

International Telecommunication Union

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

G.993.2

(02/2019)

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

Digital sections and digital line system – Metallic access
networks

**Very high speed digital subscriber line
transceivers 2 (VDSL2)**

Recommendation ITU-T G.993.2

ITU-T



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

Recommendation ITU-T G.993.2

Very high speed digital subscriber line transceivers 2 (VDSL2)

Summary

Recommendation ITU-T G.993.2 specifies an access technology that exploits the existing infrastructure of copper wires that were originally deployed for POTS services. It can be deployed from central offices, from fibre-fed cabinets located near customer premises, or within buildings. This Recommendation is an enhancement to ITU T G.993.1 that supports asymmetric and symmetric transmission at a bidirectional net data rate up to 200 Mbit/s on twisted pairs using a bandwidth up to 30 MHz.

This version of this Recommendation integrates all the previous amendments and corrigenda with the 2011 version of Recommendation ITU-T G.993.2.

This version of Recommendation ITU-T G.993.2 corrects or adds the following functionality:

- Method to address the misestimation of the SNR during MEDLEY (Amendment 2)
- Segmentation of SOC messages for profile 35b (Corrigendum 1)
- Annex D: Long reach VDSL2 (Amendment 3)
- Near-end anomalies for loss-of-power, host-reinit and spontaneous interruptions (Amendment 4)
- Addition of operation per the North American region for profile 35b (Annex Q) (Amendment 4)
- Addition of operation per the China region for profile 35b (Annex Q) (new)
- Addition of Successful SRA counter (new)
- Long reach VDSL2 corrigendum related to MAXNOMATP (new)
- Corrigendum to MAXMASK definition in Table 7-5 (new)
- Corrigendum to use of US0 with 35b profile for the North-America region (new).

History

Edition	Recommendation	Approval	Study Group	Unique ID*
1.0	ITU-T G.993.2	2006-02-17	15	11.1002/1000/8548
1.1	ITU-T G.993.2 (2006) Cor. 1	2006-12-14	15	11.1002/1000/8992
1.2	ITU-T G.993.2 (2006) Amd. 1	2007-04-06	15	11.1002/1000/8991
1.3	ITU-T G.993.2 (2006) Amd. 1 Cor. 1	2007-07-29	15	11.1002/1000/9164
1.4	ITU-T G.993.2 (2006) Cor. 2	2007-07-29	15	11.1002/1000/9166
1.5	ITU-T G.993.2 (2006) Amd. 2	2008-02-06	15	11.1002/1000/9165
1.6	ITU-T G.993.2 (2006) Amd. 3	2008-08-22	15	11.1002/1000/9387
1.7	ITU-T G.993.2 (2006) Amd. 4	2009-01-13	15	11.1002/1000/9654
1.8	ITU-T G.993.2 (2006) Cor. 3	2009-06-29	15	11.1002/1000/9890
1.9	ITU-T G.993.2 (2006) Amd. 5	2010-04-22	15	11.1002/1000/10413
1.10	ITU-T G.993.2 (2006) Amd. 6	2010-11-29	15	11.1002/1000/11022
1.11	ITU-T G.993.2 (2006) Cor. 4	2011-04-13	15	11.1002/1000/11149
1.12	ITU-T G.993.2 (2006) Amd. 7	2011-06-22	15	11.1002/1000/11148
2.0	ITU-T G.993.2	2011-12-16	15	11.1002/1000/11415
2.1	ITU-T G.993.2 (2011) Amd. 1	2012-04-06	15	11.1002/1000/11502
2.2	ITU-T G.993.2 (2011) Cor. 1	2012-06-13	15	11.1002/1000/11642
2.3	ITU-T G.993.2 (2011) Amd. 2	2012-12-07	15	11.1002/1000/11795
2.4	ITU-T G.993.2 (2011) Amd. 3	2013-04-22	15	11.1002/1000/11888
2.5	ITU-T G.993.2 (2011) Amd. 4	2013-08-29	15	11.1002/1000/11992
2.6	ITU-T G.993.2 (2011) Amd. 5	2014-01-13	15	11.1002/1000/12096
2.7	ITU-T G.993.2 (2011) Amd. 6	2015-05-22	15	11.1002/1000/12371
3.0	ITU-T G.993.2	2015-01-13	15	11.1002/1000/12370
3.1	ITU-T G.993.2 (2015) Amd. 1	2015-11-06	15	11.1002/1000/12563
3.2	ITU-T G.993.2 (2015) Amd. 2	2016-03-29	15	11.1002/1000/12796
3.3	ITU-T G.993.2 (2015) Cor.1	2016-11-13	15	11.1002/1000/13120
3.4	ITU-T G.993.2 (2015) Amd. 3	2018-02-09	15	11.1002/1000/13306
3.5	ITU-T G.993.2 (2015) Amd. 4	2018-05-07	15	11.1002/1000/13528
4.0	ITU-T G.993.2	2019-02-22	15	11.1002/1000/13747

Keywords

Broadband access, copper pairs, DMT modulation, 100 Mbit/s.

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

FOREWORD

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

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

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

NOTE

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

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

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

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Recommendation ITU-T G.993.2

Very high speed digital subscriber line transceivers 2 (VDSL2)

1 Scope

This Recommendation is an enhancement to [ITU-T G.993.1] that supports transmission at a bidirectional net data rate (the sum of upstream and downstream rates) up to 200 Mbit/s on twisted pairs. This Recommendation is an access technology that exploits the existing infrastructure of copper wires that were originally deployed for plain old telephone service (POTS).

This Recommendation specifies only discrete multi-tone (DMT) modulation and incorporates components from [ITU-T G.993.1] (VDSL), [ITU-T G.992.3] (ADSL2), and [ITU-T G.992.5] (ADSL2 plus).

Whilst POTS uses approximately the lowest 4 kHz and asymmetric digital subscriber line (ADSL) uses approximately 2 MHz of the copper wire spectrum, this Recommendation is defined to allow the use of up to 30 MHz of the spectrum. This Recommendation can be deployed from central offices, from fibre-fed cabinets located near the customer premises, or within buildings.

The availability of bandwidth up to 30 MHz allows ITU-T G.993.2 transceivers to provide reliable high data rate operation on short loops. Without the use of the US0 band, this Recommendation should operate reliably over loop lengths that are similar to those of [ITU-T G.993.1], or slightly longer lengths due to the mandatory support of trellis coding. The addition of the US0 band and means to train echo cancellers and time-domain equalizers (TEQs) also allows this Recommendation to provide reliable operation on loops up to approximately 2 500 metres of 26 American wire gauge (AWG) (0.4 mm).

This Recommendation defines a wide range of settings for various parameters (such as bandwidth and transmitter power) that could potentially be supported by a transceiver. Therefore, this Recommendation specifies profiles to allow transceivers to support a subset of the allowed settings and still be compliant with the Recommendation. The specification of multiple profiles allows vendors to limit implementation complexity and develop implementations that target specific service requirements. Some profiles are better suited for asymmetric data rate services, whereas other profiles are better for symmetric data rate services.

The annexes of this Recommendation include band plans and power spectral density (PSD) masks that address region-specific requirements.

Like [ITU-T G.993.1], this Recommendation defines upstream power back-off (UPBO) to mitigate far-end crosstalk (FEXT) caused by upstream transmissions on shorter loops to longer loops. The mechanism is the same as in [ITU-T G.993.1].

As with other ITU-T Recommendations in the ITU-T G.99x series, this Recommendation uses [ITU-T G.994.1] to initiate the transceiver training sequence.

Changes in this Recommendation relative to [ITU-T G.993.1] include:

- The definition of profiles to support a wide range of deployment scenarios (e.g., central offices, fibre-fed cabinets located near the customer premises, and within buildings).

For TPS-TC sublayer specifically, changes in this Recommendation relative to [ITU-T G.993.1] include:

- Support for STM interfaces;
- Support for PTM interfaces based on IEEE 802.3 64/65 octet encapsulation;
- Support for ToD-TC functionality for transport of time-of-day over VDSL2 links.

For PMS-TC sublayer specifically, changes in this Recommendation relative to [ITU-T G.993.1] include:

- Improved framing (based on [ITU-T G.992.3]);
- The definition of two latency paths and two bearer channels;
- Improved on-line reconfiguration (OLR) mechanisms (based on [ITU-T G.992.3]), including optional SRA, special operations channel (SOS), and dynamic interleaver change;
- Control of delay variation;
- Improved overhead channel;
- Improved forward error correction (FEC) capabilities, including a wider range of settings for the Reed-Solomon (RS) encoder and the interleaver;
- Improved interleaving with controlled memory-split between downstream and upstream;
- Support of all integer values of impulse noise protection (INP) up to 16 symbols;
- Optional impulse noise monitor (INM) function.

For PMD sublayer specifically, changes in this Recommendation relative to [ITU-T G.993.1] include:

- The definition, in annexes, of band plans up to 30 MHz to support a bidirectional net data rate up to 200 Mbit/s;
- Support for extension of the upper band edge of the US0 band to as high as 276 kHz (based on Annex M of [ITU-T G.992.3]);
- The definition of means to improve the performance of US0 (specifically, support in initialization for training of time domain equalizers and echo cancellers);
- A requirement to support the US0 band in the upstream direction for some profiles;
- Support for spectrum shaping of the US0 band in the upstream direction;
- Support for a management information base (MIB)-controlled PSD mask mechanism to enable in-band spectrum shaping (based on [ITU-T G.992.5]);
- Alternative electrical length estimation method (AELE-M1);
- Optional equalized FEXT UPBO method;
- A requirement for downstream and upstream transmitters to notch, simultaneously, 16 arbitrary operator-defined radio frequency interference (RFI) bands;
- Support for downstream maximum transmit power (profile dependent) of up to 20.5 dBm;
- Mandatory support of trellis coding (based on [ITU-T G.992.3]);
- The definition of receiver-determined tone ordering (based on [ITU-T G.992.3]);
- Mandatory support of all integer-bit constellations from 1 bit to 15 bits;
- Support for optional cyclic extension (CE) lengths as large as $\frac{1}{4}$ of a symbol period;
- Optional virtual noise (VN) mechanism;
- The definition of VTU-R receiver-selected pilot tone(s), including the option not to select a pilot tone;
- Insertion of a sync symbol after every 256 data symbols to signal OLR transitions;
- Improvements to initialization, including the definition of a channel discovery phase, a training phase, and a channel analysis and exchange phase;
- Definition of re-initialization policy parameters;
- Definition of link activation methods and procedures;
- Support for a VTU-R lineprobe stage during initialization;

- Support for a wide range of test parameters and accuracy requirements (based on [ITU-T G.992.3]);
- The definition of a loop diagnostic mode;
- Support for an optional all-digital mode;
- Definition of downstream and full vectoring-friendly operating modes.

2 References

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

- [ITU-T G.117] Recommendation ITU-T G.117 (1996), *Transmission aspects of unbalance about earth.*
- [ITU-T G.992.1] Recommendation ITU-T G.992.1 (1999), *Asymmetric digital subscriber line (ADSL) transceivers.*
- [ITU-T G.992.3] Recommendation ITU-T G.992.3 (2009), *Asymmetric digital subscriber line transceivers 2 (ADSL2).*
- [ITU-T G.992.5] Recommendation ITU-T G.992.5 (2009), *Asymmetric digital subscriber line 2 (ADSL2) transceivers – Extended bandwidth ADSL2 (ADSL2 plus).*
- [ITU-T G.993.1] Recommendation ITU-T G.993.1 (2004), *Very high speed digital subscriber line transceivers (VDSL).*
- [ITU-T G.993.5] Recommendation ITU-T G.993.5 (2019), *Self-FEXT cancellation (vectoring) for use with VDSL2 transceivers.*
- [ITU-T G.994.1] Recommendation ITU-T G.994.1 (2018), *Handshake procedures for digital subscriber line transceivers.*
- [ITU-T G.995.1] Recommendation ITU-T G.995.1 (2001), *Overview of digital subscriber line (DSL) Recommendations.*
- [ITU-T G.997.1] Recommendation ITU-T G.997.1 (2019), *Physical layer management for digital subscriber line transceivers.*
- [ITU-T G.998.4] Recommendation ITU-T G.998.4 (2018), *Improved impulse noise protection for digital subscriber line (DSL) transceivers.*
- [ITU-T G.9954] Recommendation ITU-T G.9954 (2007), *Home networking transceivers – Enhanced physical, media access, and link layer specifications.*
- [ITU-T I.361] Recommendation ITU-T I.361 (1999), *B-ISDN ATM layer specification.*
- [ITU-T I.432.1] Recommendation ITU-T I.432.1 (1999), *B-ISDN user-network interface – Physical layer specification: General characteristics.*
- [ITU-T O.9] Recommendation ITU-T O.9 (1999), *Measuring arrangements to assess the degree of unbalance about earth.*
- [ITU-T O.41] Recommendation ITU-T O.41 (1994), *Psophometer for use on telephone-type circuits.*

- [ITU-T T.35] Recommendation ITU-T T.35 (2000), *Procedure for the allocation of ITU-T defined codes for non-standard facilities*.
- [IETF RFC 5905] IETF RFC 5905 (2010), *Network Time Protocol Version 4: Protocol and Algorithms Specification*.
- [ISO 8601] ISO 8601-1:2019, *Date and time – Representations for information interchange – Part 1: Basic rules*.

3 Definitions

This Recommendation defines the following terms:

- 3.1 aggregate data rate:** The net data rate plus the overhead data rate in any one direction (see Table 5-1).
- 3.2 aggregate downstream (upstream) transmit power:** The power transmitted within the entire downstream (upstream) passband.
- 3.3 anomaly:** A discrepancy between the actual and desired characteristics of an item. The desired characteristics may be expressed in the form of a specification. An anomaly may or may not affect the ability of an item to perform a required function.
- 3.4 band plan:** The partitioning of the frequency spectrum into non-overlapping frequency bands, each of which is allocated for either upstream or downstream transmission.
- 3.5 bearer channel:** A data stream at a specified data rate between two TPS-TC entities (one in each VTU) that is transported transparently over a single latency path by the PMS-TC and PMD sublayers, also referred to as "frame bearer" (see Annex L).
- 3.6 bidirectional net data rate:** The sum of upstream and downstream net data rates.
- 3.7 blackout subcarrier:** A subcarrier selected by the receiver to be allocated no power by the transmitter.
- 3.8 channel:** A connection conveying signals between two blocks (the conveyed signals represent information). Channels also convey signals between a block and the environment. Channels may be unidirectional or bidirectional.
- 3.9 channel discovery PSD:** The PSD of signals transmitted by the VTU at every frequency (i.e., in both the passband and the stopbands) during the channel discovery phase of initialization. The channel discovery PSDs for the downstream and upstream directions are denoted as CDPSD_d and CDPSD_u, respectively.
- 3.10 connection:** An association of transmission channels or circuits, switching and other functional units set up to provide a means for a transfer of user, control and management information between two or more end points (blocks) in a telecommunication network.
- 3.11 data:** All bits or bytes transported over the channel that individually convey information. Data includes both user data and overhead bits. Data does not include bits or bytes that, by themselves, do not convey any information, such as bits in a sync frame. See also "data frame" and "data symbol".
- 3.12 data frame:** A frame composed of bits from the enabled latency paths over a single symbol time period, after the addition of FEC octets and after interleaving, which is exchanged over the δ reference point between the PMS-TC and PMD sublayers.
- 3.13 data symbol:** A DMT symbol carrying a data frame.
- 3.14 data symbol rate:** The average rate at which data symbols are transmitted (see clause 10.4.4). This is not the same as "symbol rate".

3.15 defect: A limited interruption in the ability of an item to perform a required function. It may or may not lead to maintenance action depending on the results of additional analysis. Successive anomalies causing a decrease in the ability of an item to perform a required function are considered a defect.

3.16 DMT superframe: A set of 256 consecutive data frames followed by one sync frame, modulated onto 257 consecutive symbols.

3.17 DMT symbol: The time-domain samples emerging from the DMT modulator during one symbol period, following insertion of the cyclic extension and completion of the windowing and overlap-and-add operations. During showtime, there are two types of DMT symbols: data symbols and sync symbols.

3.18 downstream: Information flow whose direction is from a service provider (operator) to a subscriber.

3.19 electrical length: An estimate of the loop attenuation, assuming that all sections of a loop obey a \sqrt{f} attenuation characteristic. Specifically, the electrical length is the attenuation, in dB at 1 MHz, of an equivalent hypothetical loop with a perfect \sqrt{f} attenuation characteristic.

NOTE – The attenuation caused by bridged taps does not follow a \sqrt{f} characteristic, and thus the effects of bridged taps may not be accurately represented in the estimate.

3.20 epoch: The origin of a timescale.

3.21 frame: A general term to describe an ordered grouping of bits. See, for example, "data frame", "sync frame", and "overhead frame".

3.22 frame bearer: See the definition for "bearer channel".

3.23 HDLC frame: A group of data bytes encapsulated into the HDLC structure (see clause 8.2.3).

3.24 indicator bits: Bits used for operations and maintenance (OAM) purposes; embedded in the overhead octets.

3.25 interface: A point of demarcation between two blocks, through which information flows from one block to the other. An interface may be a physical interface or a logical interface.

3.26 layer/sublayer: A collection of objects of the same hierarchical rank.

3.27 limit PSD mask: A PSD mask specified in an annex of this Recommendation. The limit PSD mask is defined at all frequencies (i.e., in both the passband and the stopbands). The limit PSD masks for the downstream and upstream directions are denoted LIMITMASK_{ds} and LIMITMASK_{us}, respectively.

3.28 line rate: The data rate transmitted at the U-x reference point in any one direction. This is the total data rate plus trellis coding overhead.

3.29 logical (functional) interface: An interface where 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. A logical interface can be an internal or external interface. It is defined by a set of information flows and associated protocol stacks.

3.30 loop timing: A mode of operation where the VTU-R clock is extracted from the received signal. In loop timing mode, the VTU-R operates as a slave; the VTU-R transmit and receive clocks are equal to the transmit clock of the VTU-O, within the tolerance introduced by the implementation.

3.31 MEDLEY reference PSD: The PSD of signals transmitted by a VTU at every frequency (i.e., in both the passband and the stopbands) during the training phase and the channel analysis and

exchange phase of initialization. The MEDLEY reference PSDs in the downstream and upstream directions are denoted as MREFPSDds and MREFPSDus, respectively.

3.32 MEDLEY reference PSD mask: The MEDLEY reference PSD mask is the transmit PSD mask limited at every frequency (i.e., in both the passband and the stopbands) by the PSD ceiling and limited to -80 dBm/Hz at frequencies corresponding to the designated RFI bands. In the upstream direction, the MEDLEY reference PSD mask is further reduced in accordance with the UPBO requirements. The MEDLEY reference PSD masks in the downstream and upstream directions are denoted as MREFMASKds and MREFMASKus, respectively.

3.33 MEDLEY set: A subset of the SUPPORTEDCARRIERS set. It is determined during the channel discovery phase and contains the subcarriers that will be used for transmission of initialization signals after the channel discovery phase. For each subcarrier in the MEDLEY set, a b_i and a g_i value will be exchanged during the channel analysis and exchange phase. Blackout subcarriers are not part of the MEDLEY set. The MEDLEY set is denoted MEDLEYds and MEDLEYus, respectively, for the downstream and upstream directions.

3.34 message overhead data rate of latency path p : The part of the overhead data rate assigned for the message transport for latency path p in any one direction of transmission (see Table 5-1).

3.35 MIB PSD mask: A PSD mask specified by the operator to restrict the transmit PSD in the passband to levels below those allowed by the applicable limit PSD mask. The MIB PSD mask is defined only within the passband and lies at or below the limit PSD mask. Operators may choose not to specify a MIB PSD mask for one or both transmission directions or in specific bands of the passband. The MIB PSD masks for the downstream and upstream directions are denoted as MIBMASKds and MIBMASKus, respectively. The MIB PSD mask does not incorporate PSD requirements for RFI bands, which are specified separately (see definition of "RFI bands").

3.36 monitored subcarrier: A subcarrier (but not a pilot tone) in the MEDLEY set that has $b_i = 0$ and $g_i > 0$.

3.37 mux data frame: The grouping of octets from different bearer channels within the same latency path, after the overhead data octets have been added.

3.38 net data rate of bearer channel n : The data rate of a single bearer channel n at the α/β interface of the user plane in any one direction of transmission (see Table 5-1).

3.39 net data rate of latency path p : The sum of net data rates over all bearer channels of latency path p (see Table 5-1).

3.40 net data rate: The sum of net data rates over all latency paths (see Table 5-1).

3.41 network: A collection of interconnected elements that provide connection services to users.

3.42 network timing reference: An 8-kHz timing marker used to support the distribution of a timing reference over the network.

3.43 overhead data rate: The sum of overhead data rates over all latency paths (see Table 5-1).

3.44 overhead data rate of latency path p : The data rate of the overhead channel assigned for latency path p in any one direction of transmission (see Table 5-1).

3.45 overhead (OH) frame: A frame composed of a CRC byte, followed by a Syncbyte, followed by other bytes from the overhead channel (see Table 9-4).

3.46 overhead (OH) subframe: A subdivision of an OH frame (see Figure 9-4).

3.47 overhead (OH) superframe: A specific number of consecutive overhead frames in which the first overhead frame carries a Syncbyte of value AC_{16} . The overhead superframe is not related to the DMT superframe.

- 3.48 passband:** The portion of the frequency spectrum that is allowed to be used for transmission in one direction. The passband may consist of multiple, disjointed portions of the frequency spectrum. The upstream and downstream passbands depend on the selected band plan and profile.
- 3.49 precision time protocol (PTP):** The protocol defined by IEEE 1588-2008.
- 3.50 primitives:** Basic measures of performance, usually obtained from digital signal line codes and frame formats, or as reported in overhead indicators from the far end. Performance primitives are categorized as events, anomalies and defects. Primitives may also be basic measures of other quantities (e.g., a.c. or battery power), usually obtained from equipment indicators.
- 3.51 PSD ceiling:** The PSD level, independent of frequency (and indicated by a single value), that limits the transmit PSD mask when the MEDLEY reference PSD mask is determined. The PSD ceilings in the downstream and upstream directions are denoted as MAXMASKds and MAXMASKus, respectively. The PSD ceiling determines the transmit power cut-back and is set at the end of the channel discovery phase of initialization. Initial PSD ceilings in the downstream and upstream directions, used during the channel discovery phase of initialization, are denoted as CDMAXMASKds and CDMAXMASKus, respectively (see clause 12.3.3).
- 3.52 reference point:** A set of interfaces between any two related blocks through which information flows from one block to the other. A reference point comprises one or more logical (non-physical) information-transfer interfaces, and one or more physical signal-transfer interfaces.
- 3.53 RFI bands:** One or more operator-specified frequency bands in which the PSD transmitted by a VTU is to be no higher than -80 dBm/Hz. A single set of RFI bands (RFIBANDS) is specified, which applies to both downstream and upstream transmission.
- 3.54 showtime:** The state of either the VTU-O or VTU-R that is reached after the initialization procedure has been completed in which bearer channel data are transmitted.
- 3.55 splitter:** A filter that separates VDSL2 signals from the voiceband or ISDN signals (frequently called a POTS or ISDN splitter, even though the voiceband signals may comprise more than POTS).
- 3.56 subcarrier:** A fundamental element of a discrete multi-tone (DMT) modulator. The modulator partitions the channel bandwidth into a set of parallel subchannels. The centre frequency of each subchannel is a subcarrier, onto which bits may be modulated for transmission over a channel (see clause 10).
- 3.57 subcarrier group:** A grouping of G (where $G = 1, 2, 4,$ or 8) adjacent subcarriers. Subcarrier groups are used to reduce the number of test parameter data points that need to be stored by and communicated between the VTU-O and VTU-R. Each subcarrier in a subcarrier group is characterized by the same value of a test parameter (see clause 11.4.1).
- 3.58 SUPPORTEDCARRIERS set:** The set of subcarriers allocated for transmission in one direction, as determined by the band plan and any restrictions imposed by the operator via the CO-MIB (e.g., VDSL2-CARMASK as defined in [ITU-T G.997.1]); denoted SUPPORTEDCARRIERSds and SUPPORTEDCARRIERSus, respectively, for the downstream and upstream directions.
- 3.59 symbol:** See DMT symbol.
- 3.60 symbol rate:** The rate at which DMT symbols are transmitted from the VTU-O to the VTU-R and vice versa. This is not the same as "data symbol rate".
- 3.61 sync frame:** A frame composed of all ZEROS or all ONES that is modulated onto a sync symbol as defined in clause 10.5.1.
- 3.62 sync symbol:** A DMT symbol carrying a sync frame.

- 3.63 Syncbyte:** The second octet of each overhead frame, which indicates whether the OH frame is the first in an OH superframe.
- 3.64 Syncflag:** A sync symbol in which the sync frame bits are inverted relative to the sync frame modulated by the most recently transmitted sync symbol (i.e., if the previous sync frame was all ZEROS, the Syncflag would correspond to a sync frame of all ONES, and vice versa). The Syncflag is used to signal online reconfiguration transitions.
- 3.65 system:** A collection of interacting objects that serves a useful purpose; typically, a primary subdivision of an object of any size or composition (including domains).
- 3.66 ToD phase difference value:** The value of the VTU-x Real-time Clock modulo 125 μ s at the moment the reference sample crosses the U-x reference point (i.e., phase of t_n event relative to the time-of-day, in nanoseconds, see also clause 8.4.3.2).
- 3.67 total data rate:** The aggregate data rate plus the Reed-Solomon FEC overhead rate in any one direction (see Table 5-1).
- 3.68 transmit power back-off (PBO):** Reduction of the transmitted PSD for spectral compatibility purposes, via PSD shaping using a predefined method that is dependent only on loop conditions and is independent of the service (bearer) requirements such as net data rates, INP, and delay.
- 3.69 transmit power cut-back (PCB):** Reduction of the transmitted PSD using the PSD ceiling mechanism. The PCB is dependent on the service (bearer) requirements, such as net data rates, INP, and delay, and on the desired SNR margin. The PCB also accommodates the dynamic range of the far-end receiver.
- 3.70 transmit PSD mask:** The PSD mask derived as the minimum at every frequency (i.e., in both the passband and the stopbands) of 1) the relevant Limit PSD mask; 2) the MIB PSD mask, if defined; and 3) the vendor-discretionary PSD mask restrictions imposed by the VTU-O for the downstream and upstream directions. The transmit PSD masks for the downstream and upstream directions are denoted as PSDMASKds and PSDMASKus, respectively.
- 3.71 upstream:** Information flow whose direction is from a subscriber to a service provider (operator).
- 3.72 user:** A service-consuming object or system (block).
- 3.73 voiceband:** 0 to 4 kHz; expanded from the traditional 0.3 to 3.4 kHz to deal with voiceband data services wider than POTS.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

ACTATP	Actual Aggregate Transmit Power
AGC	Automatic Gain Control
AN	Access Node
ATM	Asynchronous Transfer Mode
ATM-TC	Asynchronous Transfer Mode – Transmission Convergence
ATTNDR	Attainable Net Data Rate
BER	Bit Error Ratio
CE	Cyclic Extension
CPE	Customer Premises Equipment

CRC	Cyclic Redundancy Check
DMT	Discrete Multi-Tone
DS	Downstream
DSL	Digital Subscriber Line
EC	Echo Canceller (or Cancellation)
EIA	External OAM Interface Adapter
eoc	embedded operations channel
FCS	Frame Check Sequence
FDD	Frequency Division Duplexing
FEC	Forward Error Correction
flcd-n	far-end loss of cell delineation defect
flpr	far-end loss of power primitive
GSTN	General Switched Telephone Network
HDLC	High-level Data Link Control
HPF	High-Pass Filter
IB	Indicator Bit
IDFT	Inverse Discrete Fourier Transform
INM	Impulse Noise Monitoring
INP	Impulse Noise Protection
INS	Impulse Noise Sensor
ISDN	Integrated Services Digital Network
lcd-n	loss of cell delineation defect
LATN	Loop Attenuation
LCL	Longitudinal Conversion Loss
LOF	Loss of Frame
lom	loss of margin defect
lom-fe	far-end loss of margin defect
LOS	Loss of Signal
los	loss of signal defect
los-fe	far-end loss of signal defect
LPF	Low-Pass Filter
lpr	loss of power
LSB	Least Significant Bit
LTR	Local Timing Reference
MBDC	Minimum Bidirectional net Data rate Capability
MDF	Mux Data Frame
MIB	Management Information Base

MPS-TC	Management Protocol Specific – Transmission Convergence
MSB	Most Significant Bit
mux	Multiplex
NMS	Network Management System
<i>NSC_{us}</i>	Number of Subcarriers in MEDLEY _{us} set
<i>NSC_{ds}</i>	Number of Subcarriers in MEDLEY _{ds} set
NSF	Non-Standard Facility
NT	Network Termination
NTR	Network Timing Reference
OAM	Operations, Administration and Maintenance
OH	Overhead
OLR	On-Line Reconfiguration
ONU	Optical Network Unit
PMD	Physical Media Dependent
PMS	Physical Media Specific
PMS-TC	Physical Media Specific Transmission Convergence
POTS	Plain Old Telephone Service; one of the services using the voiceband; sometimes used as a descriptor for all voiceband services
PRBS	Pseudo-Random Binary Sequence
PSD	Power Spectral Density
PTM	Packet Transfer Mode
PTM-TC	Packet Transfer Mode Transmission Convergence
QAM	Quadrature Amplitude Modulation
rdi	remote defect indication defect
RFI	Radio Frequency Interference
rms	root mean square
ROC	Robust Overhead Channel
RS	Reed-Solomon
RTC	Real-Time Clock
RX (Rx)	Receiver
SATN	Signal Attenuation
SAVN	Showtime Adaptive Virtual Noise
SC	Segment Code
sef	severely errored frame
SNR	Signal-to-Noise Ratio
SNRM	Signal-to-Noise Ratio Margin
SOC	Special Operations Channel

SOS	Save Our Showtime
SRA	Seamless Rate Adaptation
STM	Synchronous Transfer Mode
STM-TC	Synchronous Transfer Mode – Transmission Convergence
TA	Timing Advance
TC	Transmission Convergence
TCM-ISDN	Time Compression Multiplexed – Integrated Services Digital Network
TEQ	Time-domain Equalizer
ToD	Time-of-Day
TPS	Transport Protocol Specific
TPS-TC	Transport Protocol Specific – Transmission Convergence
TX (Tx)	Transmitter
UPBO	Upstream Power Back-Off
US	Upstream
VDSL	Very High Speed Digital Subscriber Line
VME	VDSL2 Management Entity
VN	Virtual Noise
VTU	VDSL2 Transceiver Unit
VTU-O	VTU at the Optical Network Unit (or central office, exchange, cabinet, etc., i.e., operator end of the loop)
VTU-R	VTU at the Remote site (i.e., subscriber end of the loop)

5 Reference models

The functional, application, and protocol reference models of VDSL2 devices specified in this clause fit within the family of DSL Recommendations described in [ITU-T G.995.1]. Additionally, VDSL2 devices rely on constituent components described within [ITU-T G.997.1].

5.1 VTU functional model

The functional model of VDSL2, which includes functional blocks and interfaces of the VDSL2 transceiver unit at the optical network unit (VTU-O) and VDSL2 transceiver unit (VTU) at the remote site (VTU-R) referenced in this Recommendation, is presented in Figure 5-1. The model illustrates the most basic functionality of VDSL2 and contains both an application-invariant section and an application-specific section. The application-invariant section consists of the physical medium dependent (PMD) sublayer and physical media specific part of the transmission convergence sublayer (PMS-TC), which are defined in clauses 10 and 9, respectively. The application-specific parts related to the user plane are defined in clause 8.1 and Annex L and are confined to the transport protocol specific – transmission convergence (TPS-TC) sublayer and application interfaces. The management protocol specific – transmission convergence (MPS-TC) is intended for management data transport and is described in clause 8.2. The VDSL2 management entity (VME) supports management data communication protocols and is described in clause 11.2. Management plane functions at higher layers are typically controlled by the operator's network management system (NMS) and are not shown in Figure 5-1. The NTR-TC supports transport of the 8 kHz network timing reference (NTR)

to the VTU-R and is described in clause 8.3. The ToD-TC supports distribution of accurate time-of-day to the VTU-R and is described in clause 8.4.

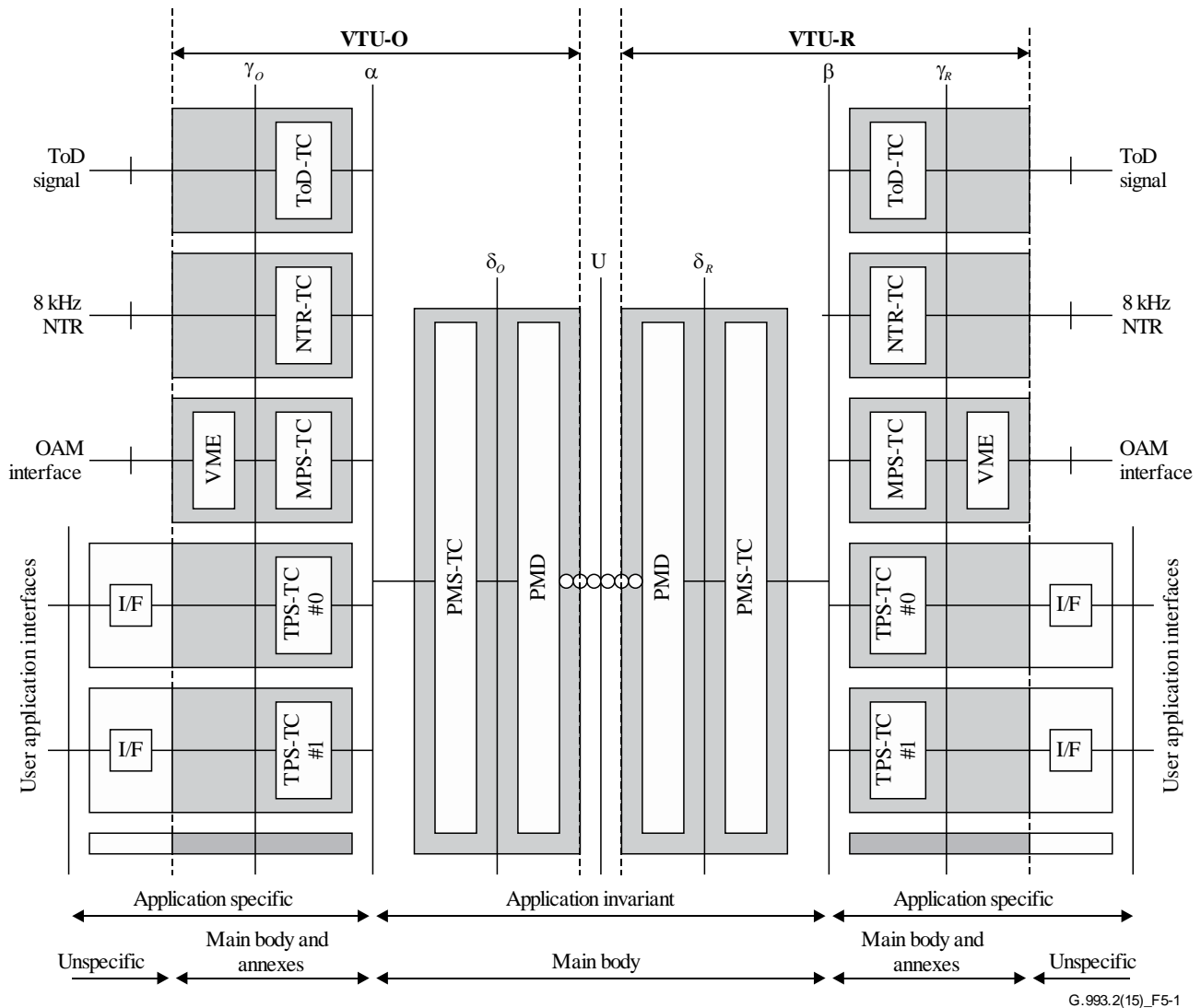


Figure 5-1 – VDSL2 and VTU functional model

The principal functions of the PMD are symbol timing generation and recovery, encoding and decoding, and modulation and demodulation. The PMD may also include echo cancellation and line equalization.

The PMS-TC sublayer contains framing and frame synchronization functions, as well as forward error correction (FEC), error detection, interleaving and de-interleaving, scrambling and descrambling functions. Additionally, the PMS-TC sublayer provides an overhead channel that is used to transport management data (control messages generated by the VME).

The PMS-TC is connected to the PMD across the δ interface, and is connected to the TPS-TC across α and β interfaces in the VTU-O and the VTU-R, respectively.

The TPS-TC is application specific and is mainly intended to convert applicable data transport protocols into the unified format required at the α and β interfaces and to provide bit rate adaptation between the user data and the data link established by the VTU. Depending on the specific application, the TPS-TC sublayer may support one or more channels of user data. The TPS-TC communicates with the user data interface blocks at the VTU-R and VTU-O across the γ_R and γ_O interfaces, respectively. The definition of the data interface blocks is beyond the scope of this Recommendation.

The MPS-TC, NTR-TC, and ToD-TC provide TPS-TC functions for management data, 8 kHz NTR signals, and ToD signal, respectively.

The VME function facilitates the management of the VTU. It communicates with higher management layer functions in the management plane as described in [ITU-T G.997.1], e.g., the NMS controlling the CO-MIB. Management information is exchanged between the VME functions of the VTU-O and VTU-R through the overhead channel provided by the PMS-TC. The MPS-TC converts the incoming management data into the unified format required at the α and β interfaces to be multiplexed into the PMS-TC. The management information contains indications of anomalies and defects, and related performance monitoring counters, and management command/response messages facilitating procedures defined for use by higher layer functions, specifically for testing purposes.

The α , β , γ_R and γ_O interfaces are only intended as logical separations and are defined as a set of functional primitives; they are not expected to be physically accessible. Concerning the user data plane, the γ_R and γ_O interfaces are logically equivalent, respectively, to the T and V interfaces shown in Figure 5-4.

5.2 User plane protocol reference model

The user plane protocol reference model is shown in Figure 5-2 and corresponds to the VDSL2 functional model shown in Figure 5-1. The user plane protocol reference model is included to emphasize the layered nature of this Recommendation and to provide a view that is consistent with the generic xDSL protocol reference model shown in [ITU-T G.995.1].

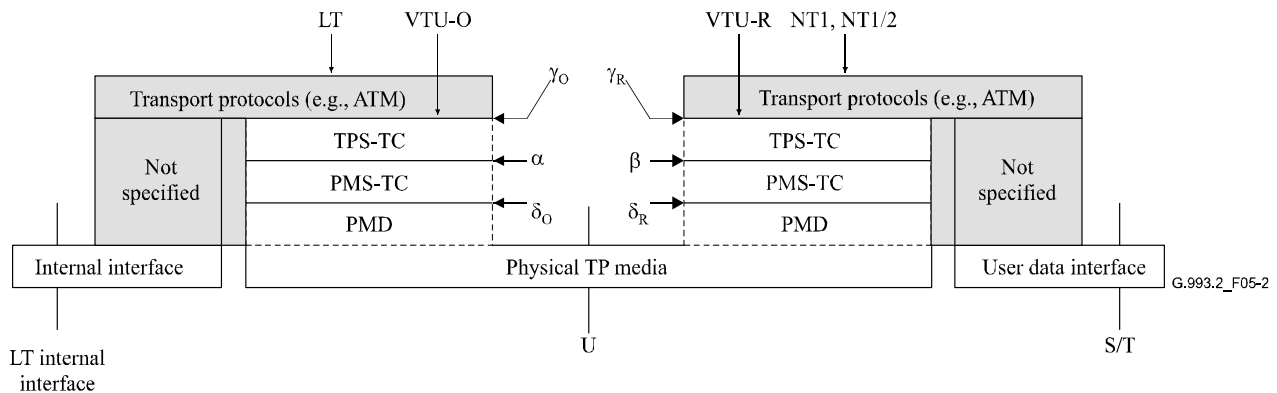


Figure 5-2 – User plane protocol reference model

Table 5-1 summarizes the data rate terminology and definitions applicable at various reference points. The reference points refer to those shown in the reference model in Figure 5-2 and the PMS-TC functional model in Figure 9-1.

Table 5-1 – Data rate terminology and definitions

Data rate	Notation/equation	Refer to	Reference point
Net data rate for bearer channel n (of latency path p)	NDR_{pn}	Table 9-8	α , β (user plane)
Net data rate for latency path p	$NDR_p = \sum_n NDR_{pn}$	Table 9-8	α , β (user plane)
Net data rate	$\sum_p NDR_p$	–	α , β (user plane)
Overhead data rate for latency path p	OR_p	Table 9-8	α , β (management plane)

Table 5-1 – Data rate terminology and definitions

Data rate	Notation/equation	Refer to	Reference point
Overhead data rate	$\sum_p OR_p$	Table 9-8	α, β (management plane)
Message overhead data rate for latency path p	msg_p	Table 9-8	α, β (management plane)
Aggregate data rate for latency path p = net data rate for latency path p + overhead data rate for latency path p	$NDR_p + OR_p$	Table 9-8, clause 9.1	A
Aggregate data rate = net data rate + overhead data rate	$\sum_p NDR_p + OR_p$	Table 9-8, clause 9.1	A
Total data rate for latency path p = aggregate data rate for latency path p + RS coding overhead for latency path p	$TDR_p = L_p \times f_s$	Table 9-8, clause 9.1	C
Total data rate = aggregate data rate + RS coding overhead	$TDR = \left(\sum_p L_p \right) \times f_s$	Table 9-8, clause 9.1	δ
Line rate = total data rate + trellis coding overhead rate	$\left(\sum_i b_i \right) \times f_s$	Clauses 10.3.3 and 10.4.4	U
Bidirectional net data rate (related to MBDC)	$\sum_p NDR_{DS_p} + \sum_p NDR_{US_p}$	Table 9-8	α, β (user plane)

5.3 Management plane reference model

The management plane protocol reference model is shown in Figure 5-3 and corresponds to the VDSL2 functional model shown in Figure 5-1. The management plane protocol reference model relates specifically to the transport of management data through the VDSL2 link.

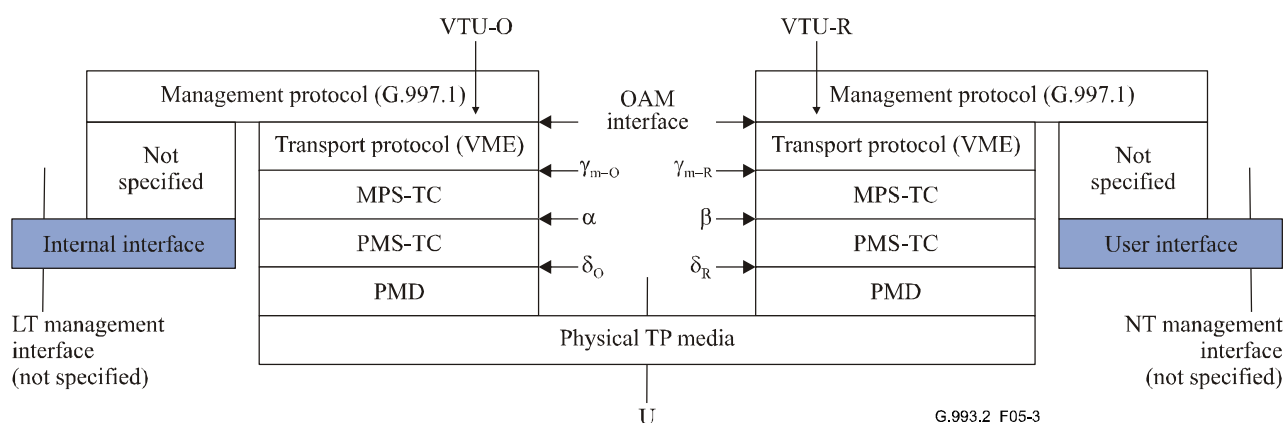


Figure 5-3 – Management plane protocol reference model

5.4 Application reference models

The application models for VDSL2 are based on the generic reference configuration described in clause 6.1 of [ITU-T G.995.1]. There are three separate application models:

- 1) Data service only;
- 2) Data service with underlying POTS service; and
- 3) Data service with underlying integrated services digital network (ISDN) service.

The application reference model for remote deployment with POTS or ISDN service facilitated by a splitter is shown in Figure 5-4. The application model for splitterless remote deployment is shown in Figure 5-5. An optional low-pass filter may be included to provide additional isolation between the VTU-R and narrow-band network customer premises equipment (CPE) such as telephone sets, voiceband modems, or ISDN terminals.

The location of the filters (high-pass filter (HPF) and low-pass filter (LPF)) in application models presented in Figures 5-4 and 5-5 is functional only; the physical location and specific characteristics of splitters and the filter may be regionally specific. The filters at the CPE side shown in Figure 5-4 may be implemented in a variety of ways, including splitters, and in-line filters, and filters integrated with VTU devices, and filters integrated with narrow-band network CPE.

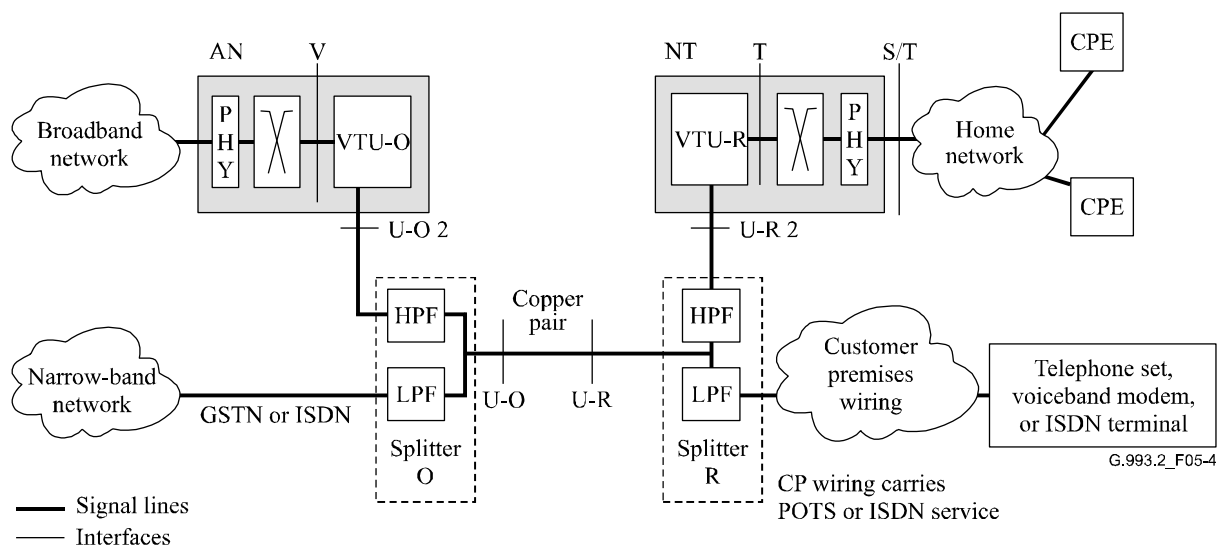


Figure 5-4 – Generic application reference model for remote deployment with splitter

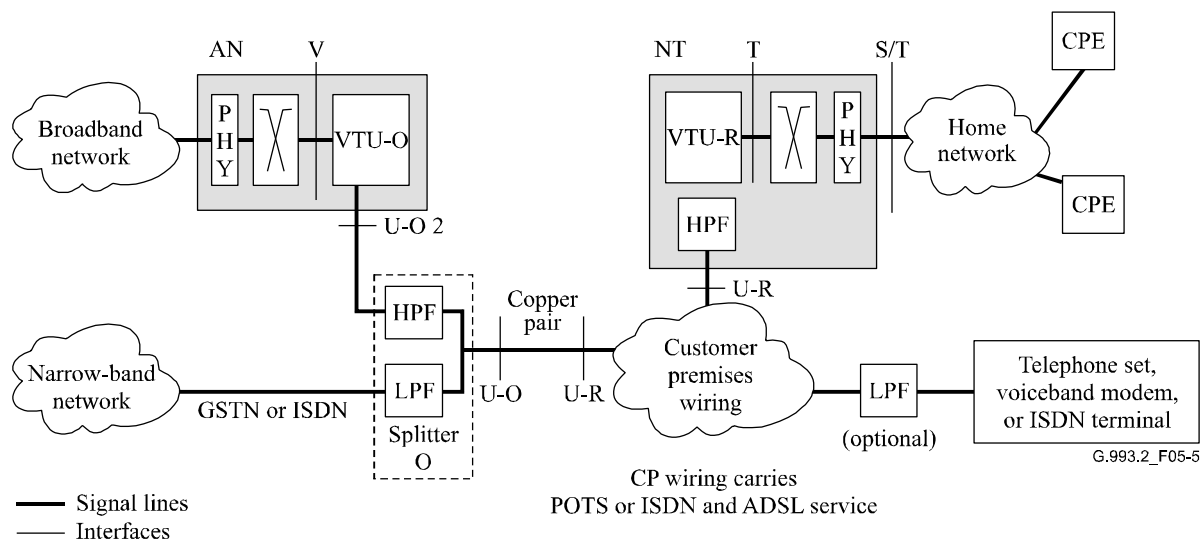


Figure 5-5 – Generic application reference model for splitterless remote deployment

NOTE 1 – The U-O and U-R interfaces are fully defined in this Recommendation. The V and T interfaces are defined only in terms of logical functions, not physical implementations. The S/T interface is not defined in this Recommendation.

NOTE 2 – Implementation of the V and T interfaces is optional when interfacing elements are integrated into a common element.

NOTE 3 – One or both of the high-pass filters, which are part of the splitters, may be integrated into the VTU. If so, the U-O2 and U-R2 interfaces become the same as the U-O and U-R interfaces, respectively.

NOTE 4 – More than one type of T interface may be defined, and more than one type of S/T interface may be provided from a VDSL2 NT (e.g., NT1 or NT2 types of functionalities).

NOTE 5 – Specifications for service splitters (Splitter O) are found in clause 14.2. Further specifications may also be found in regional annexes (see for example Annex C.3).

NOTE 6 – The low-pass filter shown at the customer premises in Figure 5-5 is also known as an in-line filter. In-line filter characteristics are outside the scope of this Recommendation, and are typically specified by regional standards bodies.

NOTE 7 – VDSL2 operating in the splitterless remote deployment mode is highly likely to suffer severe service impairments due to the topology and uncertain quality of the in-premises wiring. Star topology wiring practices, in particular, will lead to deep notches in the frequency response of the transmission path due to multiple signal reflections. In addition, poor balance, routing close to sources of electrical noise, and exposure to strong radio signals can all lead to high levels of RFI.

NOTE 8 – The access node (AN) consists of the VTU-O, the cross-connect (which includes switching and interworking functions for connection to the broadband network), and the physical interface to the broadband network (labelled PHY in Figures 5-4 and 5-5). The network terminal (NT) consists of the VTU-R, the cross-connect (which includes the switching and interworking functions for connection to the home network), and the physical interfaces to the home network (labelled PHY in Figures 5-4 and 5-5). This Recommendation only addresses the definition of the VTU-O and VTU-R.

5.4.1 Data service

To provide data-only service, VDSL2 may be operated in all-digital mode, without leaving any bandwidth for an underlying service. A data-only service may also be provided by a VDSL2 system that leaves bandwidth for underlying POTS or ISDN service, even if there is no underlying service.

Figure 5-6 illustrates the typical application model for delivering data service over VDSL2. The VTU-R is part of the VDSL2 NT, which is typically connected to one or more user terminals, and which may include data terminals, telecommunications equipment, or other devices; these connections are designated by S/T reference points. The connection between the VTU-R and VTU-O

is through a copper pair, with the customer premises endpoint designated as the U-R reference point and the network endpoint designated as the U-O reference point. The VTU-O is a part of the access node (AN), which is typically connected to a broadband access network at the V reference point. In this application model, there is no underlying narrow-band service carried on the same copper pair as VDSL2.

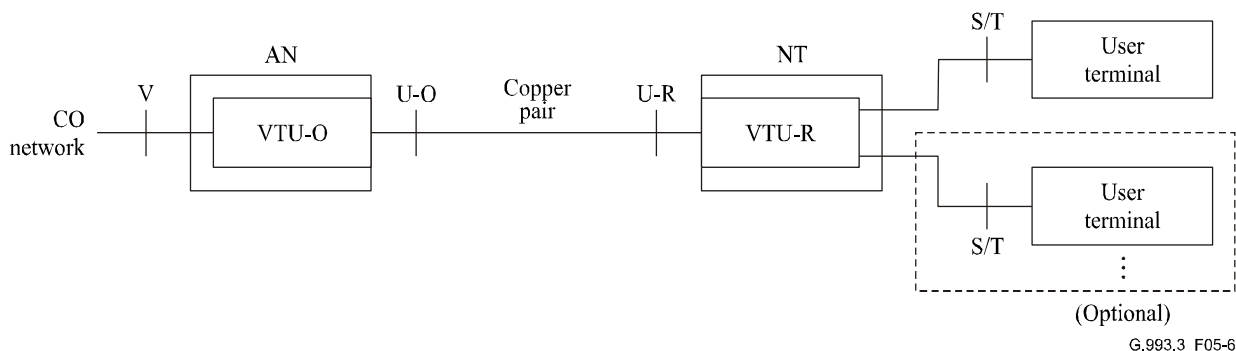


Figure 5-6 – Data service application model

5.4.2 Data with POTS service

The typical application model for delivering data service over VDSL2 with an underlying POTS service on the same copper pair is illustrated in Figure 5-7 (remote deployment with splitter). The VTU-R is part of the VDSL2 NT that typically connects to one or more user terminals, which may include data terminals, telecommunications equipment, or other devices. These connections are designated by S/T reference points. The VTU-R is separated from the narrow-band devices by a combination of an HPF and an LPF. One or more narrow-band devices (POTS telephones, telephone answering devices, voiceband analogue modems, or other devices) are also part of the application model at the customer premises. In remote deployments with a splitter, the narrow-band devices are connected to the U-R reference point through a common low-pass filter element.

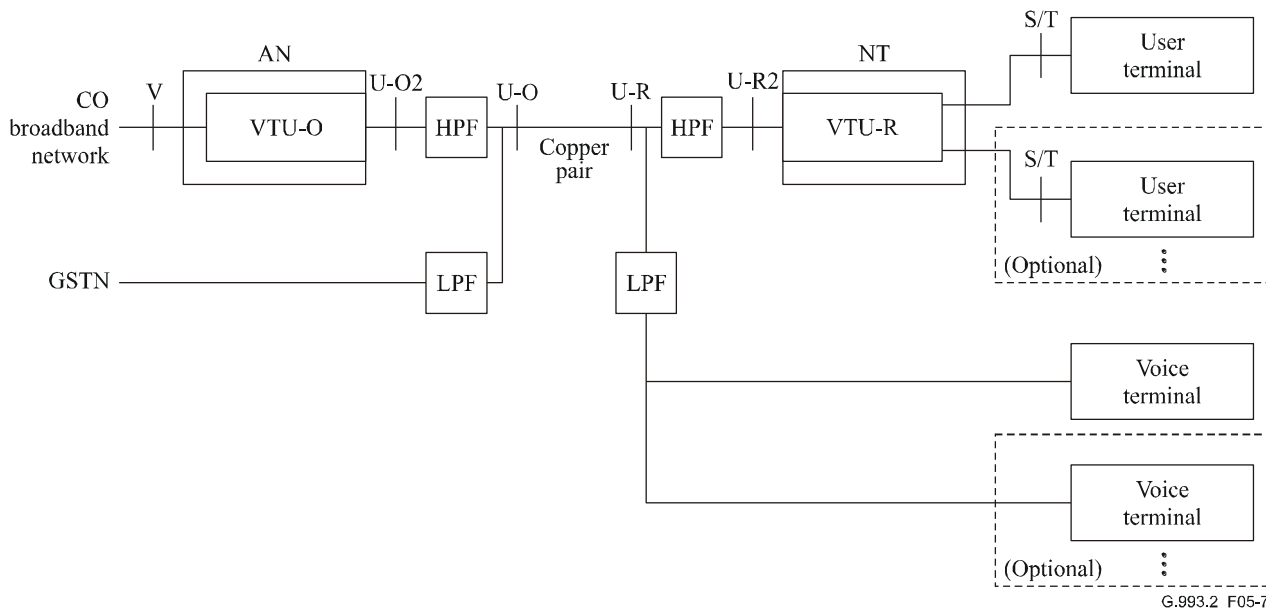


Figure 5-7 – Data with POTS service application model for remote deployment with splitter

Figure 5-8 shows a splitterless remote deployment. In splitterless remote deployments, the narrow-band devices may be connected to the U-R reference point either directly, or through an LPF per device.

The VTU-O is a part of the AN, which is typically connected to a broadband access network at the V reference point. The VTU-O is connected to the U-O reference point through an HPF; an LPF attached at the U-O reference point isolates the VTU-O from the general switched telephone network (GSTN) network.

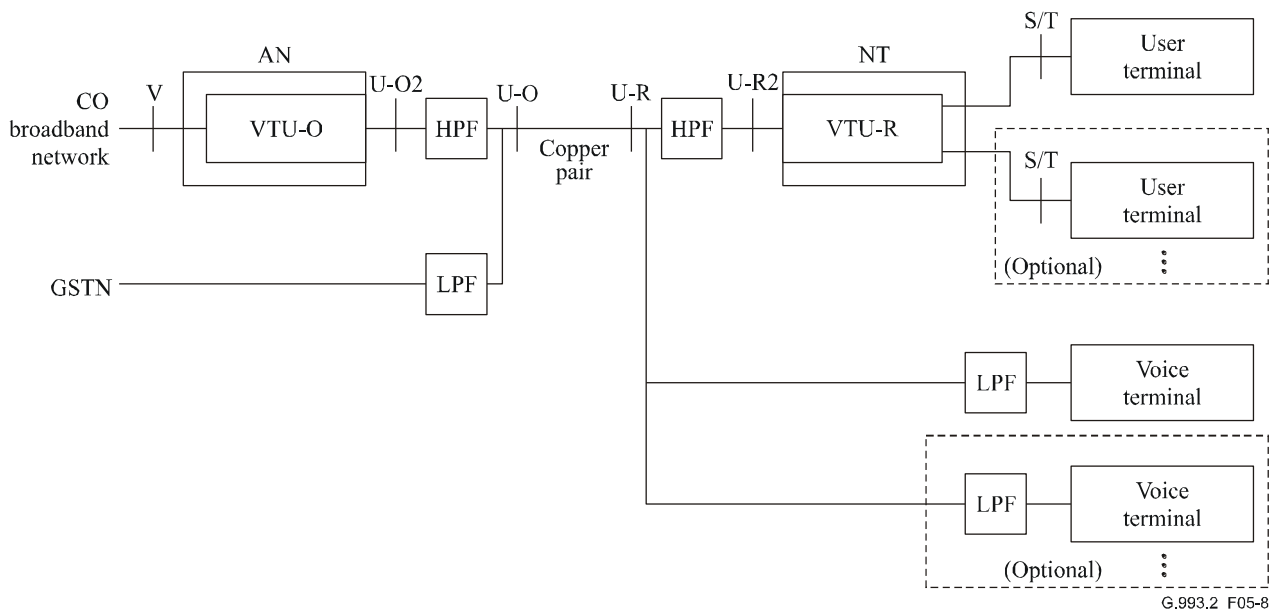


Figure 5-8 – Data with POTS service application model for splitterless remote deployment

NOTE 1 – The low-pass filters shown at the customer premises in Figure 5-8 are also known as in-line filters. In-line filter characteristics are outside the scope of this Recommendation, and are typically specified by regional standards bodies.

NOTE 2 – VDSL2 operating in the splitterless remote deployment mode is highly likely to suffer severe service impairments due to the topology and uncertain quality of the in-premises wiring. Star topology wiring practices, in particular, will lead to deep notches in the frequency response of the transmission path due to multiple signal reflections. In addition, poor balance, routing close to sources of electrical noise, and exposure to strong radio signals can all lead to high levels of RFI.

5.4.3 Data with ISDN service

Figure 5-9 illustrates the typical application model for delivering data service over VDSL2 with an underlying ISDN service on the same copper pair. The VTU-R is part of the VDSL2 NT that typically connects to one or more user terminals, which may include data terminals, telecommunications equipment, or other devices; these connections are designated by S/T reference points. The VTU-R is separated from the copper pair by an HPF. The ISDN NT at the customer premises is separated from the copper pair by an LPF. One or more voiceband or ISDN terminals (e.g., POTS or ISDN telephones, telephone answering devices, voiceband analogue modems, or other devices) are connected to the ISDN NT.

The VTU-O is a part of the AN, which is typically connected to a broadband access network at the V reference point. The VTU-O is connected to the U-O reference point through an HPF; an LPF attached at the U-O reference point isolates the VTU-O from the ISDN network.

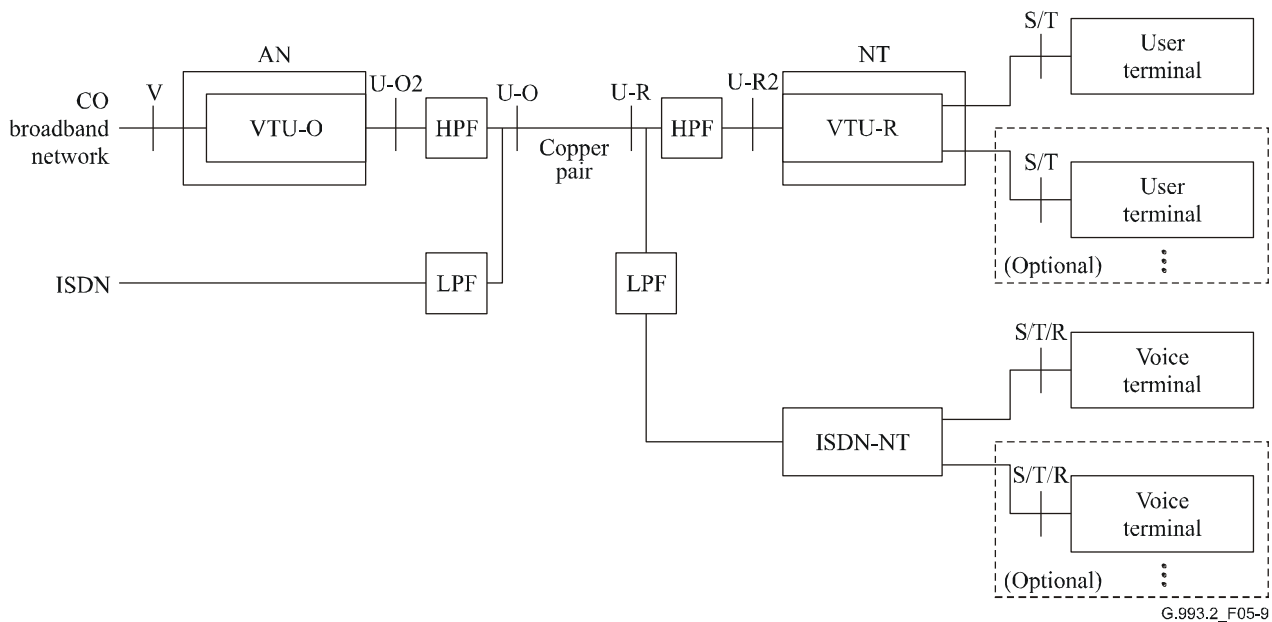


Figure 5-9 – Data with ISDN service application model

6 Profiles

6.1 Definition

This Recommendation defines a wide range of settings for various parameters that could potentially be supported by a VDSL2 transceiver. Profiles are specified to allow transceivers to support a subset of the allowed settings and still be compliant with this Recommendation. The specification of multiple profiles allows vendors to limit implementation complexity and develop implementations that target specific service requirements.

VDSL2 transceivers compliant with this Recommendation shall comply with at least one profile specified in this Recommendation. Compliance with more than one profile is allowed. In addition to complying with at least one profile, VDSL2 transceivers shall comply with at least one annex specifying spectral characteristics (see Annexes A, B and C).

The eight VDSL2 profiles (8a, 8b, 8c, 8d, 12a, 12b, 17a, and 30a) are defined in Table 6-1.

NOTE – Some parameter values are dependent on the applicable frequency plan. Explicit definitions of the parameters are provided in clauses 3 and 6.2.

Table 6-1 – VDSL2 profiles

Frequency plan	Parameter	Parameter value for profile (Note 5)							
		8a	8b	8c	8d	12a	12b	17a	30a
All	Maximum aggregate downstream transmit power (dBm)	+17.5	+20.5	+11.5	+14.5	+14.5	+14.5	+14.5	+14.5
All	Minimum aggregate downstream transmit power (dBm)	For further study	For further study	For further study	For further study	For further study	For further study	For further study	For further study

Table 6-1 – VDSL2 profiles

Frequency plan	Parameter	Parameter value for profile (Note 5)							
		8a	8b	8c	8d	12a	12b	17a	30a
All	Maximum aggregate upstream transmit power (dBm)	+14.5	+14.5	+14.5	+14.5	+14.5	+14.5	+14.5	+14.5
All	Minimum aggregate upstream transmit power (dBm)	For further study	For further study	For further study	For further study	For further study	For further study	For further study	For further study
All	Subcarrier spacing (kHz)	4.3125	4.3125	4.3125	4.3125	4.3125	4.3125	4.3125	8.625
All	Support of upstream band zero (US0)	Required	Required	Required	Required	Required	Regional annex dependent	Regional annex dependent	Not Supported
All	Minimum bidirectional net data rate capability (MBDC)	50 Mbit/s	50 Mbit/s	50 Mbit/s	50 Mbit/s	68 Mbit/s	68 Mbit/s	100 Mbit/s	200 Mbit/s
All	Aggregate interleaver and de-interleaver delay (octets)	65 536	65 536	65 536	65 536	65 536	65 536	98 304	131 072
All	Maximum interleaving depth (D_{max})	2 048	2 048	2 048	2 048	2 048	2 048	3 072	4 096
All	Parameter $(1/S)_{max}$ downstream	24	24	24	24	24	24	48	28
All	Parameter $(1/S)_{max}$ upstream	12	12	12	12	24	24	24	28
Annex A (998)	Index of highest supported downstream data-bearing subcarrier (upper band edge frequency in MHz (informative))	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	4 095 (17.660)	2 666 (23)
	Index of highest supported upstream data-bearing subcarrier (upper band edge frequency in MHz (informative))	1 205 (5.2)	1 205 (5.2)	1 205 (5.2)	1 205 (5.2)	2 782 (12)	2 782 (12)	2 782 (12)	3 478 (30)

Table 6-1 – VDSL2 profiles

Frequency plan	Parameter	Parameter value for profile (Note 5)							
		8a	8b	8c	8d	12a	12b	17a	30a
Annex B (998E)	Index of highest supported downstream data-bearing subcarrier (upper band edge frequency in MHz (informative))	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	4 095 (17.660)	3 478 (30)
	Index of highest supported upstream data-bearing subcarrier (upper band edge frequency in MHz (informative))	1 205 (5.2)	1 205 (5.2)	1 205 (5.2)	1 205 (5.2)	2 782 (12)	2 782 (12)	3 246 (14)	2 885 (24.890)
Annex B (998 ADE)	Index of highest supported downstream data-bearing subcarrier (upper band edge frequency in MHz (informative))	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	4 095 (17.660)	2 885 (24.890)
	Index of highest supported upstream data-bearing subcarrier (upper band edge frequency in MHz (informative))	1 205 (5.2)	1 205 (5.2)	1 205 (5.2)	1 205 (5.2)	2 782 (12)	2 782 (12)	2 782 (12)	3 478 (30)

Table 6-1 – VDSL2 profiles

Frequency plan	Parameter	Parameter value for profile (Note 5)							
		8a	8b	8c	8d	12a	12b	17a	30a
Annex B (997E)	Index of highest supported downstream subcarrier (upper band edge frequency in MHz (informative))	1 634 (7.05)	1 634 (7.05)	1 634 (7.05)	1 634 (7.05)	1 634 (7.05)	1 634 (7.05)	3 246 (14)	3 130 (27)
	Index of highest supported upstream subcarrier (upper band edge frequency in MHz (informative))	2 047 (8.832)	2 047 (8.832)	1 182 (5.1)	2 047 (8.832)	2 782 (12)	2 782 (12)	4 095 (17.660)	3 478 (30)
Annex C	Index of highest supported downstream subcarrier (upper band edge frequency in MHz (informative))	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	4 095 (17.660)	2 098 (18.1)
	Index of highest supported upstream subcarrier (upper band edge frequency in MHz (informative))	1 205 (5.2)	1 205 (5.2)	1 205 (5.2)	1 205 (5.2)	2 782 (12)	2 782 (12)	2 782 (12)	3 478 (30)
Annex N (CN17)	Index of highest supported downstream data-bearing subcarrier (upper band edge frequency in MHz (informative))	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	1 971 (8.5)	2 782 (12)	2 782 (12)	3 292 (14.197)	–

Table 6-1 – VDSL2 profiles

Frequency plan	Parameter	Parameter value for profile (Note 5)							
		8a	8b	8c	8d	12a	12b	17a	30a
	Index of highest supported upstream data-bearing subcarrier (upper band edge frequency in MHz (informative))	1 205 (5.2)	1 205 (5.2)	1 205 (5.2)	1 205 (5.2)	1 205 (5.2)	1 205 (5.2)	4 095 (17.660)	–
<p>NOTE 1 – The minimum aggregate transmit power values are for further study. These values may be provided in a later version of this Recommendation based on a consensus understanding of the power required to meet service objectives and practical implementation of line drivers.</p> <p>NOTE 2 – The allowed frequency band is determined by applicable PSD mask requirements defined in the annexes of this Recommendation, constrained by the capabilities guaranteed by the profile(s) that the implementation supports.</p> <p>NOTE 3 – The US0 frequency allocation is determined by applicable PSD mask requirements defined in the annexes to this Recommendation.</p> <p>NOTE 4 – D_{max} is derived from the aggregate interleaver and de-interleaver delay by dividing this amount by 32.</p> <p>NOTE 5 – The profile 35b is defined in Annex Q.</p>									

6.2 Profile parameter definitions

Each profile specifies normative values for the following parameters:

- The maximum aggregate transmit power in the downstream and upstream directions;
- The minimum aggregate transmit power in the downstream and upstream directions;
- The subcarrier spacing;
- Whether support of upstream band zero (US0) is required;
- The minimum bidirectional net data rate capability (MBDC);
- The aggregate interleaver and de-interleaver delay in octets;
- The index of the highest data-bearing subcarrier supported in the downstream and upstream directions (frequency plan dependent);
- Maximum interleaving depth; and
- Parameter $(1/S)_{max}$.

These parameters are explicitly defined in the following clauses.

6.2.1 Maximum aggregate downstream transmit power

To be compliant with a specific profile, the aggregate downstream transmit power of a VTU shall not exceed the value specified in the row labelled "maximum aggregate downstream transmit power" in Table 6-1.

6.2.2 Minimum aggregate downstream transmit power

For further study.

6.2.3 Maximum aggregate upstream transmit power

To be compliant with a specific profile, the aggregate upstream transmit power of a VTU shall not exceed the value specified in the row labelled "maximum aggregate upstream transmit power" in Table 6-1.

6.2.4 Minimum aggregate upstream transmit power

For further study.

6.2.5 Required subcarrier spacing

The subcarrier spacing is defined in clause 10.4.2. To be compliant with a profile, a VTU shall support the required subcarrier spacing specified in that profile.

6.2.6 Support of upstream band zero (US0)

This parameter specifies whether a compliant VTU is required to support upstream band zero (US0). A VTU-O compliant with a profile mandating support of US0 shall be capable of receiving US0. A VTU-R compliant with a profile mandating support of US0 shall be capable of transmitting US0.

If US0 is not supported, US0 shall be excluded from the upstream passband.

The frequency allocation for band US0 is defined in the regional annexes of this Recommendation.

6.2.7 Required minimum bidirectional net data rate capability (MBDC)

The bidirectional net data rate capability is the maximum value of the bidirectional net data rate that the VTU can support. The required MBDC is the minimum value of the bidirectional net data rate that a VTU compliant with a profile shall be capable of supporting.

6.2.8 Aggregate interleaver and de-interleaver delay

The required aggregate interleaver and de-interleaver delay is specified in terms of the sum of the end-to-end delays in the upstream and downstream directions over both latency paths, expressed in octets. Therefore, it involves both VTUs. Figure 6-1 illustrates an end-to-end connection with two latency paths and their interleavers and de-interleavers.

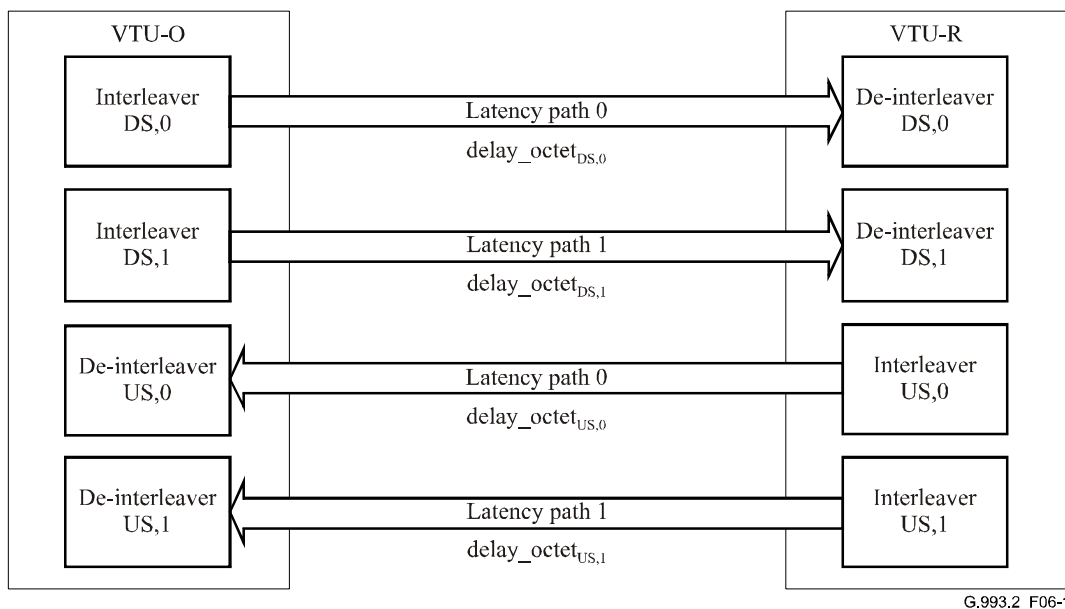


Figure 6-1 – Illustration of all latency paths composing the aggregate interleaver and de-interleaver delay specified in each profile

The end-to-end delay in octets for the interleaver and de-interleaver pair on path p , with $p = 0, 1$, is given by:

$$\text{delay_octet}_{x,p} = (I_{x,p} - 1) \times (D_{x,p} - 1)$$

where the direction of transmission x is either "DS" for downstream or "US" for upstream, $I_{x,p}$ is the interleaver block length, and $D_{x,p}$ is the interleaver depth.

Each interleaver and each de-interleaver for each latency path requires at least $(\text{delay_octet}_{x,p}/2)$ octets of memory to meet this delay. The actual amount of memory used is implementation specific.

Referring to Figure 6-1, the aggregate interleaver and de-interleaver delay is specified as the sum $\text{delay_octet}_{\text{DS},0} + \text{delay_octet}_{\text{DS},1} + \text{delay_octet}_{\text{US},0} + \text{delay_octet}_{\text{US},1}$,

which can be rewritten as:

$$\sum_p (I_{\text{US},p} - 1) \cdot (D_{\text{US},p} - 1) + (I_{\text{DS},p} - 1) \cdot (D_{\text{DS},p} - 1)$$

VTUs shall comply with the requirement:

$$\sum_p (I_{\text{US},p} - 1) \cdot (D_{\text{US},p} - 1) + (I_{\text{DS},p} - 1) \cdot (D_{\text{DS},p} - 1) \leq \text{MAXDELAYOCTET}$$

where the summation is over all latency paths and MAXDELAYOCTET is the parameter "aggregate interleaver and de-interleaver delay", in octets, specified in Table 6-1 for the profile.

The minimum amount of memory required in a transceiver (VTU-O or VTU-R) to meet this requirement is $\frac{\text{MAXDELAYOCTET}}{2}$ octets. The actual amount of memory used is implementation specific.

6.2.9 Index of the highest supported downstream data-bearing subcarrier

The index of the highest supported downstream data-bearing subcarrier is a band plan dependent parameter. It specifies the index of the highest-frequency subcarrier available for downstream transmission. A VTU-O compliant with a profile shall be capable of transmitting data-bearing subcarriers with indices up to (and including) the index specified in the profile under the heading "index of the highest supported downstream data-bearing subcarrier". The VTU shall not transmit data-bearing subcarriers with indices higher than this index.

NOTE – The upper band edge frequency from which the index of the highest downstream data-bearing subcarrier has been derived appears in parentheses after the subcarrier index. The upper band edge frequency is informative.

6.2.10 Index of the highest supported upstream data-bearing subcarrier

The index of the highest supported upstream data-bearing subcarrier is a band plan dependent parameter. It specifies the index of the highest-frequency subcarrier available for upstream transmission. A VTU-R compliant with a profile shall be capable of transmitting data-bearing subcarriers with indices up to (and including) the index specified in the profile under the heading "index of the highest supported upstream data-bearing subcarrier". The VTU shall not transmit data-bearing subcarriers with indices higher than this index.

NOTE – The upper band edge frequency from which the index of the highest upstream data-bearing subcarrier has been derived appears in parentheses after the subcarrier index. The upper band edge frequency is informative.

6.2.11 Maximum interleaving depth

The definition of the interleaving depth is in clause 9.4. To be compliant with a specific profile, a VTU shall be capable of providing interleaving depth up to and including the value of D_{max} specified in the row labelled "maximum interleaving depth (D_{max})" in Table 6-1.

6.2.12 Parameter $(1/S)_{max}$

Parameter $(1/S)_{max}$ defines the maximum number of FEC codewords that the VTU is capable of transmitting during one DMT symbol (see detailed definition in clause 9.5.5). To be compliant with a specific profile, the VTU shall be capable of transmitting up to and including $(1/S)_{max}$ FEC codewords, of any valid size, per DMT symbol, as specified in the rows labelled "parameter $(1/S)_{max}$ downstream" and "parameter $(1/S)_{max}$ upstream" in Table 6-1.

6.3 Profile compliance

To be compliant with a selected profile, a VTU-O shall:

- Be capable of transmitting subcarriers at the subcarrier spacing value specified in the profile;
- Be capable of transmitting data-bearing subcarriers with indices up to (and including) the index specified in the profile, for the applicable band plan, under the heading "index of the highest supported downstream data-bearing subcarrier";
- Be capable of receiving US0 if the profile mandates support of US0;
- Support the aggregate interleaver and de-interleaver delay in octets specified in the profile;
- Support all values of D up to and including D_{max} , both upstream and downstream;
- Support all values of $1/S$ up to and including $(1/S)_{max}$ upstream and $(1/S)_{max}$ downstream; and
- Support its MBDC.

To be compliant with a selected profile, a VTU-R shall:

- Be capable of transmitting subcarriers at the subcarrier spacing value specified in the profile;
- Be capable of transmitting data-bearing subcarriers with indices up to (and including) the index specified in the profile, for the applicable band plan, under the heading "index of the highest supported upstream data-bearing subcarrier";
- Be capable of transmitting US0 if the profile mandates support of US0;
- Support the aggregate interleaver and de-interleaver delay in octets specified in the profile;
- Support all values of D up to and including D_{max} , both upstream and downstream;
- Support all values of $1/S$ up to and including $(1/S)_{max}$ upstream and $(1/S)_{max}$ downstream; and
- Support its MBDC.

Furthermore, a VTU complying with a selected profile shall:

- Not use subcarrier spacing values not specified in the profile;
- Not transmit in a passband that includes subcarriers with indices higher than specified in the profile, for the applicable band plan and transmission direction, under the heading "index of the highest supported downstream (upstream) data-bearing subcarrier";
- Not use an aggregate interleaver and de-interleaver delay greater than the value specified in the profile; and
- Not transmit at a power level greater than the maximum aggregate transmitter power specified in the profile.

7 Transmission medium interface characteristics

This clause specifies the interface between the transceiver and the transmission medium U-O2 and U-R2 reference points as defined in clause 5.4. For the purposes of this Recommendation, the U-O2/U-R2 and U-O/U-R interfaces are considered spectrally equivalent.

7.1 Duplexing method and band plan construction

VDSL2 transceivers shall use frequency division duplexing (FDD) to separate upstream and downstream transmissions. Overlapping of the upstream and downstream passbands is not allowed. The allocation of the upstream and downstream frequency bands is defined by the band plan, which is specified by band-separating frequencies.

The VDSL2 signal can potentially utilize the frequency range up to 30 MHz, although the maximum frequency used by a VTU to transmit data depends on the selected band plan and the profile (see clause 6).

7.1.1 Band plan below 12 MHz

In the frequency range below 12 MHz, VDSL2 specifies the 5-band plan defined in Figure 7-1. The frequency band between f_{0L} and f_{0H} is denoted as US0. If used at all, this band shall be used only for upstream transmission. The four frequency bands denoted as DS1, US1, DS2, and US2, for the first downstream band, the first upstream band, the second downstream band, and the second upstream band, respectively, shall be defined by the band separating frequencies f_1, f_2, f_3, f_4 and f_5 , where $f_1 \geq f_{0H}$.

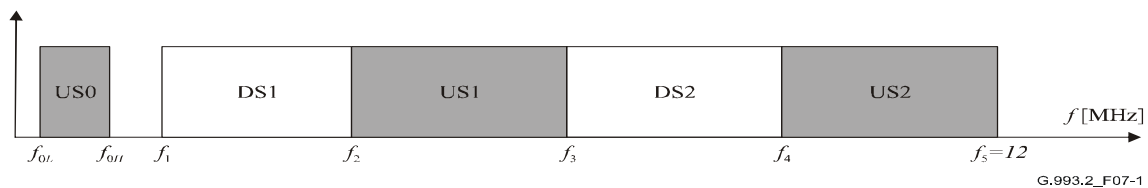


Figure 7-1 – Band plan in the frequency range up to 12 MHz

For the band plan below 12 MHz shown in Figure 7-1, the upstream passband shall be composed of the following portions of the frequency spectrum: $f_{0L} < f < f_{0H}$, $f_2 < f < f_3$, and $f_4 < f < f_5$. The downstream passband shall be composed of the following portions of the frequency spectrum: $f_1 < f < f_2$ and $f_3 < f < f_4$. The passband in each direction shall not contain frequencies above the frequency corresponding to the highest supported data-bearing subcarrier specified for that direction by the selected profile (6.1).

The values of f_{0L} , f_{0H} , f_1 , f_2 , f_3 , and f_4 are specified in Annexes A, B and C.

7.1.2 Band plan above 12 MHz

In the frequency range between 12 MHz and 30 MHz, VDSL2 specifies at least one additional downstream or upstream band. Bands above 12 MHz are specified by additional band separating frequencies. The number of additional band separating frequencies depends on the number of bands defined between 12 MHz and 30 MHz. Any values of band separating frequencies defined between 12 MHz and 30 MHz are specified in Annexes A, B and C.

When frequencies above 12 MHz are in use, the downstream (upstream) passband consists of the downstream (upstream) passband below 12 MHz plus any downstream (upstream) bands above 12 MHz. However, the passband in each direction shall not contain frequencies above the frequency corresponding to the highest supported data-bearing subcarrier specified for that direction by the selected profile (6.1).

7.2 Power spectral density (PSD)

7.2.1 Transmit PSD mask

A VTU shall confine the PSD of its transmit signal to be within the transmit PSD mask. The transmit PSD mask is the lesser, at every frequency, of the Limit PSD mask specified in the relevant annex and, if applicable, a MIB PSD mask specified by the service provider, which is provided to the VTUs via the MIB.

7.2.1.1 MIB PSD mask construction

This clause provides requirements and constraints for construction of the MIB PSD mask, which can be used to constrain the VDSL2 transmit PSD mask to levels lower than those specified by the Limit PSD masks. See Annexes A, B and C for specific Limit PSD masks defined for some geographic regions.

In this clause, the term "band" corresponds to an upstream or downstream frequency band of the band plan defined in the relevant annex. The term "frequency range" is used to indicate a part of such a band.

7.2.1.1.1 Overview

In some deployment scenarios, an operator may choose to force VTUs to transmit at levels lower than those specified by the Limit PSD masks. The MIB PSD mask is an additional tool that allows operators to shape the VTU-O and VTU-R transmit PSD masks. Power cut-back (see clause 12.3.3) and upstream power back-off (see clause 7.2.1.3) are tools that provide further reduction of the transmit PSD (below the transmit PSD mask).

The MIB PSD mask shall lie at or below the Limit PSD mask specified in the selected annex. Its definition shall be under the network management control (a MIB-controlled mechanism), as defined in [ITU-T G.997.1].

The MIB PSD mask shall be specified in the CO-MIB by a set of breakpoints. Up to 16 breakpoints may be specified to construct the MIB PSD mask for all utilized upstream bands (including US0), and up to 32 breakpoints may be specified to construct the MIB PSD mask for all utilized downstream bands. It is not required to specify breakpoints for every band defined by a band plan. In frequency ranges in which the MIB PSD mask is not specified, the transmit PSD mask shall be equal to the Limit PSD mask.

Each breakpoint used to specify the MIB PSD mask shall consist of a subcarrier index t_n and a PSD mask value PSD_n at that subcarrier expressed in dBm/Hz. The subcarrier indices shall always be calculated assuming 4.3125 kHz subcarrier spacing (i.e., independent of the subcarrier spacing actually used – see Table 6-1).

Breakpoints for each utilized band shall be represented by the set $[(t_1, PSD_1), \dots, (t_n, PSD_n), \dots, (t_{NBP}, PSD_{NBP})]$. The first breakpoint shall have the value $t_1 = \text{ceil}(f_x/4.3125 \text{ kHz})$, where "ceil" denotes the ceiling function (rounding up to the nearest integer), and f_x is the frequency of the lower band edge (see Figure 7-1). The index t_1 corresponds to the lowest-frequency subcarrier in the band, assuming that a profile with 4.3125 kHz subcarrier spacing is used. Except for the US0 band, the last breakpoint in the band shall have the value $t_{NBP} = \text{floor}(f_{x+1}/4.3125 \text{ kHz})$, where "floor" denotes the floor function (rounding down to the nearest integer), and f_{x+1} is the frequency of the upper band edge. For the US0 band, the last breakpoint is specified in clause 7.2.1.1.3. The index t_{NBP} corresponds to the highest-frequency subcarrier in the band, assuming that a profile with 4.3125 kHz subcarrier spacing is used. Additional breakpoints within a band, if needed, shall be specified so that $t_n < t_{n+1}$ for $n = 2$ to $NBP - 1$. The frequency f_n corresponding to the index t_n is $f_n = t_n \times 4.3125 \text{ kHz}$.

All t_i in a particular frequency band shall be coded in the CO-MIB as unsigned integers.

The value of the PSD at subcarrier t_n , PSD_n , shall be coded in the CO-MIB as an unsigned integer. The PSD values shall be coded from 0 dBm/Hz (coded as 0) to -127.5 dBm/Hz (coded as 255), in steps of 0.5 dBm/Hz. The valid range of PSD values is from 0 dBm/Hz to -95 dBm/Hz, although the values input via the MIB must be no higher than allowed by the Limit PSD mask.

In the case that a profile specifying 8.625 kHz subcarrier spacing is used, the VTU shall subtract 1 from any odd values of t_i for $i = 2$ to $NBP - 1$. If t_1 is an odd number, the VTU shall add 1 to t_1 and use this value as the first breakpoint. If t_{NBP} is an odd number, the VTU shall subtract 1 from t_{NBP} and use this value as the last breakpoint.

The MIB PSD mask parameter in the CO-MIB shall be a concatenation of the sets of breakpoints for all utilized bands.

7.2.1.1.2 Definition of breakpoints above US0

Breakpoints specified in the CO-MIB at frequencies above f_1 shall comply with the restrictions specified in this clause.

7.2.1.1.2.1 Definition of breakpoints for PSD_n that are greater than or equal to -80 dBm/Hz

For all breakpoints with values of PSD_n in the MIB PSD mask that are greater than or equal to -80 dBm/Hz, the values of PSD_n shall be defined with the following restrictions, except for the step upward shape defined in clause 7.2.1.1.2.3, which can be used to provide steeper upward MIB PSD mask transitions.

- For $t_n < t_{n+1}$, the slope of the MIB PSD mask levels shall comply with:

$$\left| \frac{PSD_{n+1} - PSD_n}{t_{n+1} - t_n} \right| \leq 0.75 \text{ dB/4.3125 kHz} \quad \text{for 4.3125 kHz subcarrier spacing}$$

$$\left| \frac{PSD_{n+1} - PSD_n}{t_{n+1} - t_n} \right| \leq 0.375 \text{ dB/4.3125 kHz} \quad \text{for 8.6250 kHz subcarrier spacing}$$

- $\min(PSD_n) \geq -80$ dBm/Hz, and $\max(PSD_n) - \min(PSD_n) \leq 40$ dB, where $\max(PSD_n)$ denotes the maximum and $\min(PSD_n)$ denotes the minimum of all breakpoint PSD values at or above -80 dBm/Hz.

The MIB PSD mask at an arbitrary frequency f shall be obtained by interpolation in dB on a linear frequency scale as follows:

$$\text{MIB PSD mask}(f) = PSD_n + (PSD_{n+1} - PSD_n) \times \frac{(f / 4.3125 \text{ kHz}) - t_n}{t_{n+1} - t_n}, t_n < (f / 4.3125 \text{ kHz}) \leq t_{n+1}$$

Figure 7-2 illustrates the MIB PSD mask in the case that all breakpoints are above -80 dBm/Hz (with $\min(PSD_n) = PSD_5$ and $\max(PSD_n) = PSD_3$).

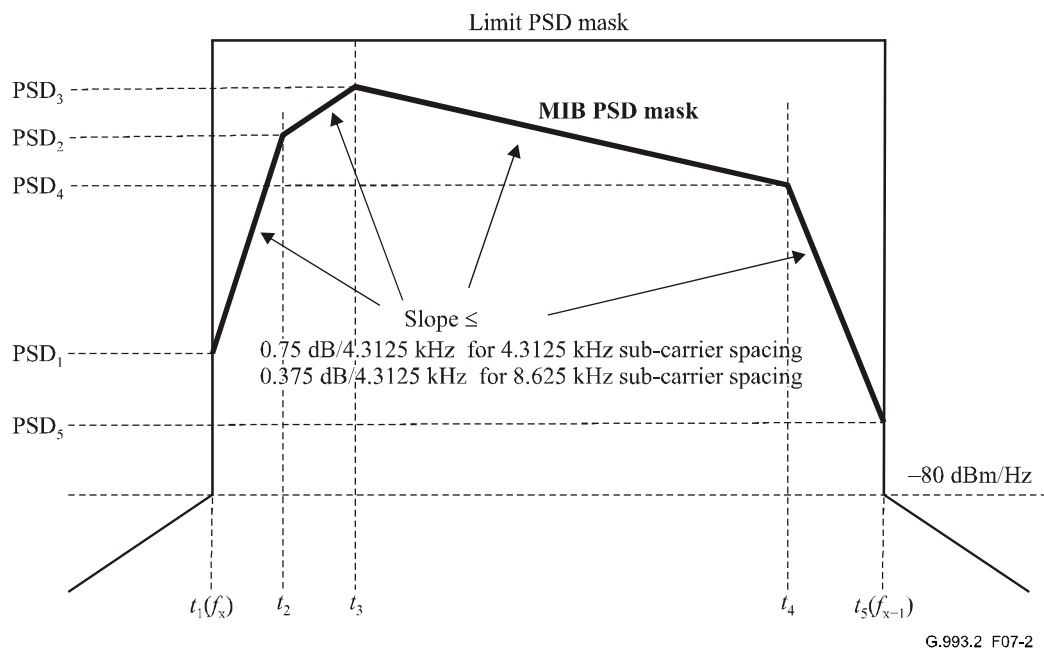


Figure 7-2 – Illustration of a MIB PSD mask in the case all breakpoint PSD_n values are greater than -80 dBm/Hz

7.2.1.1.2.2 Definition of breakpoints when some PSD_n values are less than -80 dBm/Hz

An operator may wish to specify a MIB PSD mask with some PSD_n values that are below -80 dBm/Hz within a band (between t_1 and t_{NBP}) and with one frequency range from t_{start} to t_{stop} in which the MIB PSD mask is greater than -80 dBm/Hz. Such a case is illustrated in Figure 7-3. In this case, the MIB PSD mask breakpoint values PSD_n in the ranges $t_1 \leq t < t_{start}$ and $t_{stop} < t \leq t_{NBP}$ shall be set no lower than the stopband PSD requirements defined in clause 7.2.2, where the low-edge and high-edge transition frequencies of the frequency range with the MIB PSD mask greater than -80 dBm/Hz are $f_{tr2} = t_{start} \times 4.3125$ kHz and $f_{tr1} = t_{stop} \times 4.3125$ kHz, respectively.

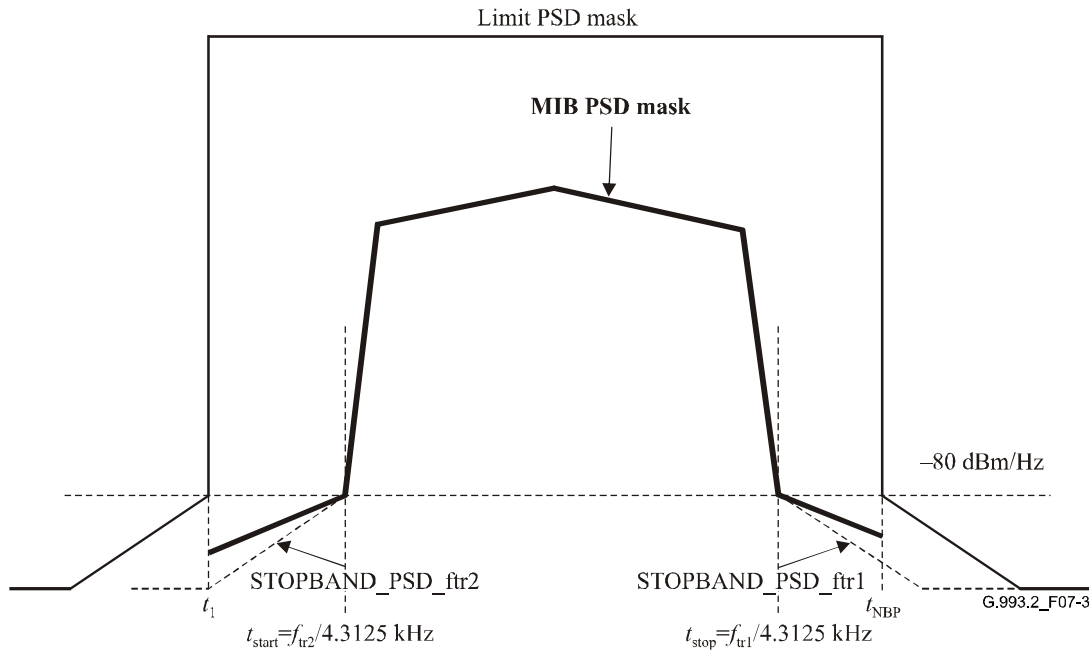


Figure 7-3 – Illustration of the restrictions on breakpoints for a case in which the MIB PSD mask lies below -80 dBm/Hz between two band separating frequencies (t_1 and t_{NBP}) but above -80 dBm/Hz for some frequency range inside the band

Alternatively, an operator may wish to specify a MIB PSD mask which is below -80 dBm/Hz in a frequency range that lies between two frequency ranges in which the MIB PSD mask is greater than -80 dBm/Hz. For example, the MIB PSD mask is above -80 dBm/Hz in the range t_{start1} to t_{stop1} (range 1) and from t_{start2} to t_{stop2} (range 2), and from t_{stop1} to t_{start2} it is below -80 dBm/Hz, as illustrated in Figure 7-4. In this case, the MIB PSD mask breakpoint values PSD_n for indices $t_{stop1} < t < t_{start2}$ shall be set not lower than the power sum of the high-edge stopband PSD of range 1 and the low-edge stopband PSD of range 2 (see clause 7.2.2), with the high-edge transition frequency of range 1 equal to $f_{tr1} = t_{stop1} \times 4.3125$ kHz and the low-edge transition frequency of range 2 equal to $f_{tr2} = t_{start2} \times 4.3125$ kHz, respectively. The power sum can be calculated using the following equation:

$$\text{MIB PSD mask } (t_{stop1} < t < t_{start2}) \geq 10 \times \log_{10} (10^{0.1 \times \text{STOPBAND_PSD_ftr1}(t)} + 10^{0.1 \times \text{STOPBAND_PSD_ftr2}(t)})$$

NOTE – The power sum may result in PSD levels higher than -80 dBm/Hz.

The one-slope steep upward shape is illustrated in Figure 7-5.

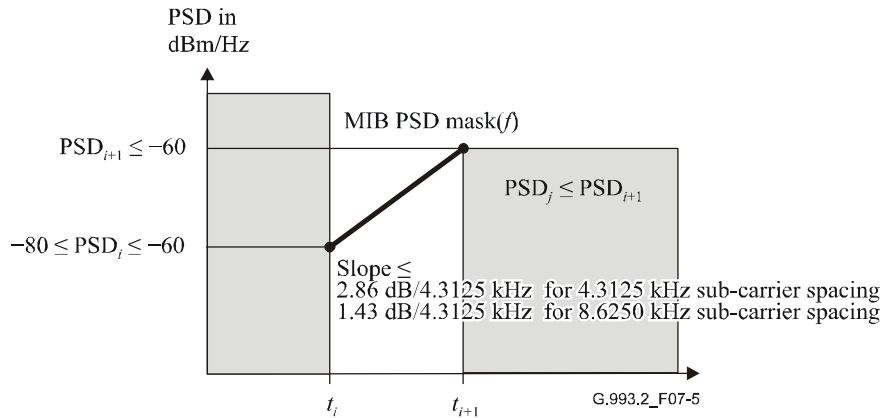


Figure 7-5 – Illustration of the one-slope steep upward shape

7.2.1.1.2.3.2 Two-slope steep upward shape

The two-slope steep upward shape is defined as:

- $-80 \text{ dBm/Hz} \leq \text{PSD}_i < -60 \text{ dBm/Hz}$;
- $\text{PSD}_{i+2} \leq -36.5 \text{ dBm/Hz}$;
- $\text{PSD}_j \leq \text{PSD}_{i+2}$ for all $j > (i + 2)$;
- If $\text{PSD}_i > -80 \text{ dBm/Hz}$ then it is required that $\text{PSD}_k \geq \text{PSD}_i$ for all $k < i$;
- $\left| \frac{\text{PSD}_{i+1} - \text{PSD}_i}{t_{i+1} - t_i} \right| \leq 0.50 \text{ dB/4.3125 kHz}$ for 4.3125 kHz subcarrier spacing;
- $\left| \frac{\text{PSD}_{i+1} - \text{PSD}_i}{t_{i+1} - t_i} \right| \leq 0.25 \text{ dB/4.3125 kHz}$ for 8.6250 kHz subcarrier spacing;

with $(t_{i+1} - t_i) \leq 47$.

- $\left| \frac{\text{PSD}_{i+2} - \text{PSD}_{i+1}}{t_{i+2} - t_{i+1}} \right| \leq 2.86 \text{ dB/4.3125 kHz}$ for 4.3125 kHz subcarrier spacing;
- $\left| \frac{\text{PSD}_{i+2} - \text{PSD}_{i+1}}{t_{i+2} - t_{i+1}} \right| \leq 1.43 \text{ dB/4.3125 kHz}$ for 8.6250 kHz subcarrier spacing;

with $(t_{i+2} - t_{i+1}) \leq 7$.

NOTE – These slopes correspond approximately to a maximum of 23 dB increase in the PSD mask level over 47 subcarriers, and 20 dB over seven subcarriers.

The two-slope steep upward shape is illustrated in Figure 7-6.

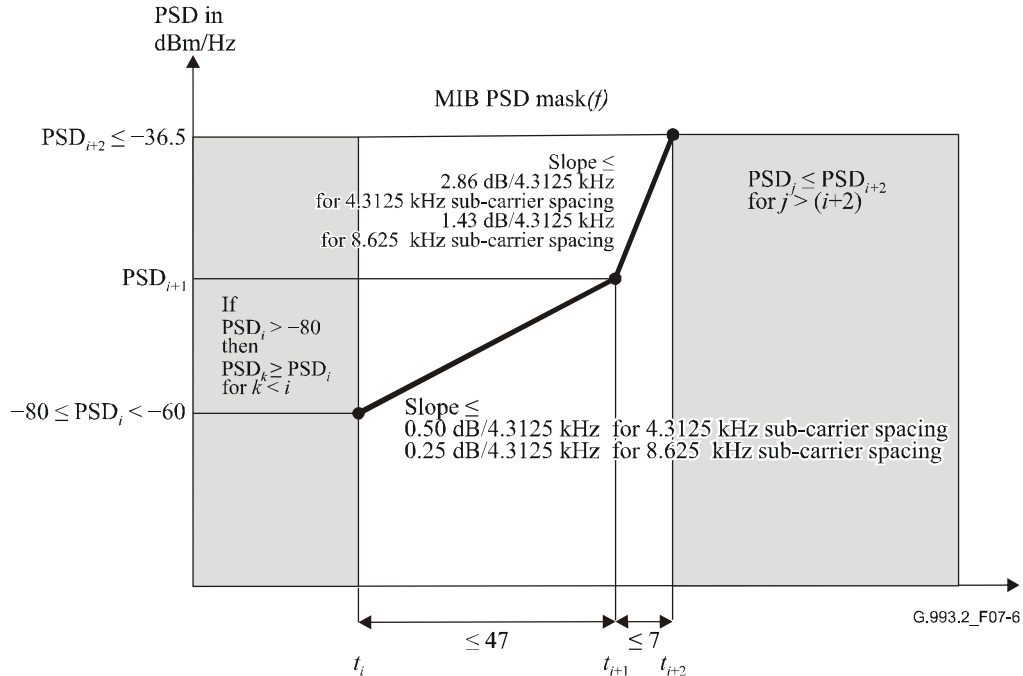


Figure 7-6 – Illustration of the two-slope steep upward shape

7.2.1.1.2.4 Definition of breakpoints at the edge of a band

No additional restrictions on the MIB PSD mask are imposed at the band edges. The values PSD_1 and PSD_{NBP} can be any value between the value of the Limit PSD mask at that frequency and -95 dBm/Hz, provided that the MIB PSD mask construction rules are not violated as a result.

7.2.1.1.3 Definition of breakpoints in US0

If US0 shaping is supported, breakpoints $[(t_1, PSD_1), \dots, (t_n, PSD_n), \dots, (t_{NBP_{US0}}, PSD_{NBP_{US0}})]$ specified in the CO MIB at frequencies between f_{0L} and f_{0H} ($f_{0L} \leq t_n \times 4.3125 \text{ kHz} \leq f_{0H}$) shall comply with the restrictions specified in the following clauses.

7.2.1.1.3.1 Restriction on breakpoints in US0

The number of breakpoints in US0 (NBP_{US0}) shall be between 2 and 6. The first breakpoint t_1 shall be equal to $\text{ceil}(f_{0L}/4.3125 \text{ kHz})$. The last breakpoint, $t_{NBP_{US0}}$, shall be smaller than or equal to $\text{floor}(f_{0H}/4.3125 \text{ kHz})$. $t_{NBP_{US0}}$ shall be between 32 and 128. If $32 \leq t_{NBP_{US0}} \leq 64$, $t_{NBP_{US0}}$ shall be a multiple of 4. If $64 < t_{NBP_{US0}} \leq 128$, $t_{NBP_{US0}}$ shall be a multiple of 8.

The breakpoint PSD values PSD_n shall be specified according to the following constraints and requirements:

- 1) The range between the minimum and maximum PSD values over all breakpoints shall be no greater than 24 dB, i.e.,

$$\max\{PSD_n\} - \min\{PSD_n\} \leq 24 \text{ dB},$$

where:

$$\max\{PSD_n\} = \max(PSD_1, PSD_2, \dots, PSD_{NBP_{US0}}) \text{ and:}$$

$$\min\{PSD_n\} = \min(PSD_1, PSD_2, \dots, PSD_{NBP_{US0}})$$

2) The maximum slope between consecutive breakpoints shall be bound by at least one of the following two restrictions:

i) $\forall n : 1 < n < NBP_{US0} :$

$$\left| \frac{PSD_n - PSD_{n-1}}{t_n - t_{n-1}} \right| \leq 0.75 \text{ dB/4.3125 kHz}$$

ii) $\forall n : 1 < n < NBP_{US0}$ and $(\max \{PSD_n\} - PSD_n \leq 6 \text{ dB}$ or $\max \{PSD_n\} - PSD_{n-1} \leq 6 \text{ dB})$:

$$\left| \frac{PSD_n - PSD_{n-1}}{t_n - t_{n-1}} \right| \leq 0.6 \text{ dB/4.3125 kHz}$$

7.2.1.1.3.2 Derivation of US0 PSD mask from defined breakpoints

The MIB PSD mask at an arbitrary frequency f between $t_1 \times 4.3125 \text{ kHz}$ and $t_{NBPUS0} \times 4.3125 \text{ kHz}$ shall be obtained by interpolation in dB on a linear frequency scale as follows:

$$\text{MIB PSD mask } (f) = PSD_n + (PSD_{n+1} - PSD_n) \times \frac{(f/4.3125 \text{ kHz}) - t_n}{t_{n+1} - t_n}, t_n < (f/4.3125 \text{ kHz}) \leq t_{n+1}$$

For frequencies below $t_1 \times 4.3125 \text{ kHz}$, the MIB PSD mask shall be equal to PSD_1 .

For $t_{NBPUS0} \times 4.3125 \text{ kHz} < f < 989 \text{ kHz}$, the MIB_PSD_mask in dBm/Hz shall be the higher of:

$$\text{MIB_PSD_Mask}(f) = PSD_{NBPUS0-1} - 72 \times \log_2((f/4.3125 \text{ kHz})/t_{NBPUS0-1})$$

and:

$$\text{MIB_PSD_Mask}(f) = \max(-100 - 15 \times \log_{10}(f/686 \text{ kHz}) - 100)$$

7.2.1.2 Egress control

VDSL2 transmitters shall be able to reduce the PSD of the transmitted signal to a level below -80 dBm/Hz in 16 arbitrary frequency bands simultaneously. An example list of frequency bands (the amateur radio bands) is shown in Table 7-1. The value of -80 dBm/Hz shall be accounted for in the determination of MREFMASK (see Tables 7-3 through 7-5).

Table 7-1 – Amateur radio bands

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

The specific RFI bands to be notched are configured in the CO-MIB by the operator and set during the ITU-T G.994.1 handshake phase of initialization (see clause 12.3.2).

The egress control parameters specified in [ITU-T G.997.1] are the start and stop frequencies of each frequency band in which the transmit PSD shall be reduced to a level below -80 dBm/Hz. The PSD slopes forming the notch are vendor discretionary.

7.2.1.3 Upstream power back-off (UPBO)

Upstream power back-off (UPBO) shall be performed by the VTU-R to improve spectral compatibility between VDSL2 systems on loops of different lengths deployed in the same binder. This UPBO mechanism does not apply during the ITU-T G.994.1 handshake phase. In addition, UPBO for US0 is for further study.

7.2.1.3.1 Power back-off mechanism

The VTU-R transmit PSD shall be reduced in a frequency-dependent manner using the procedure defined below:

- The transmit PSD mask, PSDMASK_{us}, for the VTU-R shall be calculated by the VTU-O to comply with settings from the network management system as defined in clause 7.2.1. PSDMASK_{us} is communicated to the VTU-R at the beginning of initialization (in O-SIGNATURE);
- The VTU-R shall perform UPBO as described in clause 7.2.1.3.2 autonomously, i.e., without sending any significant information to the VTU-O until the UPBO is applied;
- After UPBO has been applied, the VTU-O shall be capable of adjusting the transmit PSD selected by the VTU-R; the adjusted transmit PSD shall be subject to the limitations given in clause 7.2.1.3.2.

7.2.1.3.2 Power back-off PSD mask

The VTU-R shall explicitly estimate the electrical length of its loop, kl_0 , optionally kl_0 per band (i.e., $kl_0[band]$), and use this value to calculate the UPBO PSD mask, UPBOMASK, at the beginning of initialization. The VTU-R shall then adapt its transmit signal to conform strictly to the mask UPBOMASK(kl_0, f) during initialization and Showtime, while remaining below the PSDMASK_{us} limit determined by the VTU-O as described in clause 7.2.1.3.1, and within the limit imposed by the upstream PSD ceiling (CDMAXMASK_{us}, MAXMASK_{us}).

Two methods for upstream power back-off method are defined:

- 1) The Reference PSD UPBO method;
- 2) The Equalized FEXT UPBO method (optional).

The VTU-C and VTU-R shall support the reference PSD UPBO method, and may support the equalized FEXT UPBO method. If the equalized FEXT UPBO method is supported, it shall be supported for all upstream bands (except US0). This latter method is controlled via the parameter UPBO reference electrical length kl_{0_REF} , which is specified for each upstream band (see Table 12-25).

7.2.1.3.2.1 Electrical length estimation method

Two methods are defined for deriving the electrical length autonomously:

- 1) ELE-M0 the default method;
- 2) ELE-M1 the alternative method.

Implementation of ELE-M0 is mandatory. Implementation of ELE-M1 is optional.

The ELE-M1 shall be used if the CO-MIB parameter "Alternative Electrical Length Estimation Mode" (AELE-MODE) is set to a value of 1 or higher, and the mode is supported by the VTU-O and by the VTU-R. Otherwise, the ELE-M0 shall be used.

The actual AELE-MODE used shall be reported in the CO-MIB parameter "Actual Alternative Electrical Length Estimation Mode" (ACT-AELE-MODE). If the VTU-O supports the optional ELE-M1 and the ELE-M0 is used, then the ACT-AELE-MODE parameter shall be set to a value of 0.

7.2.1.3.2.1.1 The default electrical length estimation method (ELE-M0)

The default electrical length estimation method (ELE-M0) method is implementation dependent.

NOTE – A possible estimate of kl_0 is as follows:

$$kl_0 = \text{MIN}\left(\frac{\text{loss}(f)}{\sqrt{f}}\right) \text{ dB}$$

where the minimum is taken over the usable VDSL2 frequency band above 1 MHz. The function $\text{loss}(f)$ is the insertion loss in dB of the loop at frequency f . This definition is abstract, implying an infinitely fine grid of frequencies.

7.2.1.3.2.1.2 The alternative electrical length estimation method (ELE-M1)

The alternative electrical length estimation method (ELE-M1) method is applied in the VTU-R to separately estimate the electrical length, in each downstream band, and in the VTU-O to separately estimate the electrical length, in each upstream band, excluding US0:

$$ELE[band] = \text{PERCENTILE} \left(\left\{ \frac{\text{loss}(f, rx_thresh(band))}{\sqrt{f}} \mid f \in band \right\}, \text{UPBOELMT} \right) [dB]$$

Where:

1. $band \in \{aele_bands\}$, where $\{aele_bands\}$ is the set of all supported upstream and downstream bands except US0, and $f > 1.8 \times f_1$ for DS1.

NOTE 1 – $1.8 \times f_1$ is used as the lower limit in calculations on the basis that for most cables above this frequency the \sqrt{f} approximation is sufficiently accurate for the purposes of UPBO, and is sufficiently above the US0-DS1 boundary to limit the impact of DS1 high pass filtering. Compared to the use of 1 MHz, this frequency makes it less likely that in-premises bridge taps will have a large effect on the electrical length estimate ELE[DS1].

2. $\text{loss}(f, rx_threshold(band))$ is the estimated transmission path loss in dB at tone frequency f in MHz, which is set to the special value 307.1 dB if the minimum received signal plus noise power during loss estimation is less than $rx_threshold$ (dBm/Hz) for the particular $band$.

The maximum values for $rx_threshold(band)$ are: –130 dBm/Hz in the downstream bands, and –115 dBm/Hz in the upstream bands. However, the VTU may use lower threshold $rx_threshold(band)$ settings. The actual threshold used shall be reported in CO-MIB parameters RXTHRSHDS and RXTHRSUS.

3. The $\text{PERCENTILE}(\{x\}, y)$ function returns the maximum value w in set $\{x\}$ such that the number of elements in $\{x\}$ with value less than w is less than y percent of the total number of elements in $\{x\}$.
4. UPBO Electrical Length Minimum Threshold (UPBOELMT) is a CO-MIB parameter which determines the percentile to be used in finding the qualified minimum of a set of frequency dependent electrical length estimates in a particular VDSL2 band.

NOTE 2 – The PERCENTILE function is used to mitigate the effect of RFI ingress. It provides an estimate of the minimum of a set of per-tone electrical length estimates, ignoring a small proportion of tones affected by high level narrow band RFI ingress.

If ELE-M1 is applied, the same value for kl_0 (*ELEDS*) is applied in all upstream bands except US0, at the beginning of initialisation. This is derived from $ELE[band]$ values estimated in the VTU-R for all downstream bands:

$$ELEDS = MIN(ELE[band]), \text{ where } band \in \{ds_bands\}$$

and

$$kl_0[us_band] = ELEDS \text{ for all } us_band \in \{upbo_bands\}$$

where $\{ds_bands\}$ is the set of all supported downstream bands with $f > 1.8 \times f_1$ for DS1, and $us_band \in \{upbo_bands\}$ the set of all supported upstream bands except US0.

The intermediate value ELEDS is sent to the VTU-O as "Estimate of electrical length" in R-MSG-1, as defined in clause 12.3.3.2.2.1.

An intermediate value ELEUS is determined in the VTU-O as follows:

$$ELEUS = MIN(ELE[band]), \text{ where } band \in \{upbo_bands\}.$$

The final electrical length is determined during initialisation and sent from the VTU-O to the VTU-R during initialisation in the O-UPDATE message (see clause 12.3.3.2.1.2). Separate values are provided for each upstream band, excluding US0. The values are selected according to the CO-MIB parameter AELE-MODE:

For all upstream bands except US0, $band \in \{upbo_bands\}$

AELE-MODE = 0 $kl_0[band] = ELE-M0$ VTU-O kl_0 estimate

AELE-MODE = 1 $kl_0[band] = ELEDS$ [dB], $band \in \{upbo_bands\}$

AELE-MODE = 2 $kl_0[band] = ELE[band]$ [dB], $band \in \{upbo_bands\}$

AELE-MODE = 3 $kl_0[band] = MIN(ELEUS, ELEDS)$ [dB], $band \in \{upbo_bands\}$

If the CO-MIB parameter *UPBOKLF* (*Force CO-MIB electrical length*) is set to 1 then the final electrical length is set defined by the CO-MIB parameter *UPBOKL* (*Upstream electrical length*), and applied as follows:

$$kl_0[band] = UPBOKL, \text{ } band \in \{upbo_bands\}$$

If ELE-M1 is supported the following parameters shall be reported by the transceivers, whether or not *UPBOKLF* is set:

$ELE[band]$, $band \in \{ds_bands\}$ shall be reported by the VTU-R to the VTU-O in the R-MSG 1 message (see clause 12.3.3.2.2.1)

$ELE[band]$, $band \in \{aele_bands\}$ shall be reported by the VTU-O via the CO-MIB, where $\{aele_bands\} = \{ds_bands\} \cup \{upbo_bands\}$.

7.2.1.3.2.2 UPBO mask

If the optional equalized FEXT UPBO method is not supported, or if the optional equalized FEXT UPBO method is supported but $kl_0_{REF} = 0$ for a given upstream band, the UPBOMASK for that given band is calculated as:

$$UPBOMASK(kl_0, f) = UPBOPSD(f) + LOSS(kl_0, f) + 3.5 \text{ [dBm/Hz]},$$

where:

$$LOSS(kl_0, f) = kl_0 \sqrt{f} \text{ [dB]}, \text{ and}$$

$$UPBOPSD(f) = -a - b \sqrt{f} \text{ [dB/Hz]},$$

with f expressed in MHz.

In case ELE-M0 is used, kl_0 is defined as a single value.

In case ELE-M1 is used, kl_0 is defined separately for each band in $\{ upbo_bands \}$, i.e., $kl_0[band]$.

UPBOPSD(f) is a function of frequency but is independent of length and type of loop.

If the optional equalized FEXT UPBO method is supported, and $kl_{0_REF} \neq 0$ for a given upstream band, the UPBOMASK for that given band is calculated as:

- for $(1.8 \leq kl_0 < kl_{0_REF})$:

$$UPBOMASK(f) = -a - b\sqrt{f} + 10 \log_{10} \left(\frac{kl_{0_REF}}{kl_0} \right) + LOSS(kl_0, f) + 3.5 \quad [\text{dBm/Hz}]$$

- for $(kl_0 < 1.8)$:

$$UPBOMASK(f) = -a - b\sqrt{f} + 10 \log_{10} \left(\frac{kl_{0_REF}}{1.8} \right) + LOSS(1.8, f) + 3.5 \quad [\text{dBm/Hz}]$$

- for $(kl_0 \geq kl_{0_REF})$:

$$UPBOMASK(f) = -a - b\sqrt{f} + LOSS(kl_0, f) + 3.5 \quad [\text{dBm/Hz}]$$

where:

$$LOSS(kl_0, f) = kl_0 \sqrt{f} \quad [\text{dB}]$$

with f expressed in MHz.

For both methods of UPBO, the values of a and b , which may differ for each upstream band, are obtained from the CO-MIB as specified in [ITU-T G.997.1] and shall be provided to the VTU-R during initialization (see clause 12.3.3.2.1.1). Specific values may depend on the geographic region (see Annexes A, B and C).

For the optional equalized FEXT UPBO method, the value kl_{0_REF} is obtained from the CO-MIB as specified in [ITU-T G.997.1] and shall be provided to the VTU-R during initialization (see clause 12.3.3.2.1.1).

If the estimated value of kl_0 is smaller than 1.8, the VTU shall be allowed to perform power back-off as if kl_0 were equal to 1.8. The estimate of the electrical length should be sufficiently accurate to avoid spectrum management problems and additional performance loss.

NOTE 1 – To meet network specific requirements, network management may provide a means to override the VTU-R's autonomous estimate of kl_0 (see clause 12.3.3.2.1.2, O-UPDATE).

NOTE 2 – The nature of coupling between loops in a cable binder results in a rapidly decreasing FEXT as the loop length decreases. As the electrical length kl_0 of the loop decreases below 1.8, no further increase in power back-off is needed. An electrical length of 1.8 corresponds to, for example, a 0.4 mm loop about 70 m long.

7.2.2 Stopband PSD

The PSD of the signal transmitted in the stopbands shall comply with a Limit PSD Mask and a wide-band power limit as defined in Figure 7-7. The Limit PSD Mask applies between band separating frequencies f_{ir1} and f_{ir2} . The wide-band power limit P_{max} applies in that part of the band lying between the transition bands (width Δf_T).

The width of the transition bands Δf_T shall be independent of frequency and shall not exceed 175 kHz. Transition bands and values of the stopband PSD in the frequency range $f_{ir} < 686$ kHz are specified in regional annexes.

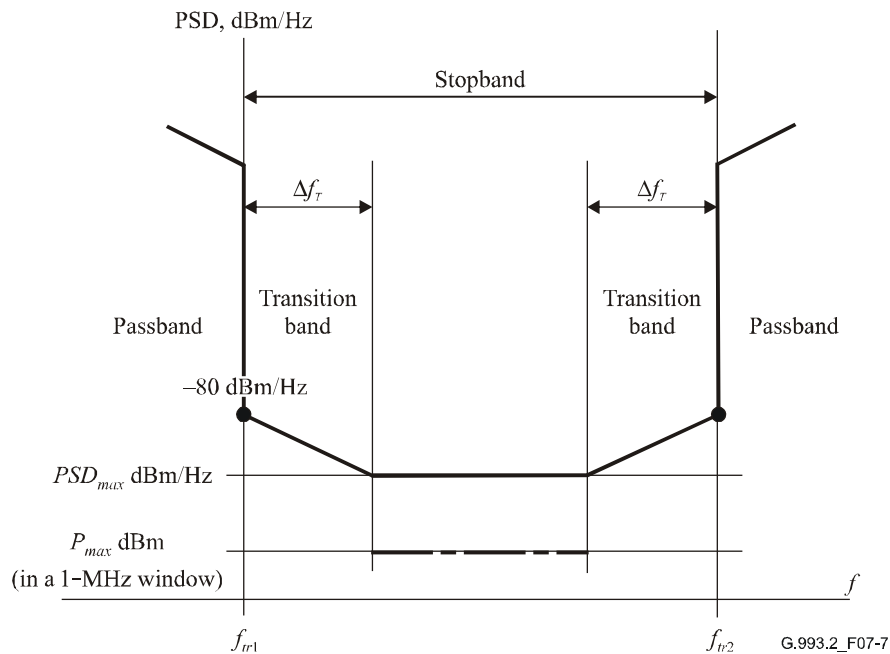


Figure 7-7 – Limit PSD mask and wide-band power limit in the stopbands

The Limit PSD mask values and the power limit values inside the stopbands shall be as listed in Table 7-2 and shown in Figure 7-7. The values between the points listed in Table 7-2 shall be found using linear interpolation over a linear scale of frequency. The signal transmitted in the stopbands shall comply with both the Limit PSD mask (verified using a 10 kHz measurement bandwidth) and the power limit in a 1-MHz sliding window presented in Table 7-2.

Table 7-2 – Stopband PSD requirements

Frequency (MHz)	Limit PSD mask value (PSD _{max} dBm/Hz)	Maximum power in a 1 MHz sliding window (P _{max} dBm)
< 0.686	Subject to regional annexes	
0.686-4.0	-100	
4.0-5.0	-100	-50
5.0-30.0	-100	-52
≥ 30.0	-110	
Frequency (MHz)	Limit PSD mask value at the transition frequency (dBm/Hz)	
Transition frequency ($f = f_{tr1}$ and $f = f_{tr2}$)	-80	

The power measured in any 1 MHz window $[f, f+1 \text{ MHz}]$ with $f \geq f_{tr1} + \Delta f_T$ and $f + 1 \text{ MHz} \leq f_{tr2} - \Delta f_T$ shall comply with the value shown in Table 7-2 (with f_{tr1}, f_{tr2} and Δf_T as shown in Figure 7-7). If the value $(f_{tr2} - f_{tr1} - 2\Delta f_T)$, is less than 1 MHz, the bandwidth of the measurement device should be reduced and set to Δf_M , so that $\Delta f_M \leq f_{tr2} - f_{tr1} - 2\Delta f_T$. The measured result shall be recalculated to the 1 MHz sliding window as:

$$P_{max} = P - 10 \times \log_{10} (\Delta f_M)$$

where:

P is the measured result in dBm

Δf_M is the bandwidth used for the measurement in MHz

7.2.3 PSD and PSD mask summary

A summary of the various PSDs and PSD masks used during initialization and showtime is presented in Table 7-3.

Table 7-3 – PSD masks and PSDs used in this Recommendation

Parameter	Description	Notation
Limit PSD mask	A PSD mask specified in an annex of this Recommendation (Annex A, B, or C).	LIMITMASKds, LIMITMASKus
MIB PSD mask	A PSD mask specified by the operator for passbands only and intended to restrict the transmit PSD to levels below those allowed by the applicable Limit PSD mask.	MIBMASKds, MIBMASKus
Transmit PSD mask	A PSD mask that is the minimum of 1) the applicable Limit PSD mask, 2) the MIB PSD mask, and 3) vendor-discretionary mask restrictions imposed by the VTU-O.	PSDMASKds, PSDMASKus
UPBO PSD mask	A PSD mask, for the upstream direction only, which is calculated by the VTU-R as a function of the electrical length of the loop (see clause 7.2.1.3.2).	UPBOMASK
Channel discovery PSD	The PSD of signals transmitted by a VTU during the channel discovery phase of initialization.	CDPSDds, CDPSDus
PSD ceiling	A PSD level, independent of frequency (and indicated by a single value), that limits the transmit PSD mask to form the MEDLEY reference PSD mask. (see clauses 12.3.3.2.1.1, 12.3.3.2.1.2, 12.3.3.2.2.1, and 12.3.3.2.2.2).	CDMAXMASKds, CDMAXMASKus, MAXMASKds, MAXMASKus
MEDLEY reference PSD mask	The transmit PSD mask limited at every frequency by the PSD ceiling and to -80 dBm/Hz inside the RFI bands. In the upstream direction, also limited in accordance with the UPBO requirements.	MREFMASKds, MREFMASKus
MEDLEY reference PSD	The PSD of signals transmitted by a VTU during the training phase and the channel analysis and exchange phase of initialization.	MREFPSDds, MREFPSDus
Showtime PSD	The PSD of signals transmitted by a VTU during showtime.	PSDds PSDus

The details of computation rules for the PSD masks and setting rules for the PSDs are presented in Table 7-4.

Table 7-4 – Summary of PSD and PSD mask calculations

Parameter	Calculation
Transmit PSD mask (PSDMASK)	Calculated by the VTU-O as (Note): $PSDMASK_{ds}(f) = \min(LIMITMASK_{ds}(f), MIBMASK_{ds}(f), ds_mask_restrictions_by_VTU-O)$ $PSDMASK_{us}(f) = \min(LIMITMASK_{us}(f), MIBMASK_{us}(f), us_mask_restrictions_by_VTU-O)$
Channel discovery PSD (CDPSD)	CDPSD _{ds} , expressed in dBm/Hz, is determined by the VTU-O, and for subcarriers from the SUPPORTEDCARRIERS _{ds} set: $CDPSD_{ds}(f) \leq \begin{cases} \min[(PSDMASK_{ds}(f) - 3.5), (CDMAXMASK_{ds} - 3.5)], f \notin RFIBANDS \\ \min[(PSDMASK_{ds}(f) - 3.5), (CDMAXMASK_{ds} - 3.5) - 83.5], f \in RFIBANDS \end{cases}$ For all other subcarriers, $CDPSD_{ds}(f) \leq PSDMASK_{ds}(f)$. For any valid setting of CDPSD _{ds} , the aggregate downstream transmit power shall not exceed the MAXNOMATP _{ds} . CDPSD _{us} , expressed in dBm/Hz, is determined by the VTU-R, and for subcarriers from the SUPPORTEDCARRIERS _{us} set: $CDPSD_{us}(f) \leq \begin{cases} \min[(PSDMASK_{us}(f) - 3.5), (CDMAXMASK_{us} - 3.5), (UPBOMASK(kl_0, f) - 3.5)], f \notin RFIBANDS \\ \min[(PSDMASK_{us}(f) - 3.5), (CDMAXMASK_{us} - 3.5), (UPBOMASK(kl_0, f) - 3.5), -83.5], f \in RFIBANDS \end{cases}$ For all other subcarriers, $CDPSD_{us}(f) \leq PSDMASK_{us}(f)$. For any valid setting of CDPSD _{us} , the aggregate upstream transmit power shall not exceed the control parameter MAXNOMATP _{us} defined in clause 10.3.4.2.1.
MEDLEY reference PSD mask (MREFMASK)	$MREFMASK_{ds}(f) = \begin{cases} \min(PSDMASK_{ds}(f), MAXMASK_{ds}), f \notin RFIBANDS \\ \min(PSDMASK_{ds}(f), MAXMASK_{ds}, -80), f \in RFIBANDS \end{cases}$ $MREFMASK_{us}(f) = \begin{cases} \min(PSDMASK_{us}(f), MAXMASK_{us}, UPBOMASK(kl_0, f)), f \notin RFIBANDS \\ \min(PSDMASK_{us}(f), MAXMASK_{us}, UPBOMASK(kl_0, f) - 80), f \in RFIBANDS \end{cases}$
MEDLEY reference PSD (MREFPSD)	$MREFPSD_{ds}(f) \leq (MREFMASK_{ds}(f) - 3.5 \text{ dB})$ for all subcarriers of the downstream passband (including downstream RFI bands allowed to carry data) and $MREFPSD_{ds}(f) \leq MREFMASK_{ds}(f)$ for all other frequencies. For any valid setting of MREFPSD _{ds} , the aggregate downstream transmit power shall not exceed the MAXNOMATP _{ds} . $MREFPSD_{us}(f) \leq (MREFMASK_{us}(f) - 3.5 \text{ dB})$ for all subcarriers of the upstream passband (including upstream RFI bands allowed to carry data) and $MREFPSD_{us}(f) \leq MREFMASK_{us}(f)$ for all other frequencies. For any valid setting of MREFPSD _{us} , the aggregate upstream transmit power shall not exceed the control parameter MAXNOMATP _{us} defined in clause 10.3.4.2.1.
NOTE – RFI bands are not incorporated in the transmit PSD mask.	

NOTE – Table 7-4 specifies PSDs and PSD masks at every frequency (i.e., in both the passband and the stopbands). To avoid communication of redundant information, the corresponding messages during initialization do not describe the PSDs in the full frequency range, nor do they describe the RFI bands.

The process of determining the PSDs and PSD masks of the VTU during initialization and showtime is summarized in Table 7-5.

Table 7-5 – Summary: Determination and use of PSDs and PSD masks

Parameter	When determined	When communicated between VTUs (Note)	When used
Limit PSD mask (LIMITMASK)	Configuration of MIB before start of initialization	Not communicated	By VTU-O, before start of initialization, to calculate downstream and upstream transmit PSD masks
MIB PSD mask (MIBMASK)	Configuration of MIB before start of initialization	Not communicated	By VTU-O, before start of initialization, to calculate downstream and upstream transmit PSD masks
RFI bands (RFIBANDS)	Configuration of MIB before start of initialization	RFIBANDS is sent by VTU-O to VTU-R during ITU-T G.994.1 handshake phase	Notches are applied in designated bands in applicable transmission direction(s) from the start of initialization and thereafter
Initial PSD ceiling (CDMAXMASK)	By the VTU-O before start of initialization, by the VTU-R at the beginning of channel discovery phase	Initial value of downstream PSD ceiling is sent by VTU-O to VTU-R in O-SIGNATURE; initial value of upstream PSD ceiling is sent by VTU-R to VTU-O in R-MSG1	For all signals during the channel discovery phase (initial downstream ceiling avoids saturation of the VTU-R over short loops)
Transmit PSD mask (PSDMASK)	By the VTU-O before start of initialization	PSDMASKds and PSDMASKus are sent by VTU-O to VTU-R in O-SIGNATURE	For all signals during channel discovery phase
UPBO PSD mask (UPBOMASK)	By the VTU-R at the beginning of the channel discovery phase	Not communicated	For all signals during channel discovery phase and thereafter
Channel discovery PSD (CDPSD)	At the beginning of channel discovery phase; VTU-O determines CDPSDds, VTU-R determines CDPSDus	CDPSDds is sent by VTU-O to VTU-R in O-SIGNATURE; CDPSDus is sent by VTU-R to VTU-O in R-MSG 1	For all signals during channel discovery phase
PSD ceiling (MAXMASK)	At the end of channel discovery phase; VTU-R determines MAXMASKds, VTU-O determines MAXMASKus	MAXMASKus is sent by VTU-O to VTU-R in O-UPDATE. MAXMASKds is sent by VTU-R to VTU-O in R-UPDATE	From the beginning of training phase and thereafter

Table 7-5 – Summary: Determination and use of PSDs and PSD masks

Parameter	When determined	When communicated between VTUs (Note)	When used
MEDLEY reference PSD mask (MREFMASK)	At the end of channel discovery phase; VTU-O determines MREFMASKds, VTU-R determines MREFMASKus	Not communicated	From the beginning of training phase and thereafter during initialization and showtime
MEDLEY reference PSD (MREFPSD)	At the end of channel discovery phase; VTU-O determines MREFPSDds, VTU-R determines MREFPSDus	MREFPSDds is sent by VTU-O to VTU-R in O-PRM; MREFPSDus is sent by VTU-R to VTU-O in R-PRM	During the training and channel analysis and exchange phases
Showtime PSD	At the end of the channel analysis and exchange phase	Determined by the MREFPSD and the gain values (g_i) communicated during the channel analysis and exchange phase (O-PMD and R-PMD messages). Shall not exceed MREFMASK.	During showtime

NOTE – Only the minimum set of relevant parameters characterizing PSDs and PSD masks is communicated during initialization. The communication protocols and formats are described in clause 12.

7.3 Termination impedance

A termination impedance of $R_V = 100$ Ohm, purely resistive, at the U interface, shall be used over the entire VDSL2 frequency band for both VTUs. In particular, $R_V = 100$ Ohm shall be used as a termination for the transmit PSD and power definition and verification.

NOTE – This termination impedance approximates the insertion-point impedance of the VDSL2 test loop and harmonizes VDSL2 and ADSL2.

7.4 Longitudinal conversion loss

Longitudinal conversion loss (LCL) is a measure of the degree of unwanted transversal signal produced at the input of the VDSL2 transceiver due to the presence of a longitudinal signal on the connecting leads. The longitudinal voltage (V_{cm}) to transversal voltage (V_{diff}) ratio shall be measured in accordance with [ITU-T G.117] and [ITU-T O.9]. During the measurement, the transceiver under test shall be powered, and in the L3 state (see clause 12.1).

$$LCL = 20 \log_{10} \left| \frac{V_{cm}}{V_{diff}} \right| \text{dB}$$

The LCL of the VDSL2 transceiver shall be greater than or equal to 38 dB in the frequency band up to 12 MHz.

In the frequency band above 12 MHz, the LCL of the VDSL2 transceiver for frequency f shall be greater than or equal to $38 \text{ dB} - 20 \log_{10}(f_{[\text{MHz}]} / 12)$ for $12 \text{ MHz} < f < F_{max}$, where F_{max} is the higher of the highest passband frequency in the upstream and downstream directions for the Limit PSD masks selected.

The termination impedance of the transceiver for LCL measurement shall be $R_V = 100$ Ohm. The LCL shall be measured at the U-O2 (U-R2) interface. LCL shall be measured in the frequency band between the lower of the lowest passband frequency in the upstream and downstream directions and F_{max} .

NOTE 1 – The equipment balance should be better than the anticipated access network balance in order to minimize the unwanted emissions and susceptibility to external RFI.

NOTE 2 – VDSL2 performance may benefit from even higher balance. Where subject to repetitive electrical impulse noise, systems operating at frequencies where the cable balance may be 50 dB could be limited in capacity by a 38 dB balance.

NOTE 3 – The required LCL may be increased in a future revision of this Recommendation.

8 Transport protocol specific transmission convergence (TPS-TC) function

The transport protocol specific transmission convergence (TPS-TC) sublayer resides between the γ reference point and the α/β reference point as presented in the VDSL2 and VTU functional model in Figure 5-1. This functional model defines the TPS-TC sublayer as containing one or more TPS-TCs providing transport of user data utilizing different transport protocols, a management TPS-TC (MPS-TC) providing eoc transport over the VDSL2 link, an NTR-TC providing transport of the network timing reference, and a ToD-TC providing transport of the time-of-day.

Functionality, parameters, and application interface (γ interface) characteristics of the user data TPS-TC are specified in clause 8.1. Functionality, parameters, and application interface (γ interface) characteristics of the MPS-TC are specified in clause 8.2. Functionality, parameters, and application interface (γ interface) characteristics of the NTR-TC are specified in clause 8.3. Functionality, parameters, and application interface (γ interface) characteristics of the ToD-TC are specified in clause 8.4.

The mandatory TPS-TC sublayer configuration shall include the MPS-TC, the NTR-TC, and at least one user data TPS-TC. Support of a second user data TPS-TC or the ToD-TC is optional. Each TPS-TC operates over a separate bearer channel, where the PMS-TC may allocate these bearer channels to a single or to separate latency paths.

8.1 The user data TPS-TC

8.1.1 User data TPS-TC types

There are three types of user data TPS-TCs defined in this Recommendation:

- 1) Type 1: Synchronous transfer mode (STM) transmission convergence (STM-TC);
- 2) Type 2: Asynchronous transfer mode (ATM) transmission convergence (ATM-TC); and
- 3) Type 3: Ethernet and generic packet transport packet transfer mode transmission convergence (PTM-TC).

Each of these three types is defined as an application option. The VTU-O selects the user data TPS-TC type for each bearer channel, both upstream and downstream, based on the type of higher layer data it chooses to support on that bearer channel. The enabled user data TPS-TC type for each of the bearer channels is indicated during initialization.

Functionality, parameters, and application interface (γ interface) characteristics of the user data TPS-TCs supporting STM transport (STM-TC), ATM transport (ATM-TC), and Ethernet and generic packet transport (PTM-TC) are specified in L.1, L.2 and L.3, respectively.

The transmit signals of the TPS-TC are submitted to the α/β interface. Signals passing via the α/β interface in both directions have an application-independent (transport protocol independent) format, as specified in clause 8.1.2. The particular bit rates for each of the multiplexed TPS-TCs at the α/β reference point are determined during system configuration.

8.1.2 α/β interface specification

The α and β reference points define corresponding interfaces between the TPS-TC and PMS-TC at the VTU-O and VTU-R sides, respectively. Both interfaces are logical, application independent, and identical. The interfaces comprise the following flows of hypothetical signals between the TPS-TC and the PMS-TC sublayers:

- Data flow;
- Synchronization flow; and
- Control flow.

The various signals are summarized in Table 8-1.

Table 8-1 – User data TPS-TC: α/β interface data and synchronization flows signal summary

Signal	Description	Direction
Data signals		
Tx	Transmit data	TPS-TC → PMS-TC
Rx	Receive data	TPS-TC ← PMS-TC
Synchronization signals		
Osync_t	Transmit octet timing	TPS-TC ← PMS-TC
Osync_r	Receive octet timing	
Control signals		
Syncflag	Reconfiguration flag	TPS-TC ← PMS-TC

8.1.2.1 Data flow

The data flow comprises two generic octet-oriented streams with the rates defined by the physical net data rate capabilities:

- Transmit data stream: Tx;
- Receive data stream: Rx.

The data flow signal description is presented in Table 8-1.

The Tx and Rx data rate values are set during initialization as described in clause 12.3.5.2.1. The bit order in the data flow shall provide that the most significant bit (MSB) of the TPS-TC data is sent to the PMS-TC first. This bit convention is clarified for the ATM-TC in Figure L.8 and for the PTM-TC in clause N.3.4 of [ITU-T G.992.3], and for the MPS-TC in clauses 8.2.3 and 9.5.2.2.

8.1.2.2 Synchronization flow

This flow provides synchronization between the TPS-TC sublayer and the PMS-TC sublayer. The synchronization flow comprises the two synchronization signals presented in Table 8-1:

- Transmit and receive data flow octet-synchronization (Osync_t, Osync_r).

All synchronization signals are asserted by the PMS-TC and directed towards the TPS-TC. The signals Osync_t and Osync_r determine the octet boundaries and the rates of the corresponding Tx and Rx data signals. In the case that the clock rate provided by the PMS-TC changes due to a reconfiguration, this change shall occur at an octet boundary, and shall be determined by the corresponding change in the Osync signal. The detailed description of the reconfiguration for specific TPS-TCs is in Annex L.

8.1.2.3 Control flow

This flow provides a time marker (Syncflag, as specified in Table 8-1) for changes of the TPS-TC parameters (see clauses L.1.11.1, L.2.11.1, and L.3.11.1). The Syncflag is asserted by the PMS-TC and indicates a specific time when the TPS-TC shall start operating with modified parameters.

8.1.3 Control parameters

The configuration of the TPS-TC functions is controlled by a set of control parameters. Some of the control parameters are defined in Table 8-2. The remaining control parameters are dependent on the TPS-TC type and are defined in Annex L.

Table 8-2 – TPS-TC parameters

Parameter	Definition
N_{BC}	The number of enabled transmit TPS-TC functions and the number of enabled bearer channels. The TPS-TC functions and bearer channels are labelled #0, #1. N_{BC} is the number of non-zero values in the $\{type_0, type_1\}$ set. The value of N_{BC} may be different for the VTU-O and VTU-R transmitters.
$type_n$	The TPS-TC type mapped to bearer channel # n ($n = 0$ to 1). The type of the specific TPS-TC shall be set to a value described in Annex L ($type_n = 1$ (STM), $type_n = 2$ (ATM), or $type_n = 3$ (PTM)). The $type_n$ value of zero shall be used to disable TPS-TC function # n and bearer channel # n .

The values of all control parameters listed in Table 8-2 shall be configured during the channel analysis and exchange phase of initialization (see clause 12.3.5), using the O-TPS SOC message (see Tables 12-6 and 12-51).

8.1.3.1 Valid configurations

A VTU may support two simultaneous TPS-TC functions in each direction. The control parameter N_{BC} shall be in the 1 to 2 range.

The valid values of the control parameter $type_n$ shall be those contained within Annex L or the value zero. All other values are reserved for use by ITU-T. If the $type_n$ parameter is non-zero for upstream and downstream, then it shall have the same value for upstream and downstream.

A VTU shall support mapping of all supported TPS-TC types to all supported bearer channels, except that PTM on one bearer channel and ATM on the other bearer channel shall not be enabled simultaneously. The valid labelling of supported bearer channels shall start from 0 and increase by one. Thus, there are only two cases:

- Single bearer channel mode: support of at least one TPS-TC function (of a type defined in Annex L) and one bearer channel. For this mode, bearer channel #0 shall be enabled.
- Dual bearer channel mode: support of at least two TPS-TC functions (of a type defined in Annex L) and two bearer channels. For this mode, bearer channels #0 and #1 shall be enabled.

8.1.3.2 Mandatory configurations

A VTU shall support single bearer channel mode in the downstream direction.

A VTU shall support single bearer channel mode in the upstream direction.

8.2 Management TPS-TC (MPS-TC)

The MPS-TC is intended to facilitate transport of eoc data between the VDSL2 management entities (VME-O, VME-R) at opposite ends of the VDSL2 link (see Figure 5-1).

8.2.1 Functional model

The MPS-TC shall provide fully-transparent eoc data transfer between the γ_{m-O} and γ_{m-R} interfaces (in the absence of non-correctable errors in the lower sublayers), and packet integrity of the transported eoc messages (commands and responses). In the transmit direction, the MPS-TC gets the eoc message from the VME over the application interface (γ_m interface), encapsulates it using the high-level data link control (HDLC) frame format, and submits it to the α/β interface to be transported via the VDSL2 link using the PMS-TC overhead messaging channel specified in clause 9.5.2. In the receive direction, the MPS-TC delineates the HDLC frames, runs the frame check sequence (FCS) check, and extracts the encapsulated eoc message from the correctly received HDLC frames. The received eoc messages are submitted to the VME over the γ_m interface. All incorrectly received HDLC frames shall be discarded.

NOTE – If the PMS-TC operates in dual latency mode (see clause 9.1), the encapsulated eoc messages are carried in the latency path which is determined by the control variable in the MSGLP field. This value is set during initialization in accordance with the type of OH frame being used, as specified in clauses 9.5.2.2 and 12.3.5.2.1.3.

8.2.2 Interface description

8.2.2.1 γ interface

The γ_{m-O} and γ_{m-R} reference points define interfaces between the VME and the MPS-TC at the VTU-O and VTU-R respectively, as shown in Figure 5-1. Both interfaces are identical, functional, and are defined by three signal flows between the VME and the MPS-TC:

- 1) Data flow;
- 2) Synchronization flow; and
- 3) Control flow.

The various signals are summarized in Table 8-3.

Table 8-3 – MPS-TC: γ_m interface data, synchronization and control flows signal summary

Flow	Signal	Description	Direction
Transmit signals			
Data	<i>Tx_eoc</i>	Transmit data	VME → MPS-TC
Sync	<i>Tx_Avbl</i>	Asserted by the VME if the message is available for transmission	VME → MPS-TC
Sync	<i>Tx_Clk</i>	Transmit clock	VME → MPS-TC
Sync	<i>Tx_SoM</i>	Start of the transmit message	VME → MPS-TC
Sync	<i>Tx_EoM</i>	End of the transmit message	VME → MPS-TC
Control	<i>Tx_stop</i>	Interruption of the transmission of the message	VME → MPS-TC
Control	<i>Tx_RF</i>	Response flag	VME → MPS-TC
Control	<i>Tx_PrF</i>	Priority flag	VME → MPS-TC
Control	<i>Sent</i>	Sent flag	VME ← MPS-TC
Receive signals			
Data	<i>Rx_eoc</i>	Receive data	VME ← MPS-TC
Sync	<i>Rx_Enbl</i>	Asserted by the MPS-TC; indicates that the VME may pull the message from the MPS-TC	VME ← MPS-TC

Table 8-3 – MPS-TC: γ_m interface data, synchronization and control flows signal summary

Flow	Signal	Description	Direction
Transmit signals			
Sync	<i>Rx_Clk</i>	Receive clock	VME → MPS-TC
Sync	<i>Rx_SoM</i>	Start of the receive message	VME ← MPS-TC
Sync	<i>Rx_EoM</i>	End of the receive message	VME ← MPS-TC
Control	<i>Rx_RF</i>	Response flag	VME ← MPS-TC
Control	<i>Rx_PrF</i>	Priority flag	VME ← MPS-TC

8.2.2.1.1 Data flow

The data flow shall consist of two contra-directional octet-based streams of messages with variable length: transmit messages (*Tx_eoc*) and receive messages (*Rx_eoc*). Bits within each octet are labelled a_1 through a_8 , with a_1 being the least significant bit (LSB) and a_8 being the MSB. Octets are labelled in numeric order. The VME shall send the eoc message to the MPS-TC with bit a_1 of the first octet sent first. The data flow signal description is presented in Table 8-3.

8.2.2.1.2 Synchronization flow

This flow provides synchronization between the VME and the MPS-TC and contains the necessary timing to provide integrity of the transported message. The synchronization flow shall consist of the following signals presented in Table 8-3:

- Transmit and receive timing signals (*Tx_Clk*, *Rx_Clk*): both asserted by the VME;
- Start of message signals (*Tx_SoM*, *Rx_SoM*): asserted by the VME and by the MPS-TC, respectively, to mark the beginning of the transported message in the corresponding direction of transmission;
- End of message signals (*Tx_EoM*, *Rx_EoM*): asserted by the VME and by the MPS-TC, respectively, to mark the end of the transported message in the corresponding direction of transmission;
- Transmit packet available signals (*Tx_Avbl*): asserted by the VME to indicate that the message is ready for transmission; and
- Enable receive signal (*Rx_Enbl*): asserted by the MPS-TC to indicate that the data packet may be pulled from the MPS-TC by the VME.

8.2.2.1.3 Control flow

This flow provides priority management of the sent messages, and consists of the following signals presented in Table 8-3:

- Stop transmission (*Tx_Stop*): asserted by the VME to indicate that the MPS-TC shall stop the transmission of the current message (to release the channel for a message with higher priority);
- Response flag (*Tx_RF*, *Rx_RF*): asserted by the VME and MPS-TC, respectively, to indicate that the eoc message contains a response;
- Priority flag (*Tx_PrF*, *Rx_PrF*): asserted by the VME and MPS-TC, respectively, to indicate the priority level of the command carried by the eoc message; and
- Sent flag (*Sent*): asserted by the MPS-TC to mark the time the last octet of the HDLC frame was sent over the α/β interface.

8.2.2.2 α/β interface

The α and β reference points define interfaces between the MPS-TC and PMS-TC at the VTU-O and VTU-R, respectively. Both interfaces are functional and shall comply with the definition for user TPS-TC as specified in clause 8.1.2. The MPS-TC shall ignore the Syncflag signal; the parameters of the MPS-TC are not subject to on-line reconfiguration.

8.2.3 Encapsulation format

The MPS-TC shall encapsulate messages for transmission using an HDLC-based frame format as shown in Table 8-4.

Table 8-4 – HDLC frame structure

Octet #	MSB	LSB
		$7E_{16}$ – Opening flag
1		Address field
2		Control field
3		Message octet #1
...	
$P + 2$		Message octet # P
$P + 3$		FCS high octet
$P + 4$		FCS low octet
		$7E_{16}$ – Closing flag

The MSB of octets of the encapsulated message shall be the MSB of the corresponding octet in the HDLC frame. The first octet of the eoc message incoming from the γ interface shall be transmitted first and the MSB of each octet shall be transmitted first.

8.2.4 Communication protocol

8.2.4.1 Transmitter

The transmitter shall encapsulate eoc messages prior to transmission using the HDLC frame structure described in clause 8.2.3. The FCS, the octet transparency mechanism, and HDLC inter-frame time filling shall be as described in [ITU-T G.997.1]. Opening and closing flags of two adjacent HDLC frames may be shared: the closing flag of one frame can serve as an opening flag for the subsequent frame.

If a Tx_Stop signal is set, the transmitter shall stop the transmission of the current message using the abort sequence described in [ITU-T G.997.1] (i.e., by a control escape octet followed by a flag), and get ready to receive a new message from the VME to be transmitted. If the transmission of the message is already completed when a Tx_Stop signal is set, the MPS-TC shall ignore it.

The transmitter shall set the two LSBs of the Address field in accordance with the priority level of the command sent, indicated by the Tx_PrF signal, as follows:

- 00 – High priority;
- 01 – Normal priority;
- 10 – Low priority;
- 11 – Near high priority.

All other bits of the Address field shall be set to ZERO.

The transmitter shall set the second LSB of the Control field with a command code (0) or a response code (1), in accordance with the signal Tx_RF . All other bits of the Control field shall be set to ZERO.

Upon the completion of the transmission of the HDLC frame, the transmitter shall set the *Sent* signal, indicating to the VME the start of the time-out timer (see Table 11-1).

8.2.4.2 Receiver

The receiver shall search for octet boundaries of HDLC frames. All incorrectly received frames, including invalid frames described in [ITU-T G.997.1] and frames with an invalid FCS, shall be discarded. Frames with an Address field or Control field not meeting the HDLC frame structure described in clauses 8.2.3 and 8.2.4.1 shall be discarded.

The MPS-TC shall extract the encapsulated eoc commands/responses from the correctly received HDLC frames and send them to the VME via the γ_m interface.

The receiver shall use the second LSB of the Control field of the received HDLC frame to distinguish between commands and responses and shall set the Response flag *Rx_RF* accordingly. The receiver shall use the last two LSBs of the Address field to identify the priority of the eoc command carried by the received HDLC frame and shall set the Priority flag *Rx_PrF* accordingly. Both *Rx_RF* and *Rx_PrF* shall be asserted upon the arrival of a valid HDLC header, which includes an Opening Flag, Address field and Control field (see Table 8-4), before the FCS verification of the received HDLC frame, to indicate the arrival time of the eoc message. After the FCS has been verified, the receiver shall set the *Rx_Enbl* signal to indicate that the correctly-received packet is ready.

NOTE – The VME uses the received Priority flag of the response messages to determine their arrival times and decide whether the response eoc message meets the time-out. Use by the VME of the received Priority flag of the command messages is currently undefined.

8.3 Network timing reference TPS-TC (NTR-TC)

Transport of an 8 kHz NTR from the VTU-O to the VTU-R shall be supported in order to support isochronous services that require the same exact timing reference at both sides of the VDSL2 line to operate the higher layers of the protocol stack. The VTU-O shall indicate NTR transport during initialization (see clause 12.3.5.2.1.1).

8.3.1 Interfaces

The γ_{m-O} and γ_{m-R} reference points define interfaces between the NTR source and the NTR-TC at the VTU-O and between the NTR-TC and the NTR receiver at the VTU-R, respectively, as shown in Figure 5-1. Both interfaces are identical, functional, and are defined by the signals specified in Table 8-5.

Table 8-5 – NTR-TC: γ interface signal summary

Flow	Signal	Description	Direction
Transmit signals (VTU-O)			
NTR	<i>Tx_NTR</i>	Transmit NTR signal	NTR source → NTR-TC
Receive signals (VTU-R)			
NTR	<i>Rx_NTR</i>	Receive NTR signal	NTR receiver ← NTR-TC

The α and β reference points define interfaces between the NTR-TC and PMS-TC at the VTU-O and VTU-R, respectively. Both interfaces are functional, and shall comply with the definition in clause 8.1.2 with the additional condition that NTR data is transmitted only in the direction from the VTU-O to the VTU-R. The NTR-TC shall ignore the Syncflag signal; the parameters of NTR-TC are not subject to on-line reconfiguration.

8.3.2 Functionality

NTR transport is facilitated by the NTR-TC. At the VTU-O the NTR-TC encodes the incoming NTR signal transitions into the NTR byte to be transported over the VDSL2 link in the NTR field of the OH frame. At the VTU-R the NTR-TC extracts the NTR byte from the OH frame and reconstructs the NTR signal.

The NTR-TC at the VTU-O shall generate the NTR bytes in the following way. The VTU-O shall derive a local 8 kHz local timing reference (LTR) by dividing its sampling clock by the appropriate number. Further, the VTU-O shall estimate the change in phase offset between the NTR and the LTR from the previous OH frame to the present OH frame (see clause 9.5.2). The change in phase offset shall be estimated at the beginning of the OH frame. The estimated value shall be expressed in cycles of the sampling clock running at frequency $8192 \times \Delta f$ and shall be mapped to the NTR byte as a 2-complement number.

The bits of the NTR byte, denoted by ntr_7 to ntr_0 , represent a signed integer in the range between -128 to $+127$. A positive value of the change in phase offset (ntr_7 is set to ZERO) indicates that the LTR has a higher frequency than the NTR; a negative value of the change in phase offset (ntr_7 is ONE) indicates that the LTR has a lower frequency than the NTR. The ntr bits shall all be set to ZERO if the VTU-O locks its' transmit PMD clock to the NTR frequency.

The NTR byte is transported in the NTR field of the OH frame. The mapping of the ntr bits to the NTR field of the OH frame is specified in clause 9.5.2.2.

The NTR-TC at the VTU-R shall reconstruct the 8 kHz NTR from the received values of the NTR byte using the encoded changes in the phase offset.

NOTE – In VDSL2, the sampling clock is proportional to the subcarrier spacing Δf . Therefore, the LTR, being proportional to the sampling clock, will have the same ± 50 ppm frequency variation as Δf (see clause 10.4.2). The NTR has a maximum variation of ± 32 ppm, thus the maximum difference in frequency between the NTR and the LTR will not exceed 82 ppm. This would result in a maximum time offset of $82 \times 10^{-6} \times PER_p$, where PER_p is the duration of the OH frame as defined in clause 9.5.4. This corresponds to $(82 \times 10^{-6} \times PER_p) \times 8192 \times \Delta f$ sampling cycles, which, for a subcarrier spacing of 4.3125 kHz, is equal to $2896 \times PER_p$ sampling cycles. With the maximum value of PER_p , which is less than 20 ms (see Table 9-8), the value of the offset to be transmitted will not exceed ± 58 . Therefore, the one-byte information field reserved for NTR is sufficient.

8.4 Time-of-day TPS-TC (ToD-TC)

Transport of time-of-day (ToD) from the VTU-O to the VTU-R should be supported in order to support services that require accurate ToD at both sides of the VDSL2 line to operate the higher layers of the protocol stack. The VTU-O shall indicate ToD transport during initialization (see clause 12.3.5.2.1.1).

NOTE 1 – Exchange of network time management information from VTU-R to VTU-O related to the quality of the ToD frequency and/or time recovery at the VTU-R is for further study.

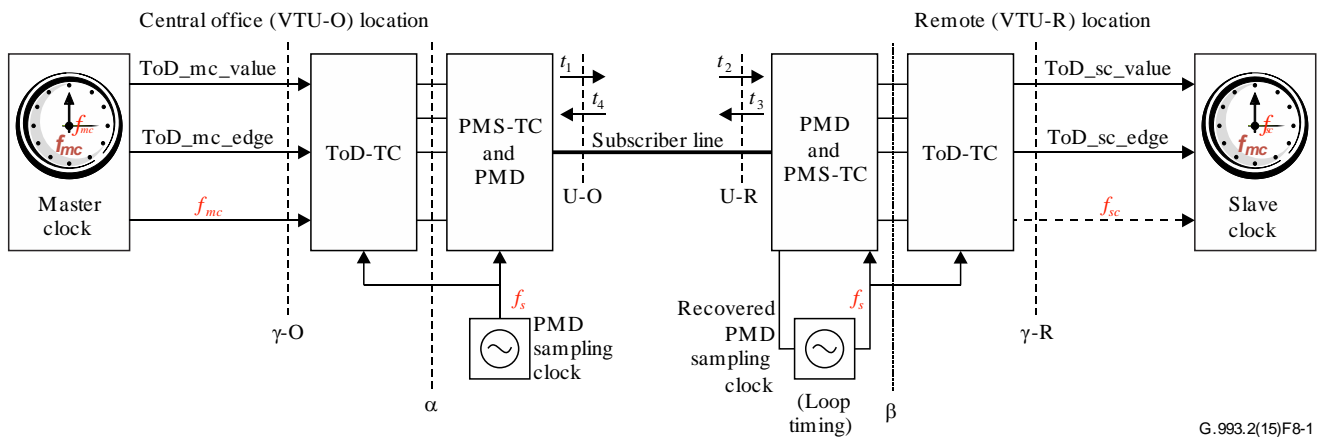
NOTE 2 – Exchange of relevant clock information from AN to CPE to support the ToD interface output from CPE is for further study. For PTP, this information includes source traceability, number of hops, and leap seconds.

NOTE 3 – The γ -O to γ -R ToD accuracy requirements are for further study; it is expected however, to be on the order of 100/200 ns.

8.4.1 Time-of-day distribution operational overview

Figure 8-1 shows the system reference model identifying the key elements in support of time-of-day transport across a VDSL2 link. The VTU-O receives a time-of-day signal from the master clock across the γ -O interface and the VTU-R outputs a time-of-day signal across the γ -R interface to slave clock external to the VTU-R that is synchronous in frequency, phase and time to the master clock. A

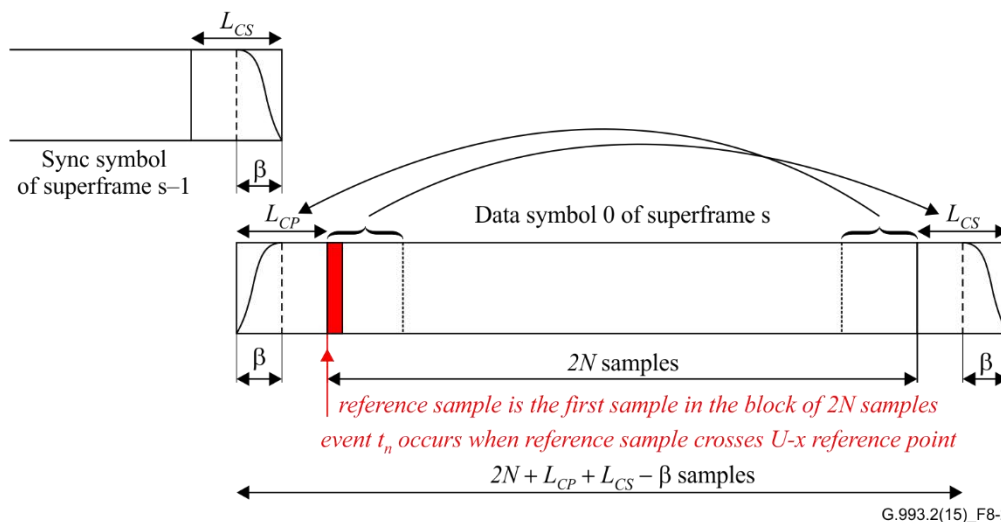
master clock source external to the VTU-O provides a time-of-day signal to the VTU-O across the γ -interface. The details of the time-of-day signal are for further study; however, the components include a time-of-day value (ToD_{mc_value}) to a corresponding clock edge (ToD_{mc_edge}) that is synchronous to the master clock's internal driving frequency. The ToD_{mc_edge} shall provide at least one edge per second. A component of the driving frequency (f_{mc}) shall be available to the VTU-O and shall be at least 8 kHz and shall be frequency and phase synchronized with the ToD_{mc_edge} to facilitate time-of-day transport processing in the VTU-O. Similarly, the time-of-day signal at the VTU-R is assumed to include a time-of-day value (ToD_{sc_value}) together with corresponding time edge marker (ToD_{sc_edge}) that is synchronous to the driving frequency of the master clock. A component of the driving frequency (f_{sc}) may be available from the VTU-R to facilitate time-of-day transport processing.



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Figure 8-1 – End-to-end system reference model for time-of-day transport in VDSL2

The VDSL2 PMD operates with a sampling clock for transmission of the DMT symbols on the subscriber line. The VTU-R's PMD sampling clock and the VTU-O's PMD sampling clock are assumed to be frequency locked, typically through loop timing in the VTU-R. For both the upstream and downstream transmit signals, the reference sample is defined as the first time-domain representation sample (see Figure 8-2 and Figure 8-3) of the first symbol in a superframe period (64.25 ms on the PMD sampling clock timebase if the CE length corresponds to $m = 5$, see clause 10.4.4).



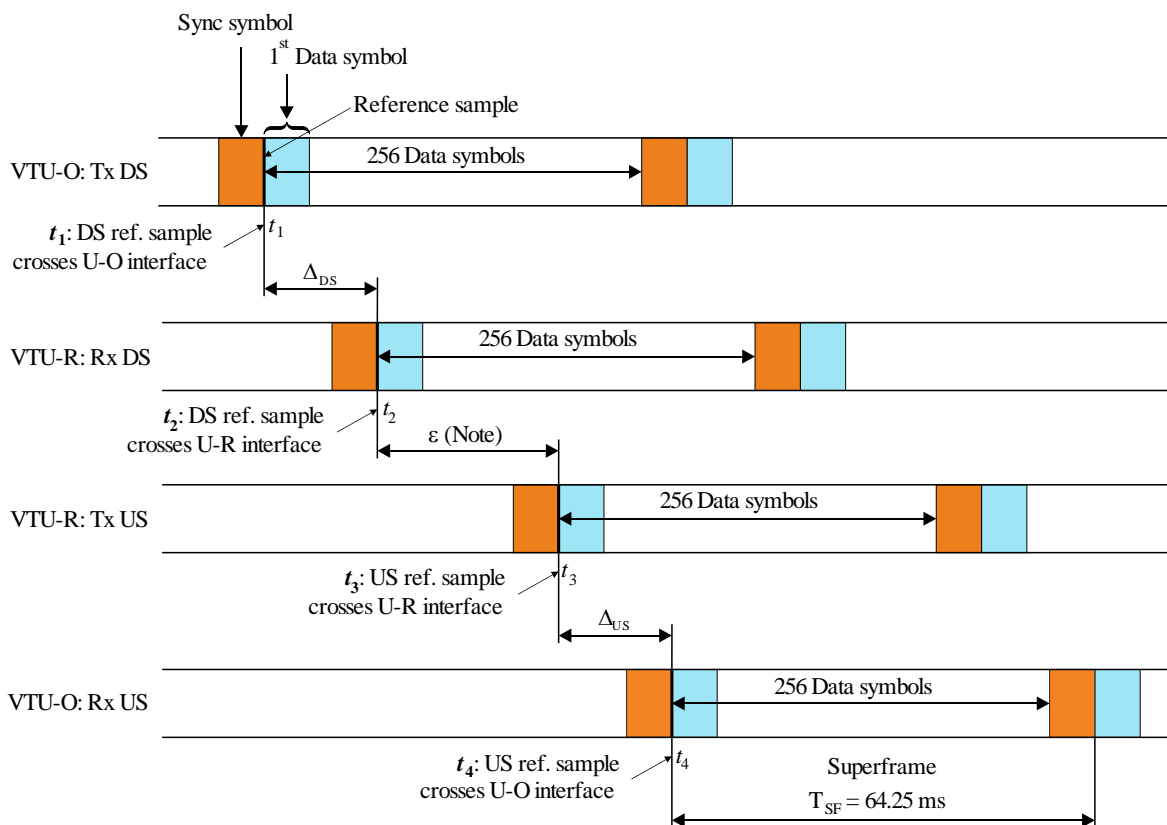
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Figure 8-2 – Cyclic extension, windowing and overlap of DMT symbols

The VDSL2 PMD in the VTU-O identifies the moment the downstream reference sample crosses the U-O interface (event t_1) and the moment (within one superframe from event t_1) the upstream reference sample crosses the U-O interface (event t_4); at the instant each event occurs, the ToD-TC (time-of-day – transmission convergence) in the VTU-O records the corresponding time values of its local real-time clock (RTC-O) to apply a time stamp to each of the respective events t_1 and t_4 . For each event t_1 , the VTU-O sends the ToD phase difference (i.e., the corresponding t_1 time stamp MOD 125 000 ns, represented in units of 2 ns) and the t_1 event number (i.e., representing the superframe counter value at the t_1 event) to the VTU-R. The VTU-R processes the ToD phase difference values to recover the ToD frequency. At a much slower rate, the VTU-O also sends the t_1 and t_4 time stamps together with a t_1 and t_4 event number to VTU-R for time/phase synchronization of the real time clocks. Similarly, the VDSL2 PMD in the VTU-R identifies the moment the downstream reference sample crosses the U-R interface (event t_2) and the upstream reference sample crosses the U-R interface (event t_3); at the instant each event occurs, the ToD-TC in the VTU-R records the corresponding time of the local slave clock to apply a time stamp to each of the respective events t_2 and t_3 . The ToD-TC in the VTU-R processes the time stamp values of events t_1 , t_2 , t_3 , and t_4 so as to synchronize in phase and time its local real-time clock (RTC-R) to the VTU-O's real-time clock (RTC-O).

NOTE 1 – The time period between consecutive reference samples is fixed and equal to the number of samples in a super-frame. This time period is therefore locked to the VTU's PMD sampling clock. With this relation, the time stamp values are recorded at regularly repeating intervals.

NOTE 2 – The VTU-R sends the values of events t_2 and t_3 to the VTU-O in response to a VTU-O command sending the corresponding t_1 and t_4 event values for phase/time synchronization.



NOTE – ϵ may be a positive or a negative time

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Figure 8-3 – Reference samples and corresponding time stamp events t_1 , t_2 , t_3 and t_4

The ToD-TC in the VTU-O and that in the VTU-R implement functionality with the objective of synchronizing the RTC-R to the RTC-O in frequency, phase and time. Two methods are defined to achieve this objective:

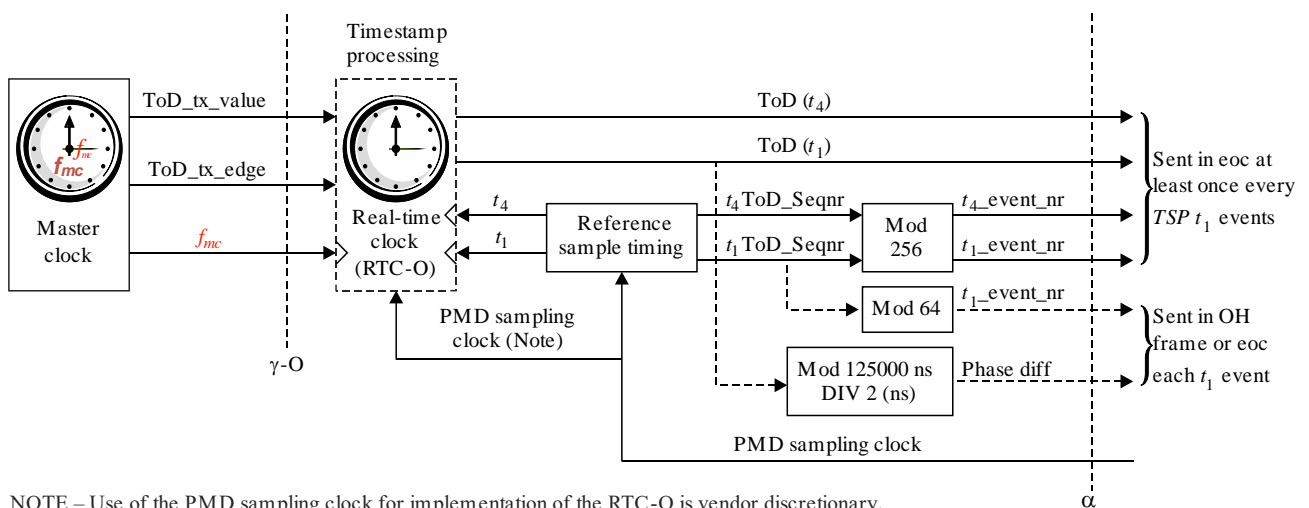
- 1) Frequency synchronization through locking the PMD sampling clock with the ToD frequency (f_{mc}): the VTU-R achieves frequency synchronization through loop timing and performs phase/time synchronization through the processing of time stamps at reference samples; or
- 2) Frequency synchronization using ToD phase difference values: the VTU-R achieves frequency synchronization through processing of ToD phase difference values (i.e., phase of t_1 event relative to ToD) and performs phase/time synchronization through the processing of time stamps (of events t_1 , t_2 , t_3 , and t_4) at the reference samples.

The frequency synchronization method adopted in the VTU-O is communicated to the VTU-R during initialization (see clause 12.3.5.2.1.2). For each of the above cases, the corresponding functional processing is described.

The block diagram in Figure 8-4 shows a functional model of the required processing in the VTU-O ToD-TC. The ToD-TC receives the time-of-day signals from the master clock and assigns time stamps to reference samples per the Real-time Clock (RTC-O), that is synchronous to the external master clock time base.

In the VTU-O, the ToD-TC implements a Real-time Clock (RTC-O) that is synchronized to the external master clock for the purpose of applying time stamps to the reference samples. The VDSL2 PMD identifies the moment that the reference samples cross the U-O interface; the Reference Sample Timing block generates pulses t_1 and t_4 , for reading the value of the RTC-O clock in recording of the respective time stamps for the downstream and upstream reference samples. The time stamp values, ToD(t_1) and ToD(t_4) together with the reference sample identification (event number) are sent to the VTU-R via the eoc.

In the VTU-R, frequency synchronization of the RTC-R clock to the RTC-O clock in the VTU-O may be performed using any of the two methods mentioned above; the frequency synchronization method is selected by the VTU-O during initialization (see clause 12.3.5.2.1.2). Shown in Figure 8-4 is the method of computing phase difference values for frequency synchronization of the Real-time Clock in the VTU-R (RTC-R) with the RTC-O. Phase difference values may be transported to the VTU-R via dedicated bytes in the OH Frame (see clause 9.5.2.2.1) or via the eoc (see clause 11.3.2.14); the transport method is selected by the VTU-R during initialization (see clause 12.3.5.2.2.1). The time stamp values for ToD phase synchronization (i.e., ToD(t_1) and ToD(t_4)) are transported to the VTU-R by dedicated eoc commands (see clause 11.2.3.15).



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Figure 8-4 – Functional reference model for ToD-TC in the VTU-O

During initialization, the VTU-O indicates to the VTU-R the configured ToD frequency synchronization method, namely via locking of the VDSL PMD sampling clock to the ToD frequency or via transport of phase difference values. If the VTU-O selects the locking of the PMD sampling clock to the ToD frequency, then the VTU-R achieves ToD frequency synchronization through normal loop timing recovery. If the VTU-O selects the mechanism of passing phase difference values to the VTU-R for ToD frequency synchronization, then the VTU-R selects the mechanism for which the VTU-O is to communicate the phase difference values: i.e., via dedicated fixed octets in the OH frame, or via phase difference messages communicated in the eoc. In either case, time synchronization is provided through processing of the time synchronization messages communicated to the VTU-R by the VTU-O.

In the VTU-R the ToD-TC processes the time stamp values placed on the downstream (event t_2) and upstream (event t_3) reference samples together with those values received from the VTU-O for events t_1 and t_4 to achieve phase/time synchronization of the RTC-R to the RTC-O. The ToD-TC then outputs a time-of-day value (ToD_sc_value) together with a corresponding timing edge marker (ToD_sc_edge) that is synchronous to the driving master clock frequency. The ToD_sc_value and ToD_sc_edge signals (and possibly a slave clock frequency f_{sc}) are transported across the γ -R interface to a device external to the VTU-R. The time stamp values placed on the downstream (event t_2) and upstream (event t_3) reference samples are sent back to the VTU-O (see clause 11.2.3.15). The VTU-O passes information related to these time stamps over the γ -O reference point. The nature and use of this information is for further study.

The time-of-day (phase) synchronization of the RTC-R to the RTC-O, is done in the ToD-TC in the VTU-R. The time stamp processing block reads the value of the local RTC-R as the downstream reference sample crosses the U-R reference point (event t_2) and upstream reference sample crosses the U-R reference point (event t_3), and assigns corresponding time stamp values ToD(t_2) and ToD(t_3). The computation of the offset value (τ) is computed from the reported time stamps using the following equation:

$$\tau = \frac{(ToD(t_2) - ToD(t_1)) - (ToD(t_4) - ToD(t_3))}{2}$$

NOTE 3 – The above computation of the offset value is based on the assumption that the downstream and upstream propagation delays between the U-C and U-R reference points are approximately identical. Any asymmetry in the propagation delay between the U-C and U-R reference points will result in an error in calculation of the offset value whose magnitude is approximately:

$$|error| = \left| \frac{(upstream_propagation_delay) - (downstream_propagation_delay)}{2} \right|$$

8.4.2 Interfaces

The γ_{m-O} and γ_{m-R} reference points define interfaces between the ToD source and the ToD-TC at the VTU-O and between the ToD-TC and the ToD receiver at the VTU-R, respectively, as shown in Figure 5-1. Both interfaces are functionally identical, and are defined in Table 8-6.

Table 8-6 – ToD-TC: γ interface signal summary

Flow	Signal	Description	Direction
Transmit signals (VTU-O)			
ToD	<i>Tx_ToD</i>	Transmit time-of-day signal	ToD source → ToD-TC
Receive signals (VTU-R)			
ToD	<i>Rx_ToD</i>	Receive time-of-day signal	ToD receiver ← ToD-TC

The α and β reference points define interfaces between the ToD-TC and PMS-TC at the VTU-O and VTU-R, respectively. Both interfaces are functional, and shall comply with the definition in clause 8.1.2 with the additional condition that ToD data is transmitted only in the direction from the VTU-O to the VTU-R. The parameters of ToD-TC are not subject to on-line reconfiguration.

8.4.3 Functionality

8.4.3.1 Frequency Synchronization by locking PMD sampling clock with ToD frequency

This clause defines a mechanism for frequency synchronization of the Real-time Clock in the VTU-R (RTC-R) with the Real-time Clock in the VTU-O (RTC-O) by locking the PMD sampling clock with the ToD frequency (f_{mc}). The VTU-R shall achieve frequency synchronization between RTC-R and RTC-O through loop timing.

8.4.3.2 Frequency Synchronization using ToD phase difference values

This clause defines a mechanism for frequency synchronization of the Real-time Clock in the VTU-R (RTC-R) with the Real-time Clock in VTU-O (RTC-O) by processing of the ToD phase difference values between the local super-frame clock (i.e., event t_1) and the ToD (i.e., RTC-O) clock.

The Real-time Clock represents the time-of-day value with a 6 octet seconds field followed by a 4 octet nanosecond field, where the nanosecond field resets to zero every 10^9 ns and the seconds field increments by one.

Figure 8-5 demonstrates the computation of the ToD phase difference value ($\Delta\phi$). The top row in the figure represents the counting of the nanoseconds in the RTC-O. The ToD nanoseconds counter counts the nanoseconds of the RTC-O modulo $125\ \mu\text{s}$ (shown by the 8 kHz waveform in the middle row of the figure). The third row in the figure represents the super-frame (SF) counter of the local clock that is synchronous with the VTU's PMD sampling clock; the rising edge of the SF local clock represents the moment that the downstream reference sample crosses the U-O reference point (i.e., the t_1 event). At the moment the downstream reference sample crosses the U-O reference point, the value of the ToD ns_counter modulo $125\ \mu\text{s}$ is recorded as the 'ToD Phase Difference Value' to be communicated to the VTU-R.

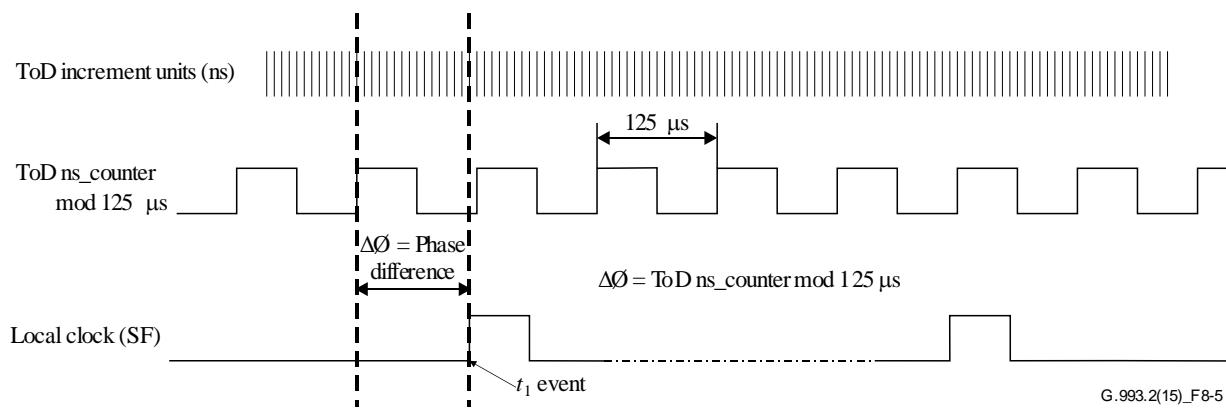


Figure 8-5 – ToD phase difference ($\Delta\phi$) computation

The ToD phase difference value ($\Delta\phi$) is calculated each t_1 event. The ToD phase difference value shall be represented by a 16-bit value, calculated as the ns_counter value of the RTC-O mod 125 000 ns divided by 2, where the resolution of the LSB is 2 ns. Each t_1 event shall be counted modulo 64 (i.e., represented by a 6-bit value). The phase difference value (16 bits) and corresponding t_1 event value (6 bits) shall be communicated to the VTU-R either via the OH Frame (see clause 9.5.2.2.1) or via the eoc (see clause 11.2.3.14). During initialization (see clause 12.3.5.2.2.1), the VTU-R shall select the use of either the OH Frame or eoc for communication of ToD phase difference value and corresponding t_1 event value.

8.4.3.3 Time synchronization of real-time clocks

Time-of-day (ToD) transport is facilitated by the ToD-TC. The VTU-O shall maintain a real-time clock at the optical network unit (ONU) (RTC-O) which is synchronized with the ToD signal. The VTU-R shall also maintain a real-time clock at the remote site (RTC-R) with an arbitrary initial time. The RTC-O shall run in a frequency which is an integer multiple of 8 kHz and is at least the PMD sampling frequency, with time adjustment to the master clock at each f_{mc} edge (see Figure 8-1). At the VTU-O, the ToD-TC receives the ToD signal to synchronize RTC-O, generates time stamps using RTC-O, and transports these time stamps to the VTU-R with EOC messages. At the VTU-R, the ToD-TC generates time stamps using RTC-R, extracts the time stamps contained in the eoc messages sent from the VTU-O, estimates the time offset between RTC-O and RTC-R using the time stamps, adjusts RTC-R using the estimated time offset, and controls the output ToD signal.

The time synchronization procedure is defined as follows. A downstream (or upstream) reference sample is defined as the first time-domain sample of specific symbols in the downstream (or upstream) direction during Showtime.

- 1) At the VTU-O, a time stamp is taken by the ToD-TC when the downstream reference sample, being transmitted to the VTU-R, arrives at the U-C reference point (event t_1). The time-of-day corresponding to event t_1 is denoted by $ToD(t_1)$;
- 2) At the VTU-R, a time stamp is taken by the ToD-TC when the same downstream reference sample arrives at the U-R reference point (event t_2). The time-of-day corresponding to event t_2 is denoted by $ToD(t_2)$;
- 3) At the VTU-R, a time stamp is taken by the ToD-TC when the upstream reference sample, being transmitted to the VTU-O, arrives at the U-R reference point (event t_3). The time-of-day corresponding to event t_3 is denoted by $ToD(t_3)$;
- 4) At the VTU-O, a time stamp is taken by the ToD-TC when the same upstream reference sample arrives at the U-O reference point (event t_4). The time-of-day corresponding to event t_4 is denoted by $ToD(t_4)$;

- 5) The time stamp values $ToD(t_1)$ and $ToD(t_4)$ are transmitted from the VTU-O to the VTU-R with eoc messages, the time stamp values $ToD(t_2)$ and $ToD(t_3)$ are transmitted from the VTU-R to the VTU-O with eoc messages (see clause 11.2.3.15).

The VTU-O shall maintain a counter of the transmitted downstream super-frames since the VTU-O entered Showtime. Each time the first symbol in a downstream super-frame (i.e., the symbol modulating downstream data frame 0 per Figure 10-2) is sent, the value of the downstream super-frame counter shall be increased by 1. The downstream reference sample shall be the first time-domain representation sample of the first symbol in a downstream super-frame period (i.e., the first sample after the cyclic prefix of the symbol modulating data frame 0 as defined in Figure 10-14 and Figure 10-2). The index of the downstream reference sample shall be the index of the downstream super-frame it belongs to. The index of the first downstream reference sample (i.e., first t_1 event index) sent in Showtime shall be 0.

The VTU-O shall maintain a counter of the received upstream super-frames since the VTU-R entered Showtime. Each time the first symbol in an upstream super-frame (i.e., the symbol modulating upstream data frame 0 per Figure 10-2) is sent, the value of the upstream super-frame counter shall be increased by 1. The upstream reference sample shall be the first time-domain sample of the first symbol in an upstream super-frame. The index of the upstream reference sample shall be the index of the upstream super-frame it belongs to. The index of the first upstream reference sample (i.e., first t_4 event index) sent in Showtime shall be 0.

The VTU-O initiates a time synchronization procedure. The increment of the t_1 event index between any two consecutive time synchronization procedures shall not exceed the value of the parameter time synchronization period (TSP), which is indicated by the VTU-R during initialization (see clause 12.3.5.2.1.5). The t_1 event index shall be a multiple of 16 super-frames.

After receiving both time stamp values $ToD(t_1)$ and $ToD(t_4)$, the VTU-R shall compute the time offset *Offset* between the Real-time Clocks RTC-O and RTC-R as:

$$Offset = (ToD(t_2) + ToD(t_3) - ToD(t_1) - ToD(t_4)) / 2$$

The RTC-R shall be adjusted with this estimated time offset *Offset* so that it is time synchronized with the RTC-O (i.e., the value of *Offset* for the next time synchronization procedure is expected to be 0).

NOTE – Instead of taking the time stamp $ToD(t_1)$ for event t_1 (i.e., when the reference sample arrives at the U-O reference point), it is easier to implement by taking a time stamp – when the same reference sample arrives at the output of the inverse discrete Fourier transform (IDFT) of the VTU-O (event t'_1). This time stamp is denoted by $ToD(t'_1)$. The time stamp $ToD(t_1)$ for event t_1 is obtained by adjusting the time stamp $ToD(t'_1)$ for event t'_1 with an estimate of $\Delta t_1 = ToD(t_1) - ToD(t'_1)$. The method of adjustment is vender discretionary. Instead of taking the time stamp $ToD(t_2)$ for event t_2 (i.e., when the reference sample arrives at the U-R reference point), it is easier to implement by taking a time stamp when the same reference sample arrives at the input of the DFT of the VTU-R (event t'_2). This time stamp is denoted by $ToD(t'_2)$. The time stamp $ToD(t_2)$ for event t_2 is obtained by adjusting the time stamp $ToD(t'_2)$ for event t'_2 with an estimate of $\Delta t_2 = ToD(t'_2) - ToD(t_2)$. The method of adjustment is vender discretionary. The time stamps t_3 and t_4 can be obtained in the same way.

9 Physical media specific transmission convergence (PMS-TC) sublayer

The PMS-TC sublayer resides between the α/β interface and δ interface of the VDSL2 transceiver reference model (see Figure 5-1). It provides transmission medium specific TC functions, such as scrambling, framing, forward error correction (FEC), and interleaving.

9.1 PMS-TC functional model

The PMS-TC functional models are presented in Figure 9-1 applicable to single latency mode and dual latency mode, and Figure 9-2 applicable to single latency with ROC mode. Up to two bearer channels of transmit user data originated by various TPS-TCs, management data originated by the MPS-TC, and NTR data are incoming via the α/β interface in a uniform format, as specified in clause 8.1.2. The incoming user data and the overhead data are multiplexed into one or two latency paths. Each bearer channel is carried over a single latency path (i.e., shall not be split across two latency paths). A Syncbyte is added to each latency path for OH frame alignment.

Three different modes are allowed:

- 1) Single latency mode: support of one latency path. The VTU shall support this mode. For this mode, latency path #0 shall be enabled.
- 2) Dual latency mode: support of two latency paths. The VTU may support this mode. For this mode, latency paths #0 and #1 shall be enabled.
- 3) Single latency with ROC mode: support of a single latency path for data with a second overhead-only latency path. The VTU may support this mode. For this mode, the data shall use latency path#1 and the ROC shall use latency path #0.

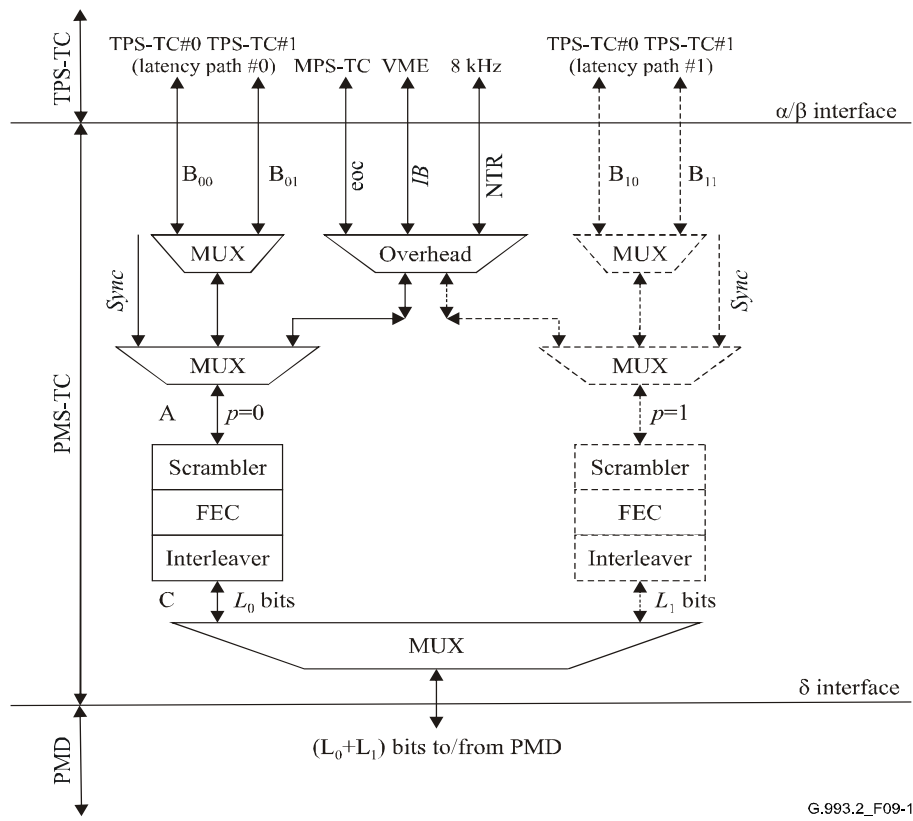
NOTE 1 – When transporting two or more applications with different latency and INP requirements and limited higher layer error resilience, a VTU should implement dual latency because, in general, under these conditions dual latency will provide improved performance and/or quality of service.

The multiplexed data in each latency path (including the overhead-only latency path, if present) is scrambled, encoded using Reed-Solomon forward error correction coding, and interleaved. The interleaved buffers of data of both latency paths are multiplexed into a bit stream to be submitted to the PMD sublayer via the δ interface.

All user data bytes incoming via the α/β interface are transmitted MSB first (see clause 8.1.2). All serial processing in the PMS-TC (e.g., scrambling, cyclic redundancy check (CRC) calculation) shall be performed LSB first, with the MSB incoming from the α/β interface considered as the LSB in the PMS-TC. As a result, the first bit of user data incoming from the α/β interface will be the first bit processed by the PMS-TC and the first bit sent towards the PMD sublayer (see clause 9.1.1).

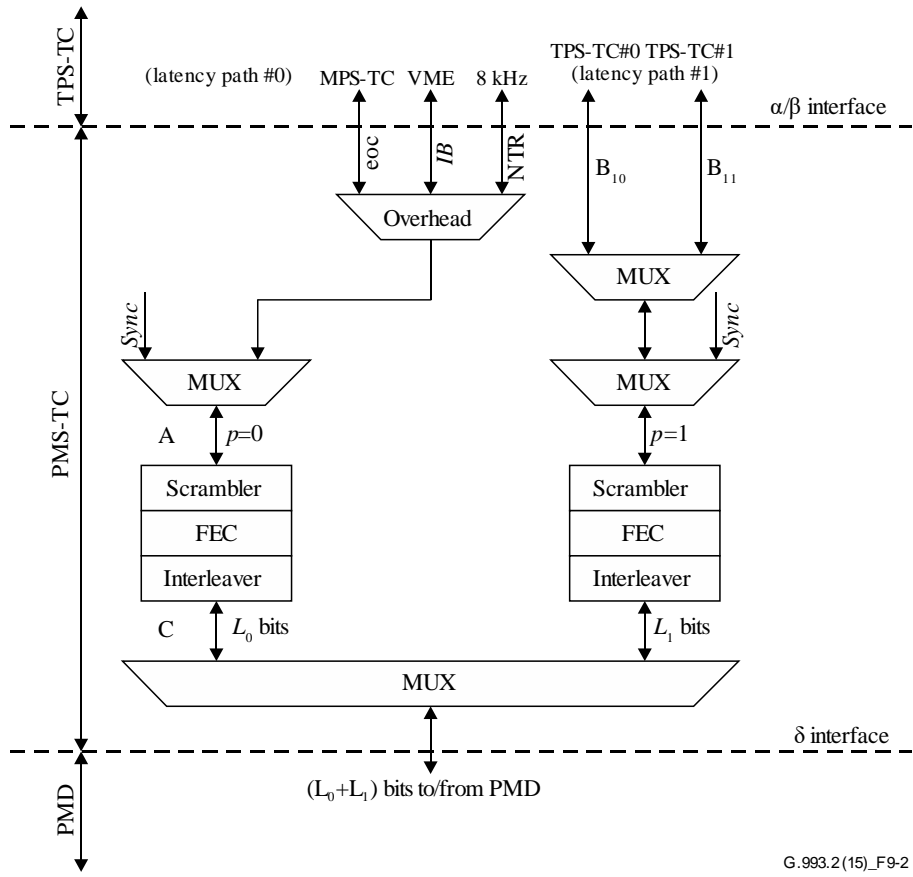
The management data bytes incoming via the α/β interface are transmitted MSB first (see clause 8.1.2). The LSB of the management data incoming from the α/β interface shall be considered as the LSB in the PMS-TC, and shall be the first bit processed by the PMS-TC and the first bit sent towards the PMD sublayer (see clause 9.1.1).

The indicator bits (IB) and NTR bits shall be sent as described in clause 9.5.2.2.



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Figure 9-1 – PMS-TC functional model applicable to single latency mode and dual latency mode



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Figure 9-2 – PMS-TC functional model applicable to single latency with ROC mode

NOTE 2 – The overhead information transmitted on the different latency paths (p_0, p_1) may be different depending on the type of OH frame used and the values of framing parameters, as specified in clause 9.5.2.

Reference points are defined within the block diagram for purposes of clarity only. The reference points are depicted in Figure 9-1 and listed in Table 9-1.

Table 9-1 – PMS-TC function internal reference points

Reference point	Definition
A: Mux data frame (MDF)	This reference point is the input of the scrambler of a single latency path. The signal at this reference point is the MDF, and is defined as the grouping of octets from different bearer channels within the same latency path, after the sync overhead data octets have been added.
C	This reference point is the output of a single latency path

9.1.1 δ interface

The δ_O and δ_R reference points at the VTU-O and VTU-R, respectively, reside between the PMS-TC and the PMD sublayers, as illustrated in Figure 5-2. Both interfaces are functional, are application independent, and are defined by the following signal flows:

- Data flow; and
- Synchronization flow.

The δ interface signals are summarized in Table 9-2.

Table 9-2 – δ interface signal summary

Signal	Description	Direction
<i>Data signals</i>		
Tx	Transmit data stream	PMS-TC → PMD
Rx	Receive data stream	PMS-TC ← PMD
<i>Synchronization signals</i>		
Clkp_t	Transmit bit timing	PMS-TC ← PMD
Clkp_r	Receive bit timing	PMS-TC ← PMD
<i>Control signals</i>		
Syncflag	Reconfiguration flag	PMS-TC ← PMD

9.1.1.1 Data flow

The data flow shall consist of two contra-directional streams of data frames:

- Transmit data frames (Tx); and
- Receive data frames (Rx).

The number of bits in each data frame and the number of incoming data frames per second are dependent on the transmission parameters of the PMD sublayer selected during initialization. The bits of the PMS-TC data frame (Figure 9-6) shall be transmitted towards the PMD in sequential order, starting from the first bit of the data frame.

9.1.1.2 Synchronization flow

The synchronization flow shall consist of transmit and receive bit-synchronization signals (Clkp_t, Clkp_r), both originating from the PMD.

9.1.1.3 Control flow

This flow provides a time marker (Syncflag, as specified in Table 9-2) for changes of the PMS-TC parameters during on-line reconfiguration (OLR). The Syncflag is asserted by the PMD and indicates a specific time when the PMS-TC shall start operating with modified parameters. The list of the relevant PMS-TC parameters is for further study.

9.2 Scrambler

A scrambler shall be used to reduce the likelihood that a long sequence of ZEROS will be transmitted over the channel. The scrambler shall be self-synchronizing such that descrambling can occur without requiring a particular alignment with the scrambled sequence. The scrambling algorithm shall be as represented by the equation below; the output bit of data $x(n)$ at the sample time n shall be:

$$x(n) = m(n) + x(n - 18) + x(n - 23)$$

where $m(n)$ is the input bit of data at the sample time n . All arithmetic shall be modulo 2.

NOTE – As long as the scrambler is initialized with values other than zero, an "all zeros" sequence for $m(n)$ will result in a pseudo-random sequence of length $2^{23} - 1$.

Incoming bytes shall be input to the scrambler LSB first. All data bytes and OH bytes of every multiplex (mux) data frame (see clause 9.5.1) shall be scrambled.

9.3 Forward error correction

A standard byte-oriented Reed-Solomon code shall be used for forward error correction (FEC). FEC provides protection against random and burst errors. A Reed-Solomon code word shall contain $N_{FEC} = K + R$ bytes, comprised of R check bytes $c_0, c_1, \dots, c_{R-2}, c_{R-1}$ appended to the K data bytes $m_0, m_1, \dots, m_{K-2}, m_{K-1}$. The check bytes shall be computed from the data bytes using the equation:

$$C(D) = M(D)D^R \text{ mod } G(D)$$

where:

$$M(D) = m_0D^{K-1} \oplus m_1D^{K-2} \oplus \dots \oplus m_{K-2}D \oplus m_{K-1} \text{ is the data polynomial}$$

$$C(D) = c_0D^{R-1} \oplus c_1D^{R-2} \oplus \dots \oplus c_{R-2}D \oplus c_{R-1} \text{ is the check polynomial}$$

$$G(D) = \prod (D \oplus \alpha^i) \text{ is the generator polynomial of the Reed-Solomon code, where the index of the product runs from } i = 0 \text{ to } R-1$$

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

Both K and R shall be programmable parameters. Valid values for the number of check bytes R in the codeword are 0, 2, 4, 6, 8, ..., 16. Valid values for the number of bytes in the codeword N_{FEC} (codeword size) are all integers from 32 to 255, inclusive. A VTU shall support all valid values of R and N_{FEC} .

The FEC for the ROC shall only use $R=16$ and N_{FEC} values from 32 to 66 with $q = 1$.

9.4 Interleaving

Interleaving shall be provided in all supported latency paths to protect the data against bursts of errors by spreading the errors over a number of Reed-Solomon codewords. The convolutional interleaver adopted for VDSL2 shall follow the rule:

- I is the interleaver block size in bytes. Each of the I bytes in an interleaver block $B_0B_1 \dots B_{I-1}$ shall be delayed by the interleaver by an amount that varies linearly with the byte index. More precisely byte B_j (with index j) shall be delayed by $\Delta[j] = (D - 1) \times j$ bytes, where D is the interleaver depth in bytes, and D and I are co-prime (have no common divisor except for 1).

For any interleaver input of size $D \times I$ bytes, the relationship between the index of each input byte (n_{in}) and the index of each output byte (n_{out}) is given by $n_{out} = (n_{in} + \Delta[j])$, where $j = n_{in} \bmod I$ and $\Delta[j] = (D - 1) \times j$.

The total delay of the interleaver/de-interleaver combination is $(D - 1) \times (I - 1)$ bytes.

The RS codeword length N_{FEC} shall be an integer multiple of I , i.e., $N_{FEC} = q \times I$, where q is an integer between 1 and 8 inclusive. All values of q shall be supported. Codewords shall be mapped to interleaver blocks such that the first I bytes of the codeword map to the I bytes $B_0B_1 \dots B_{I-1}$ of the first interleaver block.

The interleaver depth shall be set to meet the requirements for error-burst protection and latency. The VTU shall support all integer values of D from 1 to D_{max} , as specified for the particular profile (see Table 6-1). At any data rate, the minimum latency occurs when the interleaver is turned off. If both latency paths are supported, interleaving shall be supported on both latency paths. The same valid and mandatory configuration parameters shall apply to all supported latency paths.

The interleaving for the ROC shall only use D values up to 20.

A summary of interleaver parameters is given in Table 9-3.

Table 9-3 – Summary of interleaver parameters

Parameter(s)	Value for:	Value for:
	<ul style="list-style-type: none"> • single latency mode (latency path #0) • dual latency mode (latency paths #0 and #1) • single latency with ROC mode (latency path #1) 	single latency with ROC mode (latency path #0)
D and I	Co-prime	Co-prime
q	Integer between 1 and 8, inclusive	1
N_{FEC}	Integer between 32 and 255 inclusive, $N_{FEC} = q \times I$	Integer between 32 and 66 inclusive, $N_{FEC} = q \times I$
Total delay of the interleaver/de-interleaver combination	$(D-1) \times (I-1)$ bytes	$(D-1) \times (I-1)$ bytes

9.4.1 Dynamic change of interleaver depth

A method to dynamically change the interleaver depth during transmission is defined for VDSL2. This method is optional. Support shall be indicated during initialization in O-MSG 1 and R-MSG 2.

NOTE – Although this clause defines the procedure for dynamically changing the interleaver depth during transmission, the control command for initiating this procedure is not defined in this version of in this Recommendation. The calling procedure for dynamic change of interleaver depth will be defined in a future revision to this Recommendation.

A change of the interleaver depth shall only be initiated at the first byte of an RS codeword, where k is the sequence number of this byte at the input of the interleaver.

For an increase of the interleaver depth from D_{old} to D_{new} with $D_{old} < D_{new}$ the interleaver output is defined by:

$$y(n + \Delta_{old}[j]) = x(n); \text{ for } n + \Delta_{old}(j) < k, \text{ where } \Delta_{old}[j] = (D_{old} - 1) \times j$$

$$y(n + \Delta_{new}[j]) = x(n); \text{ for } n + \Delta_{old}(j) \geq k, \text{ where } \Delta_{new}[j] = (D_{new} - 1) \times j$$

For a decrease of the interleaver depth from D_{old} to D_{new} with $D_{old} > D_{new}$ the interleaver output is defined by:

$$y(n + \Delta_{old}[j]) = x(n); \text{ for } n + \Delta_{new}(j) + \delta < k$$

$$y(n + \Delta_{new}[j] + \delta) = x(n); \text{ for } n + \Delta_{new}(j) + \delta \geq k$$

where δ is the length of the transition and is given by:

$$\delta = \lceil (D_{old} - D_{new}) \cdot (I - 1) / I \rceil \cdot I$$

δ is not a persistent delay; it can be compensated by interrupting the interleaver input by the time represented by δ bytes.

The values of bytes that are not defined by the rules above are unspecified.

If a change of the interleaver depth is to be accompanied by a corresponding change of the data rate in the particular latency path (e.g., SRA – see clause 13.1), the change of D shall be coordinated with the corresponding change of parameter L_p (see Table 9-8) as described in clause 13.3.

Dynamic change of interleaver depth shall not be used for the ROC.

9.5 Framing

The framing format of a single latency path is summarized in Figures 9-2 and 9-3. Both latency paths have the same framing format, but their framing parameters (specified in Table 9-8) are independent. Index p indicates the latency path and may take values 0 and 1.

9.5.1 Mux data frame (MDF) and RS codewords

The overhead channel and the first and second bearer channels are multiplexed into the mux data frames (MDF). The format of the MDF is presented in Figure 9-3. To form the MDF, the PMS-TC pulls out sequentially O_{pi} octets from the overhead (OH) buffer and then B_{p0} and B_{p1} octets from the first and the second bearer channel buffers, respectively.

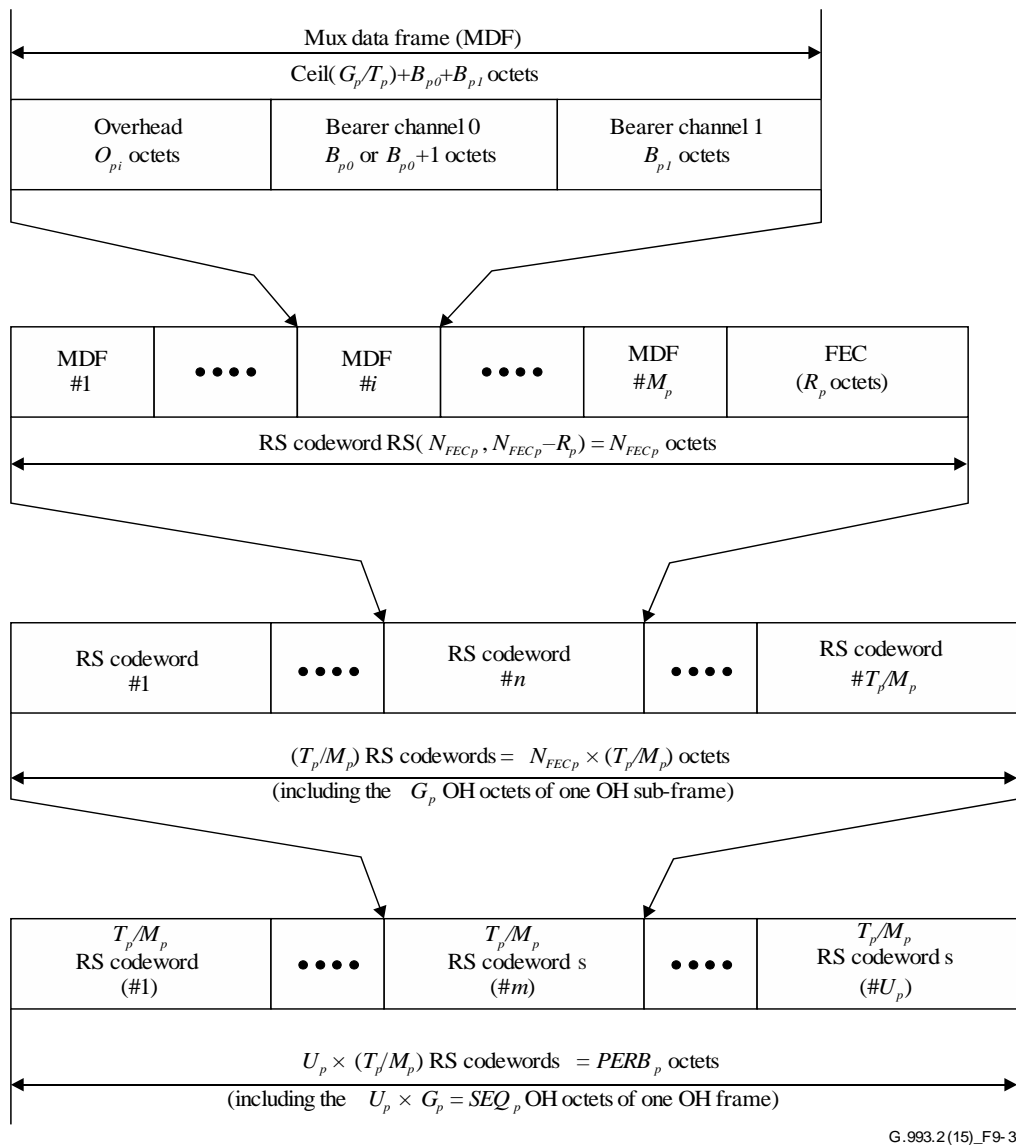


Figure 9-3 – MDF and RS codeword structure

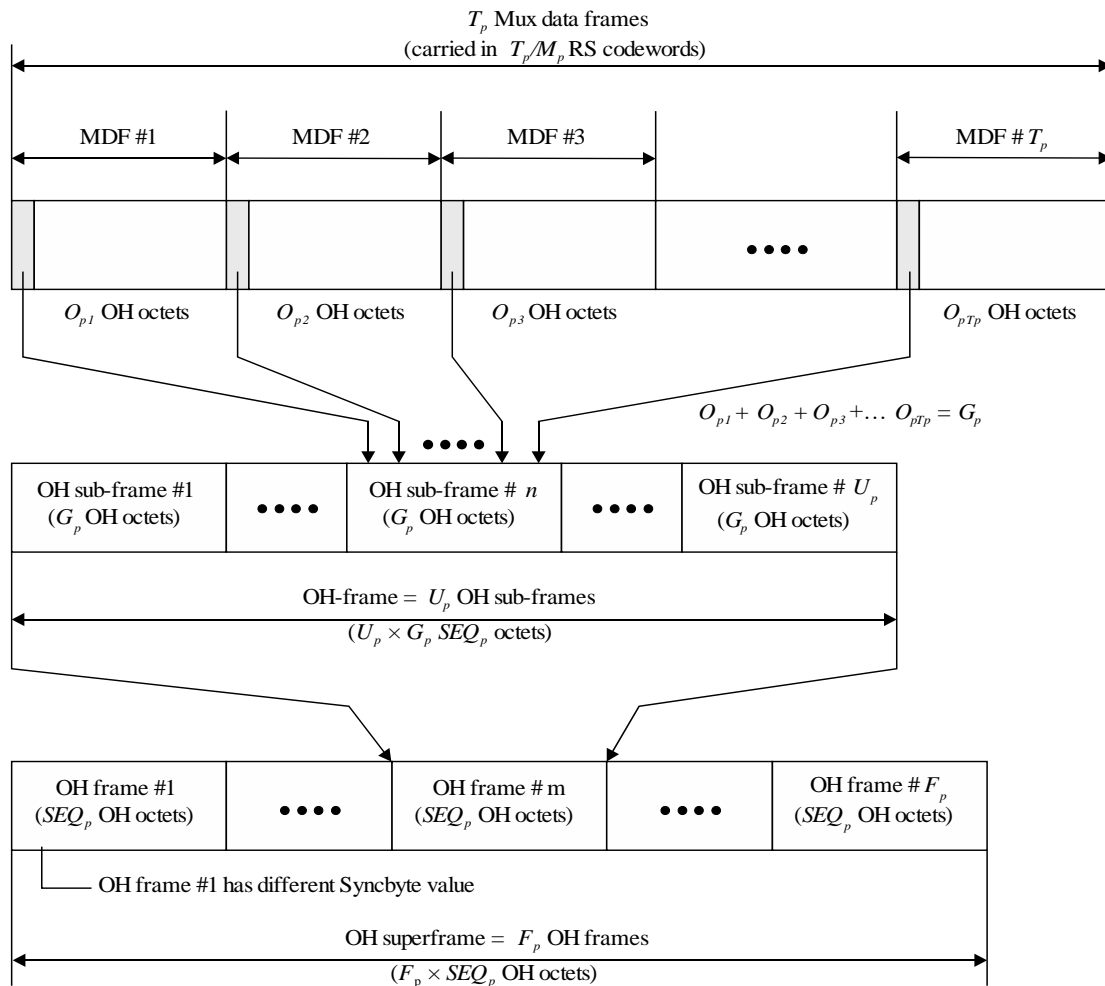
MDFs are mapped to an RS codeword as presented in Figure 9-3. Each RS codeword includes the same integer number, M_p , of MDFs and the same number of redundancy octets R_p ; the first octet of each codeword is the first octet of the first MDF of this codeword. The total size of the RS codeword is N_{FECp} bytes. All octets in the bearer channel fields of the MDF shall be mapped to transmit LSB first. The bits of the overhead octets shall be mapped as specified in clause 9.5.2.2.

The number O_{pi} of overhead octets per MDF shall be as specified in clause 9.5.2.1. Because of the way overhead octets are assigned to MDFs, the number of overhead octets in an MDF can vary by up to one octet. Those MDFs with one fewer overhead octets shall instead carry one additional octet from bearer channel #0 so that the total number of octets in all MDFs is the same.

NOTE – The ratio of the bit rates of two bearer channels may not exactly fit the real ratio of the transmitted bit rates. The setting of the bit rate ratio has a finer granularity for larger MDFs.

9.5.2 Overhead (OH) frame, subframe and superframe

The OH frame carries the OH data and framing synchronization. The OH frame consists of an integer number U_p of OH subframes, as shown in Figure 9-4. All OH subframes have the same format. The total length of the OH frame (the OH frame period) is $PERB_p$ octets. The OH frame parameters U_p and $PERB_p$ are specified in Table 9-8.



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Figure 9-4 – Overhead subframe, frame, and superframe structure

An OH superframe is composed of F_p OH frames.

9.5.2.1 OH subframe format

The OH subframe spans T_p MDFs and includes G_p OH octets distributed among these MDFs. The number of OH octets, O_{pi} , in MDF # i of the OH subframe shall be:

$$O_{pi} = \begin{cases} \left\lfloor \frac{G_p}{T_p} \right\rfloor & \text{for } i \leq G_p - T_p \times \left\lfloor \frac{G_p}{T_p} \right\rfloor, \\ \left\lceil \frac{G_p}{T_p} \right\rceil & \text{otherwise} \end{cases}, \quad i = 1, 2, \dots, T_p; 0 \leq O_{pi} \leq 8.$$

Settings for G_p and T_p shall comply with the following rules:

Rule 1: $M_p/S_p \leq 64$;

$$\text{Rule 2: } \left\lfloor \frac{G_p}{T_p} \right\rfloor \times \left\lceil \frac{M_p}{S_p} \right\rceil + \left\lceil \frac{M_p}{S_p} \right\rceil \times (G_p \bmod T_p) + \min \left(\left\lceil \frac{M_p}{S_p} \right\rceil \bmod T_p, G_p \bmod T_p \right) \leq 8$$

The valid range of the number of OH octets in MDF O_{pi} is from 0 to 8; the valid range of the number of OH octets in the OH subframe G_p is from 1 to 32.

The OH subframe shall span an integer number of RS codewords: $T_p = k \times M_p$, where k is an integer.

NOTE 1 – The average number of OH octets per MDF is equal to G_p/T_p and can be a non-integer.

NOTE 2 – Since the OH frame spans an integer number of RS codewords and an integer number of MDFs, the boundaries of the OH frame, the RS codeword, and the MDF are aligned.

9.5.2.2 Mapping of the OH data

The mapping of the OH data to the OH frame shall be as presented in Table 9-4. Two types of OH frames shall be supported:

- Type 1 – Full frame;
- Type 2 – Auxiliary frame.

For single latency, the latency path shall use OH frame Type 1. For Dual Latency, one latency path shall use OH frame Type 1 and the other shall use OH frame Type 2. For single latency with ROC, the ROC (in latency path 0) shall use OH frame Type 1 and latency path 1 shall use OH frame Type 2. The latency path selected for OH frames of Type 1 shall be indicated during initialization by the parameter value in the MSGLP field (see clauses 12.3.5.2.1.3 and 12.3.5.2.2.3). When the ROC is used, MSGLP (see Tables 12-56 and 12-60) shall have the value 0.

Table 9-4 – Contents of Type 1 and Type 2 OH frames

OH frame Type 1		
Octet number	OH field	Description
1	CRC _p	CRC (clause 9.5.2.3)
2	Syncbyte	Syncbyte = AC ₁₆ when the OH frame indicates the start of an OH superframe, otherwise Syncbyte = 3C ₁₆
3	IB-1	PMD-related primitives (Note 1, Table 9-5)
4	IB-2	PMS-TC-related primitives (Note 1, Table 9-5)
5	IB-3	TPS-TC-related and system-related primitives (Note 1, Table 9-5)
6	NTR	Network timing reference (Note 2, clause 8.3)
>6	MSG	Message overhead (Note 3, clause 11.2)
OH frame Type 2		
1	CRC _p	CRC (clause 9.5.2.3)
2	Syncbyte	Syncbyte = AC ₁₆ when the OH frame indicates the start of an OH superframe, otherwise Syncbyte = 3C ₁₆
3	Reserved for allocation by ITU-T	The value for the reserved field shall be FF ₁₆
>3	Reserved for allocation by ITU-T	The value for the reserved field shall be FF ₁₆ (Note 4)

Table 9-4 – Contents of Type 1 and Type 2 OH frames

OH frame Type 1		
Octet number	OH field	Description
NOTE 1 – The IB (indicator bits) inform the far end of anomalies and defects; valid in both directions for OH frames of Type 1. IB that are not used shall be set to ONE.		
NOTE 2 – The NTR provides an 8 kHz timing reference for the CPE; valid only in the downstream direction for OH frames of Type 1. If the VTU-O indicates that it will not transport NTR, the NTR field shall also be set to FF ₁₆ . In the upstream direction, the NTR field shall always be set to FF ₁₆ .		
NOTE 3 – The MSG field transports eoc messages; valid in both directions only for OH frames of Type 1.		
NOTE 4 – If the "flexible OH frame Type 2" is not supported (see clauses 12.3.5.2.1.1 (O-MSG1) and clause 12.3.5.2.2.1 (R-MSG2)), the number of additional reserved octets shall be equal to 5, i.e., the OH frame Type 2 shall contain 8 octets. If the "flexible OH frame Type 2" is supported, the number of additional octets is determined by the selected framing parameters.		

Mapping of the CRC, IB and NTR bits to the OH frame fields shall be as specified in Table 9-5; the LSB shall be transmitted first. Mapping of the MSG bytes into the OH frame shall be LSB first, as specified in clauses 8.2.3 and 9.1.

Table 9-5 – OH bit mapping

OH field	D7 (MSB)	D6	D5	D4	D3	D2	D1	D0 (LSB)	Defined in
CRC	<i>crc₇</i>	<i>crc₆</i>	<i>crc₅</i>	<i>crc₄</i>	<i>crc₃</i>	<i>crc₂</i>	<i>crc₁</i>	<i>crc₀</i>	9.5.2.3
IB-1	<i>los</i>	<i>rdi</i>	<i>lpr</i>	1	1	1	1	1	11.2.4, 11.3
IB-2	1	1	1	1	1	1	1	1	
IB-3	TIB#0-0	TIB#0-1	TIB#0-2	TIB#0-3	TIB#1-0	TIB#1-1	TIB#1-2	TIB#1-3	11.2.4, Annex L
NTR	<i>ntr₇</i>	<i>ntr₆</i>	<i>ntr₅</i>	<i>ntr₄</i>	<i>ntr₃</i>	<i>ntr₂</i>	<i>ntr₁</i>	<i>ntr₀</i>	8.3

9.5.2.2.1 Communication of ToD Frequency Synchronization Data via OH frame Type 1

Table 9-6 shows the modified OH frame Type1 structure for passing the ToD frequency synchronization data (i.e., ToD phase difference and corresponding t_1 event number) from the VTU-O to the VTU-R. Octet number 7, the ToD_FSsync octet, is inserted after the NTR octet prior to the MSG field. The ToD frequency synchronization data is sent in a ToD_FSsync Frame that contains three octets: one octet contains the 6 bits of the t_1 event number, and two octets identifying the 16-bit ToD phase difference value. One octet of the ToD_FSsync Frame is transmitted in each OH frame, so the ToD_FSsync Frame spans three OH frame periods (PER_p). Table 9-7 defines the frame format structure of the ToD_FSsync Frame. Special values for the Syncbyte are used to identify the beginning of the ToD_FSsync Frame.

The VTU-O shall insert the ToD frequency synchronization data in the OH frame once per super-frame for each t_1 event. The value of $PER_p \leq 20$ ms. Therefore, the ToD_FSsync frame spans less than a super-frame period, and occasionally a ToD phase difference and corresponding t_1 event number may need to be transmitted twice.

The ToD Frequency Synchronization data should be sent in the first available OH frame immediately following the t_1 event.

The value of the capacity of the MSG channel is reduced by one octet, so the message overhead data rate for the updated OH frame Type 1 is $msg_p = OR_p \times (SEQ_p - 7) / SEQ_p$ and the upper lower msg_p

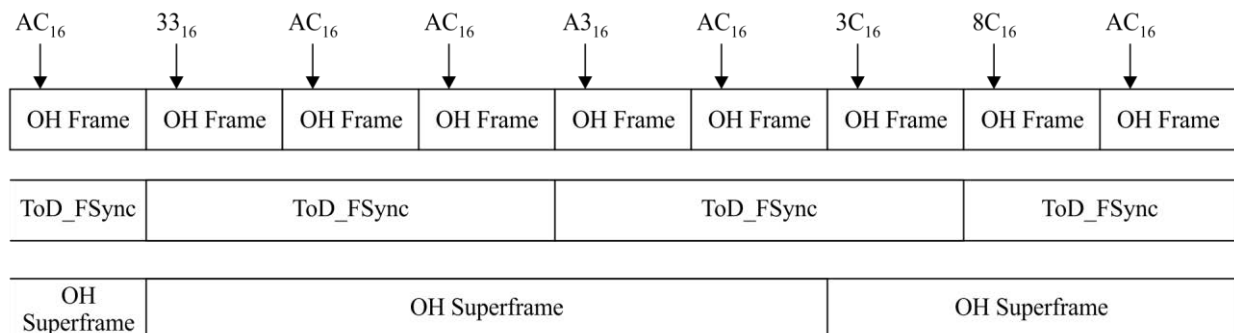
rates are scaled accordingly (see the *msg_p* entry in Table 9-8). The above frame structure shall be used if and only if during initialization the time synchronization is enabled and the OH frame is selected for the transport of the ToD phase difference values.

Table 9-6 – Modified OH frame Type 1 with ToD frequency synchronization frame extension

OH frame Type 1		
Octet number	OH field	Description
1	CRC _p	CRC (clause 9.5.2.3)
2	Syncbyte	Values for the Syncbyte are defined in Figure 9-5
3	IB-1	PMD-related primitives (Note 1, Table 9-4)
4	IB-2	PMS-TC-related primitives (Note 1, Table 9-4)
5	IB-3	TPS-TC-related and system-related primitives (Note 1, Table 9-4)
6	NTR	Network timing reference (Note 2, clause 8.3)
7	ToD_FSync	One Byte of ToD FSync Frame (Table 9-7)
> 7	MSG	Message overhead (Note 3, clause 11.2)

Table 9-7 – ToD_FSync frame structure

Octet number	OH field	Description
1	[0 0 c ₅ c ₄ c ₃ c ₂ c ₁ c ₀]	<i>t</i> ₁ event number
2	[b ₇ ... b ₂ b ₁ b ₀]	Lower byte of the ToD phase difference value
3	[b ₁₅ ... b ₁₀ b ₉ b ₈]	Higher byte of the ToD phase difference



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Key
AC₁₆ = OH frame start
3C₁₆ = Syncbyte = OH Superframe start
A3₁₆ = ToD_FSync start
33₁₆ = Common ToD_FSync and OH Superframe start

Figure 9-5 – Definition of OH sync byte values

9.5.2.3 Cyclic redundancy check (CRC)

A one-byte CRC shall be computed for each OH frame period of each latency path separately. For a *t*-bit data message transmitted during the OH frame period, the CRC shall be computed using the following equation:

$$crc(D) = M(D) \times D^8 \text{ modulo } G(D)$$

where:

$$\begin{aligned}M(D) &= m_0D^{t-1} + m_1D^{t-2} + \dots + m_{t-2}D + m_{t-1} \text{ is the data message polynomial,} \\G(D) &= D^8 + D^4 + D^3 + D^2 + 1 \text{ is the generating polynomial,} \\crc(D) &= crc_0D^7 + crc_1D^6 + \dots + crc_6D + crc_7 \text{ is the CRC polynomial, and} \\D &\text{ is the delay operator.}\end{aligned}$$

That is, $crc(D)$ shall be the remainder when $M(D) \times D^8$ is divided by $G(D)$. Each octet of the data message shall be input into the $crc(D)$ equation LSB first.

The values of crc_0 to crc_7 are the CRC bits to be carried in the next OH frame as specified in clause 9.5.2.2 so that the LSB (crc_0) is transmitted first. The CRC bits of the first OH frame (at the entrance into showtime) shall be set to ZERO.

The CRC shall be computed prior to scrambling for each subsequent period of time equal to the duration of the OH frame in bytes ($PERB_p$). The data message covered by the CRC shall include all bits of all MDFs transmitted during the period of the OH frame, except the CRC byte. The first CRC shall be computed over the data message that includes the first OH frame period (after the entrance into showtime); the second CRC shall be computed over the data message that includes the second OH frame period; and so on.

9.5.2.4 OH superframe

The OH superframe contains F_p OH frames and is intended to provide an additional timing reference. The value of F_p shall be selected so that the duration of the OH superframe is significantly longer than the time required to exchange management information between the VTU-O and the VTU-R. The first octet of the OH superframe coincides with the first octet of the OH frame and shall be marked by Syncbyte = AC₁₆. The valid range of F_p is from 1 to 255.

9.5.3 Multiplexing of data from two latency paths

9.5.3.1 Robust overhead channel (ROC)

As defined in clause 9.5.2.2, all overhead traffic is mapped into one of the latency paths. Optionally, the VTUs may negotiate a robust overhead channel (ROC) (see clause 9.1). The ROC is effectively a latency path that carries only overhead data. When the ROC is enabled (single latency with ROC mode), all overhead data (see clause 11.2.3.3) shall be sent through latency path #0. In this mode, latency path #0 is also referred to as the ROC.

9.5.3.2 Multiplexing

The assigned number of bits, L_0 and L_1 , from the RS codewords of latency paths #0 and #1, respectively, shall be mapped to the data frame as shown in Figure 9-6. The bits shall be extracted from the octets of the RS codewords in sequential order, LSB first. The first bit of each extracted group of L_0 bits shall be the first bit of the data frame. When the VTU operates in single latency with ROC mode (see clause 9.1), L_0 shall be an integer number of bytes consisting of overhead data only.

When single latency with ROC mode is enabled, the L_0 bits shall not share the same subcarriers with L_1 bits.

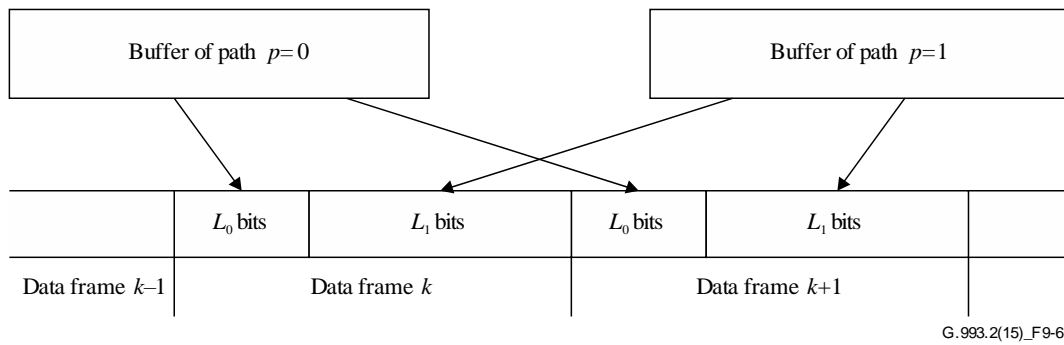


Figure 9-6 – Multiplexing of two latency paths into data frames carried by DMT symbols

9.5.4 Framing parameters

Framing parameters for latency path p are specified in Table 9-8. Two groups of parameters are specified:

- Primary framing parameters; and
- Derived framing parameters.

Primary framing parameters are those communicated to the other VTU during initialization for frame setup (see clause 12.3.5). Derived framing parameters are computed by the VTU using the primary framing parameters to establish the complete frame setting and parameters intended for verification of the data channel and overhead channel bit rates and provide other important characteristics of the PMS-TC when specific framing parameters are set.

Table 9-8 – Framing parameters for latency path p

Parameter	Definition
Primary framing parameters	
B_{pn}	The number of octets from bearer channel $\#n$ per MDF. The range of values is from 0 to 254. When G_p/T_p is not an integer, the number of octets from the bearer channel $\#0$ varies between B_{p0} and $B_{p0} + 1$.
R_p	The number of redundancy octets in the RS codeword.
M_p	The number of MDFs in an RS codeword. Only values of 1, 2, 4, 8 and 16 shall be supported.
T_p	The number of MDFs in an OH subframe; $T_p = k \times M_p$, where k is an integer. The value of T_p shall not exceed 64.
G_p	The total number of overhead octets in an OH subframe; $1 \leq G_p \leq 32$.
F_p	Number of OH frames in the OH superframe. $1 \leq F_p \leq 255$.
L_p	The number of bits from latency path p transmitted in each data symbol.
Derived framing parameters	
N_{FECp}	The RS codeword size: $N_{FECp} = M_p \times \left\lceil \left(\frac{G_p}{T_p} \right) + B_{p0} + B_{p1} \right\rceil + R_p \text{ bytes}$

Table 9-8 – Framing parameters for latency path p

Parameter	Definition
O_{pi}	<ul style="list-style-type: none"> The number of overhead octets in the i^{th} MDF of the OH subframe: $O_{pi} = \begin{cases} \left\lceil \frac{G_p}{T_p} \right\rceil & \text{for } i \leq G_p - T_p \times \left\lfloor \frac{G_p}{T_p} \right\rfloor, i = 1, 2, \dots, T_p; 0 \leq O_{pi} \leq 8. \\ \left\lfloor \frac{G_p}{T_p} \right\rfloor & \text{otherwise} \end{cases}$
$PERB_p$	<p>The number of bytes in the overhead frame:</p> $PERB_p = \frac{T_p \times N_{FECp}}{M_p} \times \left\lfloor \frac{\hat{Q} \times M_p}{T_p \times N_{FECp}} \right\rfloor \text{ bytes}$ <p>where:</p> $\hat{Q} = \begin{cases} Q & \text{if } TDR_p \geq TDR_0 \\ Q \cdot \frac{TDR_p}{TDR_0} & \text{if } TDR_p < TDR_0 \end{cases}$ <p>and where:</p> <ul style="list-style-type: none"> TDR_p is the total data rate of latency path p in kbit/s, $Q = 17\,000$ bytes, $TDR_0 = 7\,880$ kbit/s.
TDR_p	<p>The total data rate of latency path p (at reference point C):</p> $TDR_p = L_p \times f_s \text{ kbit/s,}$ <p>where f_s is the data symbol rate in ksymbols/s (see clause 10.4.4).</p>
S_p	<p>The number of data symbols over which the RS codeword spans,</p> $S_p = \frac{8 \times N_{FECp}}{L_p}$ <p>The value of S_p may be a non-integer, and shall not exceed 64.</p>
NDR_{pn}	<p>The net data rate for bearer channel #0:</p> $NDR_{p0} = \left[B_{p0} + \text{ceiling} \left(\frac{G_p}{T_p} \right) - \frac{G_p}{T_p} \right] \times \frac{8 \times M_p \times f_s}{S_p} \text{ kbit/s.}$ <p>The net data rate for bearer channel #1:</p> $NDR_{p1} = B_{p1} \times \frac{8 \times M_p \times f_s}{S_p} \text{ kbit/s.}$ <p>The settings of framing parameters shall provide $net_min_n < NDR_{pn} < net_max_n$ for all defined bearer channels over relevant latency paths.</p>
NDR_p	<p>The net data rate for latency path p:</p> $NDR_p = L_p \times f_s \times \frac{K_p}{N_{FECp}} - OR_p = \left(K_p - \frac{G_p \times M_p}{T_p} \right) \times \frac{8 \times f_s}{S_p} \text{ kbit/s.}$ <p>where $K_p = N_{FECp} - R_p$.</p>

Table 9-8 – Framing parameters for latency path p

Parameter	Definition
U_p	The number of OH subframes in the OH frame: $U_p = \frac{PERB_p}{N_{FECp}} \times \frac{M_p}{T_p}$
SEQ_p	The number of overhead bytes in the OH frame: $SEQ_p = U_p \times G_p \text{ bytes.}$
OR_p	The overhead data rate for latency path p : $OR_p = \frac{G_p \times M_p}{S_p \times T_p} \times 8 \times f_s \text{ kbit/s.}$
msg_p	The message overhead data rate (for OH frame Type 1 only, excluding the ToD_FSync octet – see Table 9-6): $msg_p = OR_p \times \frac{SEQ_p - 6}{SEQ_p} \text{ kbit/s.}$ <p>The settings of framing parameters shall provide $msg_{min} < msg_p < msg_{max}$. The settings for msg_{min} and msg_{max} shall comply with the following conditions: $16 \text{ kbit/s} \leq msg_{min} \leq 236 \text{ kbit/s}$; $msg_{max} = 256 \text{ kbit/s}$. The message overhead data rate (for OH frame Type 1 including the ToD_FSync octet – see Table 9-6): $msg_p = OR_p \times (SEQ_p - 7) / SEQ_p \text{ kbit/s.}$ </p>
PER_p	The duration of the overhead frame in ms (Note): $PER_p = \frac{T_p \times S_p \times U_p}{f_s \times M_p} = \frac{8 \times PERB_p}{L_p \times f_s} \text{ ms.}$
<p>NOTE – In clauses 7.2.1.1.3 and 7.2.1.2.3 of [ITU-T G.997.1], a one-second counter is used to declare a near-end severely errored second (SES). The one-second counter shall be incremented by the $\Delta CRCsec_p$ (the one-second normalized CRC anomaly counter increment) for each occurrence of a $crc-p$ anomaly. A $\Delta CRCsec_p$ value is defined for each downstream and upstream latency path separately, as a real value in the 0.125 to 8 range, as:</p> $\Delta CRCsec_p = \begin{cases} 1 & \text{if } 15 \leq PER_p \leq 20 \\ \frac{PER_p}{15} & \text{if } PER_p < 15 \end{cases}$	

9.5.5 Parameter 1/S

Parameter 1/S defines the total number of Reed-Solomon codewords decoded within a single data symbol. It is equal to:

$$1/S = \sum_p \text{ceiling} \left(\frac{1}{S_p} \right)$$

where S_p is the number of data symbols over which the RS codeword of latency path p spans, and the sum is over all enabled latency paths. The value of S_p may be non-integer, and shall be computed as specified in Table 9-8.

The range of 1/S values ($1/64 \leq 1/S \leq (1/S)_{max}$) is profile dependent. The mandatory values of $(1/S)_{max}$

for different profiles are defined in Table 6-1. Optional extended (valid) values of $(1/S)_{max}$ for different profiles are specified in Table 9-9.

Table 9-9 – Optional extended values of $(1/S)_{max}$

Parameter	Parameter value for profile							
	8a	8b	8c	8d	12a	12b	17a	30a
$(1/S)_{max}$ downstream	64	64	64	64	64	64	64	32
$(1/S)_{max}$ upstream	32	32	32	32	64	64	64	32

9.6 Impulse noise protection (INP_p)

INP_p (impulse noise protection for latency path p) is defined as the number of consecutive DMT symbols or fractions thereof, as seen at the input to the de-interleaver, for which errors can be completely corrected by the error correcting code, regardless of the number of errors within the errored DMT symbols.

NOTE 1 – This is equivalent to the number of consecutive errored octets within any block of $(I_p - 1) \cdot D_p + 1$ octets, as seen at the input to the de-interleaver, for which errors can be completely corrected by the error correcting code, divided by $L_p/8$, the number of octets loaded in a DMT symbol for latency path p . The interleaver block length, I_p , and interleaver depth, D_p , are defined in clause 9.4, and the number of bits from latency path p loaded into a DMT symbol, L_p , is defined in clause 9.5.4.

NOTE 2 – The value of INP_p is given in terms of DMT symbols. The time span of impulse noise protection, in ms, varies with subcarrier spacing as determined by the profile (see clause 6) and with the CE length (see clause 10.4.4).

The actual impulse noise protection INP_{act_n} of bearer channel # n shall always be set to the value of the derived parameter INP_p of the underlying PMS-TC path function (see Annex L). The receiver shall always ensure $INP_{act_n} \geq INP_{min_n}$ according to the definition of INP_p regardless of any vendor-discretionary techniques including, for example, the use of erasure decoding. When the Reed-Solomon decoder in the receiver does not use erasure decoding, the INP_p shall be computed as:

$$INP_{no_erasure_p} = \frac{8 \times D_p \times \left\lfloor \frac{R_p}{2 \times q_p} \right\rfloor}{L_p} = \frac{S_p \times D_p \times \left\lfloor \frac{R_p}{2 \times q_p} \right\rfloor}{N_{FECp}} \text{ DMT symbols}$$

where parameters D_p , R_p , L_p , and q_p are defined in clauses 9.4 and 9.5.4. When erasure decoding is used, INP_p might not equal $INP_{no_erasure_p}$.

For single latency with ROC mode, the value $INP_{no_erasure_p}$ for latency path #0 (the ROC) shall comply with:

$$INP_{no_erasure_0} \geq \text{INPMIN-ROC (see clause 12.3.5.2.1.1)}$$

Within this equation, INPMIN-ROC is expressed in DMT symbols.

The VTU-O shall calculate INPMIN-ROcus (in DMT symbols) from the CO-MIB value INPMIN-ROC-us (defined in clause 7.3.1.10.12 of [ITU-T G.997.1] in multiples of T_{4k}), and the VTU-R shall calculate INPMIN-ROcds (in DMT symbols) from the O-MSG 1 parameter INPMIN-ROC-ds value (defined in field #23 in multiples of T_{4k}) as follows:

- For 4.3125 kHz subcarrier spacing:
INPMIN-ROC in DMT symbols = INPMIN-ROC in multiples of T_{4k} .
- For 8.625 kHz subcarrier spacing:
INPMIN-ROC in DMT symbols = $2 \times$ (INPMIN-ROC in multiples of T_{4k}).

with T_{4k} as defined in clause 10.4.4.

During initialization, the VTU-O, under direction from the CO-MIB, can set a bit in initialization to require that the VTU-R receiver select framing parameters so that $INP_p = INP_{no_erasure_p}$ on both latency paths. Regardless of whether this bit is set, the receiver shall always ensure $INP_{act_n} \geq INP_{min_n}$. This bit is referred to as "INP_no_erasure_required", bit 8 in the "Impulse noise protection" field in Table 12-51, clause 12.3.5.2.1.1.

During initialization, the VTU-R declares if it is using erasure decoding on either latency path. This field is referred to as "Erasure decoding used" in Table 12-64, clause 12.3.5.2.2.3.

Erasure decoding is vendor discretionary at both VTUs.

9.7 Delay

When the interleaver is disabled (interleaver depth = 1), the one-way delay between the α and β interfaces shall not exceed 2 ms.

The actual delay in milliseconds introduced by the interleaver to latency path p shall be computed as:

$$delay_p = \frac{S_p \times (D_p - 1)}{q_p \times f_s} \times \left(1 - \frac{q_p}{N_{FECp}} \right) \text{ ms}$$

where D_p is the interleaving depth set for the latency path p , S_p is the parameter defined in Table 9-8, q_p is the number of interleaver blocks in an FEC codeword for latency path p , N_{FECp} is the FEC codeword size for latency path p , and f_s is the data symbol rate in ksymbols/s.

The interleaver delay in milliseconds for the specific bearer channel n is constrained by the value of $delay_{max_n}$ defined in the CO-MIB.

For single latency with ROC mode, the value $delay_p$ for latency path #0 (the ROC) shall comply with:

$$delay_0 \leq 8 \text{ ms}$$

Additionally, the framing parameters of the latency path #0 (the ROC) shall be chosen such that the ROC is robust to repetitive impulse noise at a frequency of 120 Hz. This may be achieved by selecting the framing parameters such that:

$$\frac{8 \times N_{FEC0} \times D_0}{L_0} \leq \left\lfloor \frac{f_s}{120 \text{ Hz}} \right\rfloor - 1$$

9.8 Bit error ratio (BER)

The bit error ratio (BER), referenced to the output of the α/β interface of the receiver, shall not exceed 10^{-7} for any of the supported bearers. The VTU shall implement appropriate initialization and reconfiguration procedures to assure this value.

9.9 Delay variation

The delay variation occurring in an OLR on latency path p .

It is defined here as:

$$DV_p = \left| (delay_{p-H} \times L_{p-H} - delay_{p-L} \times L_{p-L}) / L_{p-H} \right|$$

where:

L_{p-L} is the lower value of L_p in an OLR procedure

L_{p-H} is the higher value of L_p in an OLR procedure

$delay_{p-L}$ = the actual delay in ms in the steady state corresponding with L_{p-L}

$delay_p_H$ = the actual delay in ms in the steady state corresponding with L_p_H

The delay variation DV_n of bearer channel #n shall always be set to the value of DV_p of the underlying PMS-TC path function (see Annex L).

10 Physical media dependent (PMD) function

During showtime, the transmit PMD function shall transmit a number of data symbols per second that is dependent on the choice of CE length (see clause 10.4.4) and subcarrier spacing (see clause 10.4.2). For each data symbol, the transmit PMD function receives a symbol encoder input data frame (containing L data bits) from the transmit PMS-TC function. The data frame shall then be symbol encoded as defined in clause 10.3. The symbol encoding will generate a complex value for each subcarrier in the MEDLEY set (either MEDLEY_{us} or MEDLEY_{ds}, depending on the transmission direction, resulting in NSC_{us} and NSC_{ds} complex values respectively). These complex values shall be modulated into data symbols as defined in clause 10.4 to produce an analogue signal for transmission across the digital subscriber line.

10.1 PMD functional model

The functional model of the PMD sublayer is presented in Figure 10-1. In the transmit direction, the PMD sublayer receives input data frames from the PMS-TC sublayer via the δ interface as specified in clause 9.1. Each data frame contains an integer number of data bits equal to $L_0 + L_1$ to be modulated onto one DMT symbol. Prior to modulation, the incoming bits are encoded by the symbol encoder. The encoder divides the incoming bit stream into small groups of bits, where each group is assigned to modulate a specific subcarrier of the DMT signal. Each group is further encoded by the trellis encoder and mapped to a point in a signal constellation. The set of constellation points modulates the subcarriers of the DMT symbol using an IDFT. The number of bits assigned to each subcarrier is determined during the initialization procedure based on the SNR of the subcarrier and specific system configuration settings. After the IDFT, the resulting symbol is cyclically extended and windowed, and sent towards the transmission medium over the U interface.

In the receive direction, the signal incoming from the transmission medium via the U interface is demodulated and decoded to extract the transmitted data frame. The data frame obtained from the decoder (denoted "Data frame (output)" in Figure 10-1) is sent to the PMS-TC sublayer via the δ interface.

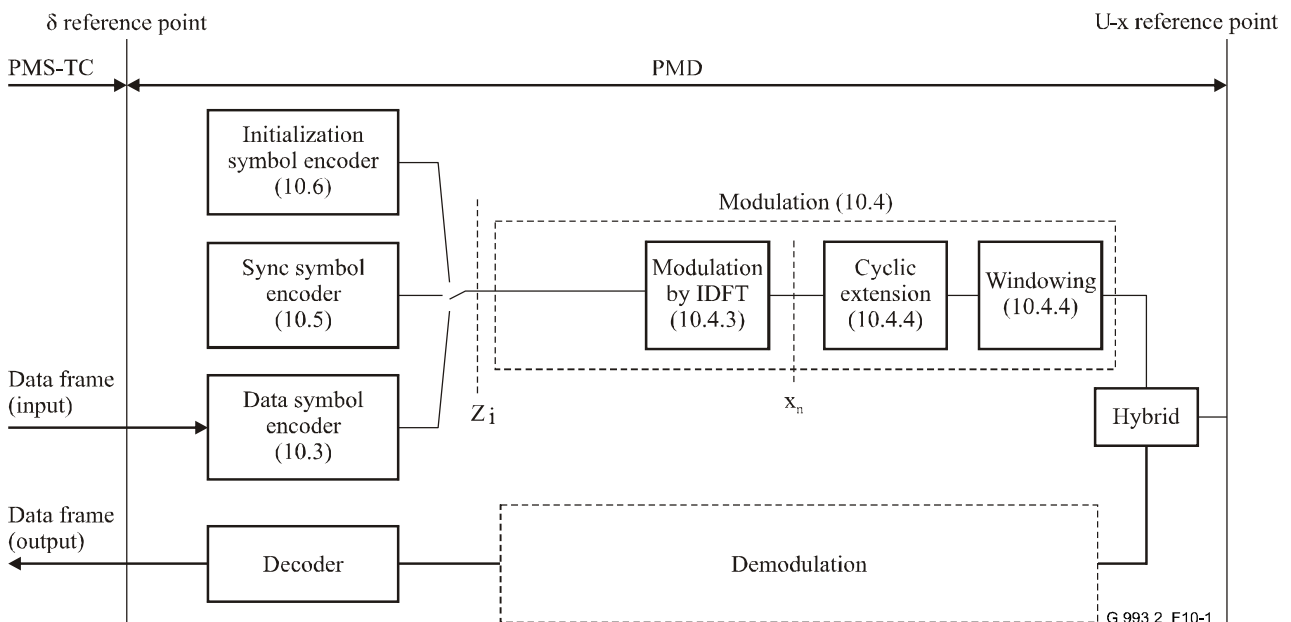


Figure 10-1 – Functional model of PMD sublayer

10.2 DMT superframe

The transmit PMD function shall use the DMT superframe structure shown in Figure 10-2. Each DMT superframe shall be composed of 256 data frames, numbered from 0 to 255, followed by a single sync frame. The content of the sync frame is dependent on whether timing for on-line reconfiguration is being signalled (see clause 10.5.3). The data frames are modulated onto 256 data symbols, and the sync frame is modulated onto a sync symbol as defined in clause 10.5.1. The sync symbol provides a time marker for on-line reconfiguration (see clause 13).

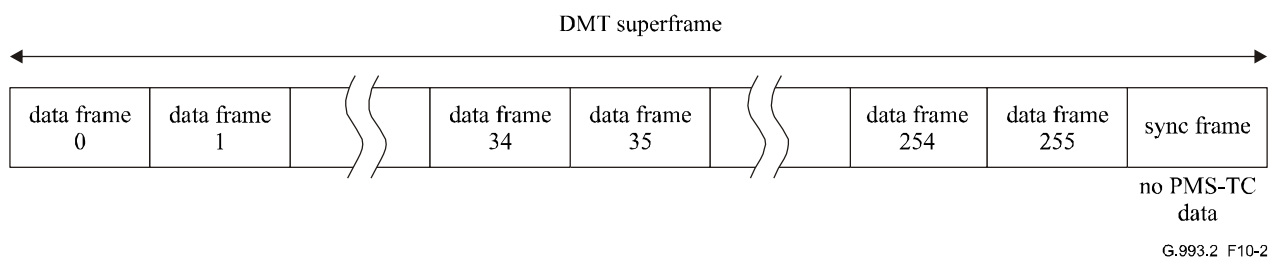


Figure 10-2 – DMT superframe structure

NOTE – The duration of a superframe depends on the subcarrier spacing and value of the cyclic extension (see clause 10.4). When the subcarrier spacing is 4.3125 kHz and the mandatory cyclic extension value is used (5/64), the duration of a superframe is 64.25 ms.

10.3 Symbol encoder for data symbols

The symbol encoder for data symbols is shown as part of the transmit PMD function in Figure 10-1. The symbol encoder for data symbols consists of the following functions:

- Tone ordering;
- Trellis coding;
- Constellation mapping;
- Constellation point scaling.

10.3.1 Tone ordering

During initialization, the receive PMD function shall calculate the numbers of bits and the relative gains to be used for every subcarrier in the MEDLEY set (either MEDLEY_{us} or MEDLEY_{ds}, depending on the transmission direction), as well as the order in which subcarriers are assigned bits (i.e., the tone ordering). The calculated bits and gains and the tone ordering shall be sent back to the transmit PMD function during the channel analysis and exchange phase of initialization (see clause 12.3.5.2). The number of subcarriers in MEDLEY_{us} and MEDLEY_{ds} is denoted by NSC_{us} and NSC_{ds} , respectively.

The pairs of bits and relative gains are defined, in ascending order of frequency or subcarrier index i , as a bit allocation table b and gain table g (i.e., b_i and g_i , for all subcarrier indices i that belong to the MEDLEY set). If trellis coding is used, the receive PMD function shall include an even number of 1-bit subcarriers ($NCONEBIT$) in the bit allocation table b .

The tone ordering table t is defined as the sequence $\{t_k\}$ in which subcarriers from the MEDLEY set are assigned bits from the input bitstream (t_k for $k = 1$ to NSC_{us} for the upstream tones, $k = 1$ to NSC_{ds} for the downstream tones) with constellation mapping beginning on the subcarrier with index $i = t_1$ and ending on the subcarrier with index $i = t_{NSC}$ (for example, $t_{75} = 160$ means that the subcarrier with index 160 is the 75th subcarrier to be assigned bits from the input bit stream). The tone ordering table t shall be created and exchanged during initialization (O-PMD, R-PMD messages, see clause 12.3.5.2) and shall remain unchanged until the next initialization.

If the ROC is enabled, the bits of buffer L_0 and buffer L_1 shall not share the same subcarrier. With

trellis encoding, this means that all the bits u_1 to u_z that are used to encode a 4-dimensional symbol belong to the same buffer (see clause 10.3.2).

Following reception of the tables b , g and t , the transmit PMD function shall calculate a reordered bit table b' and a reordered tone table t' from the original tables b and t . Constellation mapping shall occur in sequence according to the reordered tone table t' , with the number of bits per subcarrier as defined by the original bit table b . Trellis coding shall occur according to the reordered bit table b' and reordered tone table t' .

If trellis coding is not used, $b' = b$ and $t' = t$.

If trellis coding is used, the reordering of table t shall be performed by the transmit PMD function. The reordered tone table t' shall be generated according to the following rules:

- Indices of all subcarriers supporting 0 bits or 2 or more bits appear first in t' , in the same order as in table t ;
- Indices of all subcarriers supporting 1 bit appear last in table t' , in the same order as in table t .

If the bit allocation does not include any 1-bit subcarriers, the reordered tone table t' is identical to the original tone table t .

The (even number of) 1-bit subcarriers shall be paired to form 2-dimensional constellation points as input to the trellis encoder. The pairing shall be determined by the order in which the 1-bit subcarriers appear in the original tone ordering table t .

The table b' shall be generated by reordering the entries of table b according to the following rules:

- The first $NCONEBIT/2$ entries of b' shall be 0, where $NCONEBIT$ (by definition, even) is the number of subcarriers supporting 1 bit;
- The next entries of b' shall be 0, corresponding to all subcarriers that support 0 bits;
- The next entries of b' shall be non-zero, corresponding to the subcarriers that support two or more bits. The entries shall be determined using the new tone table t' in conjunction with the original bit table b ;
- The last $NCONEBIT/2$ entries of b' correspond to the paired 1-bit constellations (i.e., 2 bits per entry).

The tables b' and t' shall be calculated from the original tables b and t as shown in the subcarrier pairing and bit reordering processes below.

```
/** CONSTRUCT THE TONE RE-ORDERING TABLE **/  
/*  
Tone ordering table is denoted as array 't' and tone re-ordering  
table is denoted as array 'tp'. The indices to these arrays are  
denoted as 't_index' and 'tp_index', respectively.  
*/  
/*  
Fill out tone re-ordering table with entries of tone ordering table  
but skip 1-bit tones.  
*/  
tp_index = 1;  
for (t_index = 1; t_index ≤ NSC; t_index++) {  
    tone = t[t_index];  
    bits = b[tone];  
    if (bits != 1) {  
        tp[tp_index++] = tone;  
    }  
}  
/*  
Add the 1-bit tones to the end of tone re-ordering table.  
*/
```



```

for (t_index = 1; t_index ≤ NSC; t_index++) {
    tone = t[t_index];
    bits = b[tone];
    if (bits == 1) {
        tp[tp_index++] = tone;
    }
}
/* RE-ORDERING THE BIT ARRAY */
/*
The bit table is denoted as array 'b' and the ordered bit table is
denoted as array 'bp'.
The indexes to these arrays are denoted as 'b_index' and bp_index',
respectively.
*/
/* First, count the number of loaded tones and also 1-bit tones. */
NCONEBIT = 0; /* NCONEBIT is the number of subcarriers with 1 bit */
NCUSED = 0; /* NCUSED is the number of loaded subcarriers */
for (all i ∈ MEDLEY set) {
    if (b[i] > 0) {
        NCUSED++;
    }
    if (b[i] == 1) {
        NCONEBIT++;
    }
}
/* Fill initial zero entries for unloaded tones and half the number of
1-bit tones */
for (bp_index = 1; bp_index ≤ (NSC - (NCUSED - NCONEBIT/2));
    bp_index++) {
    bp[bp_index] = 0;
}
for (tp_index = 1; tp_index ≤ NSC; tp_index++) {
    tone = t[tp_index];
    bits = b[tone];
    if (bits == 0) {
        /* skip unloaded tones */
    }
    if (bits == 1) {
        /* pair 2 consecutive 1-bit tones and add a
        single entry with 2 bits */
        bp[bp_index++] = 2;
        tp_index++;
    }
    if (bits > 1) {
        bp[bp_index++] = bits;
    }
}
}

```

Figure 10-3 presents an example to illustrate the tone reordering and bit reordering procedures, and the pairing of 1-bit subcarriers for trellis encoding.

Tone ordering table t (as determined by the receive PMD function, $NSC=23$)

7	14	21	4	11	18	1	8	15	22	5	12	19	2	9	16	23	6	13	20	3	10	17
---	----	----	---	----	----	---	---	----	----	---	----	----	---	---	----	----	---	----	----	---	----	----

Bit table b (as determined by the receive PMD function, 37 bits/symbol, natural order of sub-carrier indices starting from 1)

0	1	2	3	2	1	2	1	0	2	0	2	1	1	3	3	3	2	1	0	2	3	2
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

Tone reordered table t' (moving 1-bit sub-carriers to the end of the table)

7	21	4	11	18	1	15	22	5	12	9	16	23	20	3	10	17	14	8	19	2	6	13
---	----	---	----	----	---	----	----	---	----	---	----	----	----	---	----	----	----	---	----	---	---	----

Reordered bit table b' (moving 0-bit sub-carriers to the beginning of the table)

0	0	0	0	0	0	0	2	2	3	2	3	3	2	2	3	2	2	2	3	1+1	1+1	1+1
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	-----	-----	-----

Trellis pairs (encoding 25 data bits into 37 trellis bits) and bit mapping to sub-carriers

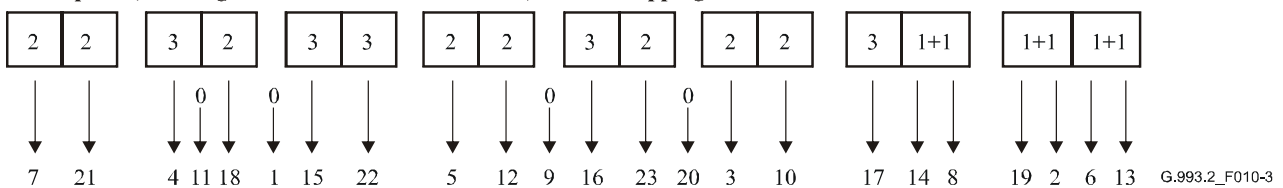


Figure 10-3 – Example of tone ordering and pairing of one-bit subcarriers

If on-line reconfiguration changes the number or indices of 0-bit subcarriers or 1-bit subcarriers, then tables t' and b' shall be recalculated from the updated table b and the original table t .

The symbol encoder takes L bits per symbol from the PMS-TC sublayer. If trellis coding is used, the L bits shall be encoded into a number of bits L' matching the bit allocation table b and the reordered bit allocation table b' , i.e., into a number of bits equal to $L' = \sum b'_i = \sum b_i$. The values of L and L' relate as:

$$L' = \sum b'_i = \sum b_i = L + \left\lceil \frac{NCUSED - \frac{NCONEBIT}{2}}{2} \right\rceil + 4$$

with the $\lceil x \rceil$ notation representing rounding to the next higher integer, and $NCUSED$ representing the number of subcarriers actually used for data transmission (with $b_i > 0$). The added 4 bits are to return the trellis to the zero state at the end of the DMT symbol, as described in clause 10.3.2.2.

The above relationship shows that using the 1-bit subcarrier pairing method, on average, one trellis overhead bit is added per set of four 1-bit subcarriers, i.e., one trellis overhead bit per 4-dimensional constellation.

In case trellis coding is not used, the value of L shall match the bit allocation table, i.e.:

$$L = \sum b_i$$

NOTE – A complementary tone reordering procedure should be performed in the receive PMD function. It is not necessary, however, to send the reordered bit table b' and the reordered tone table t' to the receive PMD function because they are generated in a deterministic way from the bit allocation table and tone ordering tables originally generated in the receive PMD function, and therefore the receive PMD function has all the information necessary to perform the constellation de-mapping and trellis decoding (if used).

10.3.2 Trellis encoder

The trellis encoder shall use block processing of Wei's 16-state 4-dimensional trellis code (see Figure 10-6) to improve system performance.

10.3.2.1 Bit extraction

Bits from the data frame buffer shall be extracted in sequential order according to the bit allocation table b' . The first bit of the data frame shall be extracted first. Because of the 4-dimensional nature of the code, the extraction is based on pairs of consecutive b' entries, rather than on individual ones, as in the non-trellis-coded case. Furthermore, due to the constellation expansion associated with coding, the bit allocation table, b' , specifies the number of coded bits per subcarrier, which can be any integer from 2 to 15.

Trellis coding shall be performed on pairs of consecutive b' values, starting with the first entry in the b' table. If the number of non-zero entries in the b' table is odd, the value b'_0 shall be prepended to the reordered bit table b' first to make an integer number of pairs and shall be set to ZERO. For subcarriers with 1-bit constellations, each (1+1)-bit b' entry will be mapped on two subcarriers, as described in Figure 10-3.

Given a pair (x, y) , $x + y - 1$ bits (reflecting a constellation expansion of 1 bit per 4 dimensions, or one half bit per subcarrier) are extracted from the data frame buffer, except for the last two 4-dimensional symbols. These $z = x + y - 1$ bits (t_z, t_{z-1}, \dots, t_1) are used to form the binary word u as shown in Table 10-1. Refer to clause 10.3.2.2 for the reason behind the special form of the word u for the case $x = 0, y > 1$.

Table 10-1 – Forming the binary word u

Condition	Binary word/comment
$x > 1, y > 1$	$u = (t_z, t_{z-1}, \dots, t_1)$
$x = 1, y \geq 1$	Condition not allowed
$x = 0, y > 1$	$u = (t_z, t_{z-1}, \dots, t_2, 0, t_1, 0)$
$x = 0, y = 0$	Bit extraction not necessary, no data bits being sent
$x = 0, y = 1$	Condition not allowed
NOTE – t_1 is the first bit extracted from the data frame buffer.	

The last two 4-dimensional symbols in each DMT symbol shall be chosen to force the convolutional encoder state to the zero state. For each of these symbols, the two LSBs of u are predetermined, and only $(x + y - 3)$ bits shall be extracted from the data frame buffer and shall be allocated to t_3, t_4, \dots, t_z .

NOTE – The above requirements imply a minimum size of the b' table of 4 non-zero entries. The minimum number of non-zero entries in the corresponding b table could be higher.

10.3.2.2 Bit conversion

The binary word $u = (u_{z'}, u_{z'-1}, \dots, u_1)$ extracted LSB first from the data frame buffer determines two binary words $v = (v_{z'-y}, \dots, v_0)$ and $w = (w_{y-1}, \dots, w_0)$, which are inserted LSB first in the encoded data bits buffer and used to look up constellation points in the constellation mapper (see Figure 10-4).

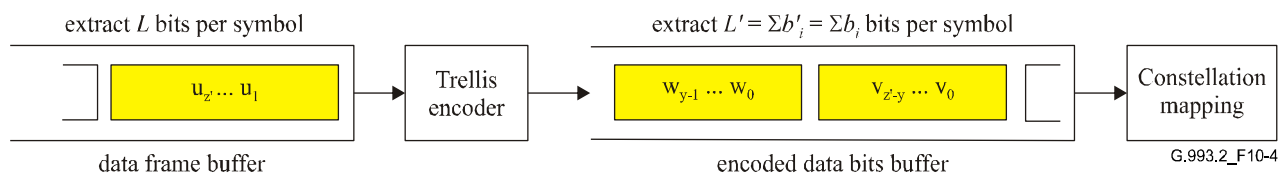


Figure 10-4 – Relationship of trellis encoder and constellation mapping

NOTE – For convenience of description, the constellation mapper identifies these x and y bits with a label whose binary representation is $(v_{b-1}, v_{b-2}, \dots, v_1, v_0)$. The same constellation mapping rules apply to both the v (with $b = x$) and the w (with $b = y$) vector generated by the trellis encoder.

For the usual case of $x > 1$ and $y > 1$, $z' = z = x + y - 1$, and v and w contain x and y bits respectively. For the special case of $x = 0$ and $y > 1$, $z' = z + 2 = y + 1$, $v = (v_1, v_0) = (0, 0)$ and $w = (w_{y-1}, \dots, w_0)$. The bits (u_3, u_2, u_1) determine (v_1, v_0) and (w_1, w_0) according to Figure 10-5.

The convolutional encoder shown in Figure 10-5 is a systematic encoder (i.e., u_1 and u_2 are passed through unchanged) as shown in Figure 10-6. The convolutional encoder state (S_3, S_2, S_1, S_0) is used to label the states of the trellis shown in Figure 10-8. At the beginning of a DMT symbol, the convolutional encoder state shall be initialized to $(0, 0, 0, 0)$.

The remaining bits of v and w are obtained from the less significant and more significant parts of $(u_{z'}, u_{z'-1}, \dots, u_4)$, respectively. When $x > 1$ and $y > 1$, $v = (u_{z'-y+2}, u_{z'-y+1}, \dots, u_4, v_1, v_0)$ and $w = (u_{z'}, u_{z'-1}, \dots, u_{z'-y+3}, w_1, w_0)$. When $x = 0$, the bit extraction and conversion algorithms result in $v_1 = v_0 = 0$. The binary word v shall be input first to the constellation mapper, and then the binary word w .

In order to force the final state of the convolutional encoder to the zero state $(0, 0, 0, 0)$, the two LSBs u_1 and u_2 of the final two 4-dimensional symbols in the DMT symbol are constrained to $u_1 = S_1 \oplus S_3$, and $u_2 = S_2$.

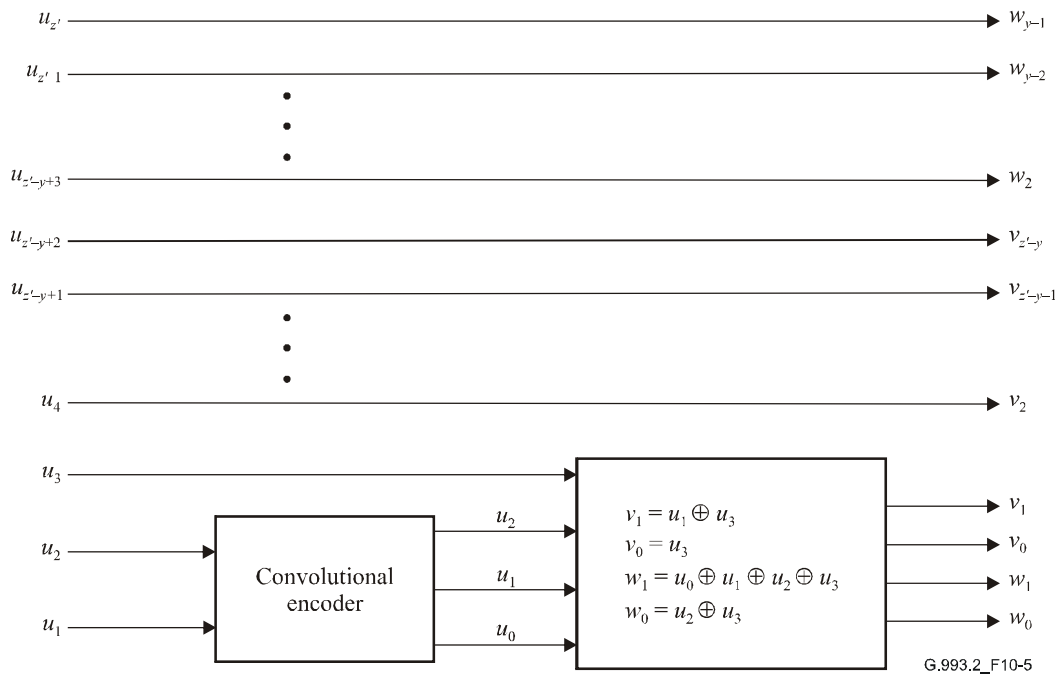


Figure 10-5 – Conversion of u to v and w

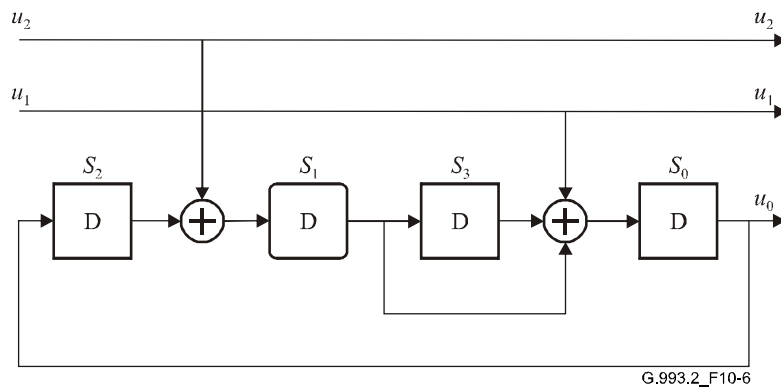


Figure 10-6 – Convolutional encoder: Finite state machine representation

10.3.2.3 Coset partitioning and trellis diagram

In a trellis code modulation system, the expanded constellation may be labelled and partitioned into subsets ("cosets") using a technique called mapping by set-partitioning. The 4-dimensional cosets in Wei's code can each be written as the union of two Cartesian products of two 2-dimensional cosets.

For example, $C_4^0 = (C_2^0 \times C_2^0) \cup (C_2^3 \times C_2^3)$. The four constituent 2-dimensional cosets, denoted by 0, 1, 2, and 3 for $C_2^0, C_2^1, C_2^2, C_2^3$, respectively, are shown in Figure 10-7.

The constellation mapping ensures that the two LSBs of a constellation point comprise the index i of the 2-dimensional coset C_2^i in which the constellation point lies. The bits (v_1, v_0) and (w_1, w_0) are in fact the binary representations of this index.

The three bits (u_2, u_1, u_0) are used to select one of the eight possible 4-dimensional cosets. The eight cosets are labelled C_4^i where i is the integer with binary representation (u_2, u_1, u_0) . The additional bit u_3 (see Figure 10-5) determines which one of the two Cartesian products of 2-dimensional cosets is chosen from the 4-dimensional coset. The relationship is shown in Table 10-2. The bits (v_1, v_0) and (w_1, w_0) are computed from (u_3, u_2, u_1, u_0) using the linear equations given in Figure 10-5.

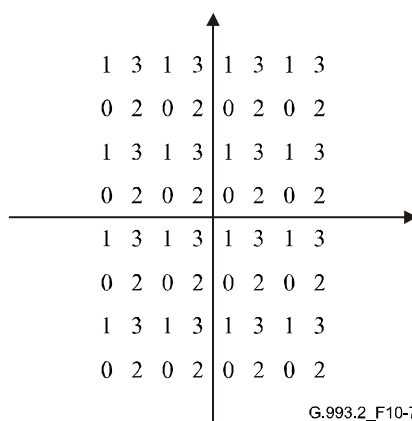


Figure 10-7 – Mapping of 2-dimensional cosets

Table 10-2 – Relation between 4-dimensional and 2-dimensional cosets

4-D coset	u_3	u_2	u_1	u_0	v_1	v_0	w_1	w_0	2-D cosets
C_4^0	0	0	0	0	0	0	0	0	$C_2^0 \times C_2^0$
	1	0	0	0	1	1	1	1	$C_2^3 \times C_2^3$
C_4^4	0	1	0	0	0	0	1	1	$C_2^0 \times C_2^3$
	1	1	0	0	1	1	0	0	$C_2^3 \times C_2^0$
C_4^2	0	0	1	0	1	0	1	0	$C_2^2 \times C_2^2$
	1	0	1	0	0	1	0	1	$C_2^1 \times C_2^1$
C_4^6	0	1	1	0	1	0	0	1	$C_2^2 \times C_2^1$
	1	1	1	0	0	1	1	0	$C_2^1 \times C_2^2$
C_4^1	0	0	0	1	0	0	1	0	$C_2^0 \times C_2^2$
	1	0	0	1	1	1	0	1	$C_2^3 \times C_2^1$
C_4^5	0	1	0	1	0	0	0	1	$C_2^0 \times C_2^1$
	1	1	0	1	1	1	1	0	$C_2^3 \times C_2^2$
C_4^3	0	0	1	1	1	0	0	0	$C_2^2 \times C_2^0$
	1	0	1	1	0	1	1	1	$C_2^1 \times C_2^3$
C_4^7	0	1	1	1	1	0	1	1	$C_2^2 \times C_2^3$
	1	1	1	1	0	1	0	0	$C_2^1 \times C_2^0$

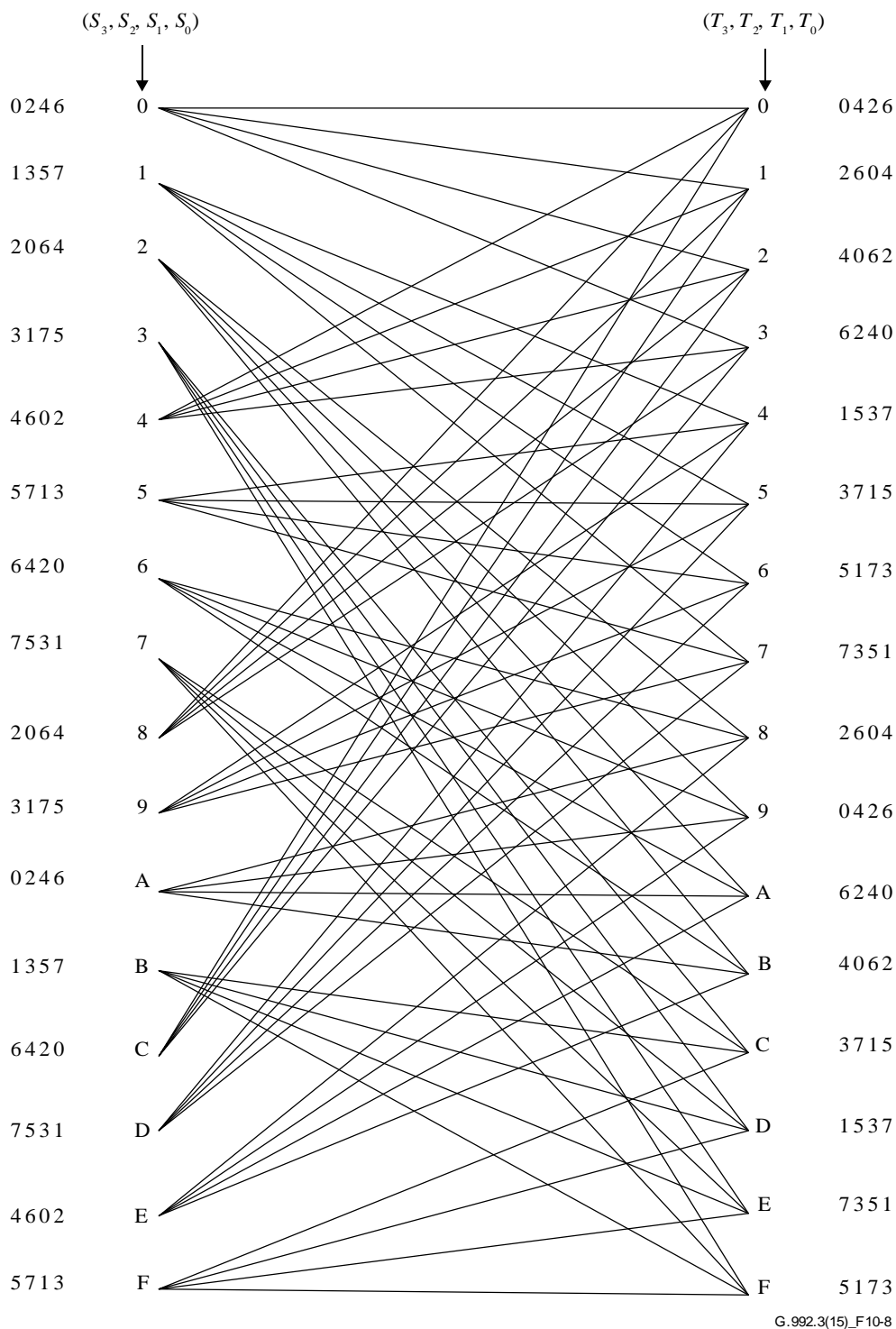


Figure 10-8 – Trellis diagram

Figure 10-8 shows the trellis diagram based on the finite state machine in Figure 10-6, and the one-to-one correspondence between (u_2, u_1, u_0) and the 4-dimensional cosets. In Figure 10-8, $S = (S_3, S_2, S_1, S_0)$ represents the current state, while $T = (T_3, T_2, T_1, T_0)$ represents the next state in the finite state machine. S is connected to T in the trellis diagram by a branch determined by the values of u_2 and u_1 . The branch is labelled with the 4-dimensional coset specified by the values of u_2, u_1 (and $u_0 = S_0$, see Figure 10-6). To make the trellis diagram more readable, the indices of the 4-dimensional coset labels are listed next to the starting and end points of the branches, rather than on the branches themselves. The leftmost label corresponds to the uppermost branch for each state. The trellis diagram may be used when decoding the trellis code by the Viterbi algorithm.

10.3.3 Constellation mapper

The constellation mapper maps a set of bits to a constellation point. The data buffer contains $\sum_i b_i$ bits, which may or may not be trellis coded. Bits shall be extracted, as defined in clause 10.3.3.1, from the data buffer or from a pseudo-random binary sequence (PRBS) generator. The extracted bits shall be mapped to constellation points as defined in clause 10.3.3.2.

10.3.3.1 Bit extraction

Bits shall be extracted from the data buffer or from a PRBS generator in the order defined by the tone ordering table.

For each subcarrier i in the MEDLEY set with $b_i > 0$ and $g_i > 0$ (linear scale), the encoder shall extract $b = b_i$ bits from the data buffer. The number of bits extracted (b_i) for each subcarrier is determined by the bit allocation table. The set of b extracted bits shall be represented as a binary word ($v_{b-1} v_{b-2} \dots v_1 v_0$), where the first bit extracted shall be v_0 , the LSB. The encoder shall select a point (X, Y) from the constellation based on the b -bit word ($v_{b-1} v_{b-2} \dots v_1 v_0$).

For each monitored subcarrier (i.e., subcarriers in the MEDLEY set with $b_i = 0$ and $g_i > 0$) and for each subcarrier used as a pilot tone during showtime (see clause 12.3.5.2.2.4), no bits shall be extracted from the data buffer. Instead, the encoder shall extract $b = 2$ bits ($v_1 v_0$) from the PRBS generator, where the first bit extracted shall be v_0 . For the pilot tone subcarrier(s), the bits extracted from the PRBS generator shall be overwritten by the modulator with a fixed 4-quadrature amplitude modulation (QAM) constellation point corresponding to the bits 00 (i.e., the two bits from the PRBS generator are effectively ignored).

The PRBS generator shall be defined by:

$$d_n = 1 \text{ for } n = 1 \text{ to } n = 23; \text{ and}$$
$$d_n = d_{n-18} \oplus d_{n-23} \text{ for } n > 23.$$

The PRBS generator shall be reset at the beginning of showtime. Upon reset of the PRBS, d_1 shall be the first bit extracted, followed by d_2, d_3 , etc. For each data symbol, the number of bits extracted from the PRBS generator shall be twice the number of subcarriers in the MEDLEY set that have $b_i = 0$ plus twice the number of showtime pilot tones. No bits shall be extracted from the PRBS generator during sync symbols.

For a given subcarrier i not in the MEDLEY set ($b_i = 0$ by definition), no bits shall be extracted from the data buffer and no bits shall be extracted from the PRBS generator. Instead, the constellation mapper may select a vendor-discretionary (X, Y) point (which may change from symbol to symbol and which does not necessarily coincide with a constellation point).

The described bit extraction mechanism is relevant only during showtime.

10.3.3.2 Constellations

An algorithmic constellation mapper shall be used to construct subcarrier QAM constellations with a minimum number of bits equal to 1 and a maximum number of bits equal to 15.

The constellation points are denoted (X, Y). X and Y shall lie at the odd integers $\pm 1, \pm 3, \pm 5$, etc. For convenience of illustration, each constellation point in Figures 10-9 through 10-13 is labelled by an integer whose unsigned binary representation is ($v_{b-1} v_{b-2} \dots v_1 v_0$).

10.3.3.2.1 Even values of b

For even values of b , the integer values X and Y of the constellation point (X, Y) shall be determined from the b bits $(v_{b-1}, v_{b-2}, \dots, v_1, v_0)$ as follows. X and Y shall be odd integers with two's-complement binary representations $(v_{b-1} v_{b-3} \dots v_1 1)$ and $(v_{b-2} v_{b-4} \dots v_0 1)$, respectively. The MSBs, v_{b-1} and v_{b-2} , shall be the sign bits for X and Y , respectively. Figure 10-9 shows example constellations for $b = 2$ and $b = 4$.

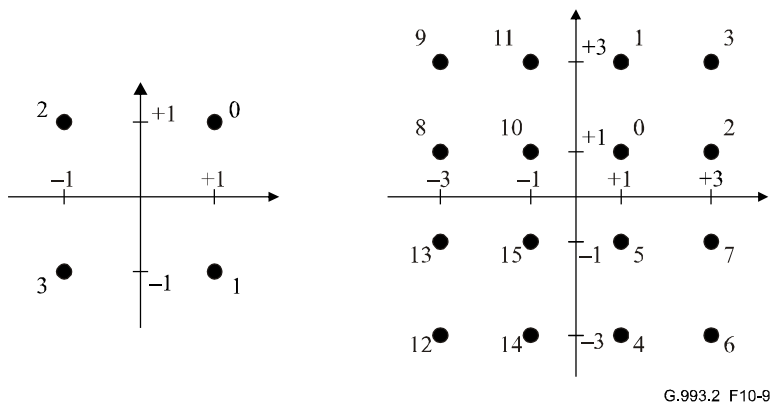


Figure 10-9 – Constellation labels for $b = 2$ and $b = 4$

NOTE – The 4-bit constellation may be obtained from the 2-bit constellation by replacing each label n by the 2×2 block of labels:

$$\begin{array}{cc} 4n+1 & 4n+3 \\ 4n & 4n+2 \end{array}$$

The same procedure may be used to construct the larger even-bit constellations recursively. The constellations obtained for even values of b are square in shape.

10.3.3.2.2 Odd values of b

10.3.3.2.2.1 $b = 1$

Figure 10-10 shows the constellation for the case $b = 1$.

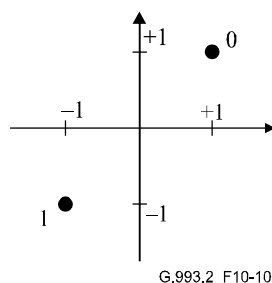
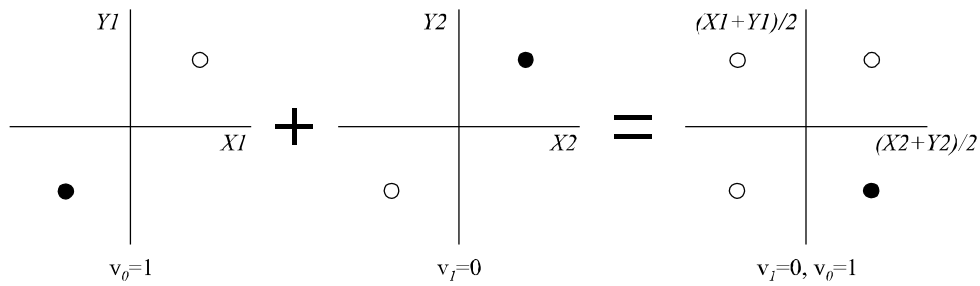


Figure 10-10 – Constellation labels for $b = 1$

When trellis coding is used, the 2-bit words generated by the trellis encoder shall be mapped on two 1-bit subcarriers using the same labelling for 1-bit and 2-bit constellations as described above. An example for $v_0 = 1$ and $v_1 = 0$ is shown in Figure 10-11, in which the constellation for the 2-bit word is on the right-hand side of the diagram.

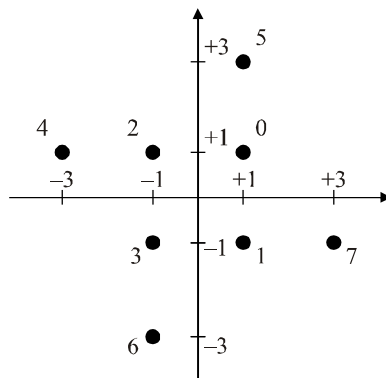


G.993.2_F10-11

Figure 10-11 – Combination of a pair of 1-bit constellations to build a 2-bit constellation

10.3.3.2.2.2 $b = 3$

Figure 10-12 shows the constellation for the case $b = 3$.



G.993.2_F10-12

Figure 10-12 – Constellation labels for $b = 3$

10.3.3.2.2.3 $b > 3$

If b is odd and greater than 3, the two MSBs of X and the two MSBs of Y shall be determined by the five MSBs of the b bits ($v_{b-1} v_{b-2} \dots v_1 v_0$). Let $c = (b+1)/2$, then X and Y shall have the two-complement binary representations ($X_c X_{c-1} v_{b-4} v_{b-6} \dots v_3 v_1 1$) and ($Y_c Y_{c-1} v_{b-5} v_{b-7} v_{b-9} \dots v_2 v_0 1$), where X_c and Y_c are the sign bits of X and Y respectively. The relationship between X_c , X_{c-1} , Y_c , Y_{c-1} , and ($v_{b-1} v_{b-2} \dots v_{b-5}$) shall be as shown in Table 10-3.

Table 10-3 – Determining the top two bits of X and Y

$\nu_{b-1} \nu_{b-2} \dots \nu_{b-5}$	$X_c X_{c-1}$	$Y_c Y_{c-1}$	$\nu_{b-1} \nu_{b-2} \dots \nu_{b-5}$	$X_c X_{c-1}$	$Y_c Y_{c-1}$
00000	00	00	10000	01	00
00001	00	00	10001	01	00
00010	00	00	10010	10	00
00011	00	00	10011	10	00
00100	00	11	10100	00	01
00101	00	11	10101	00	10
00110	00	11	10110	00	01
00111	00	11	10111	00	10
01000	11	00	11000	11	01
01001	11	00	11001	11	10
01010	11	00	11010	11	01
01011	11	00	11011	11	10
01100	11	11	11100	01	11
01101	11	11	11101	01	11
01110	11	11	11110	10	11
01111	11	11	11111	10	11

Figure 10-13 shows the constellation for the case $b = 5$.

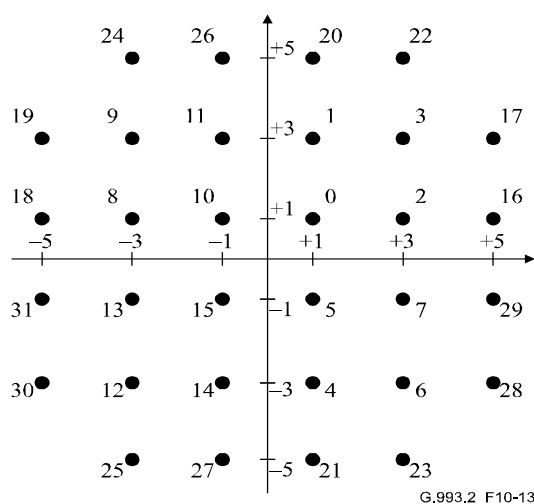


Figure 10-13 – Constellation labels for $b = 5$

NOTE – The 7-bit constellation may be obtained from the 5-bit constellation by replacing each label n by the 2×2 block of labels:

$$\begin{array}{cc} 4n+1 & 4n+3 \\ 4n & 4n+2 \end{array}$$

The same procedure may then be used to construct the larger odd-bit constellations recursively.

10.3.4 Constellation point scaling

Constellation points shall be scaled to normalize their average power, to achieve a frequency-dependent transmit PSD, and to equalize the SNR margin over the subcarriers in use.