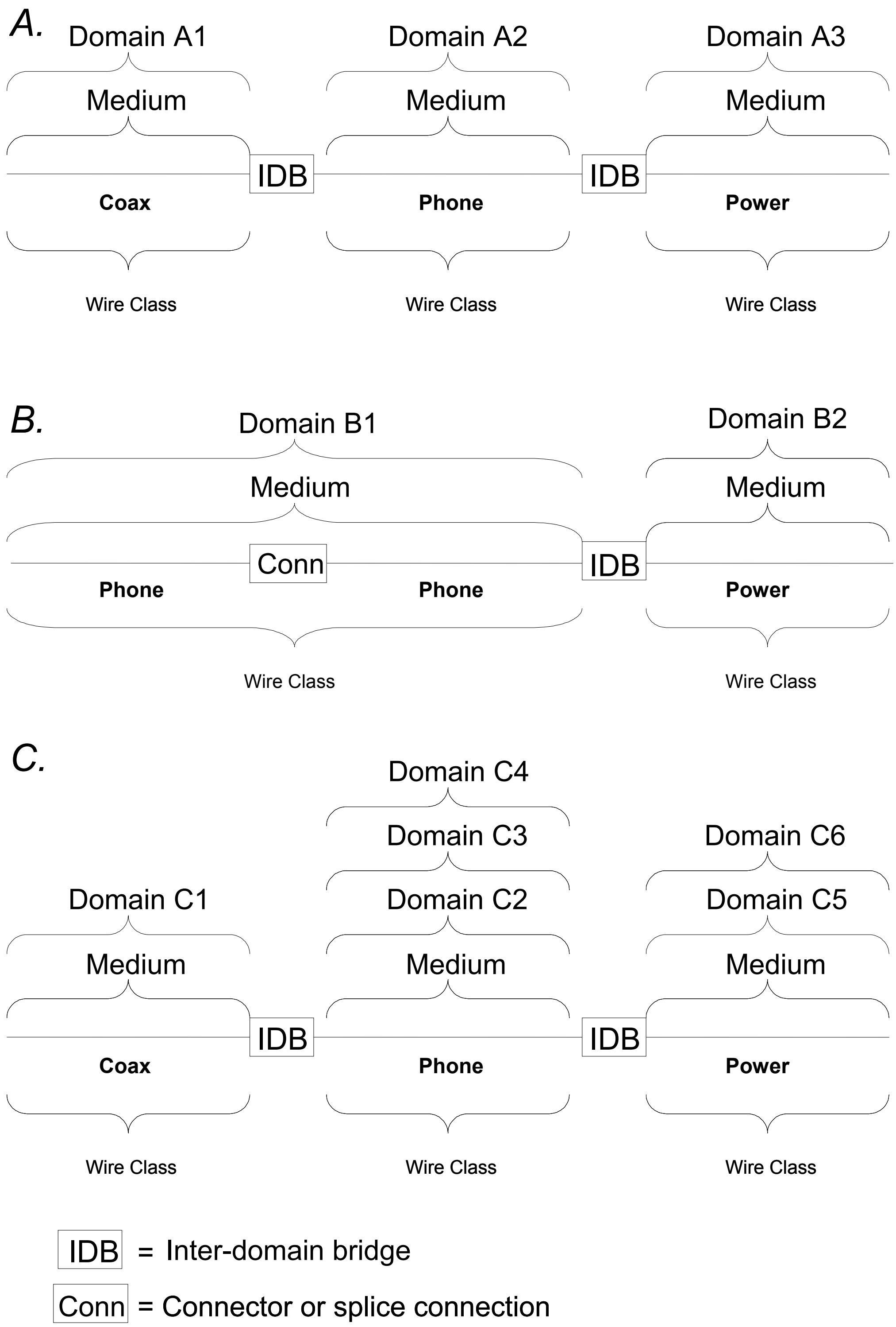

Figure 5-5/G.9960 − Relationships between domain, medium and wire class

5.1.2 Node functionality

The main functions and capabilities of a node are summarized in Table 5-1.

Table 5-1/G.9960 − Main Functions and capabilities of a node

Function	Description and Parameters
Medium access	Receives, interprets and acts upon the MAP
Support of admission control protocol	Supports admission control protocol
Support of operational modes of the domain	Supports the operational mode (PM, CM, or UM) Complies with spectrum compatibility settings for the domain
Support of medium access rules	Accesses medium using medium access rules coordinated with the domain master
Support of security	Supports authentication and encryption key management procedures
Collection and reporting of node information	Provides statistics about: - List of visible nodes - List of addresses (AAT) - List of capabilities supported by the node - Performance statistics (data rate, error count, time stamps) - Statistics on detected neighboring home networks
Request of bandwidth allocation	- Performs flow setup. - Requests bandwidth allocations from the domain master in order to meet QoS requirements of flows
Support of retransmissions	Provides acknowledgment and retransmission of data units that were received with error
Support of extended capabilities	- Domain master - Domain access point (DAP) - Data relaying - MAP repeating - Domain master selection procedure - security controller
NOTE – designation of which functions are mandatory or optional is for further study.	

5.1.2.1 Domain master functionality

A domain master controls operation of the nodes in the domain. The main functions of a domain master are summarized in Table 5-2.

Table 5-2/G.9960 − Domain master functionality

Function	Description
Indication of presence	Periodically communicates MAP to all nodes in the domain
Admission control	Admits new nodes to the domain Limits the number of nodes in a domain Facilitates departure of nodes from the domain
Determination of domain operation	Assigns mode of operation inside the domain (PM, CM, or UM) Supports hidden nodes by assigning MAP repeaters Supports synchronization of the MAC cycle to an external source (e.g., the AC line) Facilitates spectrum compatibility for the domain by assigning relevant limits on: - Frequency band - Maximum transmit power - PSD mask
Bandwidth allocation and QoS support	Assigns medium access rules to all nodes of the domain to facilitate support of QoS
Monitor status of the domain	Collects statistics of domain operation: - List of nodes in the domain - Topology - Performance statistics (data rate, error count) - Statistics on neighboring domains
Communication with the global master (for further study)	Coordinates operation of the domain with other domains using the global master function
Backup master assignment	Assigning of a backup domain master to take over the domain master role
Neighbour domain coordination	For further study
NOTE – designation of which functions are mandatory or optional is for further study.	

5.1.3 Global master function

This clause provides an overview of the global master function. Detailed specification and use of this function is for further study.

The global master (GM) function interacts with domains and coordinates their operation by exchanging relevant information with domain masters via the logical M-interface as shown in Figure 5-6.

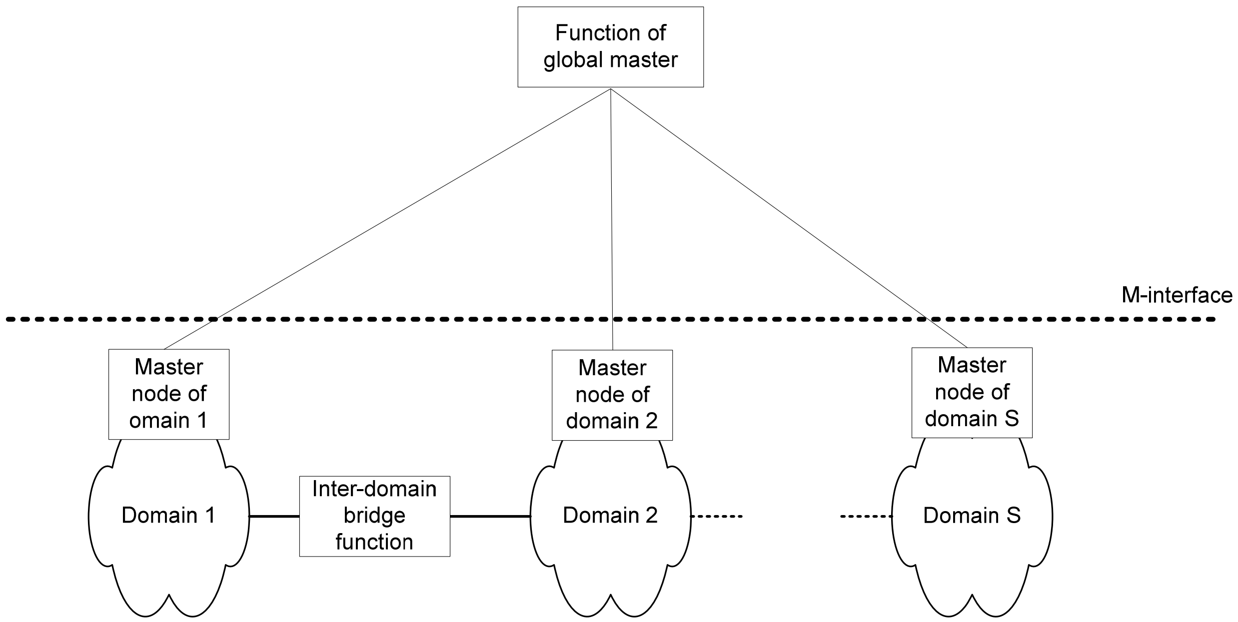

Figure 5-6/G.9960 – Functional model of GM

The following rules apply to the GM:

1. In a multi-domain home network, the GM may coordinate some or all domains. For coordination, the GM exchanges information with domain masters of all coordinated domains via the M-interface. The GM may retrieve relevant domain-related data from domain masters and send control signals and data for coordination between domains to domain masters.
2. The M-interface is functional; its physical implementation is vendor discretionary. In case a domain master is replaced (e.g., as a result of a failure), the GM shall interface to the newly selected domain master.
3. The Information exchange protocol between the GM and a domain master is unified for all domains.

NOTE – The GM doesn't limit the number of domains in the home network.

5.1.4 Quality of service (QoS)

Quality of service (QoS) is a measure of the quality of delivery of services in the home network, placing requirements on the transmission and queuing of traffic. G.9960 supports two QoS methods: Priority-based QoS and Parameter-based QoS.

The QoS requirements are supported between nodes inside the same domain and between nodes connected to different domains if services communicated between nodes belong to different domains. In the latter case, inter-domain bridges are expected to not compromise the QoS requirements (such as latency). Inter-domain bridges are also expected to facilitate provisioning of QoS between nodes connected to different domains.

The G.9960 QoS mechanism operates per flow. Flows are set up, modified and torn down on a service basis. The characteristics of the service are used to select the QoS method used to deliver the traffic associated with the flow and to determine any relevant QoS parameters. Frames belonging to a specific flow are scheduled to be sent onto the medium in accordance with the defined QoS method. The G.9960 QoS method shall handle both constant and variable bit-rate traffic.

Priority-based QoS refers to a mechanism that provides different priorities for medium access to different flows. All G.9960 transceivers shall support priority-based QoS. The number of supported priority levels associated with the incoming application data primitives (ADPs) (at A-interface) shall be 8 (denoted from 0 to 7).

With priority-based QoS, the G.9960 transceiver associates each flow with a certain priority queue, based on priority or other priority-related parameters of incoming frames. The G.9960 priority-based QoS method defines the order in which frames from each queue will be sent to the medium and in which order frames will be processed (and possibly dropped), based solely on the priority assigned to the queue. The number of supported priority queues may be less than 8. The mapping between the priority of the flow and the associated priority queue shall be as recommended by IEEE 802.1D-2004 [2] for user priority to traffic class mappings, as shown in Appendix III. Other methods of classification are for further study.

Parameter-based QoS refers to a mechanism that provides specific performance metrics (QoS parameters) for a given flow associated with the application (service), and resource allocation for medium access to meet these performance metrics. A set of these parameters may include, but is not limited to, data throughput, latency or jitter.

With Parameter-based QoS, the G.9960 transceiver associates each flow with a set of QoS parameters related to the particular service and with a certain queue. The G.9960 parameter-based QoS method provides appropriate resources (e.g., bandwidth) necessary to communicate each flow through the medium so that QoS parameters associated with this flow are met. It also determines the order in which frames from each queue will be sent to the medium and in which order frames will be processed (and possibly dropped) based on the knowledge of traffic parameters. The minimum number of supported flows (queues) depends on the profile.

5.1.5 Security

G.9960 security is designed to address operation over shared media, such as power line and coax cable. Besides admission procedures, which ensure that only permitted nodes can join a home network via one of its domains, G.9960 defines point-to-point security, allowing authentication of each pair of nodes prior to communication and unique encryption keys for each pair of communicating nodes or per multicast group.

> NOTE – Point-to-point security generally improves security by building another layer of protection against an intruder that has broken through the admission control, and maintains full confidentiality for all communications within the home network. The latter suits G.9960 to be installed in public places (hotels, small businesses, home offices), requiring at least the same grade of security and confidentiality as defined in the most recent specification for wireless LAN (IEEE 802.11-2007). See Appendix IV for a description of the threat model.

G.9960 security provides the following main features:

- Encryption based on AES-128 [3] and CCM mode [4].
- Advanced authentication and secure admission of nodes into a domain, based on ITU-T Recommendation X.1035 [1].
- Key management, including generation, secure communication, update, and termination of encryption keys.
- High confidentiality and integrity of all transactions, including point-to-point authentication and unique encryption keys.
- Support of secure operation with the presence of relay nodes

- Allows simultaneous operation of distinct, separately secured domains on the same medium per the rules specified in §5.1.1.1.
- Provides user-friendly procedures for setting up a secure network.

Security procedures that are user-friendly may require the user to set a password for each node prior to installation. The rest of the procedures necessary to establish and maintain security are facilitated automatically by the security controller (SC) function, without involvement of the user.

Nodes that don't include an appropriate user interface may use a unique manufacturer-set password.

Security and mutual confidentiality between applications associated with the same node is supposed to be resolved at the higher layers of the protocol stack and is beyond the scope of this Recommendation.

5.1.6 Inter-domain bridging

The inter-domain bridge (IDB) function connects nodes of two domains. In Figure 5-7, application entities AE1 (service originator) and AE2 (service destination) are associated with nodes A1 and B2, respectively, of two domains. The communication path between nodes A1 and B2 goes through domain 1 and domain 2, and includes in-domain flows F1, F2 and the IDB function. Interfaces between nodes B1, A2 and the IDB are AE interfaces (A-interfaces, see §5.2.1). Communication paths routed through more than two domains operate in the same way.

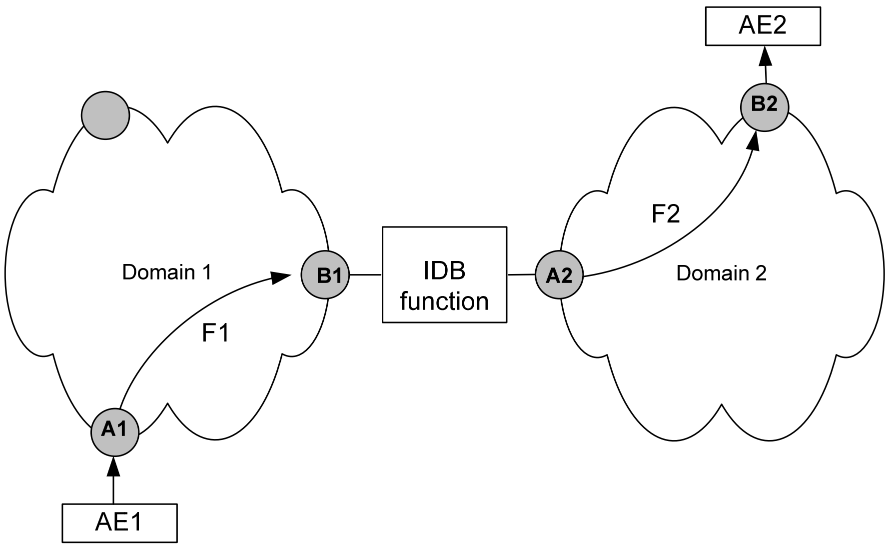

Figure 5-7/G.9960 – Communication path between nodes of two different domains

The protocol reference model for inter-domain communications shown in Figure 5-7 is presented in Figure 5-8.

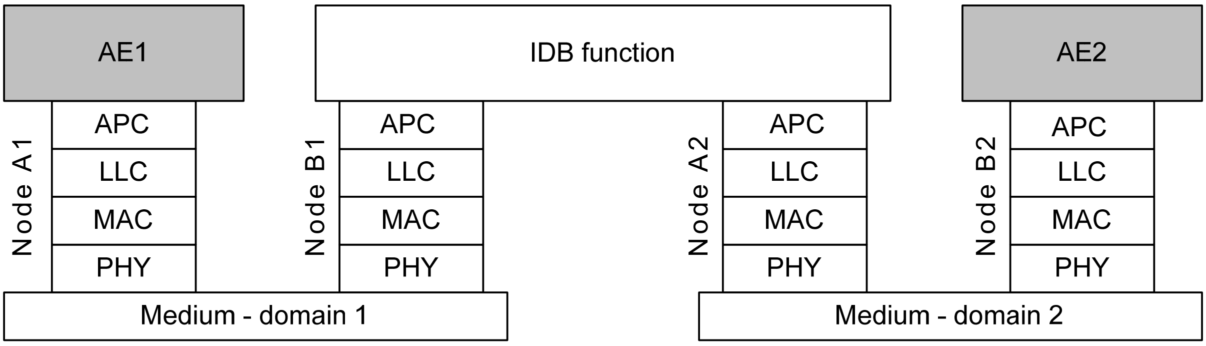

Figure 5-8/G.9960 – Protocol stack of inter-domain communication

In the case that the APC is implemented as an ethernet convergence sub-layer, the IDB function can be implemented as a standard 802.1D transparent bridge. Means to avoid loops between multiple domains are for further study.

One case of inter-domain bridging relates to implementation of multi-media devices, which are equipped with more than one physical interface and, accordingly, can be connected to more than one domain. A scenario describing a two-media device is presented in Figure 5-9. The IDB connects the AE associated with the device to both domains (via nodes B1 and A2), and provides inter-domain connection (between nodes B1, A2, similar to one presented in Figure 5-7). The IDB interfaces to nodes B1 and A2 as an AE, and also bridges the AE to either or both of these nodes.

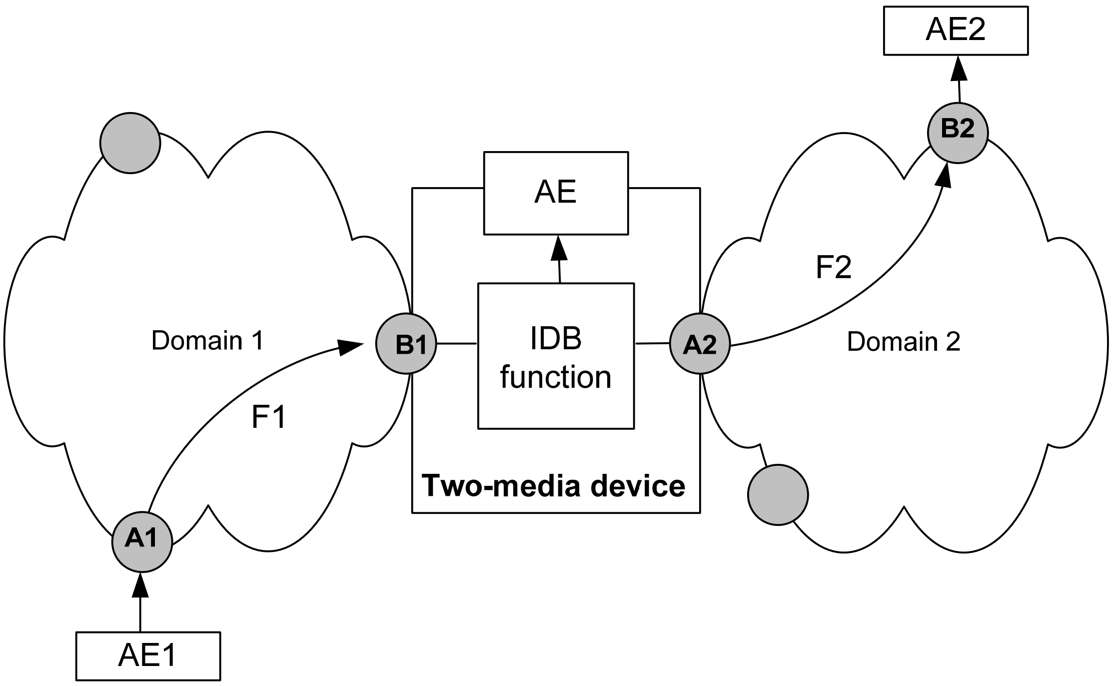

Figure 5-9/G.9960 – Example of communication with a two-media (domain) device

The protocol reference model corresponding to Figure 5-9 is presented in Figure 5-10. It assumes a vendor-proprietary interface between the IDB and the AE. However, a standard interface like IEEE 802.3 can be used too.

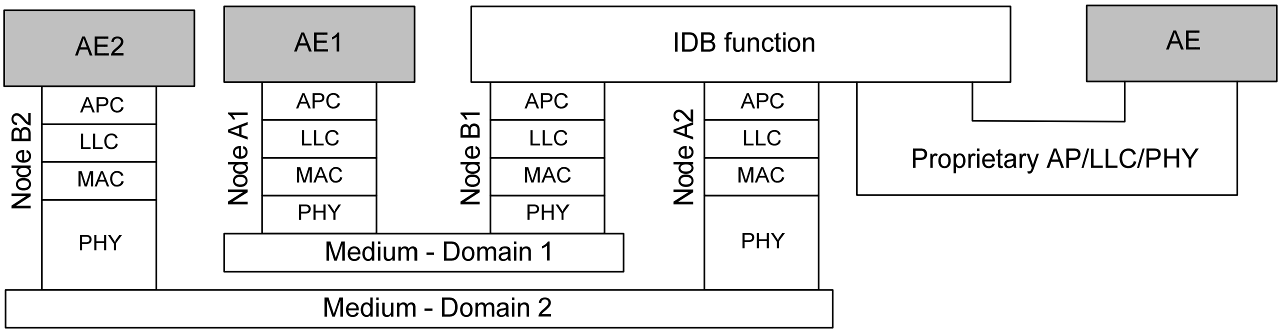

Figure 5-10/G.9960 – Protocol stack of inter-domain communication

5.1.6.1 End-to-end QoS for multi-domain connections

The end-to-end QoS requirements are defined by priority level (in case of priority-based QoS), or by traffic parameters such as bit rate and latency (for parameterized QoS). See §5.1.4. In both cases, to meet end-to-end requirements, requirements are imposed on in-domain flows forming the connection and on IDB. In Figure 5-7, the end-to-end QoS requirements for the service routed between nodes A1 and B2 determine QoS requirements for flow F1, carrying the service inside domain 1, and for flow F2, carrying the service inside domain 2, and for the delay introduced by IDB.

In the case of prioritized QoS, the end-to-end QoS requirements can be met if the IDB conveys priority requirements, so that the priority level applied to flow F1 in domain 1 corresponds with the priority level applied to flow F2 in domain 2. In the same way, prioritized QoS shall be supported for situations where the route for delivery of traffic between two nodes includes more than 2 domains.

In case of parameterized QoS, the end-to-end QoS parameters shall be distributed between in-domain flows and the IDBs. The rules of distribution of end-to-end QoS parameters between multiple domains are for further study.

The IDB throughput shall be higher than the maximum throughput available in either of the domains connected by the IDB. The delay introduced by the IDB should be minimized (the maximum allowed values are for further study). The maximum number of IDBs in the path may be limited for certain service types.

Other parameters of the IDB functionality are vendor discretionary.

5.1.6.2 Security in multi-domain connections

For a multi-domain home network, secure operation is achieved by setting all its domains to secure mode. Communications between secure and non-secure domains shall not be allowed, unless special security measures are provided by the IDB (on higher protocol levels). These measures are beyond the scope of this Recommendation, same as security measures protecting IDB from outside intrusion (i.e., when the intruder is one of the AEs connected to the IDB).

5.1.7 Power saving modes

Three modes of operation are defined with the intention of reducing the total power consumption in home networks. When the electrical power for equipment connected to the home network is switched on, operational modes for the equipment shall be one of the following:

- Full-power mode: This is the mode in which transmission up to maximum defined bit-rate is possible. In this mode the power consumption is limited only by the defined PSDs.
- Low-power mode(s): In these modes only a limited data transmission is running. The equipment enters this mode when specific traffic parameters are met. The values of these parameters are for further study.
- Idle mode: In this mode the equipment is switched on and connected physically to the home network, but no data except for control messages is transmitted or received by the connected equipment.

During all power modes and transitions between them, the node shall maintain its original DEVICE_ID. Details on operation of power saving modes are for further study.

5.2 Reference models

5.2.1 Protocol reference model of a home network transceiver

The protocol reference model of a home network transceiver is presented in Figure 5-11. 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 5-11.

The MDI is a physical interface defined in the terms of physical signals transmitted over a specific medium (see §7.2) and mechanical connection to the medium.

The PMI interface is both medium independent and application independent. It is defined in §5.2.2.2 as a functional interface, in terms of functional flows and logical signals.

The A-interface is user application protocol specific (e.g., Ethernet, IP). The functional description of the A-interface is presented in §5.2.2.1. The A-interface is for further study.

All intermediate reference points are independent of the type of medium and are defined as functional (logical) interfaces in the terms of functional flows and logical signals.

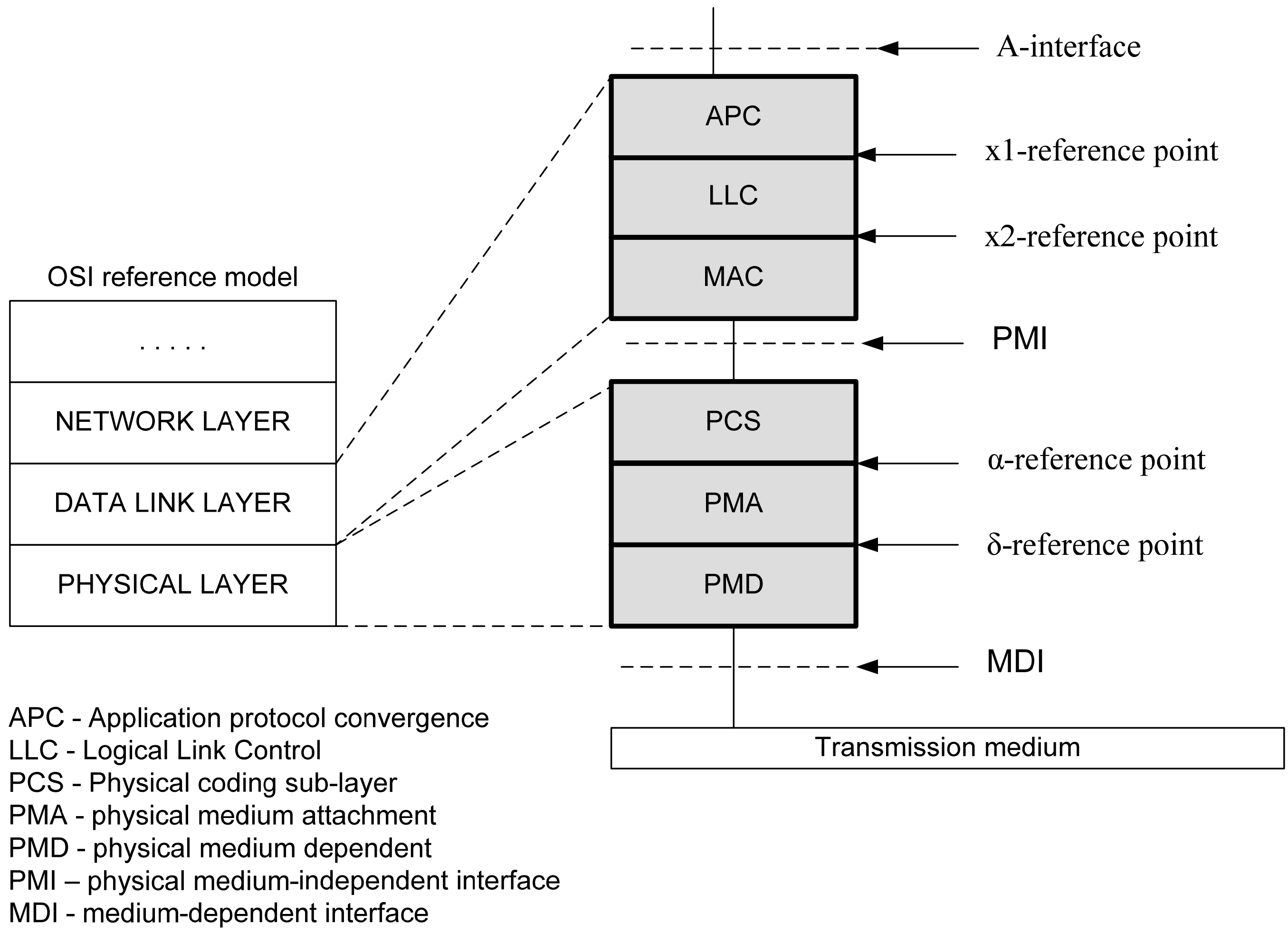

Figure 5-11/G.9960 – Protocol reference model of a home network transceiver

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

The logical link control (LLC) sub-layer coordinates transmission of nodes in accordance with requests from the domain master. In particular, it is responsible for establishing, managing, resetting and terminating all connections of the node inside the domain. The LLC also facilitates Quality of Service (QoS) constraints of the flow, defined for its various connections. Details are for further study.

The MAC sub-layer controls access of the node to the medium using various medium access protocols, which are for further study.

The 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 PMA provides encoding of PHY frame content for transmission over the medium. The PMD modulates and demodulates PHY frames for transmission over the medium using orthogonal frequency division modulation (OFDM). By implementation, the PMD may include medium-dependent adaptors for different media, including frequency shifting for passband transmission.

The layers above the data link layer (above the A-interface) are beyond the scope of G.9960. Management functions are not presented in Figure 5-11.

5.2.2 Interfaces - functional description

This section contains the functional description of the G.9960 transceiver interfaces (A, PMI, and MDI) in terms of signal flows exchanged between corresponding entities. The description doesn't imply any specific implementation of the transceiver interfaces.

5.2.2.1 A-interface

The A-interface is described in terms of primitives exchanged between the AE and DLL. There are six general types of A-interface primitives as shown in Table 5-3. Each primitive type may consist of one or more primitives, related to control or data, respectively. Data primitives represent the data path of the A-interface, while control primitives represent the control path. The format of the application data primitives (ADPs) is application specific, determined by the AE. The definition of the A-interface control and data primitives of each type is for further study.

Table 5-3/G.9960 – A-interface primitive type summary

Primitive type	Direction	Description
AIF_DATA.REQ	AE → DLL	Data from AE to DLL
AIF_DATA.CNF	DLL→AE	Data confirmation from DLL to AE
AIF_DATA.IND	DLL→ AE	Data from DLL to AE
AIF_CTRL.REQ	AE → DLL	Control from AE to DLL
AIF_CTRL.CNF	DLL → AE	Control confirmation from DLL to AE
AIF_CTRL.IND	DLL → AE	Control from DLL to AE

5.2.2.2 Physical medium-independent interface (PMI)

The PMI is described in terms of primitives exchange between the DLL and PHY layer presented in Table 5-4; the direction of each primitive flow indicates the entity originating the primitive. Both transmit and receive data primitives are exchanged in MAC protocol data units (MPDUs). The format of an MPDU is for further study. Details of the PMI primitives are for further study.

Table 5-4/G.9960 – PMI primitive description

Primitive	Direction	Description
PMI_DATA.REQ	DLL → PHY	Flow of MPDUs for transmission
PMI_CTRL-RxDis.REQ	DLL→ PHY	Disables receive of PHY frames
PMI_DATA.IND	PHY → DLL	Flow of received MPDUs
PMI_CTRL-ERR.IND	PHY → DLL	Error primitive that accompanies an MPDU received with errors
PMI_CTRL-CRS.IND	PHY → DLL	Carrier sense primitive
RX ENABLE	DLL → PHY	Enable receive function in the PHY layer
NOTE – Primitives presented in this table are exclusively for descriptive purposes and do not imply any specific implementation.		

5.2.2.3 Medium-dependent interface (MDI)

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

- transmit signal (TX DATA) is the flow of frames transmitted onto the medium
- receive signal (RX DATA) is the flow of frames received from the medium.

5.2.3 Functional model of a home network transceiver

The functional model of a home network transceiver is presented in Figure 5-12. It addresses nodes without extended capabilities as well as nodes with extended capabilities such as domain master, and relaying (including DAP), which differ by their MAC, LLC and upper layer functionalities.

The PMD function depends on the medium on which the transceiver operates. It can be configured for baseband or passband operation. The PCS provides bit rate adaptation (data flow control) between the MAC and the PHY and encapsulates transmit MAC protocol data units (MPDUs) into PHY frames. The transmit PHY frame is further encoded in the PMA to meet the corresponding PMD. The functionality of the PCS, and the PMA is the same for any medium, but their parameters are medium-specific. By appropriate parameter settings, any node can be configured to operate on any type of wiring in both baseband and passband modes.

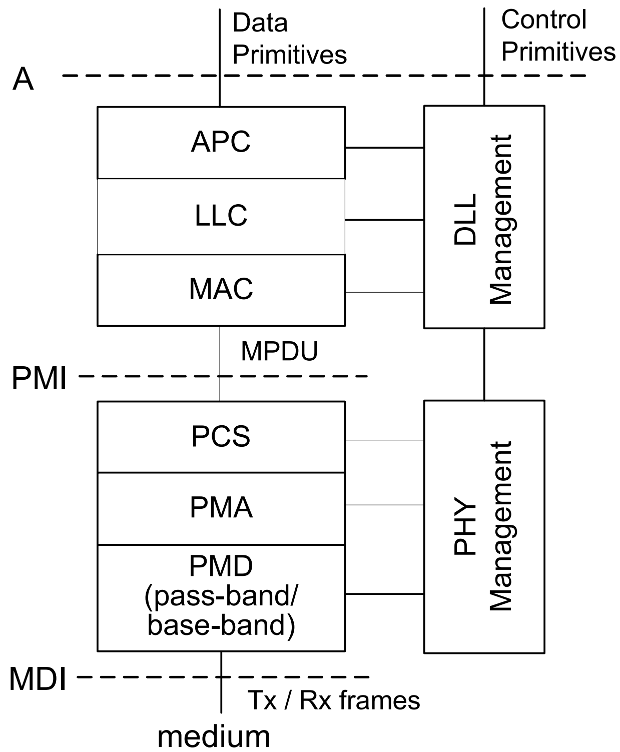

Figure 5-12/G.9960 − Functional model of a home network transceiver

The detailed description of the functional model of the PHY layer is presented in §7.1. The detailed description of the functional model of the DLL is for further study.

6 Profiles

Profiles are intended to address nodes with significantly different levels of complexity. Details are for further study.

7 Physical layer specification

7.1 Medium independent specification

7.1.1 Functional model of the 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.

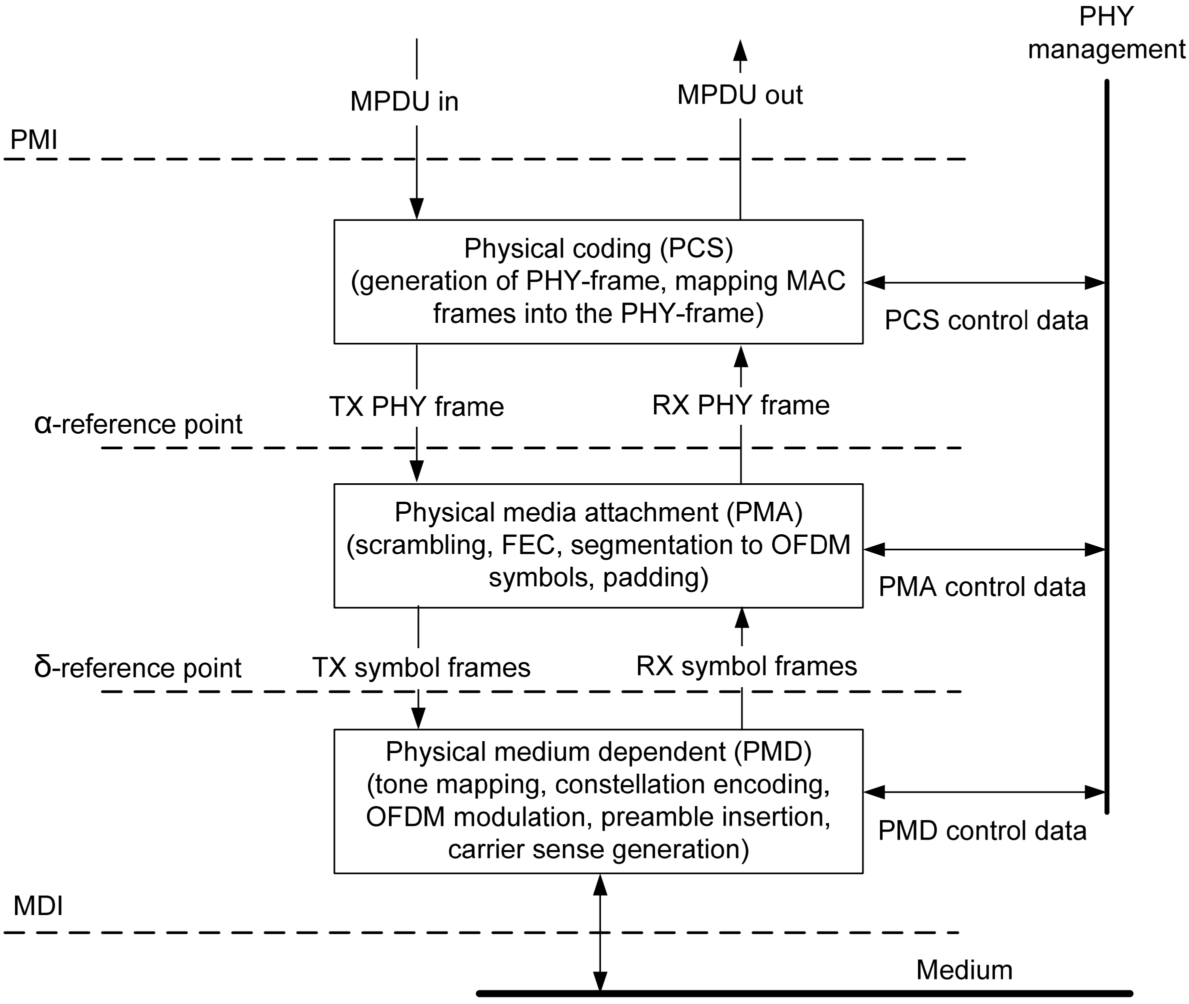

Figure 7-1/G.9960 – Functional model of the PHY

In the transmit direction, data enters the PHY from the MAC via 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 is added to assist synchronization and channel estimation in the receiver.

In the receive direction, frames entering from the medium via the MDI are demodulated and decoded. The recovered MPDUs are forwarded to MAC via the PMI. The recovered PHY-frame headers are processed in the PHY to extract the relevant frame parameters specified in §7.1.2.3.

7.1.2 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.

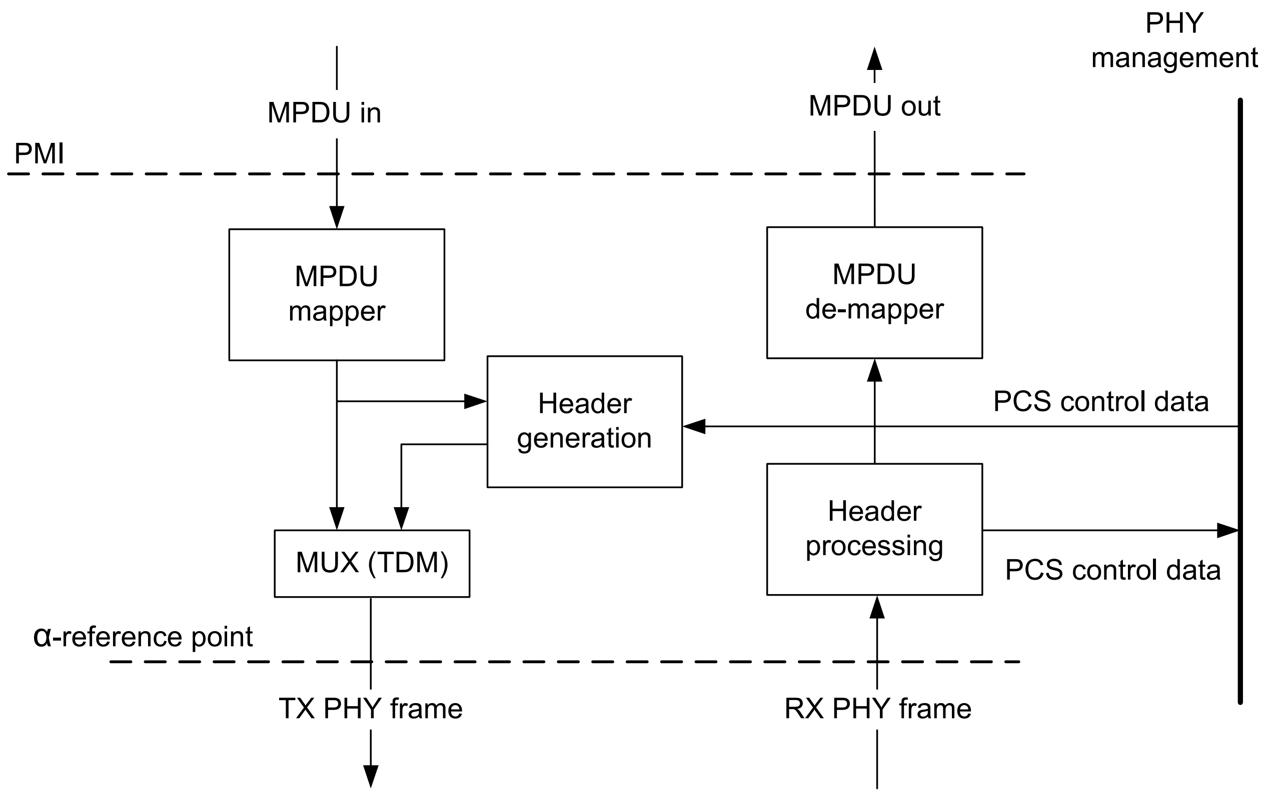

Figure 7-2/G.9960 – Functional model of PCS

In the transmit direction, the incoming MPDU is mapped into a payload field of a PHY frame (§7.1.2.1) as described in §7.1.2.2. Further, the PHY-frame header (§7.1.2.3) is 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 MPDUs are recovered from the payloads of received PHY frames and submitted to the PMI. Relevant control information conveyed in the PHY-frame header is processed and submitted to the PHY management entity, Figure 7-2.

7.1.2.1 PHY frame

The format of the PHY frame is presented in Figure 7-3. The PHY frame at the α-reference point includes header, and payload. Preamble including additional channel estimation symbol is added to the PHY frame in the PMD, as described in §7.1.4.5. Preamble does not bear any user or management data and is intended for synchronization and initial channel estimation.

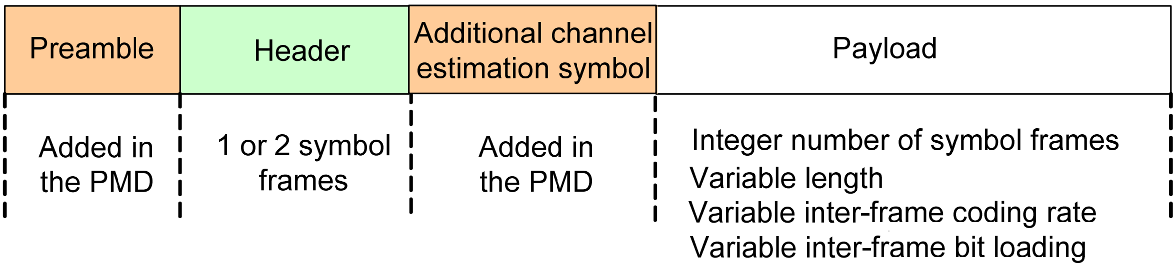

Figure 7-3/G.9960 – Format of the PHY frame

The PHY-frame header and payload shall each contain an integer number of OFDM symbols.

The length of the PHY-frame header always fits integer number of symbols and is transmitted using a single pre-defined set of modulation and coding parameters (see §7.1.3.4).

The presence of the additional channel estimation symbol is medium dependent (see §7.1.4.5, §7.1.2).

The length of the payload may vary from frame to frame; payload may be of zero length. For payload, different coding parameters and bit loading can be used in different frames, depending on channel/noise characteristics and QoS requirements.

7.1.2.2 MPDU mapping

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

7.1.2.3 PHY-frame header

The PHY-frame header is PHY_H bits long (see §7.1.3.2.2) and is composed 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. PHY-frame type is indicated by the FT field. The PAD fields fit the length of the header of different PHY frame-types to the standard value of PHY_H bits. The content of the header is protected by the 16-bit header check sequence (HCS).

The fields of the PHY-frame header are defined in Table 7-1

Table 7-1/G.9960 – PHY-frame header fields

Field	Octet	Bits	Description	
FT	0	3:0	Frame type	Common part
DOD	0	7:4	Domain ID	
SID	1	7:0	The DEVICE_ID of the source node	
DID	2	7:0	The DEVICE_ID, MULTICAST_ID or BROADCAST_ID of the destination node(s)	
MI	3	0	Multicast indication identifies whether the DID is a unicast or multicast destination	
PHI	3	1	Post header indication identifies whether the first payload symbol after the header is a PRBS symbol or a data symbol	
DRI	3	2	Duration indication identifies whether FTSF starts with a DUR_H-bit duration field	
Reserved	3	7:3	Reserved by ITU-T (NOTE)	
FTSF	4-18	7:0	Frame-type specific field	Variable part
HCS	19-20	7:0	Header check sequence	Common part
NOTE – Bits that are reserved by ITU-T shall be set to zero by the transmitter and ignored by the receiver.				

7.1.2.3.1 Common part fields

7.1.2.3.1.1 Frame Type (FT)

The Frame type (FT) field is a 4-bit field which indicates the type of the PHY frame transmitted.

Table 7-2 describes the PHY-frame types.

Table 7-2/G.9960 –PHY-frame types

Type	Value ($b_3b_2b_1b_0$)	Description
MAP	0000	MAP frame
MSG	0001	Data and management frame
ACK	0010	ACK control frame
RTS	0011	RTS control frame
CTS	0100	CTS control frame
RMAP	0101	Repeated MAP frame
PROBE	0110	Probe frame
ACKRQ	0111	ACK retransmission request frame
Reserved	1000:1111	Reserved by ITU-T

7.1.2.3.1.2 Domain ID (DOD)

The DOD is a 4-bit field that identifies the domain to which the source and destination devices of the PHY frame belong. DOD shall be represented as a 4-bit unsigned integer in the valid range from 0 to 15.

7.1.2.3.1.3 Source ID (SID)

The SID field contains the DEVICE_ID assigned to the source node of the PHY frame during its registration. The SID shall be represented by an 8-bit unsigned integer with valid values in the range from 0 to 250. Value 0 is a special value used by a node attempting to join the home network.

7.1.2.3.1.4 Destination ID (DID)

The DID field contains the value that identifies the destination node(s) of the PHY frame. The DID shall be represented by an 8-bit unsigned integer with valid values in the range from 0 to 250.

7.1.2.3.1.5 Multicast Indication (MI)

If the MI field is set to zero, the DID field contains the DEVICE_ID of the destination node (for unicast transmission). If the Multicast Indication (MI) field is set to one, the DID field contains a MULTICAST_ID or BROADCAST_ID of the destination nodes.

7.1.2.3.1.6 Post Header Indication (PHI)

The PHI bit, when set, shall indicate that the first payload symbol following the header is a PRBS symbol. Otherwise the first payload symbol shall be a data symbol.

7.1.2.3.1.7 Duration indication (DRI)

The DRI bit, when set to one, shall indicate that the FTSF starts with a duration field that is DUR_H bits long. If this bit is set to zero, it shall indicate that the PHY frame does not contain any payload (i.e., contains only preamble, PHY-frame header, and optionally an additional channel estimation symbol). The size of duration field (DUR_H) is for further study.

Table 7-3/G.9960 –Value of DRI for different frame types

Frame type	Value of DRI
MAP	1
MSG	1
ACK	0
RTS	1
CTS	1
RMAP	1
PROBE	1
ACKRQ	0

7.1.2.3.1.8 Header check sequence (HCS)

The HCS field is intended for PHY-frame header verification. The HCS is a 16-bit cyclic redundancy check (CRC) and shall be computed over all the fields of the PHY-frame header in the order they are transmitted, starting with the LSB of the first field of the PHY frame header (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 16:

$$G(x) = x^{16} + x^{12} + x^{5} + 1.$$

The value of the HCS shall be the remainder after the contents (treated as a polynomial where the first input bit is associated with the highest degree, $X^{PHYH-17}$, where PHY_H is the header length in bits , and the last input bit is associated with X^0) of the calculation fields is multiplied by x^{16} and then divided by $G(x)$.

The HCS field shall be transmitted starting with the coefficient of the highest order term.

7.1.2.3.2 Variable part fields

The following paragraph details the frame-type specific field (FTSF), a variable part of the PHY-frame header fields separately defined for each PHY-frame type.

7.1.2.3.2.1 MSG PHY-frame type specific fields

Table 7-4 lists the MSG frame type specific PHY-frame header fields.

Table 7-4/G.9960 – MSG PHY-frame type specific fields

Field	Field size [bits]
MSG_DUR	DUR_H
MDET	1
RPRQ	3
BLKSZ	2
FEC_RATE	3
FLOW_ID/PRI	8
REP	3
FCF	3
SI	4
FRMSN	2
BAT_ID	5
GRP_ID	3
GI_ID	3
APSDC-M	5
Reserved (NOTE)	padding up to PHY_H bits
NOTE: The reserved bits shall be set to zero by the transmitter and ignored by the receiver.	

7.1.2.3.2.1.1 Duration for MSG frame (MSG_DUR)

This field is for further study.

7.1.2.3.2.1.2 "Master is detected" indication (MDET)

MDET indicates reception of a MAP. It is a 1-bit field that shall be set by a node, in each PHY-frame header it transmits, when this node has received a MAP (either directly from the domain master or repeated MAP) that the current MAC cycle is associated with. This indication shall be used by nodes (including the backup domain master if it exists) to determine whether the current domain master has failed.

7.1.2.3.2.1.3 Reply required (RPRQ)

RPRQ instructs the receiver whether to respond with acknowledgement for this PHY frame. It is a 3-bit field that shall be coded as shown in Table 7-5.

Table 7-5/G.9960 – RPRQ field possible values

RPRQ value	Interpretation
000	The receiver shall not acknowledge this PHY frame
001	The receiver shall acknowledge via an Imm-ACK frame
010 - 111	Reserved by ITU-T

7.1.2.3.2.1.4 Block size (BLKSZ)

BLKSZ indicates the information block size of the FEC codeword that is used by the transmitter for the payload of the PHY frame. It is a 2-bit field that shall be coded as shown in Table 7-6.

Table 7-6/G.9960 – Interpretation of the BLKSZ field

BLKSZ value	Interpretation
00	for the 120 byte information block size used for payload
01	for the 540 byte information block size used for payload
10-11	Reserved by ITU-T

7.1.2.3.2.1.5 FEC_RATE

FEC_RATE indicates the FEC coding rate that is used for encoding of the payload. It is a 3-bit unsigned integer field that shall be coded as shown in Table 7-7.

Table 7-7/G.9960 – Interpretation of the FEC_RATE field

FEC_RATE value	Interpretation
000	Reserved by ITU
001	1/2
010	2/3
011	5/6
100	16/18
101	20/21
110-111	Reserved by ITU

7.1.2.3.2.1.6 Flow identifier (FLOW_ID) and priority (PRI)

FLOW_ID/PRI is an 8-bit unsigned integer field that shall contain the FLOW_ID of the blocks aggregated in the frame (field values in the range 8-254), or the priority of the blocks aggregated in the frame if the field value is between 0 and 7. The value 255 is reserved by ITU-T.

7.1.2.3.2.1.7 Repetitions (REP)

REP indicates the nominal number of repetitions that were used for encoding the payload in this PHY frame. It is a 3-bit unsigned integer field that shall be coded as shown in Table 7-8.

Table 7-8/G.9960 – Repetitions field possible values

REP value	Interpretation (N_{REP})
000	Reserved by ITU-T
001	1 (no repetitions)
010	2
011	3
100	4
101	6
110	8
111	Reserved by ITU-T

7.1.2.3.2.1.8 FEC concatenation factor (FCF)

FCF indicates the values of parameters *H* and z (see §7.1.3.3.1). It is a 3-bit unsigned integer field that shall be coded as shown in Table 7-9.

Table 7-9/G.9960 – FEC concatenation factor (FCF) possible values

Value	*H*	z
000	1	0
001	Reserved by ITU-T	Reserved by ITU-T
010	2	0
011	2	1
100	4	0
101	4	1
110	4	2
111	4	3

7.1.2.3.2.1.9 Scrambler initialization (SI)

SI contains the scrambler initialization value ($C_4C_3C_2C_1$, where C_1 is the LSB) that was used by the transmitter for this frame. It is a 4-bit field that shall be used to initialize the scrambler, as described in §7.1.3.1.

7.1.2.3.2.1.10 Frame sequence number (FRMSN)

FRMSN holds the transmitted frame sequence number sent to the same destination (DID). It is a 2-bit unsigned integer field.

The FRMSN shall be initialized to zero upon the first PHY frame containing payload sent for a certain DID and shall be incremented by one upon each additional PHY frame containing payload sent to the same DID. When the FRMSN value exceeds the maximum value of 3, the FRMSN shall wrap-around to zero.

7.1.2.3.2.1.11 BAT_ID

BAT_ID is a 5-bit field that shall identify the bit allocation table (BAT) of the PHY frame (see Table 7-20).

7.1.2.3.2.1.12 GRP_ID

GRP_ID is a 3-bit field that shall identify the sub-carrier grouping (see §7.1.4.2.4). It shall be formatted as shown in Table 7-10.

Table 7-10/G.9960 – Format of the GRP_ID

GRP_ID value	[Bits]	Description
0	000	Default - No sub-carrier grouping
1	001	Sub-carrier grouping of 2 sub-carriers
2	010	Sub-carrier grouping of 4 sub-carriers
3	011	Sub-carrier grouping of 8 sub-carriers
4	100	Sub-carrier grouping of 16 sub-carriers
5-7	101-111	Reserved by ITU-T

7.1.2.3.2.1.13 GI_ID

GI_ID is a 3-bit field that shall identify the guard interval used for payload (see §7.1.4.4). It shall be formatted as shown in Table 7-11.

Table 7-11/G.9960 – Format of the GI_ID

GI_ID value	[Bits]	Description
0-6	000-110	N_{GI} guard interval [samples] $k \times N/32$, $k = 1, 2, 3, \ldots, 7$ where k = GI_ID+1, N is the size of the DFT
7	111	$k = 8$ (GI_ID=7) $N_{GI} = N_{GI\text{-}DF} = N/4$

7.1.2.3.2.1.14 Actual PSD ceiling of MSG frame (APSDC-M)

APSDC-M indicates the PSDC value that is used in the PHY frame. The field shall be coded as a 5-bit unsigned value. The valid values are in the range from 0 to 25, plus 0x1F. Values from 0 to 25 correspond to an actual PSD ceiling in the range of −50 dBm/Hz to −100 dBm/Hz in 2 dB steps. The special value 0x1F indicates that no PSD ceiling is applied. Values from 26 to 30 are reserved by ITU-T.

7.1.2.3.2.2 ACK PHY-frame type specific fields

For further study.

7.1.2.3.2.3 MAP and RMAP PHY-frame type specific fields

Table 7-12 lists the MAP and RMAP frame type specific PHY-frame header fields.

Table 7-12/G.9960 – MAP and RMAP PHY-frame type specific fields

Field	Size in bits
MAP_DUR	DUR_H
NTR	32
SI	4
BLKSZ	2
REP	3
RCMSS	12
Reserved (NOTE)	padding up to PHY_H bits
NOTE: The reserved bits shall be set to zero by the transmitter and ignored by the receiver.	

7.1.2.3.2.3.1 Duration for MAP frame (MAP_DUR)

This field is for further study.

7.1.2.3.2.3.2 Network time reference (NTR)

NTR is used for synchronizing nodes to the domain master transmit clock. It is a 32-bit unsigned integer field. The NTR shall indicate the time of the first sample of the first OFDM symbol (see Figure 7-22) of the preamble of a MAP or RMAP PHY frame that is sent according to the transmitting node's clock with a resolution of 10ns.

The NTR value shall use modulo arithmetic (modulo 2^{32}).

7.1.2.3.2.3.3 Block size (BLKSZ)

BLKSZ indicates the information block size of the FEC codeword that is used by the transmitter for the payload of the MAP frame. It is a 2-bit field that shall be coded as defined in §7.1.2.3.2.1.4.

7.1.2.3.2.3.4 Repetitions (REP)

REP indicates the number of repetitions that were used for encoding the payload in the MAP frame. It is a 3-bit field that shall be coded as defined in §7.1.2.3.2.1.7.

7.1.2.3.2.3.5 RCM Section size (RCMSS)

The RCMSS field indicate the size of the repetition block, B, used in the MAP frame (see §7.1.3.3.1). The value is represented as a 12-bit unsigned integer. The valid range is between 14 and 4094.

7.1.2.3.2.3.3 Scrambler initialization (SI)

SI contains the scrambler initialization value ($C_4C_3C_2C_1$) that was used by the domain master for this frame. It is a 4-bit field that shall be used to initialize the scrambler, as described in §7.1.3.1.

7.1.2.3.2.4 RTS PHY-frame type specific fields

Table 7-13 lists the RTS PHY-frame type specific PHY-frame header fields:

Table 7-13/G.9960 – RTS PHY-frame type specific fields

Field	Size in bits
RTS_DUR	DUR_H
CID	8
Reserved (NOTE)	padding up to PHY_H bits
NOTE: The reserved bits shall be set to zero by the transmitter and ignored by the receiver.	

7.1.2.3.2.4.1 Duration for RTS frame (RTS_DUR)

This field is for further study.

7.1.2.3.2.4.2 CTS proxy ID (CID)

CID contains the DEVICE_ID of the node that should respond in CTS for multicast traffic. It is an 8-bit unsigned integer field with valid values in the range from 1 to 250.

7.1.2.3.2.5 CTS PHY-frame type specific fields

Specific fields of the CTS PHY-frame type are listed in Table 7-14.

Table 7-14/G.9960 – Specific fields of the CTS PHY-frame type

Field	Size in bits
CTS_DUR	DUR_H
Reserved (NOTE)	padding up to PHY_H bits
NOTE: The reserved bits shall be set to zero by the transmitter and ignored by the receiver.	

7.1.2.3.2.5.1 Duration for CTS frame (CTS_DUR)

This field is for further study.

7.1.2.3.2.6 PROBE PHY-frame type specific fields

Table 7-15 lists the PROBE PHY-frame type specific PHY-frame header fields:

Table 7-15/G.9960 – PROBE PHY-frame type specific fields

Field	Size in bits
PRB_DUR	DUR_H
PRBTYPE	4
PRBSYM	5
APSDC-P	5
Reserved (NOTE)	padding up to PHY_H bits
NOTE: The reserved bits shall be set to zero by the transmitter and ignored by the receiver.	

7.1.2.3.2.6.1 Duration for PROBE frame (PRB_DUR)

This field is for further study.

7.1.2.3.2.6.2 PROBE frame type (PRBTYPE)

PRBTYPE indicates the type of the PROBE frame. It is a 4-bit field that shall be coded as shown in Table 7-16.

Table 7-16/G.9960 – PRBTYPE field values

Value	Interpretation
0000	Silent PROBE frame
0001	Channel assessment PROBE frame
0010-1111	Reserved by ITU-T

7.1.2.3.2.6.3 Probe symbols (PRBSYM)

PRBSYM indicates the number of OFDM payload symbols in the PROBE frame. It is a 5-bit field that shall be coded as shown in Table 7-17

Table 7-17/G.9960 – PRBSYM field values

Value	Interpretation
00000	4 Payload symbols
00001	8 Payload symbols
00010	12 Payload symbols
00011	16 Payload symbols
….	….
01111	64 Payload symbols
1xxxx	Reserved by ITU-T

7.1.2.3.2.6.4 Actual PSD ceiling of probe frame (APSDC-P)

APSDC-P indicates the PSDC value that is used in the PHY frame. The field shall be coded as a 5-bit unsigned value. The valid values are in the range from 0 to 25, plus 0x1F. Values from 0 to 25 correspond to an actual PSD ceiling in the range of −50 dBm/Hz to −100 dBm/Hz in 2 dB steps. The special value 0x1F indicates that no PSD ceiling is applied. Values from 26 to 30 are reserved by ITU-T.

7.1.2.3.2.7 ACKRQ frame type specific fields

For further study.

7.1.3 Physical medium attachment (PMA) sub-layer

The functional model of the PMA is presented in Figure 7-4. It is intended to describe in more detail the PMA functional block presented in Figure 7-1.

In the transmit direction, the incoming PHY frame (except for preamble and channel estimation symbols) at the α-reference point has a format as defined in §7.1.2. Both the header bits and the payload bits of the incoming frame are scrambled as described in §7.1.3.1. The header bits of the incoming frame are encoded as described in §7.1.3.4. The payload bits are encoded, as described in §7.1.3.3. The parameters of payload encoder are controlled by the PHY management entity.

After encoding, the header and payload are each segmented into an integer number of symbol frames as described in §7.1.3.5.1. The obtained symbol frames of the header 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 PHY-frame header and payload are submitted to the α-reference point for further processing in the PCS.

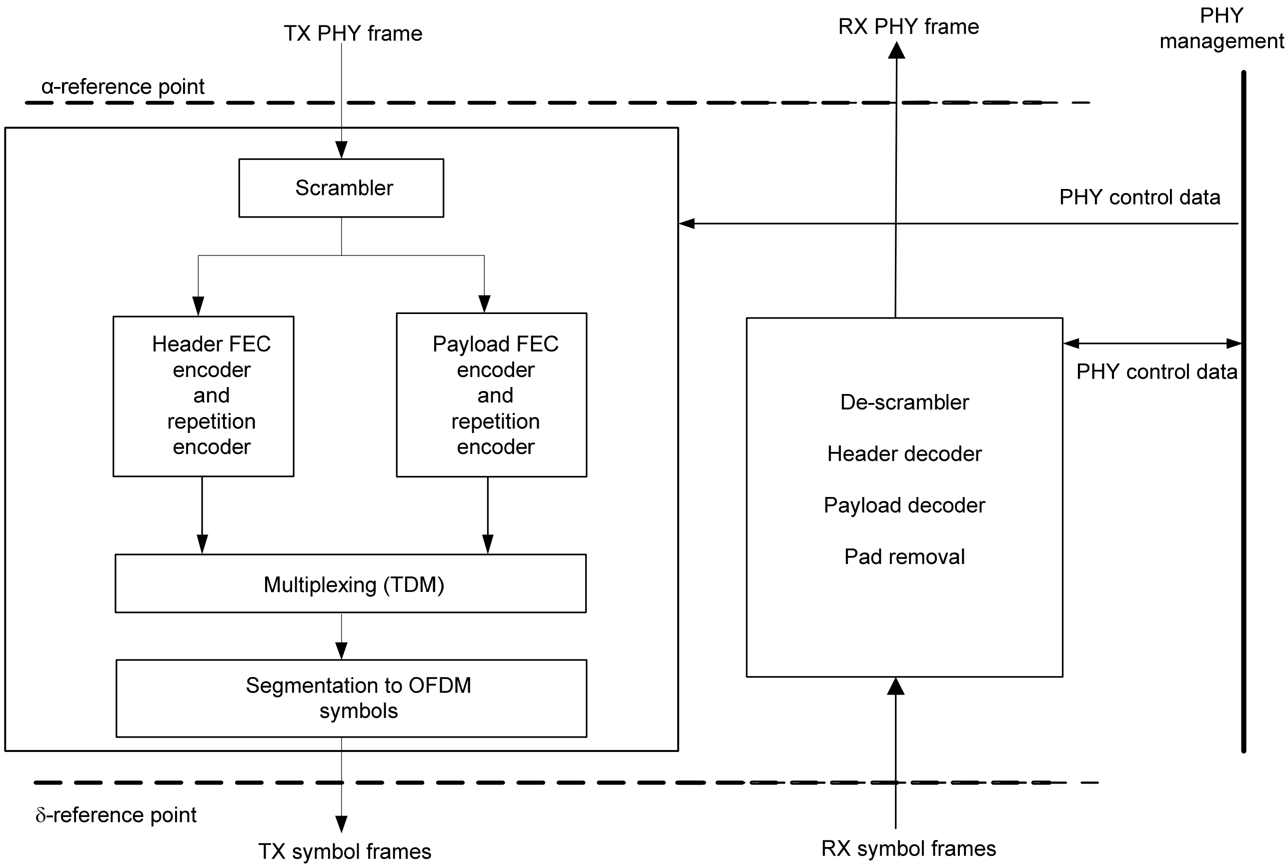

Figure 7-4/G.9960 – Functional model of PMA

7.1.3.1 Scrambling

All data starting from the first bit of the PHY-frame header 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 $p(x)=x^{23}+x^{18}+1$, as shown in Figure 7-5.

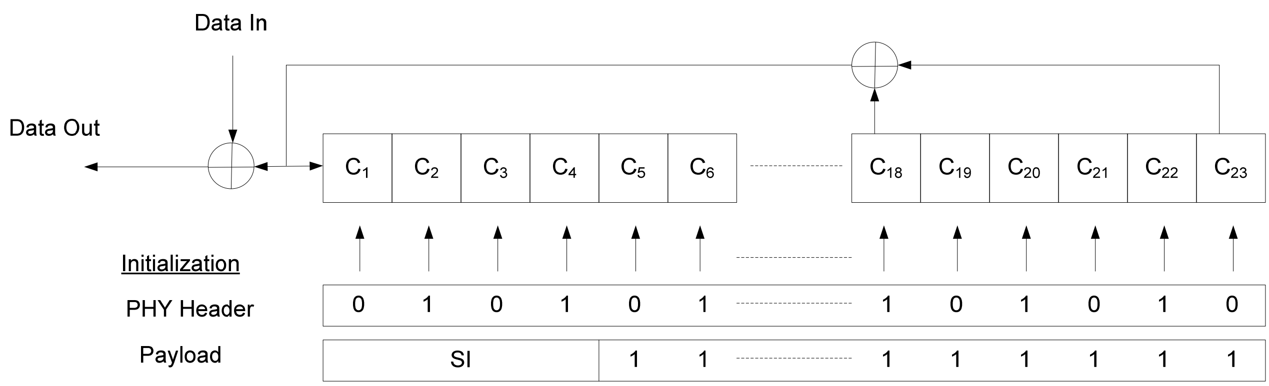

Figure 7-5/G.9960 – Scrambler; $p(x) = x^{23}+x^{18}+1$

The LFSR generator shall be initialized at the first bit of the header with the initialization vector equal to 0x2AAAAA (where the LSB corresponds to C_1); this initialization is used for scrambling of the header data. If SI is not equal to zero, a second initialization shall be performed for payload data, immediately after the last bit of the header is read from the scrambler and before the first bit of the payload is read from the scrambler. For the second initialization, the first four bits of the LFSR (C_1 to C_4) shall be set to the value of SI (Scrambler Initialization), while all other bits C_5 to C_{23} shall be initialized to 1. The value of SI = $C_4C_3C_2C_1$ is communicated in the header as described in §7.1.2.3.

The special value 0x0 for SI indicates that the scrambler is not re-initialized between the header and payload. The initialization of the SI field to values other than the special value is optional.

NOTE – the method for generating SI values is beyond the scope of this Recommendation.

7.1.3.2 FEC encoding

The FEC encoding scheme is shown in Figure 7-6. The scheme consists of a systematic QC-LDPC-BC encoder and a puncturing mechanism. The parameters of the FEC encoding scheme are:

- the number of incoming information bits, K (information block of bits);
- the number of coded bits, N_M (coded block of bits);
- the number of parity-check bits, $N_M - K$;
- the number of output bits, $N_{FEC} \leq N_M$, (FEC codeword, whose size depends on the puncturing pattern);
- the mother coding rate, $R_M = K/N_M$, defined as the coding rate before puncturing.
- the coding rate, $R = K/N_{FEC}$, defined as the coding rate after puncturing.

The information block size shall be one of the values specified in Table 7-19.

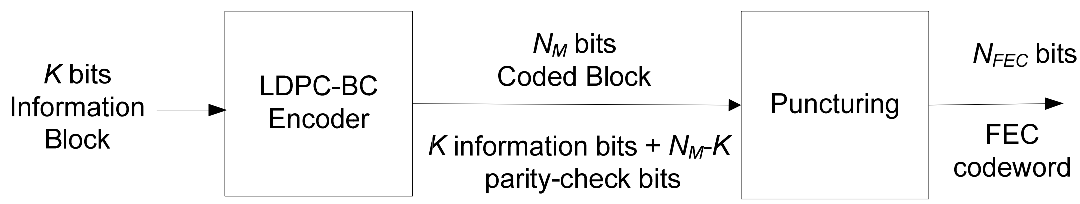

Figure 7-6/G.9960 – FEC Encoder

The encoder shall support mother codes with rates $R_M = 1/2$, $R_M = 2/3$ and $R_M = 5/6$. From these mother codes, codes with higher coding rates shall be obtained through puncturing, as described in §7.1.3.2.1.1. The Puncturing block shall support patterns providing all coding rates presented in Table 7-19.

The coding rate of the mother code, $R_M = K / N_M$, is determined by a $(N_M - K) \times N_M$ size parity-check matrix $\mathbf{H}$ composed by an array of $c \times t$ circulant $b \times b$ sub-matrices $\mathbf{A}_{i,j}$:

$$\mathbf{H} = \begin{bmatrix} \mathbf{A}_{1,1} & \mathbf{A}_{1,2} & \cdots & \mathbf{A}_{1,t} \\ \mathbf{A}_{2,1} & \mathbf{A}_{2,2} & \cdots & \mathbf{A}_{2,t} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}_{c,1} & \mathbf{A}_{c,2} & \cdots & \mathbf{A}_{c,t} \end{bmatrix}.$$

The parameters c, t ($0 < c \leq t$) imply a rate $R_M = (t-c)/t$. By selecting different sets of c, t, different rates can be obtained.

The sub-matrices $\mathbf{A}_{i,j}$ are either a rotated identity or a zero matrices and have a size of $b \times b$, where parameter $b = N_M / t$ is called the *expansion factor* of $\mathbf{H}$ and controls the code block size, N_M.

The parity-check matrix, **H**, is described in its compact form:

$$\mathbf{H}_c = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,t} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,t} \\ \vdots & \vdots & \ddots & \vdots \\ a_{c,1} & a_{c,2} & \cdots & a_{c,t} \end{bmatrix}$$

A zero sub-matrix in position (i, j) is labeled with $a_{i,j} = -1$, and a rotated identity sub-matrix is labelled with a positive integer number $a_{i,j}$ defining the number of right column shifts $\hat{a}_{i,j}$ modulo b of the identity matrix. The relation between $a_{i,j}$ and $\hat{a}_{i,j}$ is given by

$$\hat{a}_{i,j} = \begin{cases} a_{i,j} & a_{i,j} < 0, \\ \left\lfloor a_{i,j} \cdot \dfrac{b}{96} \right\rfloor & a_{i,j} \geq 0. \end{cases}$$

where $\lfloor x \rfloor$ is the integer part of variable x.

The compact form of parity-check matrix of mother code $\mathbf{H}_c$ with rate R_M =1/2 (t = 24, c = 12) shall be:

```
-1 94 73 -1 -1 -1 -1 -1 55 83 -1 -1  7  0 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1
-1 27 -1 -1 -1 22 79  9 -1 -1 -1 12 -1  0  0 -1 -1 -1 -1 -1 -1 -1 -1 -1
-1 -1 -1 24 22 81 -1 33 -1 -1 -1  0 -1 -1  0  0 -1 -1 -1 -1 -1 -1 -1 -1
61 -1 47 -1 -1 -1 -1 -1 65 25 -1 -1 -1 -1 -1  0  0 -1 -1 -1 -1 -1 -1 -1
-1 -1 39 -1 -1 -1 84 -1 -1 41 72 -1 -1 -1 -1 -1  0  0 -1 -1 -1 -1 -1 -1
-1 -1 -1 -1 46 40 -1 82 -1 -1 -1 79  0 -1 -1 -1 -1  0  0 -1 -1 -1 -1 -1
-1 -1 95 53 -1 -1 -1 -1 -1 14 18 -1 -1 -1 -1 -1 -1 -1  0  0 -1 -1 -1 -1
-1 11 73 -1 -1 -1  2 -1 -1 47 -1 -1 -1 -1 -1 -1 -1 -1 -1  0  0 -1 -1 -1
12 -1 -1 -1 83 24 -1 43 -1 -1 -1 51 -1 -1 -1 -1 -1 -1 -1 -1  0  0 -1 -1
-1 -1 -1 -1 -1 94 -1 59 -1 -1 70 72 -1 -1 -1 -1 -1 -1 -1 -1 -1  0  0 -1
-1 -1  7 65 -1 -1 -1 -1 39 49 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1  0  0
43 -1 -1 -1 -1 66 -1 41 -1 -1 -1 26  7 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1  0
```

The compact form of parity-check matrix of mother code $\mathbf{H}_c$ with rate R_M=2/3 (t = 24, c = 8) shall be:

2	-1	19	-1	47	-1	48	-1	36	-1	82	-1	47	-1	15	-1	95	0	-1	-1	-1	-1	-1	-1
-1	69	-1	88	-1	33	-1	3	-1	16	-1	37	-1	40	-1	48	-1	0	0	-1	-1	-1	-1	-1
10	-1	86	-1	62	-1	28	-1	85	-1	16	-1	34	-1	73	-1	-1	-1	0	0	-1	-1	-1	-1
-1	28	-1	32	-1	81	-1	27	-1	88	-1	5	-1	56	-1	37	-1	-1	-1	0	0	-1	-1	-1
23	-1	29	-1	15	-1	30	-1	66	-1	24	-1	50	-1	62	-1	-1	-1	-1	-1	0	0	-1	-1
-1	30	-1	65	-1	54	-1	14	-1	0	-1	30	-1	74	-1	0	-1	-1	-1	-1	-1	0	0	-1
32	-1	0	-1	15	-1	56	-1	85	-1	5	-1	6	-1	52	-1	0	-1	-1	-1	-1	-1	0	0
-1	0	-1	47	-1	13	-1	61	-1	84	-1	55	-1	78	-1	41	95	-1	-1	-1	-1	-1	-1	0

The compact form of parity-check matrix of mother code $\mathbf{H}_c$ with rate R_M=5/6 (t = 24, c = 4) shall be:

1	25	55	-1	47	4	-1	91	84	8	86	52	82	33	5	0	36	20	4	77	80	0	-1	-1
-1	6	-1	36	40	47	12	79	47	-1	41	21	12	71	14	72	0	44	49	0	0	0	0	-1
51	81	83	4	67	-1	21	-1	31	24	91	61	81	9	86	78	60	88	67	15	-1	-1	0	0
50	-1	50	15	-1	36	13	10	11	20	53	90	29	92	57	30	84	92	11	66	80	-1	-1	0

The codeword at the output of the Puncturing block is of size $N_{FEC} \le N_M$. The bits shall be output in the ascending order of codeword indices determined by vector **v**' (see §7.1.3.2.1.1); with this order the first information bit input to the encoder will be the first at the output of the puncturing.

7.1.3.2.1 Encoder

The encoder shall support coded block sizes and rates presented in Table 7-19. The parity-check matrix $\mathbf{H}$ used to encode a block of information bits is selected according to the mother code indicated in Table 7-19.

The encoding process shall be as follows:

1. A group of incoming K information bits $\mathbf{u} = [u_0, u_1, ..., u_{K-1}]$ are collected and copied to the output of the encoder to form a block of systematic code bits.
2. N_M-K parity-check bits, $\mathbf{p} = [p_0, ..., p_{N_M-K-1}]$, are computed using the parity-check matrix $\mathbf{H}$ and the information block $\mathbf{u}$. The resulting coded block $\mathbf{v} = [\mathbf{u} \mid \mathbf{p}]$ shall satisfy the parity check equations $\mathbf{vH}^T = \mathbf{0}$. Here $\mathbf{0}$ is a zero row vector of dimension N_M–K.
3. The N_M–K parity check bits **p** are copied to the output of the encoder as a block of parity-check bits $\mathbf{p} = [p_0, ..., p_{N_M-K-1}]$ to form the output coded block $\mathbf{v} = [\mathbf{u} \mid \mathbf{p}] = [v_0, v_1, ..., v_{N_M-1}]$
4. The output of the encoder **v** is the input to the Puncturing block (see Figure 7-6)

NOTE – One method of encoding is to determine a systematic generator matrix $\mathbf{G}$ from $\mathbf{H}$ such that $\mathbf{GH}^T = \mathbf{0}$. A K-bit information block $\mathbf{u} = [u_0, u_1, ..., u_{K-1}]$ can be encoded by the systematic generator matrix $\mathbf{G}$ via the operation $\mathbf{v} = \mathbf{uG}$ to become a N_M-bit coded block $\mathbf{v} = [v_0, v_1, ..., v_{N_M-1}] = [\mathbf{u} \mid \mathbf{p}]$, where $\mathbf{p} = [p_0, ..., p_{N_M-K-1}]$ are the parity-check bits. Encoding an LDPC code from $\mathbf{G}$ can be quite complex. However, the QC-LDPC-BC codes specified here are such that very low complexity encoding directly from $\mathbf{H}$ is possible.

7.1.3.2.1.1 Puncturing

Puncturing shall discard some of the coded block bits to achieve a higher coding rate (R). Puncturing is applied to both information and parity-check bits. The puncturing block uses puncturing patterns specified in Table 7-18. The puncturing patterns are denoted as $\mathbf{pp}_T^{(i)}$, where T is the length of the puncturing pattern and i is the number of zeros in the pattern.

Table 7-18/G.9960 – Puncturing patterns

	Puncturing pattern
$\mathbf{pp}_{16}^{(0)}$	[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1]
$\mathbf{pp}_{16}^{(1)}$	[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0]
$\mathbf{pp}_{1152}^{(144)}$	$[\underbrace{1\ 1\ \cdots\ 1}_{240}\ \underbrace{0\ 0\ \cdots\ 0}_{48}\ \underbrace{1\ 1\ \cdots\ 1}_{720}\ \underbrace{0\ 0\ \cdots\ 0}_{96}\ \underbrace{1\ 1\ \cdots\ 1}_{48}]$
$\mathbf{pp}_{5184}^{(648)}$	$[\underbrace{1\ 1\ \cdots\ 1}_{216}\ \underbrace{0\ 0\ \cdots\ 0}_{216}\ \underbrace{1\ 1\ \cdots\ 1}_{4320}\ \underbrace{0\ 0\ \cdots\ 0}_{432}]$

NOTE:

The pattern $\mathbf{pp}_{16}^{(0)}$ doesn't result in any coding rate changes and is introduced to be consistent with the puncturing notation.

The coded block **v** input to the puncturing block shall be processed using the puncturing pattern $\mathbf{pp}_T^{(i)}$ as follows:

For the pattern $\mathbf{pp}_T^{(i)} = [pp_0^{(i)},...,pp_{T-1}^{(i)}]$, the puncturing block shall omit all incoming coded bits $v_t, t = 0,..., N_M - 1$ for which $pp_{t \bmod T}^{(i)} = 0$. Hence, the resulting output FEC codeword will be $\mathbf{v}' = [v'_0, v'_1,..., v'_{N_{FEC}-1}]$ with $N_{FEC} \leq N_M$.

7.1.3.2.2 FEC encoding parameters

The FEC encoding scheme shall support encoding parameters specified in Table 7-19.

Table 7-19/G.9960 – FEC encoding parameters

	Coding rate, *R*	Information block size, *K*	Puncturing pattern, pp	Mother code rate, R_M	FEC codeword size, N_{FEC}
For Header	1/2	$PHY_H = 168$	$\mathbf{pp}_{16}^{(0)}$	1/2	336
For Payload	1/2	960	$\mathbf{pp}_{16}^{(0)}$	1/2	1920
	1/2	4320	$\mathbf{pp}_{16}^{(0)}$	1/2	8640
	2/3	960	$\mathbf{pp}_{16}^{(0)}$	2/3	1440
	2/3	4320	$\mathbf{pp}_{16}^{(0)}$	2/3	6480
	5/6	960	$\mathbf{pp}_{16}^{(0)}$	5/6	1152
	5/6	4320	$\mathbf{pp}_{16}^{(0)}$	5/6	5184
	16/18	960	$\mathbf{pp}_{16}^{(1)}$	5/6	1080
	16/18	4320	$\mathbf{pp}_{16}^{(1)}$	5/6	4860
	20/21	960	$\mathbf{pp}_{1152}^{(144)}$	5/6	1008
	20/21	4320	$\mathbf{pp}_{5184}^{(648)}$	5/6	4536

7.1.3.3 Payload encoding

The functional model of the payload encoder is presented in Figure 7-7. It contains an FEC encoder and a Payload Repetition Encoder (PRE) to support robust communication mode (RCM).

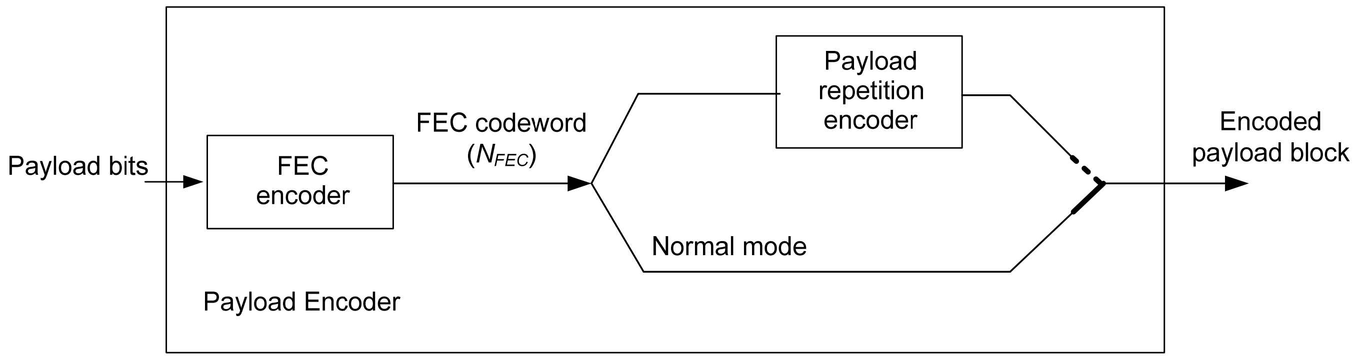

Figure 7-7/G.9960 – Functional diagram of the Payload Encoder (set to Normal mode)

The incoming PHY-frame payload shall be divided into sequential blocks of information bits, *K* bits per block. Each block of information bits shall be encoded by the FEC, as described in §7.1.3.2. The valid values of *K*, the coded block size N_{FEC}, and the coding rate *R*, are presented in Table 7-19. The bits of each information block shall be in the same order as they are in the payload; the payload bit to be transmitted first shall be the first in the corresponding information block.

In normal mode of operation, PRE is disabled. The FEC codewords shall be passed directly to the output of the Payload Encoder and concatenated into the encoded payload block; their order shall be the same as the order of corresponding information blocks at the input of the Payload Encoder.

In case of RCM, each FEC codeword is further encoded by the PRE, as described in §7.1.3.3.1. The PRE-encoded FEC codewords are concatenated into the encoded payload block as defined in §7.1.3.3.1.

7.1.3.3.1 Payload repetition encoding

Payload Repetition Encoder (PRE) shall support the number of repetitions N_{REP} specified in Table 7-8. The used number of repetitions shall be advertised in the REP field in the PHY-frame header.

The PRE shall operate as follows. Each incoming FEC codeword shall be first copied N_{REP} times. Each copy shall be divided into S sections, numbered from 0 to S-1, with B bits in each section, as follows:

- Bits of the FEC codeword shall be mapped into sections in ascending sequential order; the bit of the FEC codeword to be transmitted first shall be the first bit (b_0) of Section 0;
- If after all bits of the FEC codeword are mapped, the last q bit positions of the last section remain empty, these position shall be filled by the first q bits of Section 0 in ascending sequential order.

Mapping of an FEC codeword onto sections is shown in Figure 7-8.

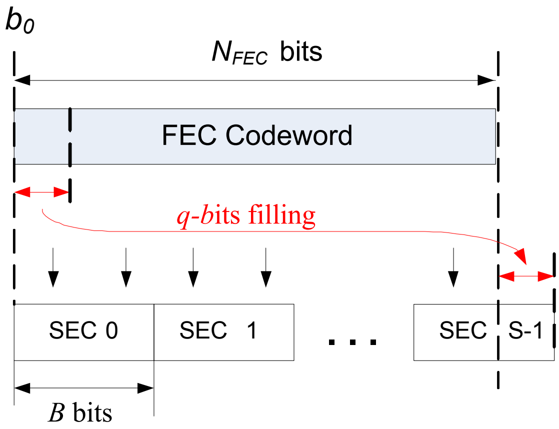

Figure 7-8/G.9960 – Mapping of a FEC codeword onto sections

If $floor(k_P/N_{REP})$ is divisible by 4, the number of bits per section shall be set to $B = floor(k_P/N_{REP}) - 1$, otherwise it shall be set to $B = floor(k_P/N_{REP})$, where k_P is the total number of bits that can be loaded onto the payload OFDM symbol according to the current BAT. The number of sections per FEC codeword is: $S = ceiling(N_{FEC}/B)$.

If the computed value of S is 1, H consecutive FEC codewords may be concatenated. The number of sections in this case shall be: $S = ceil(H \times N_{FEC}/B)$, where H is selected to provide $S > 1$ for the given values of N_{FEC}, N_{REP} and k_P. Concatenation of codewords may only be applied when an FEC information block size of 960 is used. The total size of the concatenated codewords shall not exceed the maximum FEC codeword size.

If the number of FEC codewords in the payload is not a multiple of H, the necessary $z < H$ dummy FEC codewords shall be added. These dummy codewords shall be copies of the last FEC codeword of the same payload. The values of H (1, 2 and 4) and z (0 to H–1) are indicated in the FCF field of the PHY-frame header (see Table 7-9).

The PRE shall output sections sequentially, in groups of *S* sections. Each group carries a copy of the FEC codeword. The number of groups per each FEC codeword is N_{REP}. The order of bits in each section shall be the same as these bits appear in the incoming FEC codeword.

The format of the encoded payload block with PRE enabled is presented in Figure 7-9. The total number of sections in the encoded payload block is $N_{REP} \times S$.

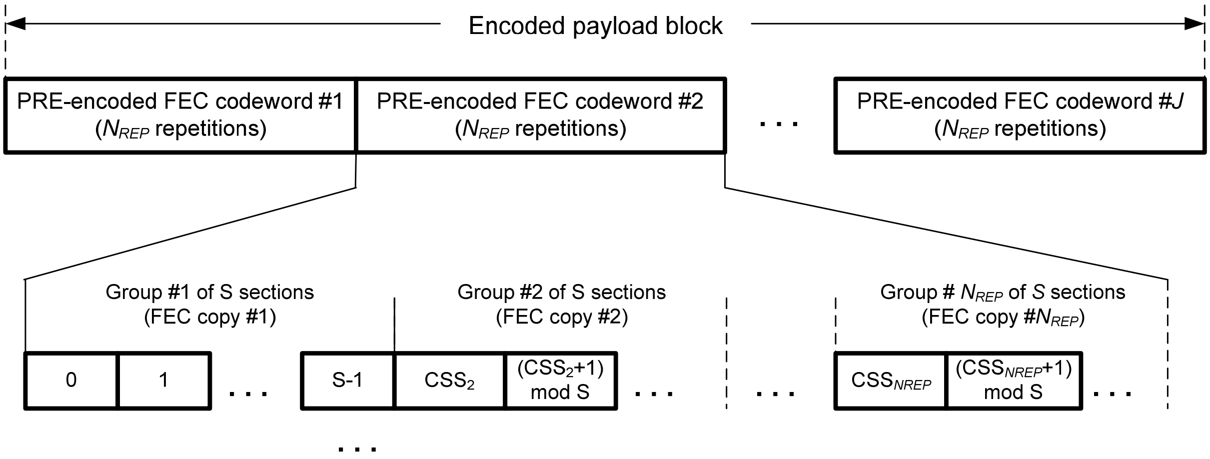

Figure 7-9/G.9960 – The format of the encoded payload block (payload consists of *J* FEC codewords)

The order of sections in the first group shall be ascending, from 0 to *S*-1; the order of sections in all subsequent groups shall be cyclically shifted. The shift is defined by the Cyclic Section Shift (CSS) vector $\{0\ CSS_2\ CSS_3\ \ldots\ CSS_{NREP}\}$ with a length of N_{REP}, where CSS_L is the sequential number of the section to be transmitted first in the *L*-th group of sections. The value of CSS shall be computed using the following rule:

For $N_{REP} = 2$:

if (*S* mod 2) = 0 CSS:= {0,1};

else CSS:= {0,0};

For $N_{\mathrm{REP}} = 4$:

if (*S* mod 4) = 0 CSS:= {0,1,2,3};

else if (*S* mod 2) = 0 CSS:= {0,0,1,1};

else CSS:= {0,0,0,0};

For $N_{REP} = 3$:

if (*S* mod 3) = 0 CSS:= {0,1,2};

else CSS:= {0,0,0};

For $N_{REP} = 6$:

if (*S* mod 6) = 0 CSS:= {0,1,2,3,4,5};

else if (*S* mod 3) = 0 CSS:= {0,0,1,1,2,2};

else if (*S* mod 2) = 0 CSS:= {0,0,0,1,1,1};

else CSS:= {0,0,0,0,0,0};

For N_{REP} = 8:

if (S mod 8) = 0 CSS:= {0,1,2,3,4,5,6,7};

else if (S mod 4) = 0 CSS:= {0,0,1,1,2,2,3,3};

else if (S mod 2) = 0 CSS:= {0,0,0,0,1,1,1,1};

else CSS:= {0,0,0,0,0,0,0,0};

NOTE: As an example, with CSS = 3_L for a group of S = 4 sections, these sections will be transmitted in the following order: 3, 0, 1, 2. The first group of sections, for comparison, is transmitted: 0, 1, 2, 3.

7.1.3.4 Header encoder

The functional model of the header encoder is presented in Figure 7-10. It contains an FEC encoder and a Header Repetition Encoder (HRE).

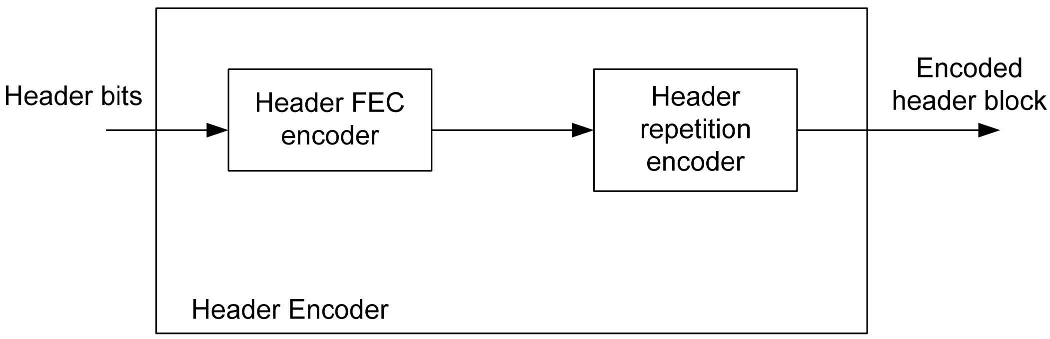

Figure 7-10/G.9960 – Functional diagram of the Header Encoder

The bits of the PHY-frame header shall input the Header FEC encoder in their original order and encoded as described in §7.1.3.2. The size of the FEC codeword and the coding rate of the Header FEC encoder are described in Table 7-19.

The FEC codeword enters the HRE. The HRE shall operate as follows:

- The FEC codeword shall be first copied M times, where M = ceiling (k_H/N_{FEC}), k_H is the number of bits to be loaded onto the OFDM symbol carrying the header
- The first encoded header block shall be formed by concatenation of M copies of the header FEC encoder output. The bits (b_i) within each codeword shall be cyclically shifted by 2 bits as follows:
  - The 1st FEC codeword copy shall be formed as $\{b_0, b_1, \ldots, b_{NFEC-2}, b_{NFEC-1}\}$.
  - The 2nd FEC codeword copy shall be formed as $\{b_2, b_3, \ldots, b_{NFEC-1}, b_0, b_1\}$.
  - The 3rd FEC codeword copy shall be formed as $\{b_4, b_5, \ldots, b_{NFEC-1}, b_0, b_1, b_2, b_3\}$.
  - …
  - The Mth FEC codeword copy, where $M > 3$, shall be formed as $\{b_{(2\times M-2)}, b_{(2\times M-1)}, \ldots, b_{NFEC-1}, b_0, b_1, \ldots, b_{(2\times M-4)}, b_{(2\times M-3)}\}$.

- The second encoded header block shall be formed by cyclic shifting of each copy by $N_{FEC}/2$ bits and concatenation of M copies of the shifter FEC codeword. The bits (b_i) within each codeword shall be cyclically shifted by 2 bits as follows:
  - The 1st FEC codeword copy shall be formed as $\{b_{NFEC/2}, b_{NFEC/2+1}, \ldots, b_{NFEC-2}, b_{NFEC-1}, b_0, b_1, \ldots, b_{NFEC/2-2}, b_{NFEC/2-1}\}$
  - The 2nd FEC codeword copy shall be formed as $\{b_{NFEC/2+2}, b_{NFEC/2+3}, \ldots, b_{NFEC-2}, b_{NFEC-1}, b_0, b_1, \ldots, b_{NFEC/2}, b_{NFEC/2+1}\}$
  - The 3rd FEC codeword copy shall be formed as $\{b_{NFEC/2+4}, b_{NFEC/2+5}, \ldots, b_{NFEC-2}, b_{NFEC-1}, b_0, b_1, \ldots, b_{NFEC/2+2}, b_{NFEC/2+3}\}$
  - …
  - The Mth FEC codeword copy, where M > 3, shall be formed as $\{b_{NFEC/2+(2\times M-2)}, b_{NFEC/2+(2\times M-1)}, \ldots, b_{NFEC-1}, b_0, b_1, \ldots, b_{NFEC/2+(2\times M-4)}, b_{NFEC/2+(2\times M-3)}\}$.

  NOTE: Since the coding rate used for header encoding is ½, the number of bits in the FEC codeword is always even, and the number of bits in the encoded header block is even.

7.1.3.5 Segmentation into symbol frames

The encoded payload block from the output of Payload encoder and the encoded header block from the output of the Header encoder shall be segmented into symbol frames. The maximum number of bits in the symbol frame shall not exceed the values of k_P for payload symbol frames and k_H for header symbol frame. Payload and header symbol frames shall be passed to the PMD, as described in Figure 7-4.

7.1.3.5.1 Payload segmentation

The encoded payload block shall be segmented into one or more symbol frames.

In normal mode, 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. If the number of bits in the last symbol frame is less than k_P, the unused sub-carriers of the OFDM symbol for the last symbol frame shall be modulated by a pseudo-random sequence of bits, as described in §7.1.4.2.6. Payload segmentation is illustrated in Figure 7-11.

In RCM, the first symbol frame shall contain the first N_{REP} sections of the encoded payload block, the second frame shall contain the second N_{REP} sections of the encoded payload block, and so on, until the last symbol frame. If the number of bits in N_{REP} sections is less than k_P, the unused sub-carriers of the corresponding OFDM symbols shall be modulated by a pseudo-random sequence of bits, as described in §7.1.4.2.6.

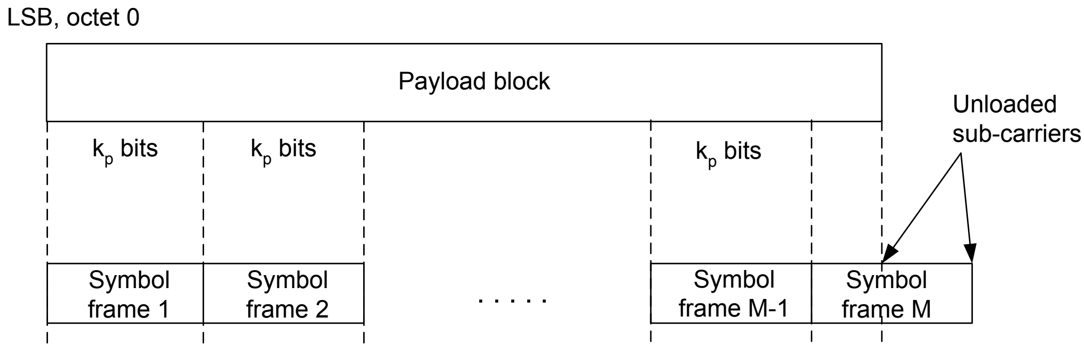

Figure 7-11/G.9960 – Payload segmentation

7.1.3.5.2 Header segmentation

The encoded header block shall be segmented into *D* symbol frames (valid values of *D* are 1 and 2). Selection of the value of *D* to be used is for further study.

The first k_H bits of the first encoded header block shall be mapped into the first symbol frame of the header, so that b_0 is transmitted first.

If $D = 2$, the first k_H bits of the second encoded header block shall be mapped into the second symbol frame of the header, so that $b_{NFEC/2}$ is transmitted first.

The rest of the bits of the first and the second encoded header blocks shall be discarded.

Header segmentation is illustrated in Figure 7-12.

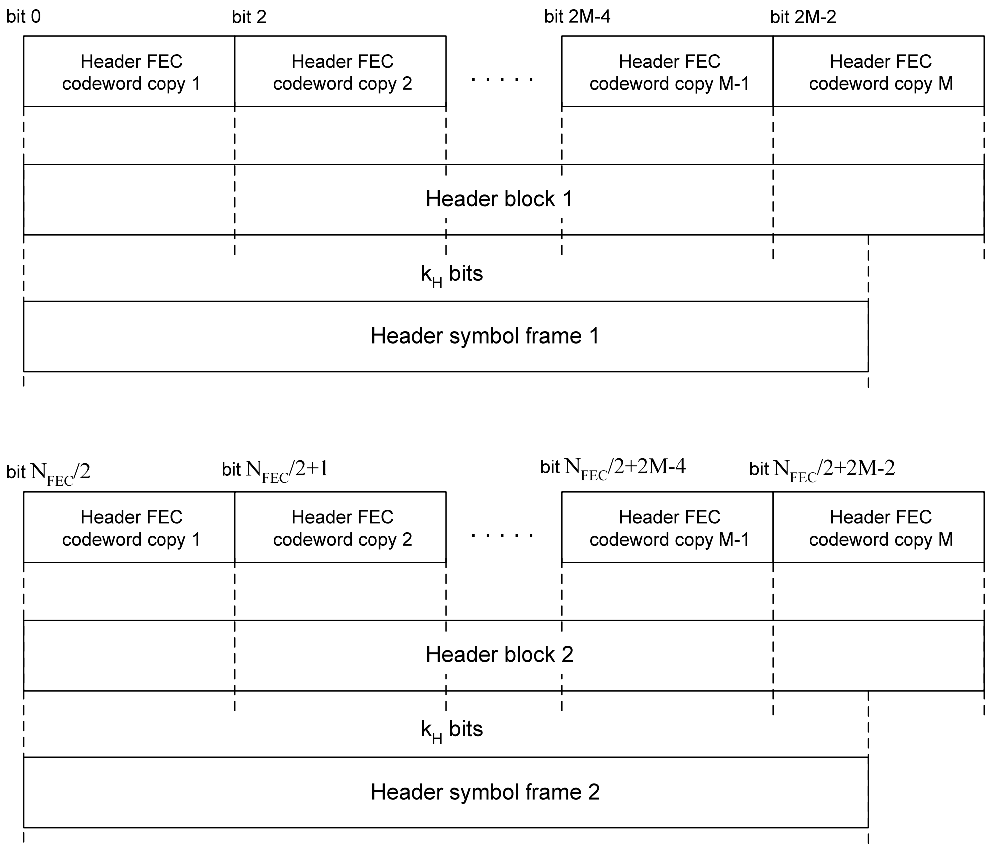

Figure 7-12/G.9960 – Header segmentation

7.1.3.6 Probe frame

The Probe frame is intended for the channel assessment procedure. The header of the Probe frame shall be as defined in §7.1.2.3. The payload of the Probe frame (at the δ-reference point) shall contain a number of symbol frames with no data (all supported sub-carriers (SSCs) are inactive sub-carriers (ISCs)) as described in field PRBSYM in §7.1.2.3.2.6.1. The number of the symbols shall be indicated via the PRBSYM field in §7.1.2.3.2.6.1. The inactive sub-carriers of the corresponding OFDM symbols shall be modulated by a pseudo-random sequence of bits, as described in §7.1.4.2.6.

The number of symbol frames (and OFDM symbols) in the Probe frame is indicated in the PHY-frame header.

7.1.4 Physical medium dependent (PMD) sub-layer

The functional model of the PMD is presented in Figure 7-13. In the transmit direction, the Tone mapper divides the incoming symbol frames of the Header and Payload into groups of bits and associates each group of bits with a specific sub-carrier onto which this group shall be loaded, as specified in §7.1.4.2. 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 §7.1.4.3.1. The unused sub-carriers are modulated by a pseudo-random bit sequence generated as described in §7.1.4.2.6.

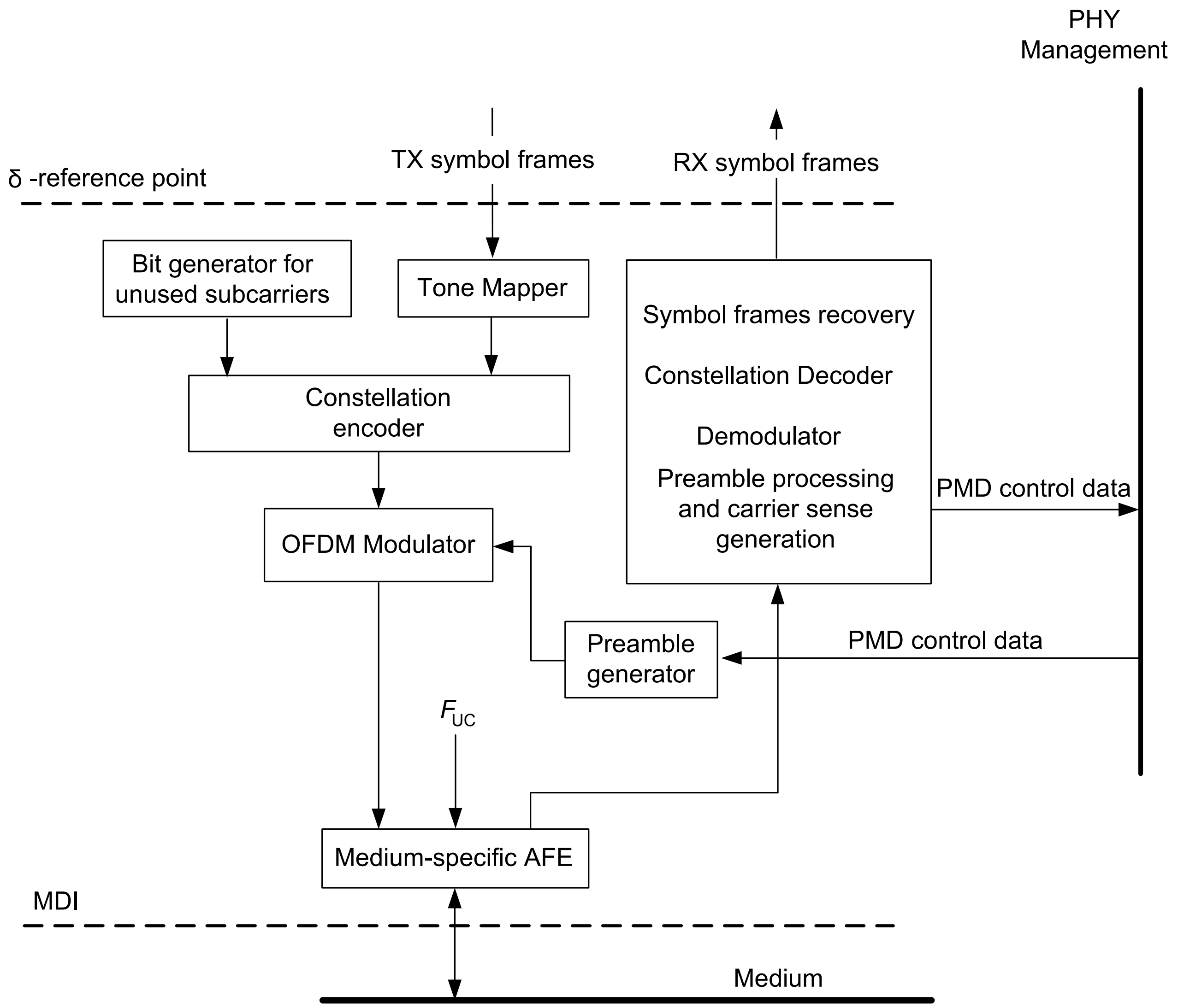

Figure 7-13/G.9960 – Functional model of the PMD

The OFDM modulator (§7.1.4.4) converts the stream of the N complex numbers at its input into the stream of N complex valued time-domain samples. After adding the Preamble, the transmit signal is up-shifted by F_{US}. For RF applications, the transmit signal is further up converted by F_{UC} to fit the required spectrum of the transmit signal. The real part of the resultant signal is transmitted onto the medium. Parameters of the Preamble (§7.1.4.5) are determined by the PHY management and depend on the type of the transmitted PHY frame.

Frames are output onto the medium with inter-frame gaps the details of which are for further study.

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

7.1.4.1 Sub-carrier spacing and logical indexing

The sub-carrier spacing F_{SC} is the frequency spacing between any two adjacent sub-carriers. Valid values of sub-carrier spacing are presented in Table 7-29.

The logical index t_i indicates the order in which data is loaded on sub-carriers. The index i goes from 0 to N-1. t_i is equal to the sub-carrier index on which the i^{th} group of bits from a symbol frame is loaded. (i.e. t_0 contains the index of the sub-carrier that is loaded first, t_1 contains the index of the sub-carrier that is loaded second, etc …)

Two indexing rules are defined for the logical index:

Rule #1: $t_i=i$, i.e., the sub-carriers are loaded in ascending order.

The sub-carrier with index i shall be centered at frequency $f = F_{US} – (N/2 – i) × F_{SC}$.

Rule #2: $t_i=N/2+i/2$ for even values of i, $t_i=N/2-(i+1)/2$ for odd values of i

The sub-carriers with even indices from $i = 0$ to $i = N – 2$ shall be centered at frequencies $f = F_{UC} + F_{US} + (i/2) × F_{SC}$ while those with odd indices from $i = 1$ to $i = N – 1$ shall be centered at frequencies $f = F_{UC} + F_{US} – ((i+1)/2) × F_{SC}$.

Logical indexing rules shall be applied in accordance with the domain type and the bandplan, as specified in Table 7-31, Table 7-35, and Table 7-40.

Not all sub-carriers may always be used for data transmission; some of them have to be switched off in special circumstances. Others may be only used with reduced power. The latter functions are performed by sub-carrier masking and gain scaling (§7.1.5.1, 7.1.5.3).

NOTE – The particular sub-carriers used for data transmission between two particular nodes depend on channel characteristics, such as loop attenuation and noise, and on the specific spectrum-use requirements, such as notching of amateur radio bands; some sub-carriers may be subject to PSD reduction, e.g., at high and low frequencies to share the medium with other services.

7.1.4.2 Tone Mapper

The tone mapper divides the incoming symbol frames of the Header and Payload into groups of bits (according to the BATs and sub-carrier grouping being used) and associates each group of bits with specific sub-carriers onto which these groups shall be loaded. This information along with sub-carrier-specific gain scaling values as described in §7.1.4.3.2.3 are passed to the constellation encoder.

7.1.4.2.1 Summary of sub-carrier types

For the purpose of tone mapping, the following types of sub-carriers are defined.

1. Masked sub-carriers (MSC) are those on which transmission is not allowed, i.e., the gain on this sub-carrier shall be set to zero. Two types of MSC are defined:

- Permanently masked sub-carriers (PMSC) – those that are never allowed for transmission. The list of PMSC forms a PMSC mask, which depends on the type of medium and is defined in §7.2. Data bits are never mapped on PMSC.

- Regionally masked sub-carriers (RMSC) – those that are not allowed for data transmission in some regions, while may be allowed in other regions. The list of RMSC forms a RMSC mask, which depends on the type of media and on the region/application. The number of RMSC, #RMSC = #MSC – #PMSC.

2. Supported sub-carriers (SSC) are those on which transmission is allowed under restrictions of the relevant PSD mask. The number of SSC, #SSC = N – #MSC. The following types of SSC are defined:

- Active sub-carriers (ASC) – those that have loaded bits ($b \geq 1$) for data transmission. ASC are subject to constellation point mapping, constellation scaling and constellation scrambling as described in §7.1.4.3. Data bits shall be mapped on ASC as described in §7.1.4.2.2.

- Inactive sub-carriers (ISC) – those that don't have any data bits loaded (e.g., because SNR is low). The number of ISC, #ISC = #SSC – #ASC. ISC can be used for measurement purposes or other auxiliary purposes. ISC are subject to transmit power shaping. The signals transmitted on ISC are defined in §7.1.4.2.6.

7.1.4.2.2 Bit Allocation Tables (BAT)

Tone mapping is defined by a Bit Allocation Table (BAT) that associates sub-carrier indices with the number of bits to be loaded on the sub-carrier. The order of sub-carrier 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 on the sub-carriers in the order of indices in the BAT, according to subcarrier indexing defined in §7.1.4.1.

The BATs used by the node in the particular PHY frame shall be indicated to the receiving node(s) in the BAT_ID field of the MSG PHY-frame type specific fields of the PHY-frame header, as described in §7.1.2.3.2.1. Up to 32 BATs with BAT_ID values in the range from 0 to 31 can be defined. One or more BAT_IDs can be assigned for each destination (per unicast or multicast DID, see §7.1.2.3.1.5). The assignment of BAT_IDs shall be as described in Table 7-20.

Table 7-20/G.9960 – Assignment of BAT_ID

BAT_ID	Type of BAT	Reference
0	Pre-defined, Type 0	§7.1.4.2.2.1
1	Pre-defined, Type 1	
2	Pre-defined, Type 2	
3	Pre-defined, Type 3	
4-15	Reserved by ITU-T for pre-defined BATs	
16-31	Reserved by ITU-T for runtime BATs	§7.1.4.2.2.2

Every node shall support at least pre-defined BATs of Type 0 and Type 1. Support of other BATs is profile-dependent. This dependency is for further study.

7.1.4.2.2.1 Pre-defined BATs

The following pre-defined BATs are defined.

1. Pre-defined BAT Type 0: Uniform 2-bit loading on all sub-carriers except the PMSC set.
2. Pre-defined BAT Type 1: Uniform 1-bit loading on all sub-carriers except the PMSC set.
3. Pre-defined BAT Type 2: Uniform 2-bit loading on a particular selected ASC set.
4. Pre-defined BAT Type 3: Uniform 1-bit loading on a particular selected ASC set.

NOTE: Pre-defined BAT Type 0 and Type 1 may be used when channel characteristics are unknown (i.e., no knowledge is available on whether particular tones could be loaded bits or not).

NOTE: Pre-defined BATs that are implemented using a particular ASC set (e.g., Type 2) are always associated with a reference, such as a runtime BAT, which defines this ASC set. The coding is for further study.

7.1.4.2.2.2 Runtime BATs

A runtime BAT associates indices of SSCs with the number of bits to be loaded on each sub-carrier. The subset of indices in the BAT with the number of loaded bits $b > 0$ identifies the ASC. Runtime BAT can be defined by the receiving node (receiver-defined BAT) or selected by the transmitting node (transmitter-determined BAT) for a specific unicast or multicast channel. Runtime BATs shall be communicated from the node which generates the BAT to the peer (e.g., a node sourcing multicast transmission to several other nodes will communicate the BAT to all receiving nodes prior to sending data).

The number of bits loaded on any sub-carrier shall not exceed the maximum number of bits allowed (see §7.1.4.3). The number of bits shall also meet the bit loading capabilities of the communicating nodes, as advertised by them prior to communication.

7.1.4.2.3 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 pre-defined BAT or it shall be communicated to all destination nodes prior to transmission. With receiver-determined mapping, the BAT is defined by the receiver of the destination node and communicated back to the transmitter.

For unicast transmission, the node shall use either one of the pre-defined BATs (transmitter-determined) or a BAT defined by the receiver of the destination node for the PHY frame. For multicast transmission both pre-defined BATs (transmitter determined) and runtime BATs can be used. If a runtime BAT is used, it shall be defined by the node sourcing the multi-cast (transmitter-determined); this node shall generate the BAT and communicate it to all multi-cast destinations.

The BAT communication protocol is for further study.

A node shall support both transmitter-determined and receiver-determined types of mapping, with the minimum number of simultaneously supported BATs depending on the profile.

7.1.4.2.4 BAT with sub-carrier grouping

A node shall be capable to define any runtime BAT using sub-carrier grouping of $G = 1$ (no grouping), 2, 4, 8, and 16 sub-carriers with subsequent frequencies. The default value of $G = 1$. If grouping is used ($G > 1$), all sub-carriers of the same group shall use the same bit loading. The first group shall include G sub-carriers in ascending order of subcarrier indices defined in §7.1.4.1. If a group includes sub-carriers that are masked (e.g., MSC) or extends beyond the applicable sub-carrier set, the node shall apply the bit loading assigned for this group only to the applicable sub-carrier set.

The group index G shall be indicated when the BAT is communicated, details of which are for further study. Additional methods for BAT compression are for further study.

7.1.4.2.5 Special mappings

7.1.4.2.5.1 Tone mapping for PHY-frame header

The PHY-frame header shall use a uniform loading of 2 bits per sub-carrier on all sub-carriers except the PMSC set.

7.1.4.2.5.2 Tone mapping for RCM

Payload transmission in robust communication mode RCM shall use pre-defined BAT Types with uniform 2 bit per sub-carrier loading.

7.1.4.2.5.3 Tone mapping for probe frame

The payload of the Probe frame shall be modulated using a uniform loading of 1 bit per sub-carrier on all SSC set. For Probe frames, ISC = SSC.

7.1.4.2.6 Modulation of unloaded sub-carriers

Supported sub-carriers (SSC) that are not loaded with payload bits or that are partially loaded with payload bits shall be loaded with a pseudo-random sequence defined by the Linear Feedback Shift Register (LFSR) generator with the polynomial $p(x)=x^{23}+x^{18}+1$ shown in Figure 7-14. The LFSR generator shall be initialized at the beginning each OFDM symbol with a seed from Table 7-21. The i^{th} payload symbol shall use the seed S_k where k is equal to (i-1, modulo 64) +1, where i=1,2,3,4,...

NOTE – Seeds S_1 to S_{64} are used to initialize the LFSR for payload symbols 1-64, 65-127 and so on.

The LFSR shall be advanced by two bits for each sub-carrier (for both SSC and MSC) of each symbol of the payload. If a special channel-estimation symbol is used after the PHY-frame header, it shall be considered as a payload symbol.

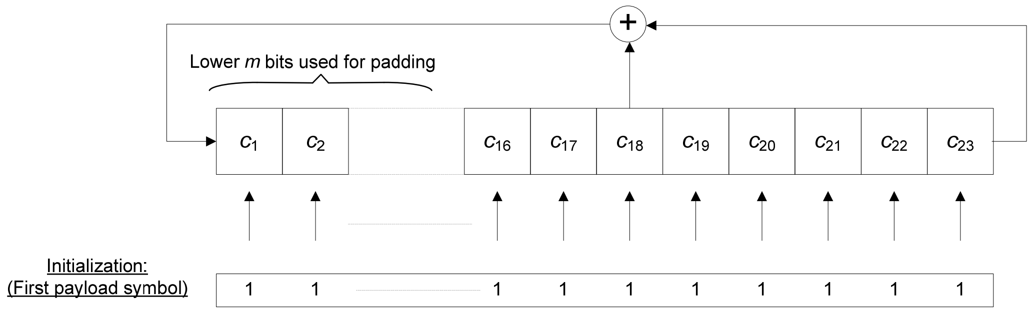

Figure 7-14/G.9960 – LFSR for modulation of unloaded and partially loaded sub-carriers

Table 7-21/G.9960 – LFSR seeds

Seed index k	Seed (S_k)
1	0x7FFFFF
2	0x26B489
3	0x278A91
4	0x15F4ED
5	0x5B4CB1
6	0x2F021F
7	0x7A64C1
8	0x414CD7
9	0x649D5E
10	0x134826
11	0x2A3DFC
12	0x2B9570
13	0x3C6777
14	0x757986
15	0x103962
16	0xDB87B
17	0x76287
18	0x3E1A31
19	0x5DE6D
20	0x5C5B4E
21	0x596413
22	0x613D9
23	0x19504A
24	0x50FDE0
25	0x5CD048
26	0x66C646
27	0x7169B3
28	0x480497
29	0x53FE3
30	0x51F1B1
31	0x7D2BA0
32	0x11E4D8
33	0x37144
34	0x278587
35	0x2CF7F7
36	0x27D46
37	0x70A7EB
38	0x4C622C
39	0x54DC68
40	0x1715E
41	0x274A7B
42	0x55238D
43	0x8B06
44	0x3FA255
45	0x777A6A
46	0x5154DD

47	0x55C203
48	0xD21F9
49	0x1BEDE6
50	0x608D6B
51	0x4B75D3
52	0x22BA64
53	0x7D0646
54	0x7F56E6
55	0x614333
56	0x4F1368
57	0x7359EF
58	0x2D86A9
59	0x25373D
60	0x258466
61	0x4CE92A
62	0x6B7E3D
63	0x760B34
64	0x761EA6

The modulation of sub-carriers that are not loaded with payload bits shall be as follows:

1) Starting at the beginning of the first payload OFDM symbol, each sub-carrier from the ISC set shall be modulated with the two bits which are the LSBs of the LFSR, c_1, and c_2 using 2-bits constellation mapping defined in §7.1.4.3.1.1 (c_1 is transmitted first). All SSC of a channel-estimation symbol are ISC.
2) In every OFDM symbol of payload, if the number of bits in the symbol frame doesn't fill the entire symbol, the bits from the LFSR shall be used to fill the remainder of the symbol frame, by taking the sequential groups of *m* LSBs of the LFSR and mapping them onto the remaining sub-carriers so that LSB of LFSR is transmitted first and in the order defined by the current BAT, where *m* is the number of bits allocated for that sub-carrier by the BAT. For the first padded sub-carrier, if *n* bits of the *m* loaded bits are data bits, these *n* data bits shall be loaded as the LSBs of the group of bits mapped on the constellation point, and the $m-n$ bits of the LFSR shall be used as the MSBs of the group of bits mapped on the constellation point starting from LSB of LFSR.
3) In the case of a Probe frame, starting at the beginning of the first payload OFDM symbol, each sub-carrier from the ISC set shall be modulated with the one bit, which is the LSB of the LFSR, c_1, using 1-bit constellation mapping defined in §7.1.4.3.1.2.

Bits from LFSR are generated and loaded on sub-carriers in the order of logical indices, according to subcarrier indexing defined in §7.1.4.1. Modulation of unloaded sub-carriers shall start from the unloaded SSC sub-carrier with the first logical index (t_0) of the first payload symbol, continue in ascending order of logical indices till the unloaded SSC sub-carrier with the last logical index (t_{N-1}) of the first payload symbol, continue with the unloaded SSC sub-carrier with the first logical index of the second payload symbol, continue in ascending order of logical indices till the unloaded SSC sub-carrier with the last logical index of the second payload symbol, and so on till the unloaded SSC sub-carrier with the last logical index of the last payload symbol.

The ASC from the SSC set are loaded according to the corresponding BAT as defined. in §7.1.4.2.2.

7.1.4.3 Constellation Encoder

7.1.4.3.1 Constellation mapping

Constellation mapping associates every group of bits loaded onto a sub-carrier, with the values of *I* (in-phase component) and *Q* (quadrature component) of a constellation diagram. Each incoming group of *b* bits $\{d_{b-1}, d_{b-2}, \ldots d_0\}$ shall be associated with a specific values of *I* and *Q* computed as described in this section.

Each group of bits $\{d_{b-1}, d_{b-2}, \ldots d_0\}$ shall be mapped onto the constellation mapper with the LSB bit, d_0, first.

7.1.4.3.1.1 Constellations for even number of bits

If the number of bits, *b*, loaded onto the sub-carrier is even (2, 4, 6, 8, 10, 12), square-shaped constellations with mappings described in this section shall be used. Support of all the specified even order constellations (2, 4, 6, 8, 10 and 12) shall be mandatory at both the transmitter and the receiver. With square-shaped constellations 2^b constellation points are set as a square, and 2^{b-2} points reside in each quadrant with odd values (positive or negative) of *I* and *Q*.

Constellation and mapping for *b* = 2 shall be as presented in Figure 7-15 and described in Table 7-22.

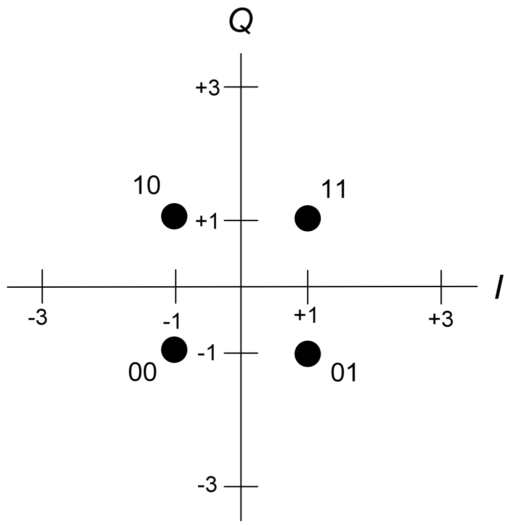

Figure 7-15/G.9960 - Constellation and mapping for *b* = 2

Table 7-22/G.9960 - Mapping for *b* = 2 (QPSK)

Bit d_0	*I*		Bit d_1	*Q*
0	-1		0	-1
1	1		1	1

Constellation mapping for *b* = 4 shall be as described in Table 7-23. The first quadrant of the mapping is presented in Figure 7-16.

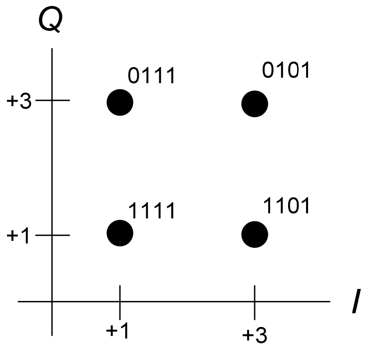

Figure 7-16/G.9960 – Constellation and mapping for *b* = 4 (first quadrant)

Table 7-23/G.9960 - Mapping for *b* = 4

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

Constellation mappings for even values of $b \geq 4$ shall be derived by the following steps.

1. Divide the incoming group of *b* bits into two equal sub-groups, so that *b*/2 LSBs form the first sub-group (*I*-group) and *b*/2 MSBs form the second sub-group (*Q*-group); both sub-groups are incoming LSB (which are d_0 and $d_{b/2}$, respectively) first.

2. Compute values of *I* and *Q* for the incoming group $\{d_{b-1}, d_{b-2}, \ldots d_0\}$ as:

$$I = sgn_I \times val_I$$

$$Q = sgn_Q \times val_Q$$

The values of *sgn* and *val* shall be computed as presented in Table 7-24 using bits of *I*-group to compute *I* and bits of *Q*-group to compute *Q*.

Table 7-24/G.9960 – Computation rule for *sgn* and *val*

I - component	*Q* - component
- compute $sgn_I = 2 \times d_0 - 1$ - compute $val_I = \lvert I_{b-2} - 2^{b/2-1} \rvert$	- compute $sgn_Q = 2 \times d_{b/2} - 1$ - compute $val_Q = \lvert Q_{b-2} - 2^{b/2-1} \rvert$
NOTES: 1. I_{b-2} and Q_{b-2} are the values of *I* and *Q* computed for the incoming (b–2)-bit group $\{d_{b-1}, d_{b-2}, \ldots d_{b/2+1}, d_{b/2-1}, \ldots d_1\}$, i.e., with d_0 and $d_{b/2}$ removed. 2. The values of *I* and *Q* for 2-bit groups shall be as presented in Table 7-22 3. $\lvert X \rvert$ is the absolute value of *X*	

7.1.4.3.1.2 Constellations for odd number of bits

If the number of bits, b, loaded onto the sub-carrier is odd (1, 3, 5, 7, 9, 11), constellations with mappings described in this section shall be used. The support of all the specified odd order constellations (1, 3, 5, 7, 9 and 11) shall be mandatory at the transmitter. The support of all the specified odd order constellations with $b \geq 5$, shall be optional at the receiver.

For multi-cast transmission, odd constellations with $b \geq 5$ shall not be used.

Constellation and mapping for $b = 1$ shall be as presented in Figure 7-17.

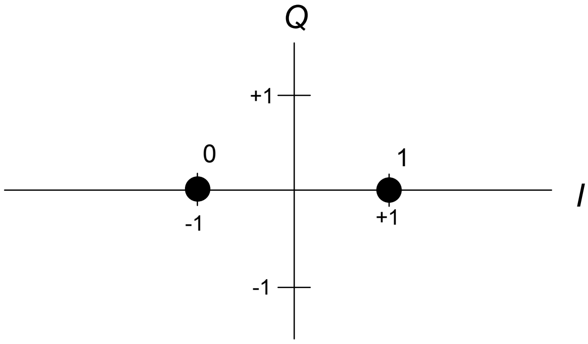

Figure 7-17/G.9960 - Constellation shape and mapping for *b* = 1

Constellation and mapping for $b = 3$ shall be as presented in Figure 7-18.

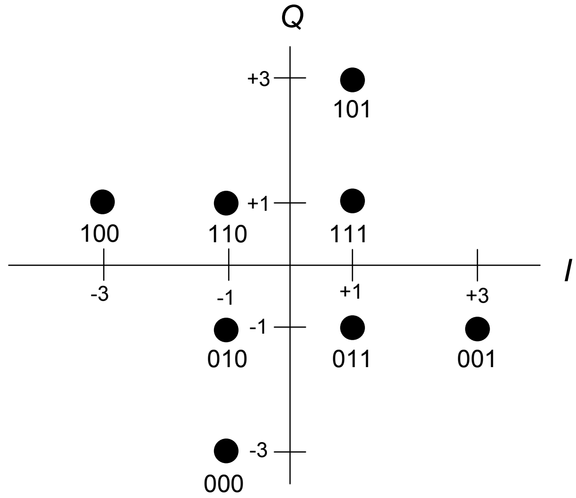

Figure 7-18/G.9960 - Constellation and mapping for *b* = 3

For $b > 3$ cross-shaped constellations shall be used. First, 2^b constellation points shall be set as a rectangle, with $M_I = 2^{B1}$ columns (M_I points on the I-axis) and $M_Q = 2^{B2}$ rows (M_Q points on the Q-axis), where $B1 = ceiling(b/2)$ and $B2 = floor(b/2)$. The mapping of these points shall be computed using the following steps.

1. Divide the incoming group of bits into two sub-groups, so that $B1$ LSBs form the first sub-group (I-group) and $B2$ MSBs form the second sub-group (Q-group); both sub-groups are incoming LSB (which are d_0 and d_{B2+1}, respectively) first.

2. Compute values of I and Q of a rectangular constellation for the incoming group $\{d_{b-1}, d_{b-2}, \ldots d_0\}$ as:

$$I = sgn_I \times val_I$$

$$Q = sgn_Q \times val_Q$$

The values of *sgn* and *val* shall be computed as presented in Table 7-25 using bits of *I*-group to compute *I* and bits of *Q*-group to compute *Q*.

Table 7-25/G.9960 – Computation rule for *sgn* and *val*

I - component	*Q* - component
- compute $sgn_I = 2\times d_0 - 1$ - compute $val_I = \|I_{2\times B1}\|$	- compute $sgn_Q = 2\times d_{B1} - 1$ - compute $val_Q = \|Q_{2\times B2}\|$
NOTES: 1. $I_{2\times B1}$ is the value of *I* for (2×*B*1)-bit group $\{0, d_{b-1}, d_{b-2}, \dots d_0\}$ computed as defined in Table 7-24. 2. $Q_{2\times B2}$ is the value of *Q* for (2×*B*2)-bit group $\{d_{b-1}, d_{b-2}, \dots d_1\}$ computed as defined in Table 7-24. 3. |X| is the absolute value of X	

3. Transform $s = (M_I - M_Q)/4$ columns of constellation points in each quadrant having highest absolute values of *I* (positive or negative) into rows of *Q* by changing their $\{I, Q\}$ coordinates to $\{I', Q'\}$ in the following way:

- $|Q'| = |I| - 2s$, and sign (Q') = sign (I);
- $|I'| = M_Q - |Q|$, and sign (I') = sign (Q).

The described transformation of $\{I, Q\}$ coordinates for $b = 7$ is presented in Figure 7-19 with $B1 = 4$ and $B2 = 3$ (the MSB and LSB in Figure 7-19 are separated by "/").

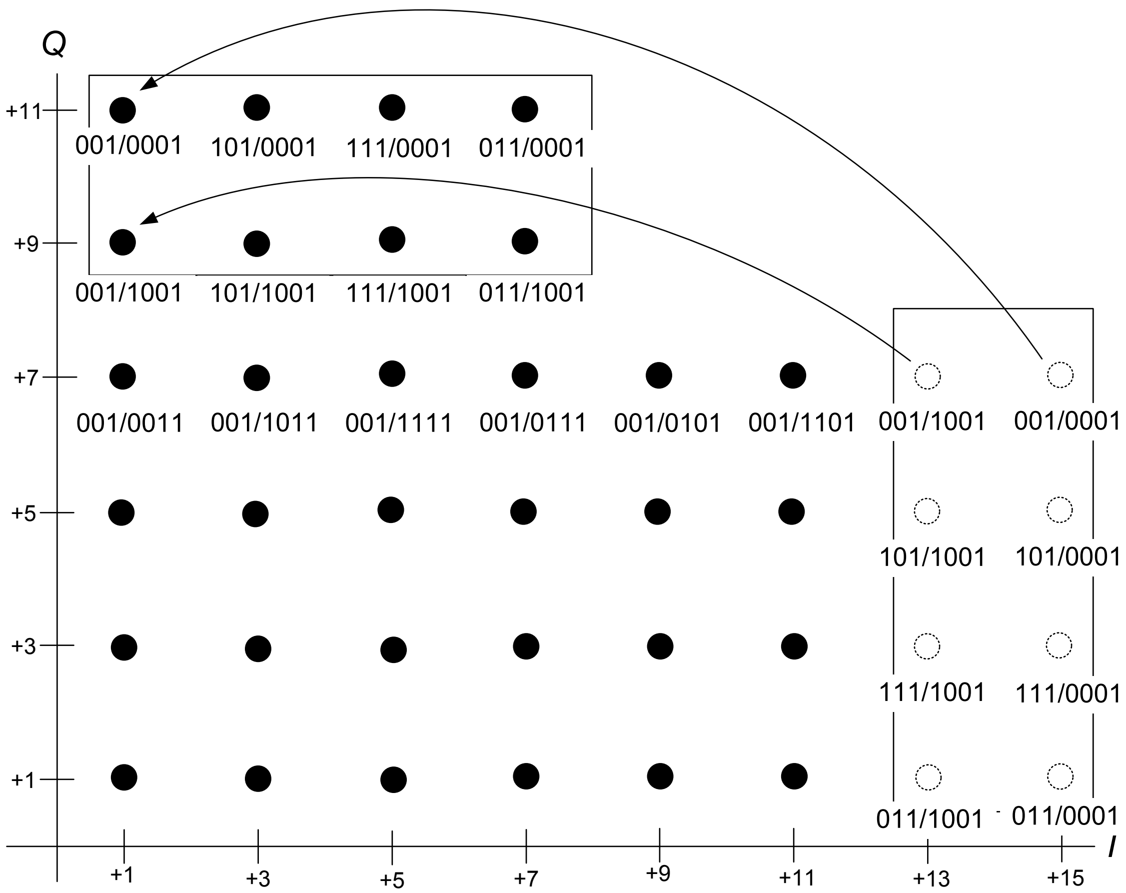

Figure 7-19/G.9960 - Transformation of rectangular constellation into cross-shaped constellation for *b* = 7 (first quadrant)

7.1.4.3.2 Constellation point scaling

Each constellation point (*I*, *Q*), corresponding to the complex value $I + jQ$ at the output of the constellation mapper, shall be scaled by the power-normalization factor χ(*b*), the frequency-domain spectrum shaping coefficient *tss*, and the gain adjuster *g*:

$$Z = \chi(b) \times tss \times g \times (I + jQ).$$

7.1.4.3.2.1 Power normalization factor

The values (*I, Q*) for each constellation point of each sub-carrier shall be scaled such that all constellations, regardless of their size, have the same average power. The required scaling, χ(*b*), for a sub-carrier with *b*-bit loading depends only on the value of *b* and shall be set as presented in Table 7-26.

Table 7-26/G.9960 – Power normalization factor

Number of bits loaded (*b*)	Scaling factor (χ) (linear scale)
1	1
2	$1/\sqrt{2}$
3	$1/\sqrt{6}$
4	$1/\sqrt{10}$
5	$1/\sqrt{20}$
6	$1/\sqrt{42}$
7	$1/\sqrt{82}$
8	$1/\sqrt{170}$
9	$1/\sqrt{330}$
10	$1/\sqrt{682}$
11	$1/\sqrt{1322}$
12	$1/\sqrt{2730}$

7.1.4.3.2.2 Transmit spectrum shaping

Frequency-domain spectrum shaping of the transmit signal is achieved by a scaling factor *tss* defined for each sub-carrier. The *tss* values are set by the transmitter and shall be in the range between 0 and −30 dB in steps of −0.5 dB. Smaller values of *tss* provide attenuation and the value *tss* = 0 dB corresponds to no power attenuation on the particular sub-carrier. If no spectrum shaping is applied, the *tss* values shall be equal to 0 dB for all sub-carriers. The values of tss_i are relevant only for sub-carriers that are actually transmitted (not masked), and shall be ignored for masked sub-carriers (see §7.1.5.3).

The communication protocol for *tss* is for further study.

7.1.4.3.2.3 Gain adjustment

The gain adjuster *g* is intended for fine gain adjustment of the power transmitted at a particular sub-carrier, which may be used to equalize the SNR margin over all sub-carriers.

The value of gain adjuster shall be set to 1. Other values are left for further study.

7.1.4.3.3 Constellation Scrambler

The phase of constellation points generated by the Constellation Mapper shall be shifted in accordance with the pseudo-random sequence generated by a Linear Feedback Shift Register (LFSR) generator, as shown in Figure 7-20.

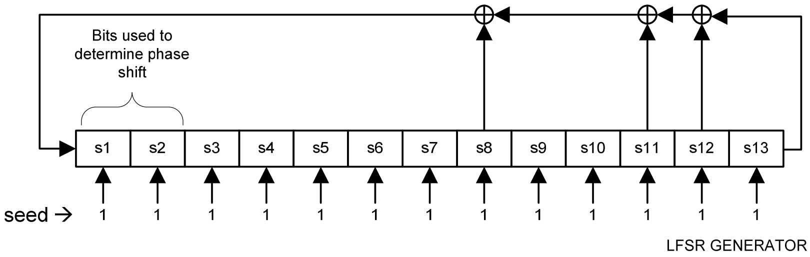

Figure 7-20/G.9960 – Constellation scrambler

The LFSR generator shall implement the polynomial $g(x) = x^{13}+ x^{12}+ x^{11}+x^{8}+1$ and shall be advanced by 2 bits for each sub-carrier. Bits shall be assigned to sub-carriers in order of logical index (see §7.1.4.1). The two LSBs of the register shall be taken to determine the phase shift as shown in Table 7-27. The shift of the LFSR for sub-carrier index t_k will be $2k$.

Table 7-27/G.9960 – Constellation phase shift versus LSFR output

LFSR OUTPUT		**PHASE SHIFT (rad)**
s2	s1	
0	0	0
0	1	π/2
1	0	π
1	1	3π/2

The LFSR generator shall be initialized with the seed 0x1FFF for each OFDM symbol. The constellation scrambling shall be applied to the PHY-frame header and all payload symbols by rotating the originally mapped constellation point $Z^0_{i,1}$ by the phase shift θ to obtain the complex value for the $Z_{i,1}$ for input to the IFFT (see §7.1.4.4.1).

$$Z_{i,l} = Z^0_{i,l} \cdot \exp(j\theta)\,.$$

7.1.4.4 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 sub-carrier, with index i, is the complex value $Z_{i,l}$

generated by the Constellation encoder as described in §7.1.4.3.2 (for symbols of the header and the payload) or by Preamble Generator as described in §7.1.4.5.2.1 (for symbols of the preamble). 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. RF up-converter facilitates G.9960 operation in RF frequency range.

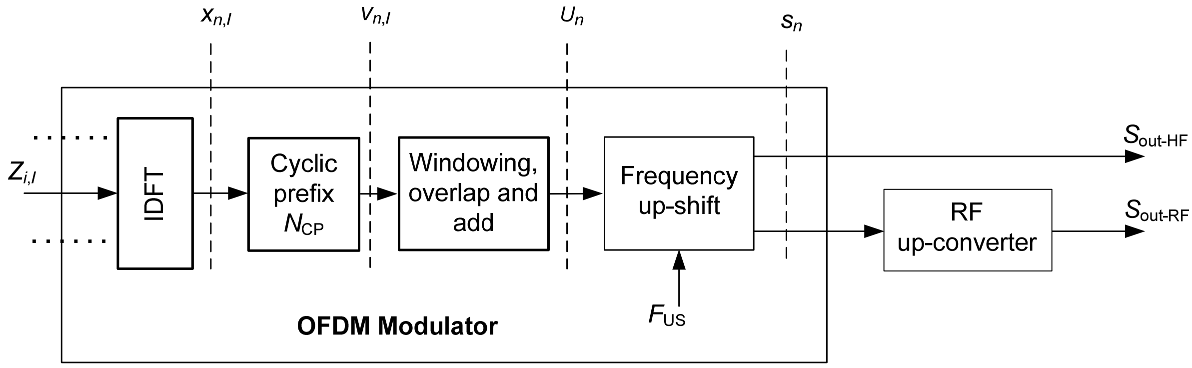

Figure 7-21/G.9960 – Functional model of the OFDM modulator

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

7.1.4.4.1 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 numbers 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 sub-carrier of the OFDM signal, where $i = 0, 1, \ldots N\text{-}1$ is the sub-carrier 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 sub-carriers in the OFDM spectrum and shall be a power of 2: $N = 2^k$, where k shall be an integer. The value of $Z_{i,l}$ for all masked sub-carriers shall be set to 0. If some non-masked sub-carriers with indices $i < N$ are not modulated (not in use), the corresponding values of $Z_{i,l}$ shall be generated as described in §7.1.4.2.6

7.1.4.4.2 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).

In OFDM, the guard interval of the l-th OFDM symbol in the frame shall be implemented by prepending 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 $\upsilon_{n,1}$ in Figure 7.19 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 frame. The value of $N_{CP}(l)$ (and the duration of the symbol $N_w(l)$, accordingly) may change during the course of the frame, as following:

- All symbols of the header shall have the value of $N_{GI-HD}+\beta$ defined in §7.1.4.6;
- The first two symbols of the payload shall have the default value $N_{GI-DF}+\beta$, defined in §7.1.4.6. If a special channel-estimation symbol is used after the PHY-header, it shall be considered as a payload symbol for this purpose;
- All the rest of the payload symbols shall have the same value of N_{GI} selected from the valid values defined in §7.1.4.6 and indicated in the header, as described in §7.1.2.1.

7.1.4.4.3 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 PHY-header) 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 $N_S(k)$ may be different for symbols of the header and payload, as described in §7.1.4.6.

7.1.4.4.4 Windowing, overlap and add

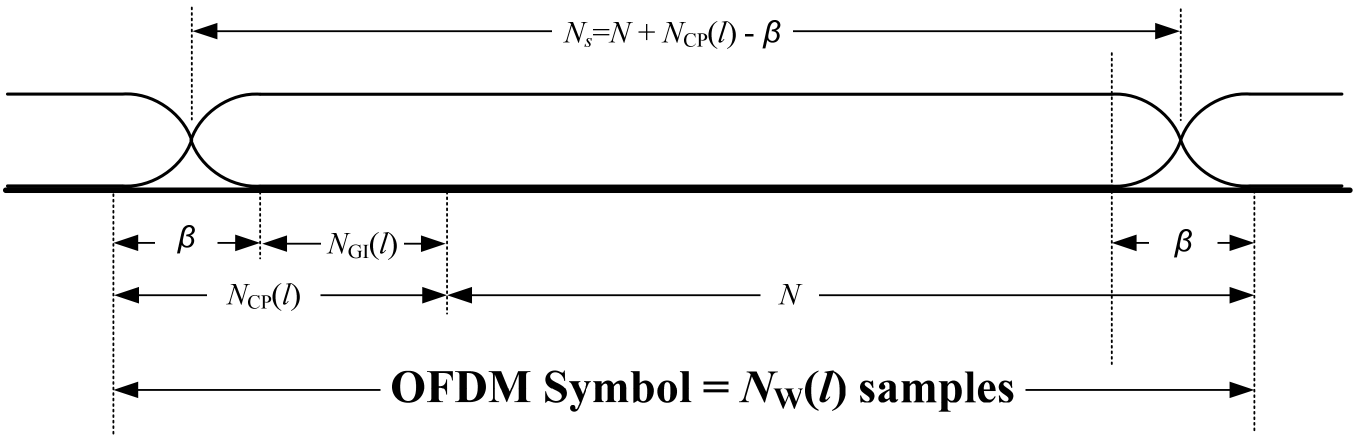

Figure 7-22/G.9960 – Structure of an OFDM symbol with cyclic extension and overlapped windowing

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 of the same frame, as well as the PHY-header and preamble.

To reduce the modulation overhead, 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 duration of the *l-th* OFDM symbol is thus $N_S(l) = N + N_{CP}(l) - \beta$.

After windowing, overlap and add, time-domain samples at the reference point u_n in Figure 7.19 shall comply with the following equations:

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

where $u_n^{(pr)}$ is the n'th sample of the preamble, as defined in §7.1.4.5 (Note: the signal $u_n^{(pr)}$ already includes windowing as necessary), $w(n,l)$ 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, $w_\beta(n)$ 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 rate f_{OFDM} (number of symbols per second) and symbol period T_{OFDM} for the given value of N_{CP} and β shall be computed, respectively, as:

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

and $T_{OFDM} = 1/f_{OFDM}$.

7.1.4.4.5 Frequency up-shift

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

$F_{US} = m*F_{SC}$, where m is an integer and $N/2 \le m$.

The valid values of m are are medium dependent and are specified in §7.2.

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

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

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

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

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: The minimum value of p sufficient to avoid distortions depends on the ratio between the up-shift frequency F_{US} 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: 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).

7.1.4.4.6 Output signal

For all applications which don't use RF up-converter (further referred to as HF-applications), the output signal of the modulator shall be the real component of s_n:

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

For RF applications, the RF up-converter shall produce the following output signal:

$$S_{out-RF}(t) = \mathrm{Re}\left[s(t) \times \exp(j2\pi F_{UC}t)\right] = \mathrm{Re}\left[s(t)\right] \times \cos(2\pi F_{UC}t) - \mathrm{Im}\left[s(t)\right] \times \sin(2\pi F_{UC}t).$$

where F_{UC} is the frequency shift introduced by the RF modulator. The range of F_{UC} and its valid values are specified in §7.1.4.6.

After RF up-conversion, the center frequency around which the spectrum of the transmit OFDM signal will be placed is $F_C = F_{UC} + F_{US}$.

7.1.4.5 Preamble

7.1.4.5.1 General preamble structure

The preamble is prepended to every PHY frame defined in §7.1.2.1. It is intended to assist the receiver in detecting, 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 PSD mask (i.e., notches, shapes) as the header and the payload symbols.

Table 7-28 presents the general structure of the G.9960 preamble. Each section I comprises N_I repetitions of an OFDM symbol (S_I) employing sub-carrier spacing $k_I \times F_{SC}$, where F_{SC} denotes the sub-carrier spacing of the payload. A zero value for N_I means that section I is not included in the preamble. The values of k_I shall be selected from the set 1, 2, 4 or 8. The preamble sub-carriers of section I shall be one in every k_I sub-carriers with respect to the sub-carriers used for the payload OFDM symbol starting from sub-carrier zero. Each preamble section shall be windowed as necessary in order to comply with the PSD mask. This is illustrated in Figure 7-23.

Table 7-28/G.9960 – General structure of the preamble

	1st Section	**2nd Section**	**3rd Section**	**Header**	**4th Section**
Number of Symbols (N_I) (Note 1)	N_1	N_2	N_3	Note 5	N_4
Sub-carrier spacing ($k_I \times F_{SC}$)	k_1	$k_2 = k_1$ (Note 2)	k_3		$k_4 = 1$ (Note 3)
OFDM Symbol (S_I)	S_1	$S_2 = -S_1$ (Note 4)	S_3		S_4

Note 1: N_I does not include windowing.
Note 2: The sub-carrier spacing of the 2nd section shall be equal to the sub-carrier spacing of the 1st section.
Note 3: The sub-carrier spacing of the 4th section shall be the same as sub-carrier spacing of PHY-frame header and payload.
Note 4: The OFDM symbol of the 2nd section shall be an inverted time-domain waveform of the 1st section.
Note 5: Header contains a field (PHI) that indicates $N_4 = 1$ or $N_4 = 0$

Figure 7-23 shows the G.9960 preamble waveform.

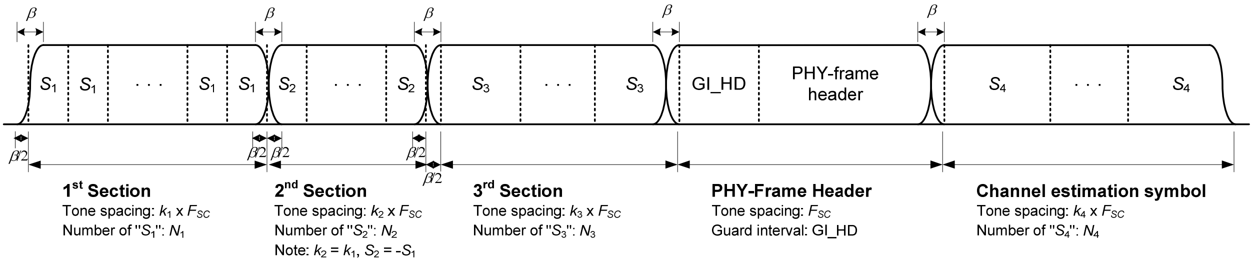

Figure 7-23/G.9960 − Preamble waveform

The number of repetitions of OFDM symbol S_I (N_I) in each of the preamble sections may be a non-integer number to incorporate optional guard interval between sections provided that a fraction of N_I is consistent with the guard interval specified in Table 7-29. The specific preamble types and construction methods are defined in §7.2.

7.1.4.5.2 Preamble generation

This section contains the description of preamble generation method, which is not medium dependent. The preamble generation method specific to the type of medium is described under §7.2.

7.1.4.5.2.1 Frequency-domain symbol generation

The sub-carriers of the I^{th} section of the preamble shall be those with indices 0, k_I, $2k_I$, $3k_I$, ….. The preamble generator shall output complex values Z_i for each sub-carrier following the order given by logical indices t_i with i = 0, 1, 2, … to be modulated onto symbols of the preamble in accordance with the relevant sub-carrier mask.

7.1.4.5.2.1.1 Modulation of the preamble symbol

For the non-masked sub-carriers of the preamble, a bit sequence of all 1’s shall be mapped using the 1-bit constellation as specified in §7.1.4.3.1.2. Other bit sequences are for further study.

The LFSR generator shall be initialized at the beginning of each one of the used preamble sections to a seed that is preamble section and medium dependent as defined in §7.2.

The output of the mapper shall be subsequently rotated using the two bits that are the LSBs of the LFSR, $s1$, and $s2$, as defined in Table 7-27 (constellation scrambler) resulting in constellation point Z_i.

The LFSR shall be advanced by 2 bits for each preamble’s sub-carrier (either masked or not) in the order specified in §7.1.4.3.3.

7.1.4.5.2.2 Time-domain symbol generation

The Z_i values shall be modulated onto OFDM symbols as described in §7.1.4.4.1.

The output time-domain symbol shall be repeated N_I times where N_I denotes the number of replicas within section I. If either N_1 or N_3 are non-integer numbers, the fraction of the symbol replica shall be at the beginning of the section. If N_2 is a non-integer number, the fraction of the symbols replica shall be at the end of the section.

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

1. First section:

a. The first short symbol of the first section is cyclically extended by prepending $\beta/2$ samples
b. The last short symbol of the first section is cyclically extended by appending $\beta/2$ samples
c. 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.

2. Second section:
   a. The first short symbol of the second section is cyclically extended by prepending $\beta/2$ samples
   b. The last short symbol of the second section is cyclically extended by appending $\beta/2$ samples
   c. The first and last β samples of the extended second section are windowed with a window function $w_\beta(n)$ and $w_\beta(\beta\text{-}n\text{-}1)$ respectively.
3. Third section:
   a. The beginning of the third section is cyclically extended by prepending β samples.
   b. The first and last β samples of the extended third section are windowed with a window function $w_\beta(n)$ and $w_\beta(\beta\text{-}n\text{-}1)$ respectively.
4. 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 and at the beginning of the third section are overlapped and added.
   c. The β windowed samples at the end of the third section are overlapped and added with the β windowed samples at the beginning of the PHY-frame header as described in §7.1.4.4.4

$w_\beta(n)$ shall comply with the rules specified in §7.1.4.4.4
This is illustrated in Figure 7-24.

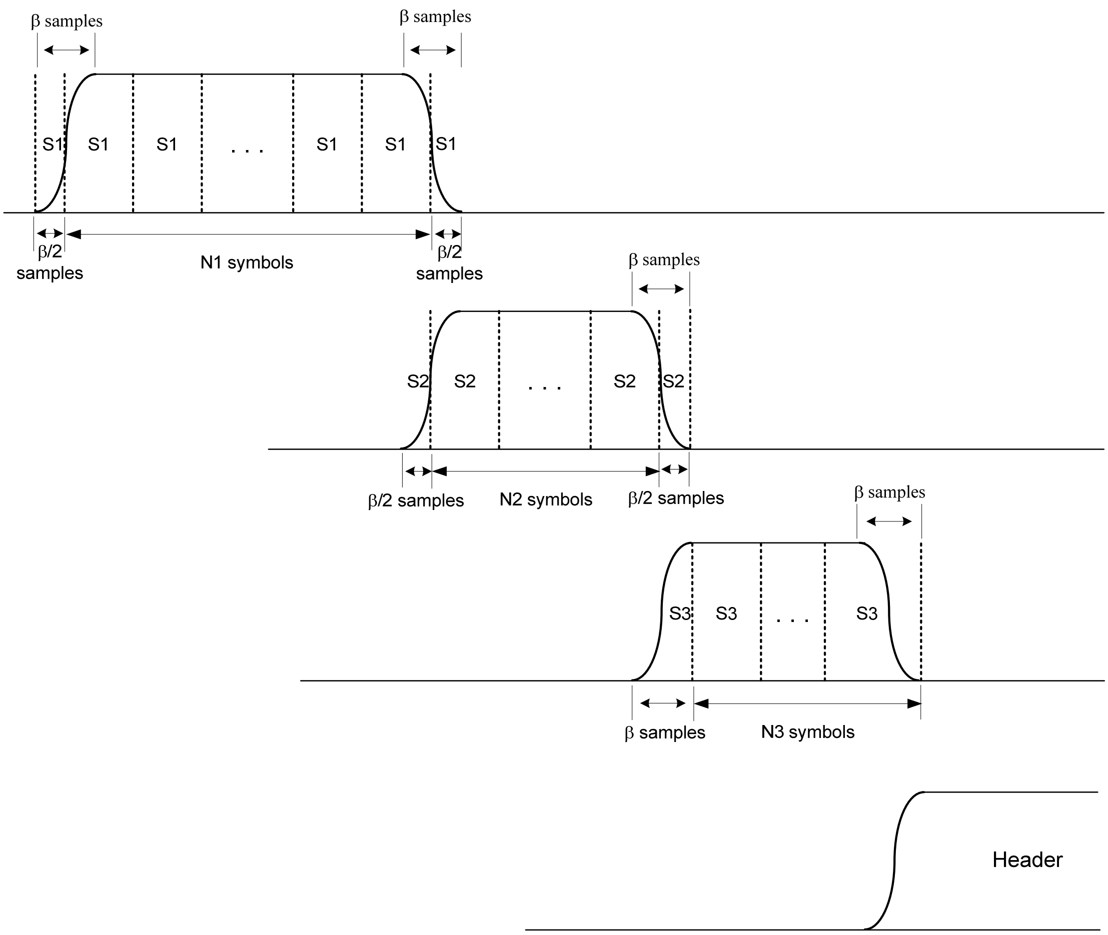

Figure 7-24/G.9960 – Preamble time-domain generation

The number of samples in the preamble shall be:

$$N_{pr} = \beta + N_1 \frac{N}{k_1} + N_2 \frac{N}{k_2} + N_3 \frac{N}{k_3}$$

7.1.4.6 PMD control parameters

Table 7-29 summarizes valid values of control parameters of an OFDM modulator described in the sections above. This list is a superset of parameters used over different media; a list of valid values of modulation parameters and their valid combinations for particular media is presented in §7.2.

Table 7-29/G.9960 – Valid OFDM control parameters

Notation	Parameter	Valid values or range	Note
N	Number of sub-carriers	256, 512, 1024, 2048, 4096	
F_{SC}	Sub-carrier spacing [kHz]	24.4140625×k, k = 1, 2, 4, 8, 16, 32, 64	
N_{GI}	Guard interval [samples]	k×N/32, k = 1, 2, 3, … 8	
$N_{\text{GI-HD}}$	Guard interval of the header	N/4	
$N_{\text{GI-DF}}$	Default guard interval of the payload	N/4	$N_{GI\text{-}DF} \geq N_{GI}$
β	Window size [samples]	Any integer between 0 and N/4	Range 0-N/4
F_{US}	Up-shift frequency, [kHz]	m×F_{SC}, $m \geq N/2$	m is an integer; valid values of m are specified in §7.2
F_{UC}	Up-convert frequency, [kHz]	$F_{\text{UC}} = l \times F_{\text{G}}$ where valid values for l are a subset of the range of integers between 12 and 100 – ($2 \times F_{\text{US}}/F_{\text{G}}$) and F_{G} = 25 MHz	RF applications. Additional constraints on F_{UC} may be specified in regional Annexes.
NOTE – Guard interval and Window size are expressed in samples at Nyquist rate.			

Secondary parameters of the OFDM modulator are presented in Table 7-30.

Table 7-30/G.9960 – Secondary parameters of the modulator

Notation	Parameter	Note
BW	Total bandwidth [Hz]	$BW = N \times F_{SC}$
N_W	Total number of samples in an OFDM symbol	$N_W = N + N_{CP}$
f_{OFDM}	Symbol rate [symbols/s]	$f_{OFDM} = \frac{N \times F_{SC}}{N + N_{CP} - \beta}$
T_{OFDM}	Symbol period [s]	$T_{OFDM} = 1/f_{OFDM}$
N_{GI}	Guard interval	$N_{GI} = N_{CP} - \beta$
F_C	Center frequency	$F_C = F_{US} + F_{UC}$
f_s	Transmit clock	$f_s = N \times F_{SC}$

7.1.4.7 Symbol boost

Symbols of preamble and header can be sent with higher power (boosted) relative to the symbols of the payload. The boosting shall be achieved by increasing the power of each active sub-carrier in the boosted symbol by the same value in dB. Details of symbol boost are for further study.

7.1.5 Transmit PSD Mask

Transmit PSD mask is determined by a Sub-carrier Mask (SM), a PSD Shaping Mask (PSM), and a PSD ceiling (PSDC) defined in this section, and the Limit PSD Mask (LPM) defined for each particular medium. The PSD of the transmit signal at any frequency shall never exceed the Transmit PSD Mask.

The LPM (see §7.2.1.3, §7.2.2.3 and §7.2.3.3) specifies the absolute limit of the transmit PSD, intended for deployments with no special conditions. The SM, PSDC, and PSM provide further reduction and shaping of the transmit PSD using three mechanisms: sub-carrier masking (notching), PSD ceiling (limit on PSD level), and PSD shaping.

G.9960 transceivers shall support sub-carrier masking, notching of International Amateur radio bands, and PSD ceiling. Support of PSD shaping is optional.

7.1.5.1 Sub-carrier masking (notching)

Sub-carrier masking shall be used to eliminate transmission on one or more sub-carriers. Sub-carrier masking is defined by a Sub-carrier Mask (SM). Transmit power of sub-carriers specified in SM shall be set to zero. SM shall override all other instructions related to the transmit power of the sub-carrier.

SM is defined as a number of masked frequency bands. Each band is specified by a start sub-carrier index (x_L) and a stop sub-carrier index (x_H), as $\{x_L, x_H\}$. An SM including S bands can be represented in the following format:

$$SM(S) = [\{x_{L1}, x_{H1}\}, \{x_{L2}, x_{H2}\}, \dots \{x_{LS}, x_{HS}\}].$$

All sub-carriers within the band, i.e., with indices equal or higher than x_L and lower than or equal to x_H, shall be switched off (transmitted with zero power).

International Amateur radio bands (see Annex D) are not a part of SM. In case Amateur radio bands are used for transmission, the node shall be capable to turn off one or more of Amateur radio bands using SM, by configuring one or more of SM bands coinciding with the Amateur radio bands.

7.1.5.2 PSD ceiling

PSD ceiling (PSDC) specifies the PSD level that is used to impose a limit (i.e., a ceiling function) on the transmit PSD mask. PSDC is independent of frequency and indicated by a single value in dBm/Hz. The valid range of PSDC values is from −50 dBm/Hz to −100 dBm/Hz with steps of 2 dB.

PSDC shall be supported by all G.9960 transceivers.

7.1.5.3 PSD shaping

PSD shaping allows transmit PSD reduction of PSD in some parts of the spectrum, mainly for spectrum compatibility and coexistence with alien home network technologies. PSD shaping is specified by a PSM.

PSM is defined on the frequency range between the lowest sub-carrier x_1 and the highest sub-carrier x_H allowed for transmission, and consists of one or more frequency segments. The boundaries of the segments are defined by set breakpoints. Inside each segment, the PSD may either be constant or form a linear slope, Figure 7-25.

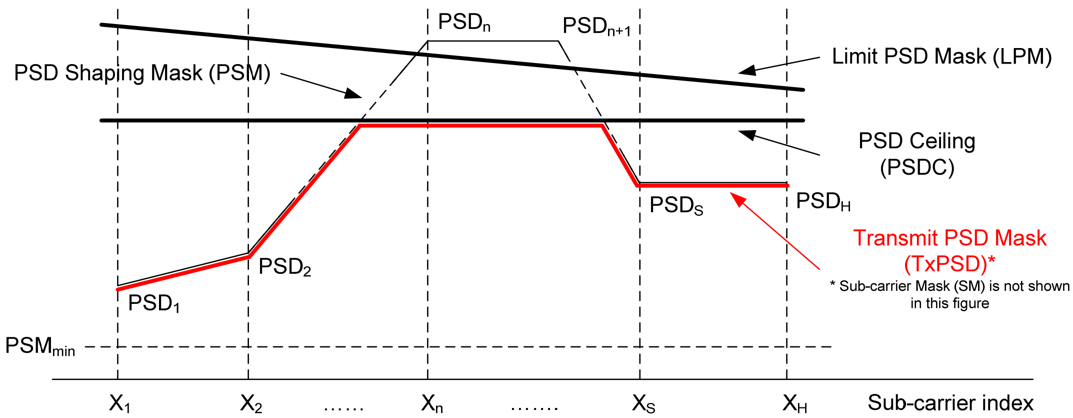

Figure 7-25/G.9960 – Construction of PSM

Each breakpoint of PSM is specified by a sub-carrier index x_n and a value of PSD_n at that sub-carrier expressed in dBm/Hz, $\{x_n, PSD_n\}$. The first breakpoint is always set to the lowest sub-carrier allowed for transmission (index x_1) and the last breakpoint is set to the highest sub-carrier allowed for transmission (index x_H). A PSM including S segments can be represented by (S+1) breakpoints in the following format:

$$PSM(S) = [\{x_1, PSD_1\}, \{x_2, PSD_2\} \ldots \{x_S, PSD_S\}, \{x_H, PSD_H\}].$$

A node supporting PSD shaping shall support up to 8 PSM breakpoints.

The maximum steepness of PSM slopes is for further study.

If one or more PSM breakpoints are set above the LPM or PSDC, the transmit PSD mask shall be set to: TxPSD = min(PSM, LPM, PSDC).. All values of PSD_n of PSM breakpoints shall be set above PSM_{min}. The value of PSM_{min} shall not be more than 30 dB below the peak of the PSD shaping mask.

NOTE: PSM breakpoints do not have any relation with SM breakpoints; SM and notched International Amateur radio bands always overrides PSM if defined over the same indices.

7.1.5.4 Notching of International Amateur radio bands

Any node operating over phone line or power line shall be able to reduce the PSD of the transmitted signal to a level below −80 dBm/Hz in all International Amateur radio bands (see Annex D) simultaneously or in any selected group of them. The band to be notched is specified by the start and stop sub-carrier indices, same as described in §7.1.5.1. The PSD slopes forming a notch are vendor discretionary.

7.1.6 Electrical specifications

7.1.6.1 Transmit clock tolerance

The tolerance of the transmit clock (defined in Table 7-30) shall be ±50 ppm.

7.1.6.2 Relative Transmit Clock Accuracy

All G.hn nodes shall synchronize the frequency of their transmit clocks to a domain master clock (see the NTR field of the PHY frame header in §7.1.2.3.2.3.1). When synchronized, the difference between the transmit clock frequency of a G.hn node and the transmit clock frequency of the domain master shall not exceed ±0.5 ppm.

Nodes that are not synchronized with a domain master shall not transmit.

These accuracy requirements shall apply to all bandplans and media types.

7.2 Medium dependent specification

7.2.1 Physical layer specification over phone lines

7.2.1.1 Control parameters

Table 7-31 shows the valid OFDM control parameters for various bandplans defined in phone lines.

Table 7-31/G.9960 – OFDM control parameters for phone lines

Domain type	Phone-line baseband	
Bandplan name	**50MHz-TB (NOTE 2)**	**100MHz-TB (NOTE 3)**
N	1024	2048
F_{SC}	48.828125 kHz	48.828125kHz
N_{GI}	$N/32\times k$ for k=1,…,8 samples @ 50 Msamples/s	$N/32\times k$ for k=1,…,8 samples @ 100 Msamples/s
$N_{GI\text{-}HD}$	$N/4$ = 256 samples @ 50 Msamples/s	$N/4$ = 512 samples @ 100 Msamples/s
$N_{GI\text{-}DF}$	$N/4$=256 samples @ 50 Msamples/s	$N/4$=512 samples @ 100 Msamples/s
β	$N/32$ = 32 samples @ 50 Msamples/s	$N/32$ = 64 samples @ 100 Msamples/s
F_{US}	25 MHz	50 MHz
F_{UC}	0 MHz	0 MHz
Sub-carrierIndexing rule (NOTE 1)	Rule #1	Rule #1
NOTES: 1. See §7.1.4.1 for more details on sub-carrier indexing rules. 2. The range of sub-carrier frequencies is between 0 and 50 MHz 3. The range of sub-carrier frequencies is between 0 and 100 MHz		

7.2.1.2 Preamble

7.2.1.2.1 Preamble structure

Table 7-32 illustrates the preamble structure for phone line.

Table 7-32/G.9960 –Preamble structure for baseband transmission over phone lines

	1st Section	2nd Section	3rd Section	Header	4th Section
Number of Symbols (N_i)	8	2	0	NOTE	1.25
Sub-carrier spacing ($k_i \times F_{SC}$)	8	8	0		1
NOTE – The value for PHI in the PHY-frame header shall be set to 1 (N_4).					

7.2.1.3 PSD mask specifications

The Limit PSD mask for operation over phone lines (bandplans 50MHz-TB and 100MHz-TB) shall be as presented in Figure 7-26 with the values of frequencies f_L-f_H as presented in Table 7-33 and Table 7-34.

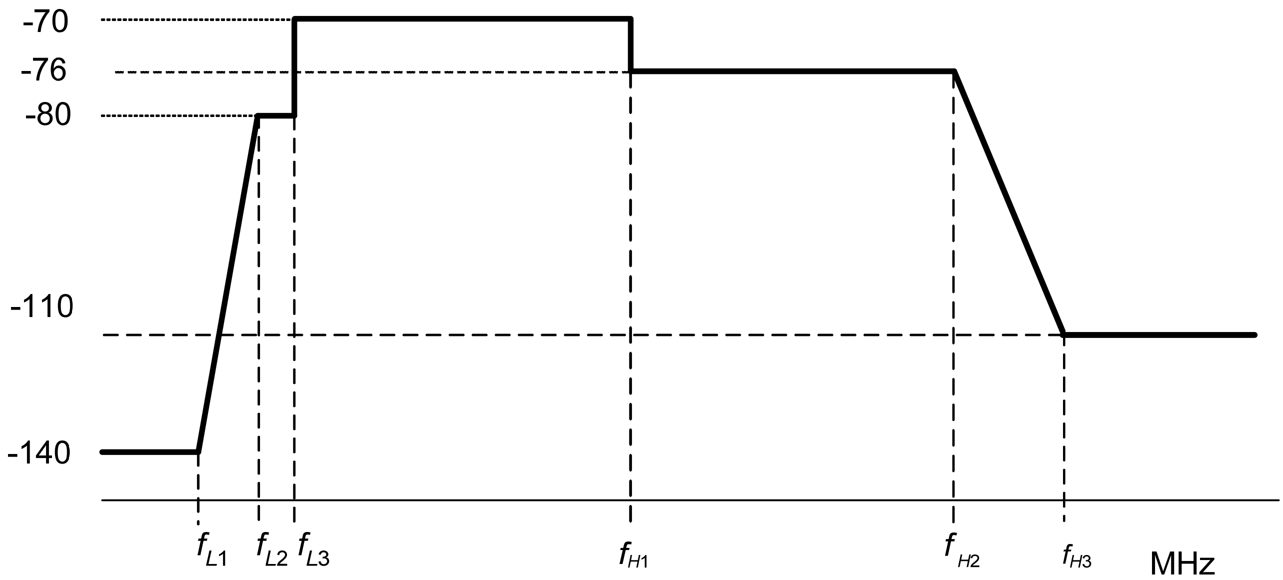

Figure 7-26/G.9960 – Limit PSD mask for transmission over phone lines (Amateur radio-band notches are not shown)

NOTE: Figure 7-26 doesn't include Amateur radio notches.

The values of frequency spectrum parameters for 50MHz-TB and 100MHz-TB are presented in Table 7-33 and Table 7-34, respectively. Intermediate points between those defined in Figure 7-26 shall be obtained by linear interpolation (in dB over linear frequency scale).

Table 7-33/G.9960 – Parameters of Limit PSD mask for the 50MHz-TB bandplan

Parameters	Frequency, MHz	PSD, dBm/Hz	Note/Description
f_{L1}	1.7	−140	Provides protection of splitter-less ADSL
f_{L2}	3.5	−80	Coincides with the Amateur radio band
f_{L3}	4.0		
$f_{L3} + \Delta F$	$4.0 + \Delta F$	−70	ΔF is an arbitrary small positive value
f_{HAM}	As defined in Table D-1	−80	Additional notches can be added based on regional regulations
$f_{H1} - \Delta F$	$30 - \Delta F$	−70	ΔF is an arbitrary small positive value
f_{H1}	30	−76	
f_{H2}	50		
f_{H3}	60	−110	
NOTE – All sub-carriers above $f_{H2} - \Delta F$ shall not be used for transmission (neither data nor any auxiliary information).			

Table 7-34/G.9960 – Parameters of Limit PSD mask for the 100MHz-TB bandplan

Parameters	Frequency, MHz	PSD, dBm/Hz	Note/Description
f_{L1}	1.7	−140	Provides protection of splitter-less ADSL
f_{L2}	3.5	−80	Coincides with the Amateur radio band
f_{L3}	4.0		
$f_{L3} + \Delta F$	$4.0 + \Delta F$	−70	ΔF is an arbitrary small positive value
f_{HAM}	As defined in Table D-1	−80	Additional notches can be added based on regional regulations
$f_{H1} - \Delta F$	$30 - \Delta F$	−70	ΔF is an arbitrary small positive value
f_{H1}	30	−76	
f_{H2}	100		
f_{H3}	120	−110	
NOTE – All sub-carriers above $f_{H2} - \Delta F$ shall not be used for transmission (neither data nor any auxiliary information).			

NOTES:

1. The Limit PSD mask shown in Figure 7-26 presents for the case when all sub-carriers allowed for transmission are in use, each with its maximum transmit power. In case of additional spectrum shaping is used as described in §7.1.5.3 (e.g. to provide spectrum compatibility, comply with wide-band power limit, or other), various parts of this PSD mask could be reduced by switching sub-carriers off or reducing their transmit power. Additional frequency notches may be applied if required.

2. VDSL is usually deployed using a service splitter (G.993.2 doesn't encourage splitterless VDSL installations). This allows the use of the G.9960 spectrum down to f_{L3}. If splitterless VDSL is used, the low frequency of G.9960 spectrum shall be moved up and set above the upper downstream sub-carrier of VDSL2.

7.2.1.4 Permanently Masked Sub-Carriers

Sub-carriers 0 – 72 (inclusive) shall be permanently masked over phone lines. They shall not be used for transmission (neither data nor any auxiliary information).

7.2.2 Physical layer specification over power lines

7.2.2.1 Control parameters

Table 7-35 shows the valid OFDM control parameters for various bandplans defined in power lines.

Table 7-35/G.9960 – OFDM control parameters for power lines

Domain type	**Power-line baseband**		**Power-line passband**
Bandplan name	**50MHz – PB (NOTE 3)**	**100MHz – PB (NOTE 4)**	**100MHz – PP (NOTE 5)**
N	2048	4096	1024
F_{SC}	24.4140625 kHz	24.4140625 kHz	97.65625 kHz
N_{GI}	$N/32 \times k$ for k=1,…,8 samples @ 50 Msamples/s	$N/32 \times k$ for k=1,…,8 samples @ 100Msamples/s	$N/32 \times k$ for k=1,…,8 samples @ 100Msamples/s
N_{GI-HD}	$N/4$=512 samples @ 50 Msamples/s	$N/4$=1024 samples @ 100 Msamples/s	$N/4$=256 samples @ 100 Msamples/s
N_{GI-DF}	$N/4$=512 samples @ 50 Msamples/s	$N/4$=1024 samples @ 100 Msamples/s	$N/4$=256 samples @ 100 Msamples/s
β	$N/8$ = 256 samples @ 50 Msamples/s	$N/8$ = 512 samples @ 100 Msamples/s	$N/32$ = 32 samples @ 100 Msamples/s
F_{US}	25 MHz	50 MHz	150 MHz
F_{UC}	0 MHz	0 MHz	0 MHz
Sub-carrier indexing rule (NOTE 1)	Rule #1	Rule #1	Rule #1
NOTES: 1. See §7.1.4.1 for more details on sub-carrier indexing rules. 2. The 50 MHz and 100 MHz bandplans may be used by nodes operating in the same power-line baseband domain. 3. The range of sub-carrier frequencies is between 0 and 50 MHz 4. The range of sub-carrier frequencies is between 0 and 100 MHz 5. The range of sub-carrier frequencies is between 100 MHz and 200 MHz			

7.2.2.2 Preamble

7.2.2.2.1 Preamble structure

Table 7-36 illustrates the preamble structure for baseband transmission over power lines.

Table 7-36/G.9960 –Preamble structure for baseband transmission over power lines

	1st Section	2nd Section	3rd Section	Header	4th Section
Number of Symbols (N_i)	7	2	0	NOTE	1.25
Sub-carrier spacing ($k_i \times F_{SC}$)	8	8	0		1
NOTE – The value for PHI in the PHY-frame header shall be set to 1 (N_4).					

The preamble structure for passband transmission over power lines is for further study.

7.2.2.3 PSD mask specifications

The baseband Limit PSD masks for operation over power lines shall be as presented in Figure 7-27 for the 50 MHz-PB and in Figure 7-28 for the 100 MHz-PB with the values of frequencies f_L-f_H as presented in Table 7-37 and Table 7-38. The passband Limit PSD mask for operation over power lines (bandplan 100MHz-PP) shall be as defined in Figure 7-29 and Table 7-39.

NOTE – PSD levels may be further limited by EMC regulatory requirements.

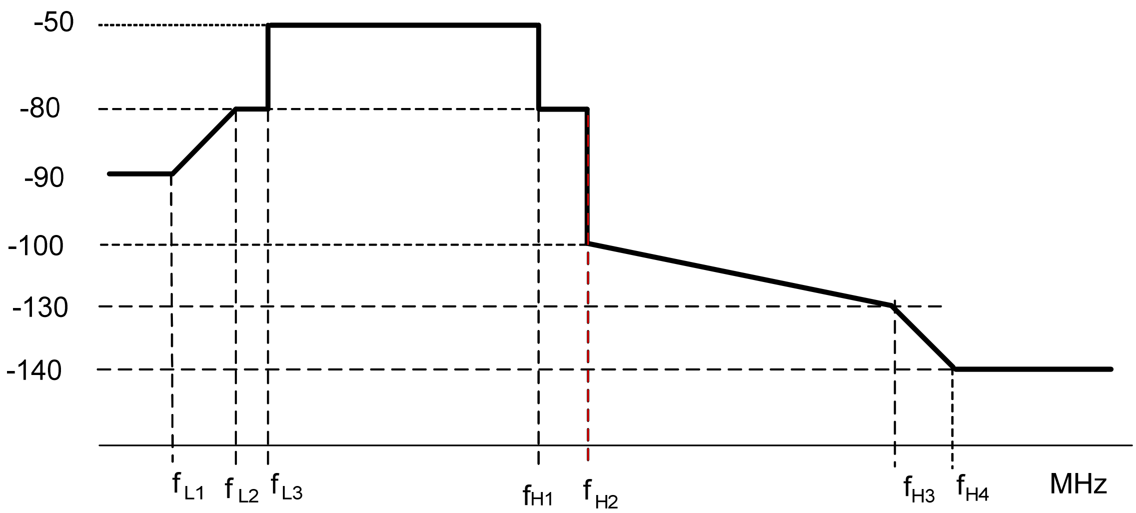

Figure 7-27/G.9960 – Limit PSD mask for baseband transmission over power lines for 50 MHz-PB bandplan (Amateur radio-band notches are not shown)

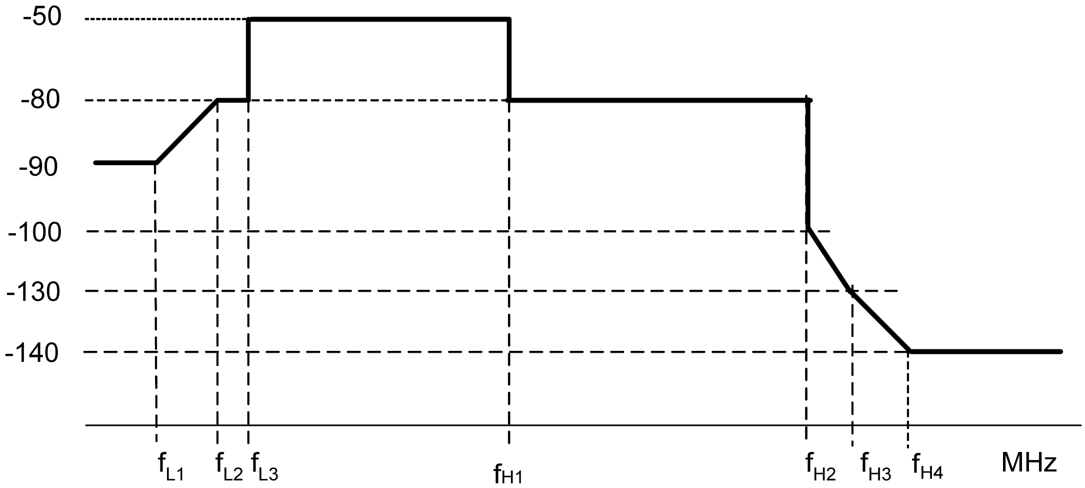

Figure 7-28/G.9960 – Limit PSD mask for baseband transmission over power lines for 100 MHz-PB bandplan (Amateur radio-band notches are not shown)

NOTE: Figure 7-27 and Figure 7-28 don't include Amateur radio notches.

The values of frequency spectrum parameters for 50MHz-PB and 100MHz-PB are presented in Table 7-37 and Table 7-38, respectively. Intermediate points between those defined in Figure 7-27 are obtained by linear interpolation (in dB over linear frequency scale).

Table 7-37/G.9960 – Parameters of Limit PSD mask for the 50MHz-PB bandplan

Parameters	Frequency (MHz)	PSD (dBm/Hz)	Note/Description
f_{L1}	1.1	−90	Additional reduction below 1.1 MHz is to reduce crosstalk into ADSL
f_{L2}	1.8	−80	Coincides with the Amateur radio band
f_{L3}	2.0		
$f_{L3} + \Delta F$	$2.0 + \Delta F$	−50	ΔF is an arbitrary small positive value
f_{HAM}	As defined in Table D-1	−80	Additional notches could be added based on regional regulations
$f_{H1} - \Delta F$	$30 - \Delta F$	−50	ΔF is an arbitrary small positive value
f_{H1}	30	−80	ΔF is an arbitrary small positive value
$f_{H2} - \Delta F$	$50 - \Delta F$		
f_{H2}	50	−100	
f_{H3}	110	−130	
f_{H4}	120	−140	
NOTE – All sub-carriers above $f_{H2} - \Delta F$ shall not be used for transmission (neither data nor any auxiliary information).			

Table 7-38/G.9960 – Parameters of Limit PSD mask for the 100MHz-PB bandplan

Parameters	Frequency (MHz)	PSD (dBm/Hz)	Note/Description
f_{L1}	1.1	−90	Additional reduction below 1.1 MHz is to reduce crosstalk into ADSL
f_{L2}	1.8	−80	Coincides with the Amateur radio band
f_{L3}	2.0		
$f_{L3} + \Delta F$	$2.0 + \Delta F$	−50	ΔF is an arbitrary small positive value
f_{HAM}	As defined in Table D-1	−80	Additional notches could be added based on regional regulations
$f_{H1} - \Delta F$	$30 - \Delta F$	−50	ΔF is an arbitrary small positive value
f_{H1}	30	−80	ΔF is an arbitrary small positive value
$f_{H2} - \Delta F$	$100 - \Delta F$		
f_{H2}	100	−100	
f_{H3}	110	−130	
f_{H4}	120	−140	
NOTE – All sub-carriers above $f_{H2} - \Delta F$ shall not be used for transmission (neither data nor any auxiliary information).			

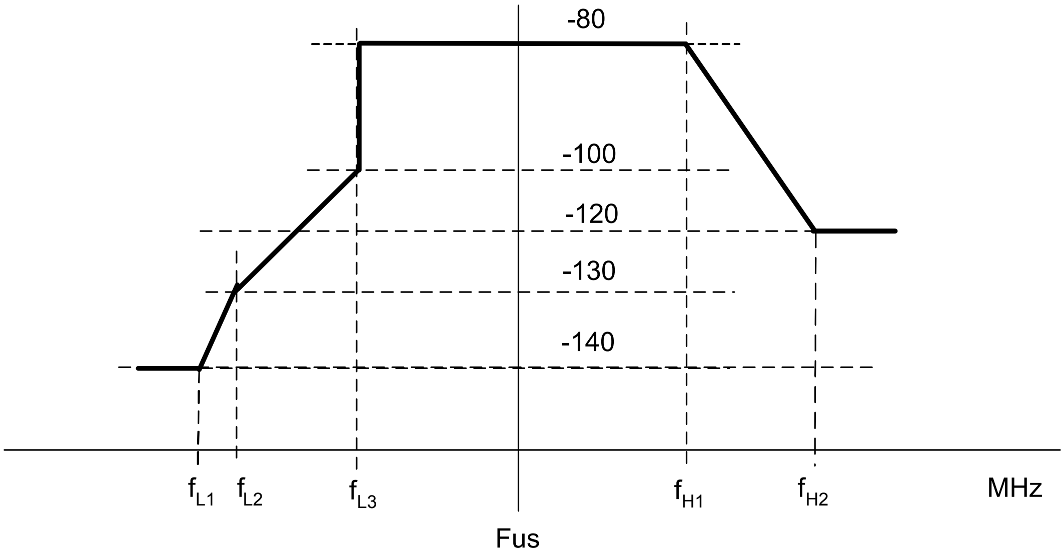

Figure 7-29/G.9960 – Limit PSD mask for passband transmission over power lines

The frequency spectrum parameters for passband bandplans are presented in Table 7-39. Intermediate points between those defined in Figure 7-29 are obtained by linear interpolation (in dB over linear frequency scale).

Table 7-39/G.9960 – Parameters of Limit PSD mask for the 100MHz-PP bandplan

Parameters	Frequency (MHz)	PSD (dBm/Hz)	Note/description
f_{L1}	80	−140	
f_{L2}	90	−130	
f_{L3}	100	- 100	
$f_{L3} + \Delta F$	$100 + \Delta F$	-80	ΔF is an arbitrary small positive value
f_{H1}	200	−80	
f_{H2}	240	−120	
All sub-carriers above $f_{H1} - \Delta F$ shall not be used for transmission (neither data nor any auxiliary information).			

NOTES:

1. The Limit PSD mask shown in Figure 7-27 and Figure 7-29 presents the case when all sub-carriers allowed for transmission are in use, each with its maximum transmit power. In case of additional spectrum shaping is used as described in §7.1.5.3 (e.g. to provide spectrum compatibility with VDSL, comply with wide-band power limit, or other), various parts of this PSD mask could be reduced by switching sub-carriers off or reducing their transmit power. Additional frequency notches may be applied if required.

2. The value of −80dBm/Hz for the required attenuation in Amateur radio bands is adopted from [V.2]. This value might be revised for G.9960 due to concerns of reduced balance of power-line wires.

7.2.2.4 Permanently Masked Sub-Carriers

For baseband transmissions, sub-carriers 0 – 74 (inclusive) shall be permanently masked over power lines. They shall not be used for transmission (neither data nor any auxiliary information).

7.2.3 Physical layer specification over coax

7.2.3.1 Control parameters

Table 7-40 shows the valid OFDM control parameters for various bandplans defined in coax cable.

Table 7-40/G.9960 – OFDM control parameters for coax cables

Domain type	Coax baseband		Coax RF	
Bandplan name	**50MHz-CB (NOTE 4)**	**100MHz-CB (NOTE 5)**	**50MHz-CRF (NOTE 6)**	**100MHz-CRF (NOTE 7)**
N	256	512	256	512
F_{SC}	195.3125 kHz	195.3125 kHz	195.3125 kHz	195.3125 kHz
N_{GI}	$N/32 \times k$ for k=1,…,8 samples @ 50 Msamples/s	$N/32 \times k$ for k=1,…,8 samples @ 100 Msamples/s	$N/32 \times k$ for k=1,…,8 samples @ 50 Msamples/s	$N/32 \times k$ for k=1,…,8 samples @ 100 Msamples/s
$N_{GI\text{-}HD}$	N/4=64 samples @ 50 Msamples/s	N/4=128 samples @ 100 Msamples/s	N/4=64 samples @ 50 Msamples/s	N/4=128 samples @ 100 Msamples/s
$N_{GI\text{-}DF}$	N/4=64 samples @ 50 Msamples/s	N/4=128 samples @ 100 Msamples/s	N/4=64 samples @ 50 Msamples/s	N/4=128 samples @ 100 Msamples/s
β	N/32=8 samples @ 50 Msamples/s	N/32=16 samples @ 100 Msamples/s	N/32=8 samples @ 50 Msamples/s	N/32=16 samples @ 100 Msamples/s
F_{US}	25 MHz	50 MHz	25 MHz	50 MHz
F_{UC}	0 MHz	0 MHz	X (NOTE 3)	Y (NOTE 3)
Sub-carrier indexing rule (NOTE 1)	Rule #1	Rule #1	Rule #1 if $X = Y$, or rule #2 if X+ 25 MHz = Y + 50 MHz. (NOTE 8)	Rule #1 if $X = Y$, or rule #2 if X + 25 MHz = Y + 50 MHz. (NOTE 8)

NOTES:
1. See §7.1.4.1 for more details on sub-carrier indexing rules.
2. The 50MHz and 100MHz bandplans may be used by nodes operating in the same Coax Baseband domain. The same principle applies to 50MHz and 100MHz bandplans defined for Coax RF domain.
3. The values of F_{UC} shall be selected from the valid set defined in Table 7-29 and may be subject to regional spectrum management rules (see regional Annexes).
4. The range of sub-carrier frequencies is between 0 and 50 MHz
5. The range of sub-carrier frequencies is between 0 and 100MHz
6. The range of sub-carrier frequencies is between X MHz and (X + 50) MHz
7. The range of sub-carrier frequencies is between Y MHz and (Y + 100) MHz
8. The specific indexing rule is specified in each regional Annex.

7.2.3.2 Preamble

7.2.3.2.1 Preamble structure

Table 7-41 illustrates the preamble structure for coax baseband.

Table 7-41/G.9960 –Preamble structure for baseband transmission over coax

	1st Section	2nd Section	3rd Section	Header	4th Section
Number of Symbols (N_i)	10	4	2.5	NOTE	0
Sub-carrier spacing ($k_i \times F_{SC}$)	4	4	1		N/A
NOTE – The value for PHI in the PHY-frame header shall be set to 0 (N_4).					

Table 7-42 illustrates the preamble structure for coax RF.

Table 7-42/G.9960 –Preamble structure for RF transmission over coax

	1st Section	2nd Section	3rd Section	Header	4th Section
Number of Symbols (N_i)	10	4	2.5	NOTE	0
Sub-carrier spacing ($k_i \times F_{SC}$)	4	4	1		N/A
NOTE – The value for PHI in the PHY-frame header shall be set to 0 (N_4).					

7.2.3.3 PSD mask specifications

The Limit PSD mask for operation over coax RF (bandplans 50MHz-CRF, 100MHz-CRF) is presented in Figure 7-30 with the frequencies as presented in Table 7-43 and with the bandwidth $BW = f_{H1} - f_{L3}$.

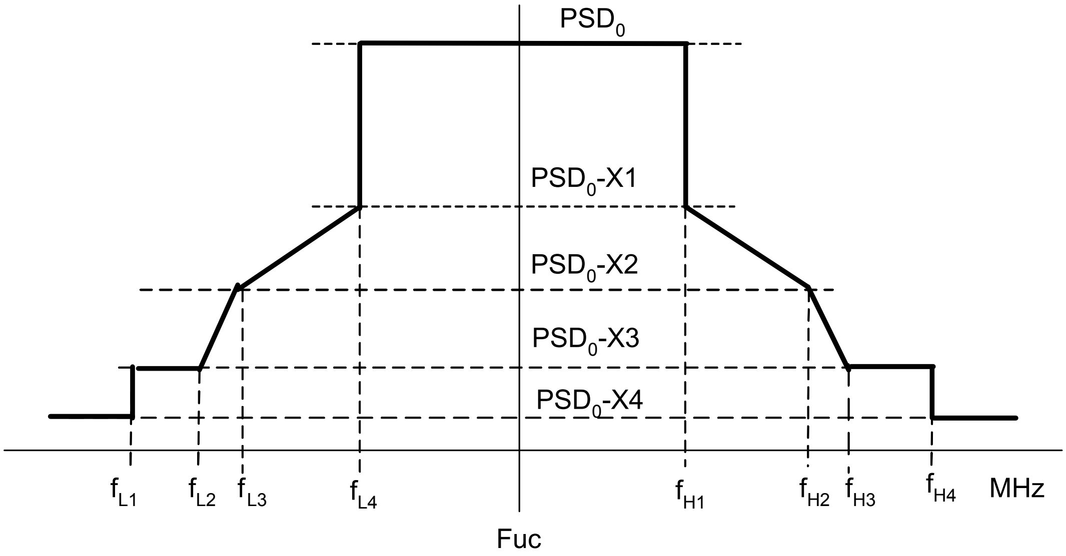

Figure 7-30/G.9960 - Limit PSD mask of a single channel for RF transmission over coax

The proposed values of frequency spectrum parameters for coax are presented in Table 7-43 and Table 7-44. It is assumed that intermediate points between those defined in Figure 7-30 are obtained by linear interpolation (dB over linear frequency scale).

Table 7-43/G.9960 – Parameters of Limit PSD mask over coax RF for the 50MHz-CRF bandplan

Parameters	**Frequency, MHz**	**PSD, dBm/Hz** (NOTE 1)	**Note/Description**
$F_{UC} - f_{L1}$	75	$PSD_0 - 50$	
$F_{UC} - f_{L2}$	50	$PSD_0 - 45$	
$F_{UC} - f_{L3}$	35	$PSD_0 - 40$	
$F_{UC} - f_{L4}$	25	$PSD_0 - 20$	
	$f_{L4} + \Delta F$	PSD_0	ΔF is an arbitrary small positive value
F_{UC}	M*25MHz	PSD_0	
	$f_{H1} - \Delta F$	PSD_0	ΔF is an arbitrary small positive value
$f_{H1} - F_{UC}$	25	$PSD_0 - 20$	
$f_{H2} - F_{UC}$	35	$PSD_0 - 40$	
$f_{H3} - F_{UC}$	50	$PSD_0 - 45$	
$f_{H4} - F_{UC}$	75	$PSD_0 - 50$	
NOTE 1 – PSD_0 = –68 dBm/Hz NOTE 2 – All sub-carriers below $f_{L4} + \Delta F$, and above $f_{H1} - \Delta F$ shall not be used for transmission (neither data nor any auxiliary information).			

Table 7-44/G.9960 – Parameters of Limit PSD mask over coax RF for the 100MHz-CRF bandplan

Parameters	**Frequency, MHz**	**PSD, dBm/Hz** (NOTE 1)	**Note/Description**
$F_{UC} - f_{L1}$	150	$PSD_0 - 50$	
$F_{UC} - f_{L2}$	100	$PSD_0 - 45$	
$F_{UC} - f_{L3}$	70	$PSD_0 - 40$	
$F_{UC} - f_{L4}$	50	$PSD_0 - 20$	
	$f_{L4} + \Delta F$	PSD_0	ΔF is an arbitrary small positive value
F_{UC}	M*25MHz	PSD_0	
	$f_{H1} - \Delta F$	PSD_0	ΔF is an arbitrary small positive value
$f_{H1} - F_{UC}$	50	$PSD_0 - 20$	
$f_{H2} - F_{UC}$	70	$PSD_0 - 40$	
$f_{H3} - F_{UC}$	100	$PSD_0 - 45$	
$f_{H4} - F_{UC}$	150	$PSD_0 - 50$	
NOTE 1 – PSD_0 = –68 dBm/Hz NOTE 2 – All sub-carriers below $f_{L4} + \Delta F$, and above $f_{H1} - \Delta F$ shall not be used for transmission (neither data nor any auxiliary information).			

NOTES:

1. The Limit PSD mask shown in Figure 7-30 presents the case when all sub-carriers allowed for transmission are in use, each with its maximum transmit power. In case additional spectrum shaping is used, as described in §7.1.5.3, the transmit PSD mask can be reduced in the relevant parts of this spectrum by switching sub-carriers off or reducing their transmit power.

2. In cases when more than one channel is established over the same coax cable, appropriate gaps between center frequencies of the channels should be set to account values of the out-of-band PSD presented in Table 7-43 and Table 7-44.

3. Out-of-band spurious signals at the output of a node operating over coax in RF mode are supposed to meet the Limit PSD mask defined in Table 7-43 and Table 7-44. The limit for total power of out-of-band spurious signals is for further study. The requirements for in-band spurious signals are for further study.

4. Specification of guard bands are for further study.

The Limit PSD mask for operation over baseband coax (bandplans 50MHz-CB, 100MHz-CB) is presented in Figure 7-31 with the frequencies and PSD levels presented in Table 7-45, Table 7-46 and with the bandwidth $BW = f_{H1} - f_{L2}$.

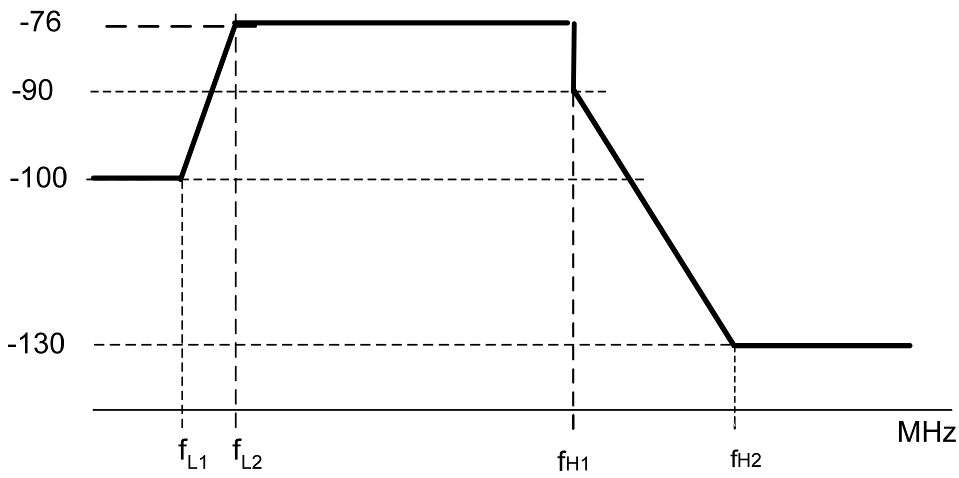

Figure 7-31/G.9960 - Limit PSD mask of baseband coax

The intermediate points between those defined in Figure 7-31 are obtained by linear interpolation (dB over linear frequency scale).

Table 7-45/G.9960 – Parameters of Limit PSD mask over coax for the 50 MHz-CB bandplan

Parameters	Frequency, MHz	PSD, dBm/Hz	Note/Description
f_{L1}	1	−100	
f_{L2}	5	−76	
$f_{H1} - \Delta F$	$50 - \Delta F$	−76	ΔF is an arbitrary small positive value
f_{H1}	50	−76	
f_{H2}	70	−135	
NOTE – All sub-carriers above f_{H1} - ΔF shall not be used for transmission (neither of data nor of any auxiliary information).			

Table 7-46/G.9960 – Parameters of Limit PSD mask over coax for the 100MHz-CB bandplan

Parameters	Frequency, MHz	PSD, dBm/Hz	Note/Description
f_{L1}	1	−100	
f_{L2}	5	−76	
$f_{H1} - \Delta F$	$100 - \Delta F$	−76	ΔF is an arbitrary small positive value
f_{H1}	100	−76	
f_{H2}	140	−135	
NOTE – All sub-carriers above $f_{H1} - \Delta F$ shall not be used for transmission (neither of data nor of any auxiliary information).			

NOTE:

1. The Limit PSD mask shown in Figure 7-31 presents the case when all sub-carriers allowed for transmission are in use, each with its maximum transmit power. In case additional spectrum shaping is used, as described in §7.1.5.3, the transmit PSD mask can be reduced in the relevant parts of this spectrum by switching sub-carriers off or reducing their transmit power.

7.2.3.4 Permanently Masked Sub-Carriers

For baseband transmissions, sub-carriers 0 – 74 (inclusive) shall be permanently masked over power lines. They shall not be used for transmission (neither data nor any auxiliary information).

7.2.3.5 Coexistence on coax

Nodes on coax shall use specified detection and frequency agility capabilities and procedures to avoid interfering with alien home networks and other services (e.g., communication and broadcast services) operating on the same coax plant. Details of these capabilities and procedures will be specified in a future version of this Recommendation.

7.2.4 Transmitter EVM Requirements

EVM requirements are for further study.

Annex A – Regional requirements for North America

For further study

Annex C – Regional requirements for Japan

C.1 Scope

This annex describes domestic practices, standards for each medium (coax cable, phone line and power line) and the way to apply the G.9960 system under those conditions in Japan.

C.2 Medium dependent specification

C.2.1 Physical layer specification over phone lines

For further study.

C.2.2 Physical layer specification over power lines

C.2.2.1 Frequency use for power lines

All nodes over power lines shall comply with national regulations in Japan [V.3], which states the frequency band that one can use without any license is restricted to between 2 MHz and 30 MHz, and the interference level due to power-line communication is also restricted.

Furthermore, the regulations give limitations of where they can be used; that is, the usage of power-line communications is only limited inside buildings and not allowed outside buildings.

C.2.3 Physical layer specification over coax

C.2.3.1 Bandplan

In addition to the OFDM control parameters in Table 7-40, the OFDM control parameters shown in Table C-1 may be used. It should be noted that a coaxial home network connected to a cable access network should not interfere with services offered by the cable television operator to customers.

Table C-1/G.9960 – Optional OFDM control parameters for coax cables in Japan

Domain Type	**Coax RF**
Bandplan Name	**200MHz-CRF** **(NOTES 2, 3)**
N	1024
F_{SC}	195.3125 kHz
N_{GI}	For further study
N_{GI-HD}	For further study
N_{GI-DF}	For further study
β	For further study
F_{US}	100 MHz
F_{UC}	Z (NOTE 4)
Sub-carrier indexing rule (NOTE 1)	Rule #1 if $X = Y = Z$, or rule #2 if $X + 25$ MHz $= Y + 50$ MHz $= Z + 100$ MHz. (NOTE 5)
NOTES: 1. See §7.1.4.1 for more details on sub-carrier indexing rules. 2. The 200MHz bandplan on this table and the 50MHz and 100MHz bandplans shown in Table 7-40 may be used by nodes operating in the same Coax RF domain. 3. The range of sub-carrier frequencies is between Z MHz and (Z + 200) MHz 4. The values of F_{UC} shall be selected from the valid set defined in Table 7-29 and may be subject to regional spectrum management rules. 5. X and Y are F_{UC} of bandplan 50MHz-CRF and 100MHz-CRF respectively (See Table 7-40).	

C.2.3.2 Transmitter EVM Requirements for coax RF

The EVM requirements are for further study.

Annex D – International Amateur radio bands

Table D-1/G.9960 – International Amateur radio bands in the frequency range 0-30 MHz

Band start (kHz)	Band stop (kHz)
1 800	2 000
3 500	4 000
7 000	7 300
10 100	10 150
14 000	14 350
18 068	18 168
21 000	21 450
24 890	24 990
28 000	29 700

Appendix I: Examples of home network topologies

An example of a home network containing a single domain is shown in Figure I-1 where a single domain master coordinates nodes of the domain (i.e. assigns bandwidth resources and priority). In this example, the domain is bridged to the access network via node D (it is also a domain master) that is assumed to be part of the residential gateway. In PM, nodes A, B, C, and D communicate directly to each other. In CM, one of the nodes is assigned as DAP (node D in this example), and all nodes can communicate to each other only via this node. In UM, each of the nodes A-D can communicate directly to each other or indirectly, via other nodes operating as relay nodes. In this example, node D (domain master) serves as a relay node, while other nodes use either P2P or node D as a relay if required.

While in either PM, CM or UM, nodes A-D can transmit under limitation of bandwidth resources and priorities assigned by the domain master.

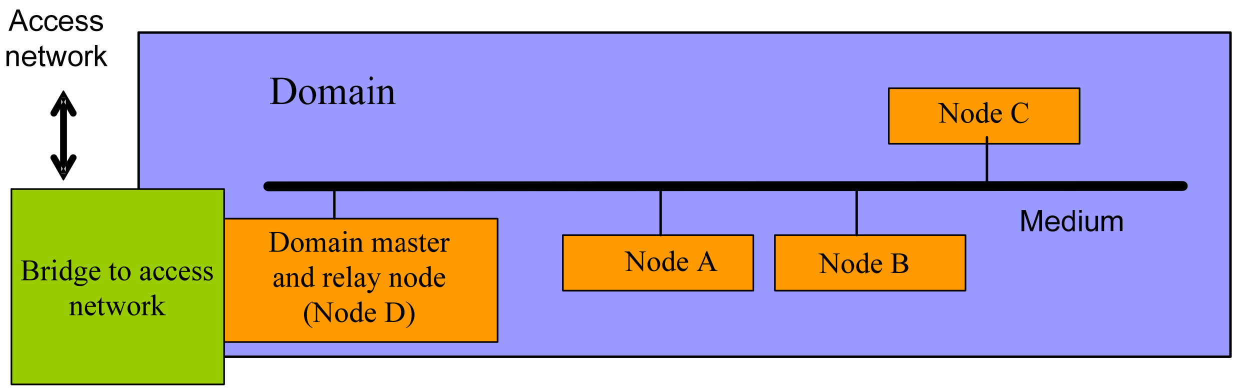

Figure I-1/G.9960 − Example of a home network containing a single domain

An example of a home network containing a single domain that operates in UM using both P2P and REL is depicted in Figure I-2. The subset of nodes that use RELincludes nodes B, C, D and F where Node D operates as a relay node for this group of nodes. All other nodes can communicate directly (i.e., using P2P) or via a relay node (i.e., using REL). A single domain master (in this case node A) coordinates the nodes of the domain. The domain is bridged to the access network via node A, which is assumed to be part of the residential gateway. While either using P2P or REL, nodes A through G can transmit under the limitation of bandwidth resources and priorities assigned by the domain master. Frames from nodes B, C and F addressed to nodes outside the domain are sent to node A via relay node D; node A is connected to the inter-domain bridge. Frames from nodes D, E and G addressed to nodes outside the domain are sent to node A directly.

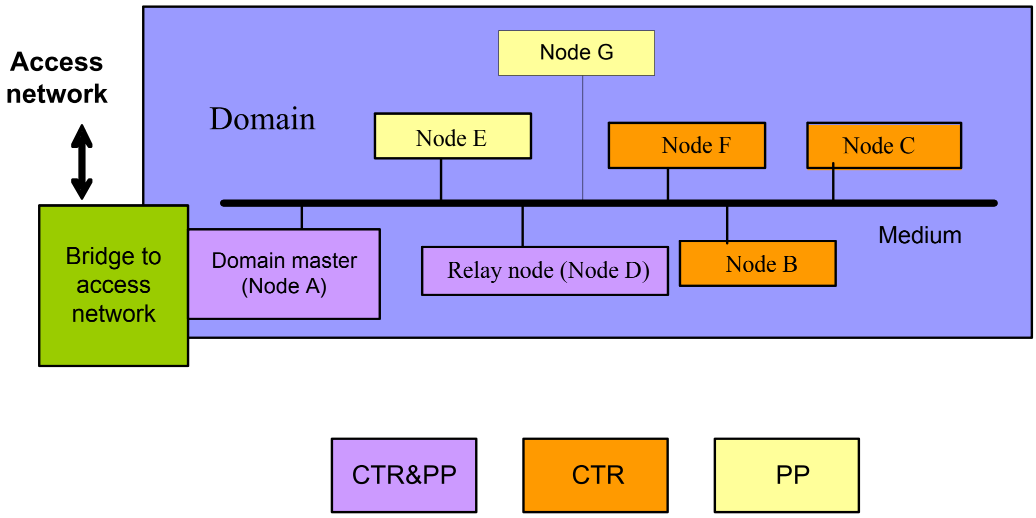

Figure I-2/G.9960 − Example of a home network containing a single domain operating in UM (using a combination of P2P& REL)

An example of a home network containing three domains with corresponding domain masters established on two different media is depicted in Figure I-3. Nodes of domain 1 and of domain 3 operate over the same medium (medium 1). In this example, it is assumed that domain 1 and domain 3 operate in different spectral bands. Those two domains are bridged via an inter-domain bridge (on layer 2 or layer 3). Domain 2 operates on a different medium (denoted as medium 2). Domains 1 and 2 are bridged to the access network. In Figure I-3 it is assumed that the domain master of domain 2 and node A of domain 1 are parts of the residential gateway. Domains 1 and 3 are connected by an inter-domain bridge. Each of three domains can operate in either PM, UM or CM, independently of the operational mode used by other domains.

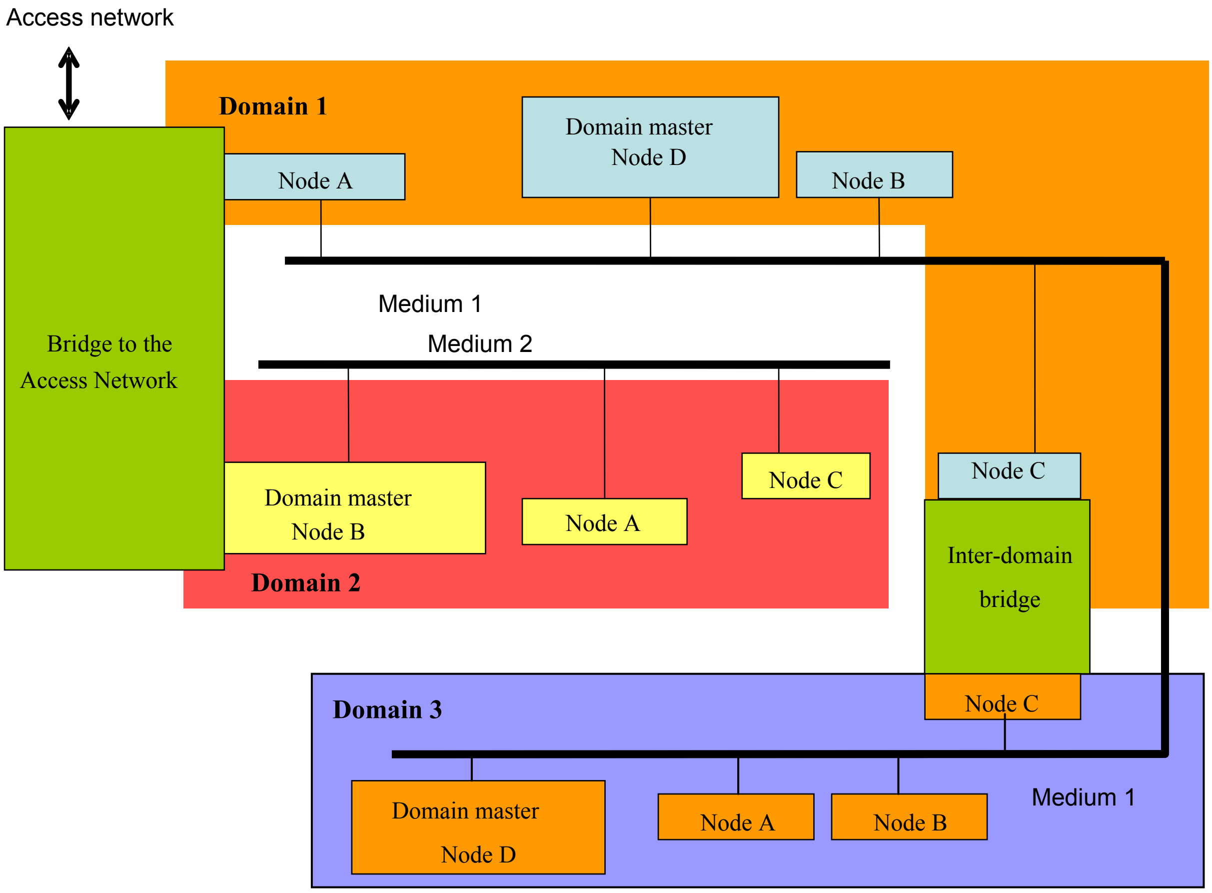

Figure I-3/G.9960 – Example of a home network comprising three domains

An example of a home network connected to an alien domain is shown in Figure I-4. The example shows a home network containing two domains (domains 1 and 2) with corresponding domain masters established on two different media, bridged via an inter-domain bridge (layer 2 or layer 3) to the alien domain. The alien domain is established on the same medium as domain 1. Nodes of domain 1 and of domain 2 in Figure I-4 operate over different media, while nodes A1-A3, which are alien nodes, share the same medium with domain 1. The domain master of domain 1 considers the alien domain as another AE connected to the corresponding node of domain 1. Operation of this alien domain and its interconnection with a G.9960 home network is out of scope of G.9960.

In this example, node A of domain 1 is bridged to the access network. This bridge is usually a part of the residential gateway.

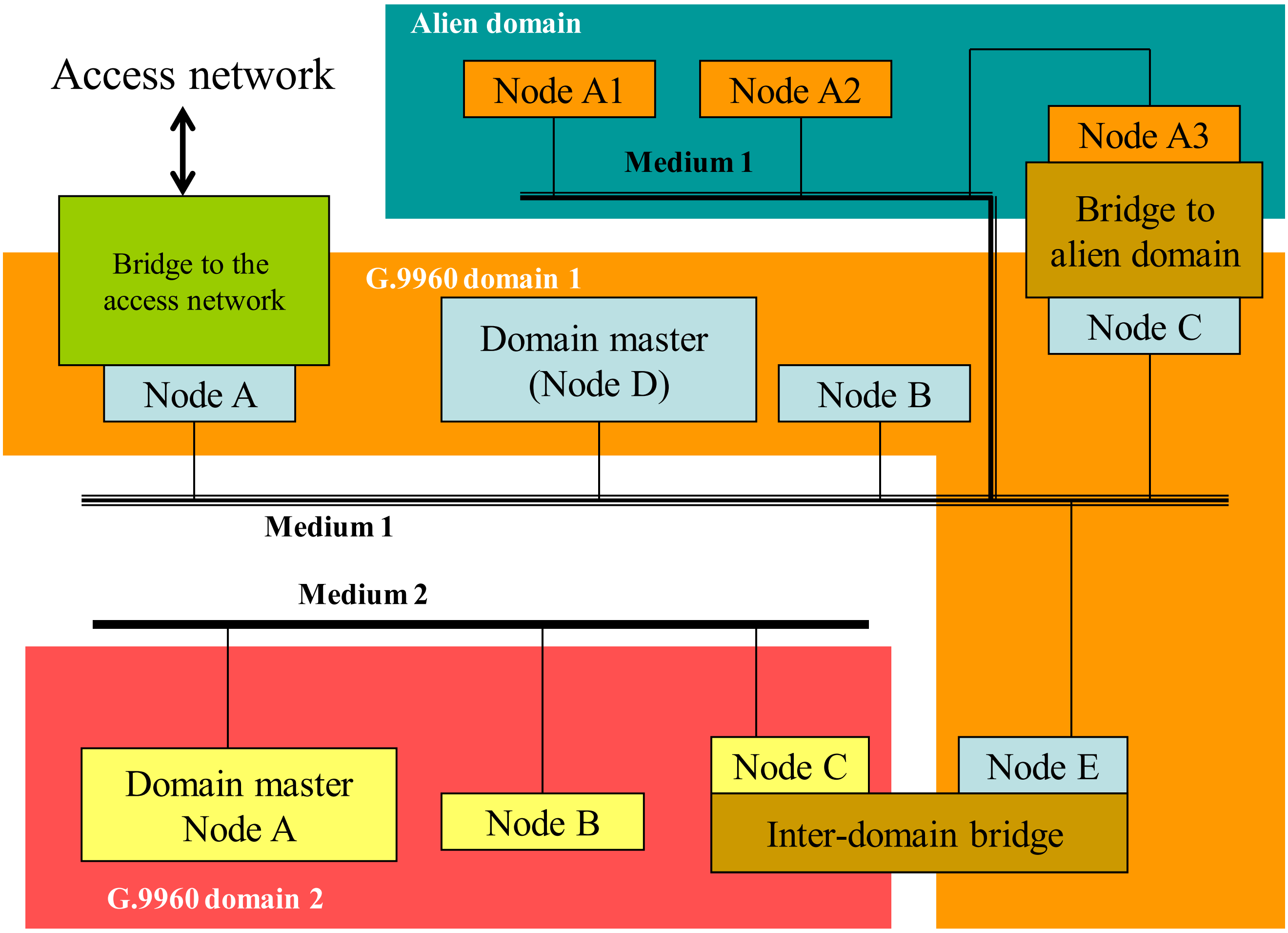

Figure I-4/G.9960 − Example of a G.9960 sharing a medium with an alien domain

An example of a home network associated with residential broadband access is presented in Figure I-5. In the example, the home network includes three domains established over coax, phone, and power-line wiring. Alien domains are established by the residential gateway and may include WLAN IEEE 802.11, USB2, and IEEE 802.3 (Ethernet). The RG serves as a bridge allowing communication with alien domains (e.g., 802.11) and with an access network (e.g. PON or DSL).

Each node in Figure I-5 is configured for the medium it is connected to. It can communicate with any other node of the same domain using either P2P or REL. Communication between nodes of different domains (e.g., between coax and phone line in Figure I-5) is via inter-domain bridges or via the RG. Communication with alien nodes and with the access network is via bridges, which are a part of the RG.

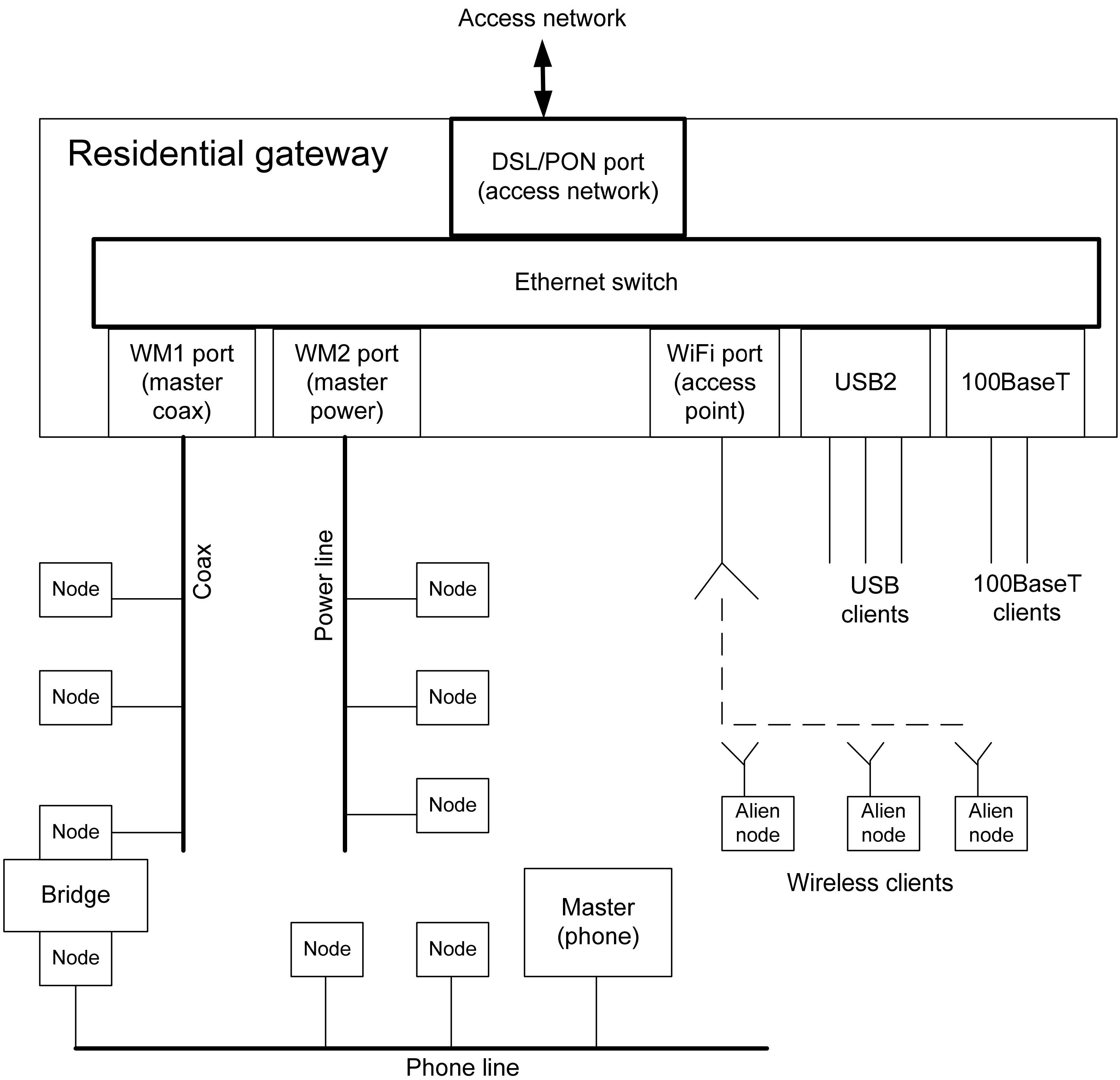

Figure I-5/G.9960 − Example of a home network supporting residential broadband access

Appendix II: Spectral usage

II.1 Scope

This appendix describes information on spectral usage on each medium (coax cable, phone line and power line).

II.2 Spectral usage in Japan

II.2.1 Frequency allocation for coax

There are mainly three types of services which are mapped to in-home coax medium:

- Terrestrial broadcasting
- Satellite broadcastings
- CATV services

The frequency allocations for all cases are shown in this clause.

It should be noted that a coaxial home network connected to a cable access network should not interfere with services offered by the cable television operator to customers. The general use of the frequency by the cable television operator is 5 to 770MHz.

II.2.1.1 Terrestrial broadcast signal mapped to coax cable

Table II-1 shows the frequency allocation for terrestrial TV broadcasting mapped to coax cable. Currently, both analog TV broadcasting (VHF/UHF) and digital TV broadcasting (UHF) are in service [V.4]. But analog TV broadcasting services will be discontinued on 24th July 2011 [V.5][V.6] and non-TV broadcasting and other telecommunications are planned to use these bands after that. G.9960 is one of the candidate services for empty bands if available, but this is for further study.

Table II-1/G.9960 – Frequency allocation for terrestrial broadcast signals mapped to a coax cable

	Frequency [MHz]	Remarks
	90 – 108 *	• Used for analog TV broadcasting till 24th July 2011 • The use after 25th July 2011 is not determined at the time of publication • Retransmission of terrestrial digital TV broadcasting (OFDM)
	108 – 170 *	• Retransmission of terrestrial digital TV broadcasting (OFDM)
	170 – 222 *	• Used for analog TV broadcasting till 24th July 2011 • The use after 25th July 2011 is not determined at the time of publication • Retransmission of terrestrial digital TV broadcasting (OFDM)
	222 – 470 *	• Retransmission of terrestrial digital TV broadcasting (OFDM)
	470 – 710 *	• Used for analog TV broadcasting till 24th July 2011 • Used for digital TV broadcasting • Retransmission of terrestrial digital TV broadcasting (OFDM)
	710 – 770 *	• Used for TV broadcasting till 24th July 2012 • The use after 25th July 2012 is not determined at the time of publication • Retransmission of terrestrial digital TV broadcasting (OFDM)
*	Frequency band usage for G.9960 including guard band is for further study.	

II.2.1.2 Broadcast Satellite (BS) and Communication Satellite (CS) signal mapped to coax cable

Satellite broadcastings (BS and CS) using around 12 GHz of frequency [V.4] are down-converted to intermediate frequency (BS-IF/CS-IF) at an antenna before transmission to a coax cable. The BS and CS need dedicated receiver antennas and there are various cases to use in-home coax cables depending on locations of antennas and connection points to in-home coax system. Basically, BS-IF/CS-IF signals come from an antenna or CATV. Table II-2 shows satellite broadcast signals mapped to a coax cable.

Table II-2/G.9960 – Frequency allocation for satellite broadcast signals mapped to a coax cable

Broadcast satellite services	BS-IF/CS-IF [MHz]	Remarks
BS *	1035.95 – 1331.50	BS-IF transmission
110˚ CS *	1596 – 2070	CS-IF transmission
JC SAT-3,4 *	968 – 2055	CS-IF transmission
Superbird C *	1020 – 2040	CS-IF transmission
* Frequency band usage for G.9960 including guard band is for further study.		

II.2.1.3 CATV services on coax cable

Table II-3 shows the frequency allocation of other services [V.7][V.8]. Since frequencies below 770MHz are currently used for various services listed in Table II-3, the usage for other services such as G.9960 is for further study.

Table II-3/G.9960 – Frequency allocation of other services on coax cable

Frequency [MHz]	Usage	Remarks
5 – 60 *	• Upstream CATV signal (cable internet signal, VoIP, VOD, relay broadcast, pilot signal etc.)	• Being used for cable modem up-stream signals [V.9][V.10][V.11] • Being used for control signals between cable modem and cable modem termination
70 – 76 *	• Downstream pilot signal, analog HT (Home Terminal) control signal, monitoring signal of amplifier	• Being used for cable modem up-stream signals [V.9][V.10][V.11]
76 – 90 *	• Retransmission of radio broadcasting on cable (FM radio signal)	• Being used for cable modem up-stream signals [V.11]
90 – 770 *	• Analog cable broadcasting (NTSC-VSB) • Digital cable broadcasting (64/256QAM) • Retransmission of terrestrial analogTV broadcasting (NTSC-VSB) • Retransmission of terrestrial digitall TV broadcasting (OFDM) • Downstream cable internet signal, VoIP, VOD control signal etc.	• Covered by regulation [V.7]
770 – 1035 **	• Alien home network services	
1035 – 2070 *	• BS-IF/CS-IF retransmission	
>2070 **	• Currently not in use at the time of publication	
* Frequency band usage for G.9960 including guard band is for further study. ** Candidate frequency band for G.9960 including guard band.		

II.2.2 Frequency allocation for phone line

(For further study)

II.2.3 Frequency allocation for power line

(For further study)

Appendix III - Priority Mapping

Priority mapping recommended by IEEE 802.1D (sub-clause 7.7.3) are presented in Table III-1.

Table III-1/G.9960 – Recommended Flow Priority to Priority Queue Mappings according to 802.1D

		Number of Available Traffic Classes							
		1	2	3	4	5	6	7	8
User Priority	0 (default)	0	0	0	1	1	1	1	2
	1	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	1
	3	0	0	0	1	1	2	2	3
	4	0	1	1	2	2	3	3	4
	5	0	1	1	2	3	4	4	5
	6	0	1	2	3	4	5	5	6
	7	0	1	2	3	4	5	6	7

Appendix IV – Threat Model

G.hn threat model considers two kinds of threats:

- External – A neighbor may be able to eavesdrop on transmissions within the home network, and may also be able to transmit to stations within the home network, without the awareness of the legitimate users. The goal is to protect against knowledgeable attackers with reasonable resources. As a point of reference, it is assumed that the attacker has access to 10-20 of the fastest commercially available PCs.
- Internal – A legitimate user of the network of the network may have an illegitimate interest in the communications of another user of the network, or in illegitimate access to specific equipment connected to the network. The resources assumed for an internal attacker are similar to those for an external attacker. The determination of what is legitimate and what is illegitimate is a decision made by the administrator of the network, and can include restrictions of access to equipment or to information.

Because G.hn networks may involve hidden nodes or multiple domains, applications may arise in which the communications between two particular nodes always pass through a specific third node (a relay node). Such a situation is vulnerable to a “man-in-the-middle” attack by either a neighbor or an illegitimate user obtained control over the relay node.

In all cases, it is assumed that the attacker will not have access to specialized non-commercial hardware for signal processing inside nodes, but can utilize any spoofing or header-manipulation capabilities which can be implemented on a commercially available PC.

Appendix V – Bibliography

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[V.9] ITU-T Rec.J.112 “Transmission systems for interactive cable television services”

[V.10] ITU-T Rec.J.122 “Second-generation transmission systems for interactive cable television services – IP cable modems”

[V.11] ITU-T Rec. J.222.1 “Third-generation transmission systems for interactive cable television services – IP cable modems: Physical layer specification”