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Abstract

This document is the latest draft of the VDSL Alliance's Syncronized DMT proposal for VDSL. The proposal specifies both a time-division duplexed (TDD) system and a frequency-division duplexed (FDD) system. In both cases, symmetric and asymmetric transmission are supported. Support of 1:1, 2:1, 3:1, 4:1, 6:1, and 8:1 transmission is mandatory, as is rate adaptivity. Support of ATM is also required. Comments about this proposal are invited and should be directed to the editor for consideration. This document is submitted for information.

NOTICE

This contribution has been prepared to assist ETSI Working Group TM6. This document is offered to TM6 as a basis for discussion and is not a binding proposal on the authors. The requirements are subject to change after further study. The authors specifically reserve the right to add to, ammend, or withdraw the statements contained herein.

VDSL Alliance

SDMT VDSL Draft Standard Proposal

Participating companies and contacts

The individuals and companies listed below are working together to specify a proposal that would be recommended should SDMT be selected by ETSI TM6 as the VDSL linecode. Appearance of a name, whether a company or an individual, does not yet imply full agreement with all contents of this document, which are subject to change, but it does indicate an effort to refine the document and generate a future draft with the hope of agreement.

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NOTICE

The VDSL Alliance is open to all who wish to participate in the specification of a DMT VDSL proposal. Parties interested in contributing to the VDSL Alliance’s efforts should contact the document editor, Krista S. Jacobsen, by e-mail (jacobsen@ti.com), phone (408.879.2039), or FAX (408.879.2912).

1 General

1.1 Scope and purpose

This document describes the interface between the telecommunications network and the customer installation in terms of their interaction and electrical characteristics. The requirements of this specification apply to a single very high-speed digital subscriber line (VDSL). VDSL allows the provision of Plain Old Telephone Service (POTS) or Integrated Services Digital Network (ISDN) service and a multi-megabit per second digital channel over a single metallic, unshielded twisted-pair transmission line. This specification describes the physical medium-dependent (PMD) and transmission convergence (TC) sublayer functions for Asynchronous Transfer Mode (ATM) and Synchronous Transfer Mode (STM). The specification is based on the synchronized discrete multitone (SDMT) transmission method.

The transmission system is designed to operate on existing two-wire twisted metallic cable pairs with mixed gauges. The specification is intended only for cables without loading coils, but bridged taps are acceptable with the exception of unusual situations.

For the purpose of compatible interconnection of equipment using SDMT-based VDSL, this specification:

1. Provides a general description of the VDSL architecture.
2. Defines the minimal set of requirements to provide satisfactory simultaneous SDMT transmission between the network and the customer interface of POTS or ISDN, and high-speed data channels.
3. Specifies the minimal set of Layer 1 aspects required to ensure compatibility between equipment in the network and equipment at remote locations.
4. Defines the data formats for upstream and downstream transmission, including the forward error correction and framing.
5. Provides a set of transmission loops and noise scenarios for testing purposes and specifies the required system performance in each case.
6. Defines the mechanical and electrical specifications for VDSL equipment.
7. Etc.

This interface specification defines the minimal set of requirements to provide satisfactory simultaneous transmission between the network and the customer interface of POTS or ISDN and high-speed, time-division duplexed channels. The specification enables network providers to expand the use of existing copper facilities. All Layer 1 aspects required to ensure compatibility between equipment in the network and equipment at a remote location are specified. This specification defines the minimum functionality that must be provided to ensure interoperability; however, equipment may be implemented with additional functions and procedures.

1.2 Normative references

The following standards, specifications, and documents contain information and provisions that impact or relate to this specification.

[1] ETSI Draft Technical Specification DTS/TM-06003-1, “Transmission and multiplexing TM; Access transmission systems on metallic access cables; Very high speed Digital Subscriber Line (VDSL); Part 1; Functional requirements,” November 1997.

[2] T1E1.4/95-51R4, “Standards project for network interfaces associated with twisted-pair transmission systems capable of operating at speeds in excess of 10 Mbps,” G. Tennyson (BellSouth), August 1995, Silver Creek, CO.

[3] ETSI Draft Technical Report DTR/TM-03068, “Transmission and multiplexing (TM); Very high bit-rate digital transmission on metallic local lines (VDSL),” December 7, 1995.

[4] ANSI T1.413-1995; Telecommunications - Asymmetric Digital Subscriber Line (ADSL) metallic interface.

[5] ANSI T1.231-1993; Telecommunications - In-service Layer 1 digital transmission performance monitoring.

[6] ANSI T1.401-1993; Telecommunications - Interface between carriers and customer installations - Analog voice-grade switched access lines using loop-start and ground-start signaling.

[7] ETSI ETS 300 001 - The general technical requirements for equipment connected to an analogue subscriber interface in the PSTN (Public Switched Telephone Network).

[8] ETSI prTBR21 - Terminal Equipment (TE); Attachment requirements for the connection of terminal equipment to the analogue PSTN in Europe (excluding terminals supporting voice telephony service).

[9] ITU-T Recommendation G.227 (1988) - Conventional telephone signal.

[10] ITU-T Recommendation Q.552 (1996) - Transmission characteristics at 2-wire analogue interfaces of digital exchanges.

[11] ITU-T Recommendation O.9 (1988) - Measuring arrangements to assess the degree of unbalance about earth.

[12] ITU-T Recommendation G.117 (1996) - Transmission aspects of unbalance about earth.

[13] ANSI T1.601-1992; Telecommunications - Integrated Services Digital Network (ISDN) - Basic access interface for use on metallic loops for application on the network side of the NT (Layer 1 specification).

[14] ANSI T1.605-1991; Telecommunications - Integrated Services Digital Network (ISDN) - Basic access interface for S and T reference points (Layer 1 specification).

[15] ETSI ETS-080 (1993): Transmission & Multiplexing (TM); Integrated Services Digital Network (ISDN) basic rate access; Digital transmission on metallic local lines.

[16] ANSI T1.105.07-199x, Synchronous Optical Network (SONET) - Sub STS-Interface rates and format specification, see ANSI Contribution T1X1.5/06-002R1.

[17] ANSI T1.403-1989, Carrier-to-customer installation - DS1 metallic interface.

[18] ANSI/EIA/TIA-571-1991 Environmental considerations for telephone terminals.

[19] Bellcore TR-NWT-000063 (September 1993). Network Equipment-Building System (NEBS) generic equipment requirements, Issue 5.

[20] Bellcore TR-NWT-000499 (November 1991). Transport Systems Generic Requirements (TSGR) common requirements, Issue 4.

[21] Bellcore TR-NWT-001089. (October 1991). Electromagnetic compatibility and electrical safety generic criteria for network telecommunications equipment, Issue 1.

[22] ETSI ETS 300 019-1: Equipment Engineering (EE); Environmental conditions and environmental tests for telecommunication equipment; Part-1: Classification of environmental conditions.

[23] ETSI ETS 300 019-2: Equipment Engineering (EE); Environmental conditions and environmental tests for telecommunication equipment; Part-2: Specification of environmental conditions.

[24] ITU-T Recommendation G.703 (1991) - Physical/electrical characteristics of hierarchical interfaces.

[25] FCC Rules and Regulations, Part 15, Subpart J.

[26] IIT Reference Data for Radio Engineers, 6th Edition, Howard Sams & Co., 1975, Indianapolis, IN.

[27] ITU-T Recommendation G.704 (1995) - Synchronous frame structures used at 1544, 6312, 2048, 8488, & 44736 kbit/s hierarchical levels.

[28] ITU-T, Rec. G.227.

[29] HDSL references

[30] RF noise references

[31] References on ATM and its impact on PMD layer

[32] SDH, PDH references

1.3 Abbreviations, acronyms and symbols

ABR	Available bit rate
ADC	Analog-to-digital converter
ADSL	Asymmetric digital subscriber line
ATM	Asynchronous transfer mode
ATP	Access termination point
AWG	American wire gauge
BER	Bit error rate
CBR	Constant bit rate
CER	ATM cell error ratio
CO	Central office (or local exchange)
COF	Coordination function
CPE	Customer premise equipment
DFT	Discrete Fourier transform
DMT	Discrete multitone
DS	Downstream
DSA	Distribution service area
DSL	Digital subscriber line (or loop)
EMC	Electro-magnetic compatibility
EMI	Electro-magnetic interference
EOC	Embedded operations channel
FEC	Forward error correction
FEQ	Frequency-domain equalizer
FEXT	Far-end crosstalk
FTTC	Fiber to the curb
FTTCab	Fiber to the cabinet
FTTN	Fiber to the node
HDSL	High-rate digital subscriber line
IDFT	Inverse discrete Fourier transform
IFI	Inter-frame interference
ISDN	Integrated services digital network
LT	Line termination
MSB	Most significant bit
NEXT	Near-end crosstalk
NID	Network interface device
NT	Network termination
NTR	Network timing reference
OAMP	Operations, administration and maintenance provisioning
ONU	Optical network unit
PMD	Physical medium-dependent
PMS	Physical medium-specific
PMS-TC	PMD-specific transmission convergence layer
PON	Passive optical network

POTS	Plain old telephone service
PRBS	Pseudo-random binary sequence
PRC	Payload rate change
P/S	Parallel-to-serial conversion
PSD	Power spectral density
PSTN	Public switched telephone network
QAM	Quadrature amplitude modulation
QoS	Quality of service
RF	Radio-frequency
RFI	Radio-frequency interference
RMS	Root mean squared
SDMT	Synchronized discrete multitone
SM	Service module
SNR	Signal-to-noise ratio
SONET	Synchronous optical network
S/P	Serial-to-parallel conversion
STM	Synchronous transfer mode
TA	Timing advance
TBD	To be determined
TC	Transmission convergence
TDD	Time-division duplexed
TE	Terminal equipment
TPS-TC	Transport protocol specific transmission convergence layer
UBR	Unspecified bit rate
UNI	User-network interface
US	Upstream
UTP	Unshielded twisted-pair
VBR	Variable bit rate
VDSL	Very high-speed digital subscriber line
VTU	VDSL transceiver unit
VTU-O	VTU at the ONU
VTU-R	VTU at the remote site
xDSL	Generic term for the family of DSL technologies, including HDSL, ISDN, ADSL, VDSL, etc.

1.4 Definitions

For the purpose of this specification, the following definitions shall apply. Some definitions, several of which have been modified slightly for VDSL, are from ANSI T1.413, “Network and Customer Installation Interfaces - Asymmetric Digital Subscriber Line (ADSL) Metallic Interface.”

1.4.1 aggregate bit rate: the data rate transmitted by a VDSL system in one direction. The aggregate data rate includes both net data rate and data rate overhead used by the system for cyclic redundancy checks, the embedded operations channel, synchronization of the various data streams, and fixed indicator bits for operations, administration, and maintenance. The aggregate data rate does not include forward error correction code redundancy.

1.4.2 asymmetric: a condition occurring when the bit rate supported in one transmission direction exceeds the bit rate supported in the opposite direction. Typically, asymmetric implies that the downstream bit rate exceeds the upstream bit rate.

1.4.3 ATM cell: a digital information block of fixed length (53 octets) identified by a label at the asynchronous transfer mode level.

1.4.4 available bit rate: an ATM service whose bit rate varies between upper and lower limits and is characterized by an average bit rate. The minimum, maximum, and average bit rates may vary while a connection is established.

1.4.5 bridged taps: sections of unterminated twisted-pair cable connected in parallel across the cable under consideration.

1.4.6 broadband: a service or system that supports data using one or more frequency bands above the POTS band. Broadband typically implies transmission of bit rates greater than 100 kbps.

1.4.7 central office: Definition is TBD.

1.4.8 connection: Definition is TBD.

1.4.9 constant bit rate: an ATM service characterized by a deterministic bit rate that remains constant with time.

1.4.10 downstream: direction from the ONU to the subscriber premise.

1.4.11 dynamic range: the ratio between the largest and smallest usable signals that meet the requirements defined in this specification.

1.4.12 embedded operations channel: Definition is TBD.

1.4.13 errored second: a one-second interval of received signal containing one or more bit errors.

1.4.14 fast channel: a channel with low latency but high BER with respect to the slow channel

1.4.15 impulse noise: a short-duration noise source characterized by sharp rise and fall times and a large amplitude.

1.4.16 line rate: total bit rate supported by a connection in one direction. Line rate is the sum of the payload bit rate and all bit rate overhead required for forward error correction, synchronization, cyclic redundancy checks, the embedded operations channel, the VDSL overhead channel, and fixed indicator bits for operations, administration, and maintenance.

1.4.17 management interface: Definition is TBD.

1.4.18 network termination: termination of a point-to-point VDSL transmission system.

1.4.19 optical network unit: Definition is TBD.

1.4.20 payload bit rate: total data rate that is available to user data in any one direction.

1.4.21 protocol: Definition is TBD.

1.4.22 quality of service: a set of parameters characterizing the success or failure of an end-to-end connection to meet the service contract negotiated for the transfer of ATM cells.

1.4.23 slow channel: a channel with high latency but low BER with respect to the fast channel

1.4.24 splitter: a low-pass/high-pass pair of filters that separate high-frequency (VDSL) and low-frequency (POTS/ISDN) signals.

1.4.25 subchannel: a frequency band used by a DMT transceiver. Using an inverse discrete Fourier transform (IDFT), the total system bandwidth is partitioned into a set of orthogonal, independent subchannels.

1.4.26 subscriber premise: the location at which the remote transceiver resides. It is presumed that the remote transceiver may be located either inside or outside the subscriber premise.

1.4.27 superframe: a set of successive DMT symbols, some of which support upstream transmission, and others of which support downstream transmission. Superframes also contain silent intervals whose durations may or may not be integer multiples of a symbol period.

1.4.28 symmetric: a condition occurring when the same bit rate is supported in both transmission directions.

1.4.29 synchronized discrete multitone: an implementation of DMT that requires transmissions of all VTU-Os in a common binder to be time-synchronized.

1.4.30 unspecified bit rate: a “best effort” ATM service for which no traffic parameters are specified and no level of performance is guaranteed.

1.4.31 upstream: in the direction from the subscriber premise to the ONU.

1.4.32 variable bit rate: an ATM service whose bit rate is characterized by the average and peak bit rates. These parameters remain constant for the duration of a connection.

2 Architecture

VDSL serves the general fiber-to-the-node architecture illustrated in Figure 1. An optical network unit (ONU) situated in the existing access network (or, in some cases, at the serving central office or local exchange) services up to 200 customers. Existing twisted-pair lines transfer narrowband (for example, POTS or ISDN) and broadband (such as ADSL, HDSL, and VDSL) signals between the ONU and customer premise (CP). For VDSL applications, a network termination (NT) at the customer premise is defined as the termination of point-to-point VDSL. The NT provides a standardized set of user network interfaces (UNIs) for the various applications served by VDSL. In addition, the NT allows the network operator to test the network up to the NT to determine if the cause of service problems is inside the CP or between the CP and the ONU.

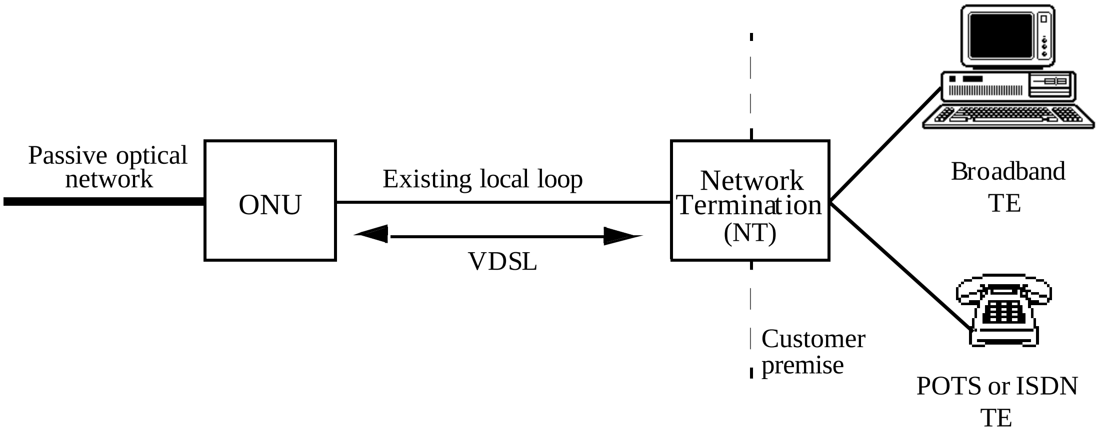


Figure 1: General fiber-to-the-node architecture for VDSL

All twisted-pair lines between the ONU and the NT are considered to be part of the VDSL loop. Thus, any vertical drop or rise segments of twisted-pair lines at either the CP or ONU end of the network shall be considered specifically within the node. Consequently, bridged tap configurations are covered by this specification.

2.1 Reference models

2.1.1 System reference model

Figure 2 illustrates the generic VDSL functional reference model for the copper access section of the VDSL network. The vertical lines indicate the seven specification interfaces.

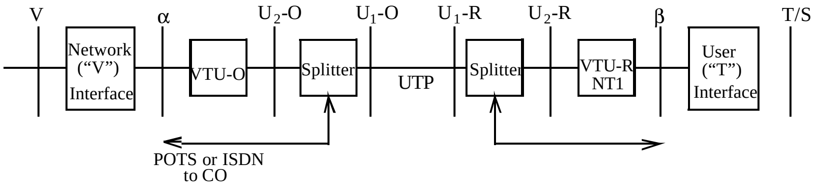


Figure 2: VDSL functional reference model

VDSL will find applications in the transport of various protocols; this specification covers the ATM and STM (SDH) transport, but the VDSL core transceiver is capable of supporting future additional applications. Internal structures of the different Transport Protocol Specific - Transmission Convergence (TPS-TC) layers are developed for those applications. Figure 3 shows the functional decomposition of the VDSL with their reference points.

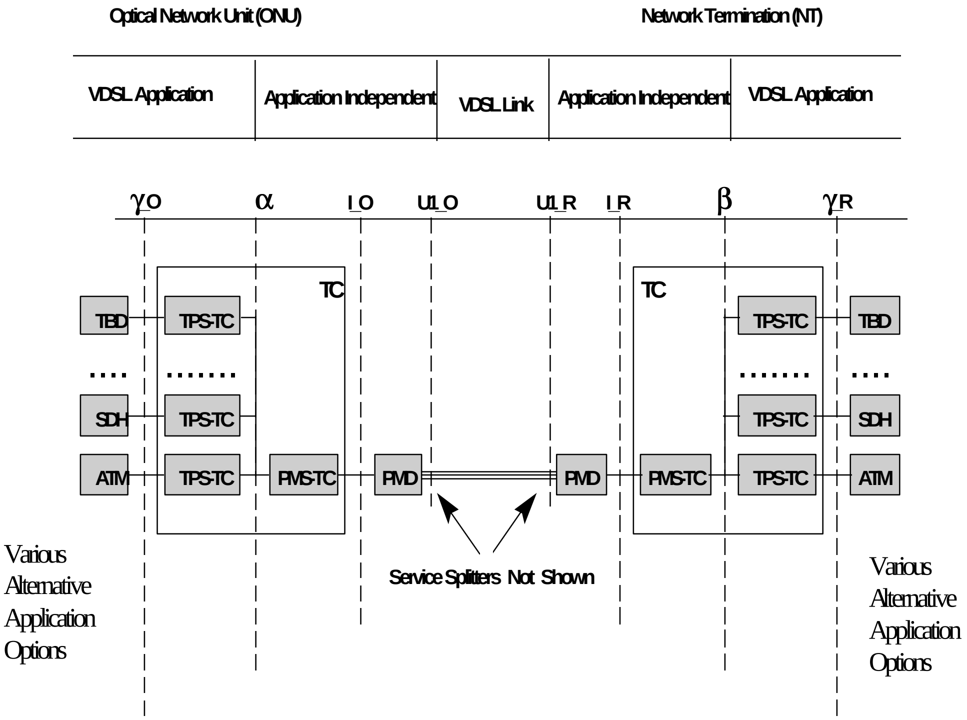
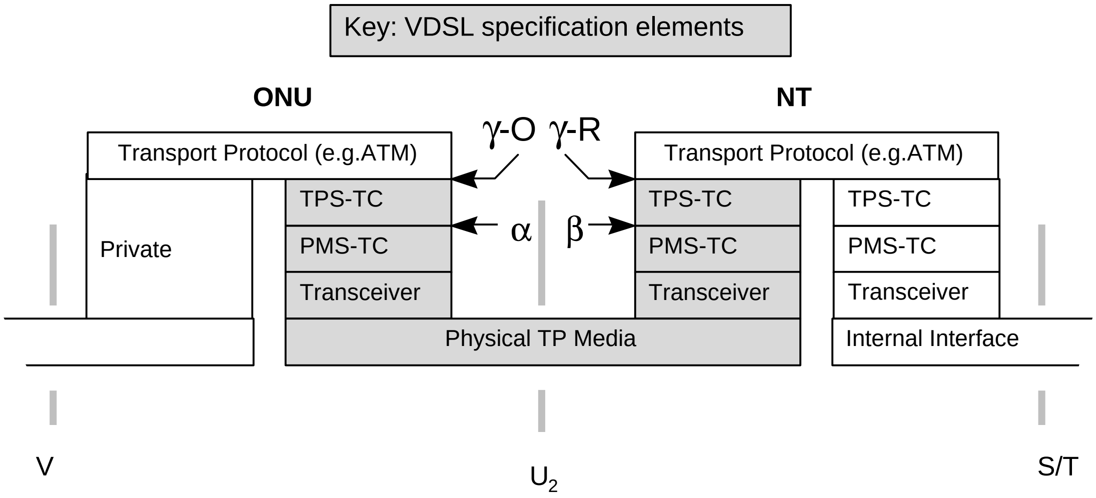


Figure 3: Functional decomposition

The Transmission Convergence (TC) layer is split into a protocol specific part (TPS-TC part) and an application independent part (the Physical Medium Specific-Transmission Convergence (PMS-TC) part). The application independent part contains Physical Medium Specific transmission convergence layer functions (PMS-TC) and the transceiver (PMD) functions. The respective positions of the different interfaces, with respect to the VDSL sublayers, are shown in Figure 4.



TPS-TC	Transport Protocol Specific Transmission Convergence Layer
PMD-TC	PMD Specific Transmission Convergence Layer
VDSL-TP-RP	VDSL Tansport Protocol ReferencePoint

Figure 4: VDSL application reference model

2.1.1.1 Network termination

The network termination NT1 in Figure 2 performs termination of the VDSL modulation scheme, link control and maintenance functions, and provides one or more application-specific interfaces (S- or T-proprietary) to customer equipment. The reference model does not imply specific ownership of the NT1 equipment by customer or network operator.

2.1.1.2 Splitters

The splitters separate VDSL signals from signals of other services, such as PSTN/POTS or ISDN signals.

2.1.1.3 V reference point

The V reference point is at the physical network interface between the VTU-O and the ONU. A logical α interface is embedded within the V-interface in the VTU-O reference model of Figure 5.

2.1.1.4 U reference points

PSTN/POTS signals can occupy the same physical media as the VDSL signal by using splitters. Thus, the U_1 reference point refers to copper-pair media carrying composite signals, whereas the U_2 reference point specifies the VDSL modem ports only.

2.1.1.5 S and T reference points

The access termination point (ATP) specifies the protection and distribution cable termination.

2.1.2 VTU-O reference model

The VTU-O, which is the VDSL transmission unit located at the ONU, converts digital data to and from the continuous-time physical layer VDSL signals. Figure 5 illustrates the VTU-O reference model. Four channels are provided, two each for upstream and downstream transmission. Each of the four channels supports a constant bit rate. Dual latency is provided in both directions: one channel supports a low-latency, higher BER bitstream and the other a higher-latency, lower BER bitstream. The low-latency and higher-latency channels are also called the “fast” and “slow” channels, respectively. Appropriate forward error correction (FEC) and interleaving are used on all four channels. Specific FEC and interleaving parameters are presented in Sections 5.1.2 and 5.1.3, respectively.

The α interface is a logical application-independent reference interface. The application-specific V interface converts between the logical interface and the ONU interface. The core modem handles all modulation functions and presents (accepts) an analog signal to (from) the U_2 interface. Link maintenance and control are discussed in Section 6.

Associated with each data flow is implicit or explicit byte synchronization, which is maintained across the VDSL link. The modem provides the master clock for the downstream channels, which may be expressed at bit or byte frequency. Clock-rate adaptation is the responsibility of the transport protocol-specific TC layer (for example, by idle cell insertion/deletion in the case of ATM).

Because the interfaces are logical interfaces, data may be transferred in any format. In particular, both constant bit rate transmission and burst transmission can be supported. However, the average bit rate supported by each channel is constant; the depth of buffering required to support variable bit rate applications is implementation-dependent and outside the scope of this specification. Both the α and β interface flows are determined by OAM parameters at the VTU-O.

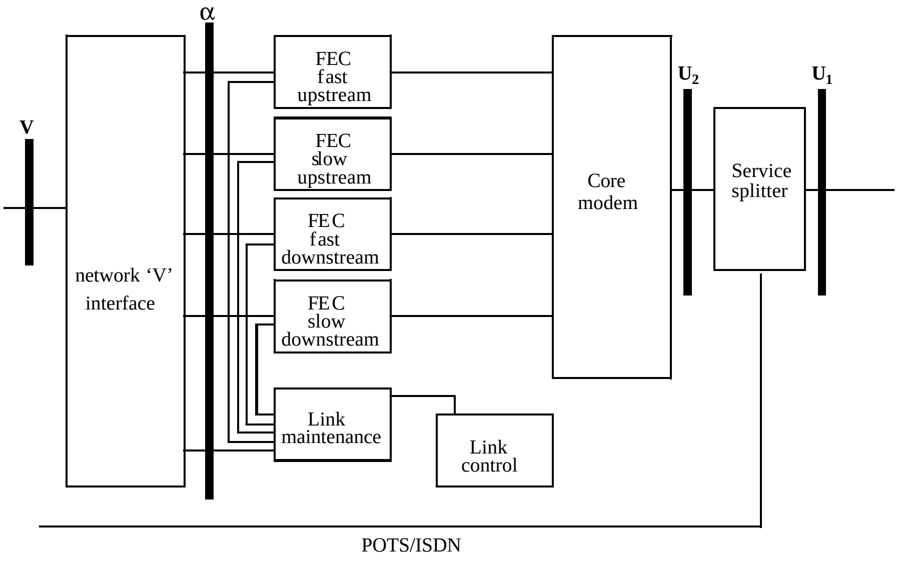


Figure 5: VTU-O reference model

2.1.3 VTU-R reference model

The VTU-R, which is the VDSL transmission unit at the remote location (typically the CP), converts digital data to and from the continuous-time physical-layer VDSL signals. The VTU-R is nearly identical to the VTU-O, as illustrated by the VTU-R reference model shown in Figure 6. The four constant bit rate channels discussed in the preceding section (fast and slow upstream, and fast and slow downstream) are shown.

The β interface is a logical application-independent reference interface. The application-specific S/T interface converts between the logical interface and the premises wiring. The core modem performs all modulation functions and presents (accepts) an analog signal to (from) the U_2 interface. Link control and maintenance are described in Section 6.

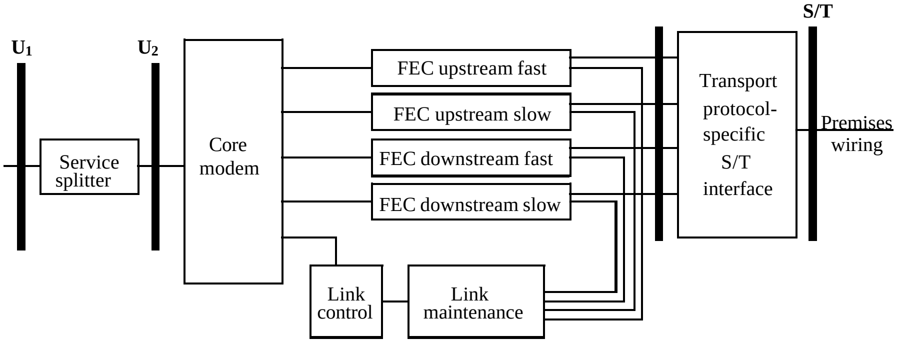


Figure 6: VTU-R reference model

2.1.4 Elemental information flow across the α and β interfaces

Furthermore, as shown in Figure 7, in the VDSL functional reference model, two α interfaces are defined for the LT:

α1: Interface between TPS-TC and PMS-TC Transport functions
α2: Interfaces between PMD-TC & PMD-LM PMS-TC & PMS-LM

For the NT, β1 and β2 apply, respectively.

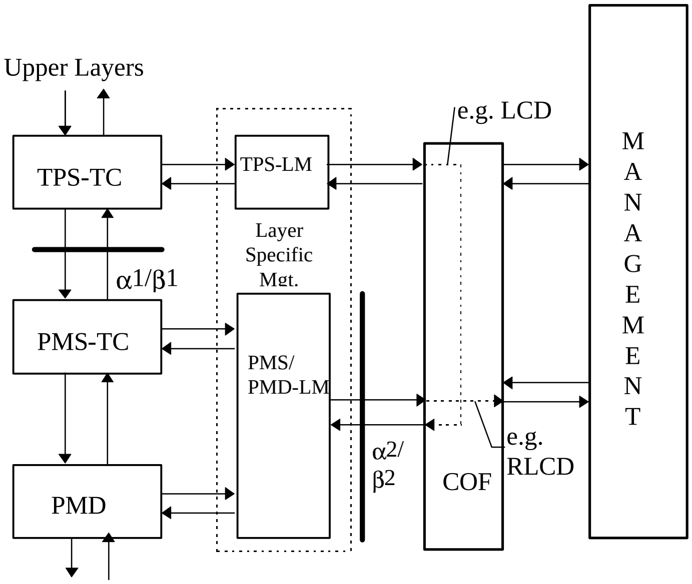


Figure 7: VDSL functional reference model

Five elemental information flows across the α and β interfaces are identified :

- Data flow (α1 and α1);
- Synchronization flow (α1 and β1);
- Link control flow (α2 and β2);
- Link performance and path characterization flow (α2 and β2);
- VDSL TPS-TC performance information flow (between LT and NT).

The flows across the α1 interface are described in Table 1.

Table 1. Information flows across the α1 interface

α1	**Data flow**	**Signal**	**Size (bits)**
->	Downstream low-latency (fast) channel	data	1
<-		bit sync	1
->		byte sync	1
->	Downstream high-latency (slow) channel	data	1
<-		bit sync	1
->		byte sync	1
->	Upstream low-latency (fast) channel	data	1
<-		bit sync	1
->		byte sync	1
->	Upstream high-latency (slow) channel	data	1
<-		bit sync	1
->		byte sync	1

2.1.4.1 Data flow

The data flow shall be supported by one or two data pipes with different error protection properties and therefore different latency characteristics; it shall be byte oriented, and the data shall be treated as unstructured by the application independent part.

2.1.4.2 Synchronization flow

This flow provides the means through which synchronization between the PMD level and the TC level is performed. The different considered items are:

- Data (bit synchronization or byte synchronization or other synchronization flows);
- Performance and Path Characterization Primitives;
- Control and Performance Parameters (asynchronous);
- Network Timing Reference (downstream).

With the exception of Control and Performance parameter passing synchronization flows are based on a fixed timing regime. Synchronization of Control and Performance Parameter passing is implied by a message transfer protocol.

2.1.4.3 Link control flow

The Link Control flow comprises all the relevant control, configuration and status messages for VDSL link. A non-exhaustive list of Control Primitives is (common to both the α and β interfaces):

- Activation;
- Deactivation;
- Alarms and Anomalies (e.g. Dying Gasp);
- Link status;
- Synchronization status.

Control Parameters may be include the Requested Data Rate, Link Status parameters and specific bandwidth allocation parameter (at the α interface).

2.1.4.4 Link performance and path characterization flow

The Link Performance and Path Characterization flow provides all the relevant performance and physical characteristics of the VDSL link.

Performance Primitives typically report defects and errors (e.g. Loss of Signal, Loss of Frame, FEC anomalies etc.) and Performance Parameters include counts of errored blocks, CRC and FEC anomalies.

Typical Path Characterization Parameters are the line attenuation, the Signal to Noise Ratio (SNR) and the Return Loss.

2.1.4.5 VDSL TPS-TC performance information flow

The application independent part shall provide means for transporting indication of remote anomalies detected in the TPS-TC (such loss of cell delineation), not relying on the correct operation of the TPS TC sub-layer.

2.1.5 VDSL reference model for SDH transport

Figure 8 shows the VDSL functional reference model as applied to the SDH application.

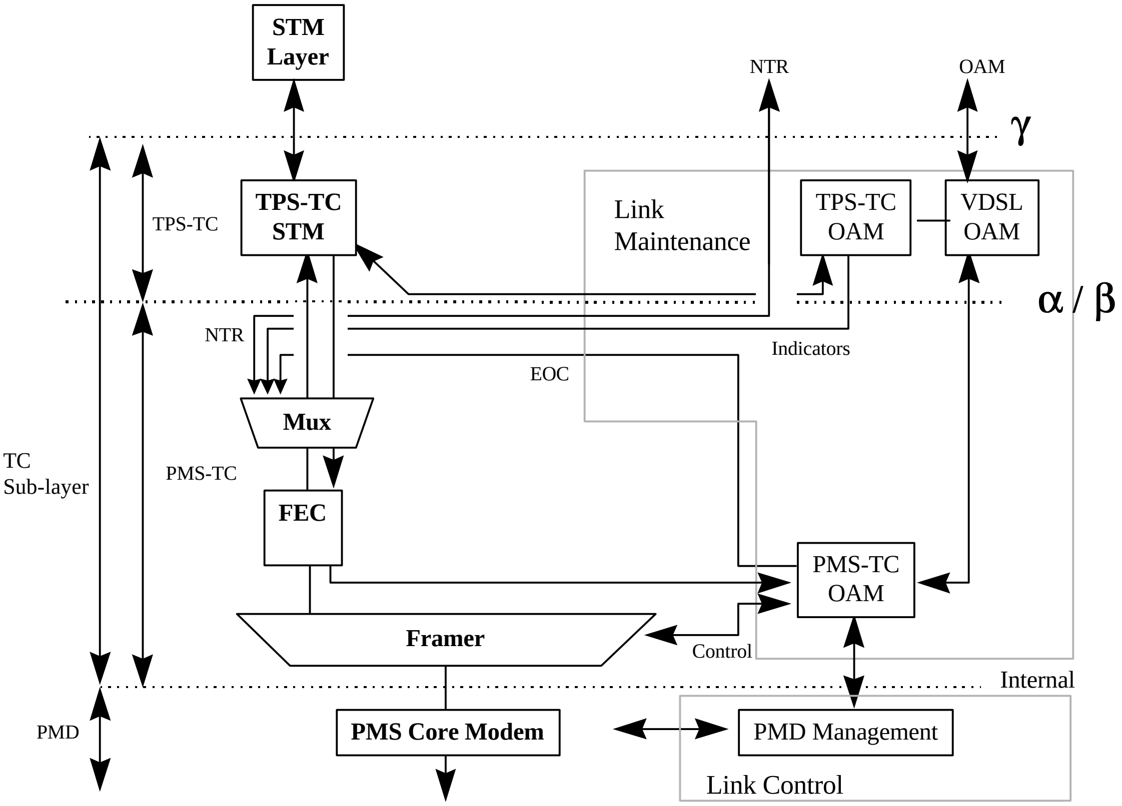
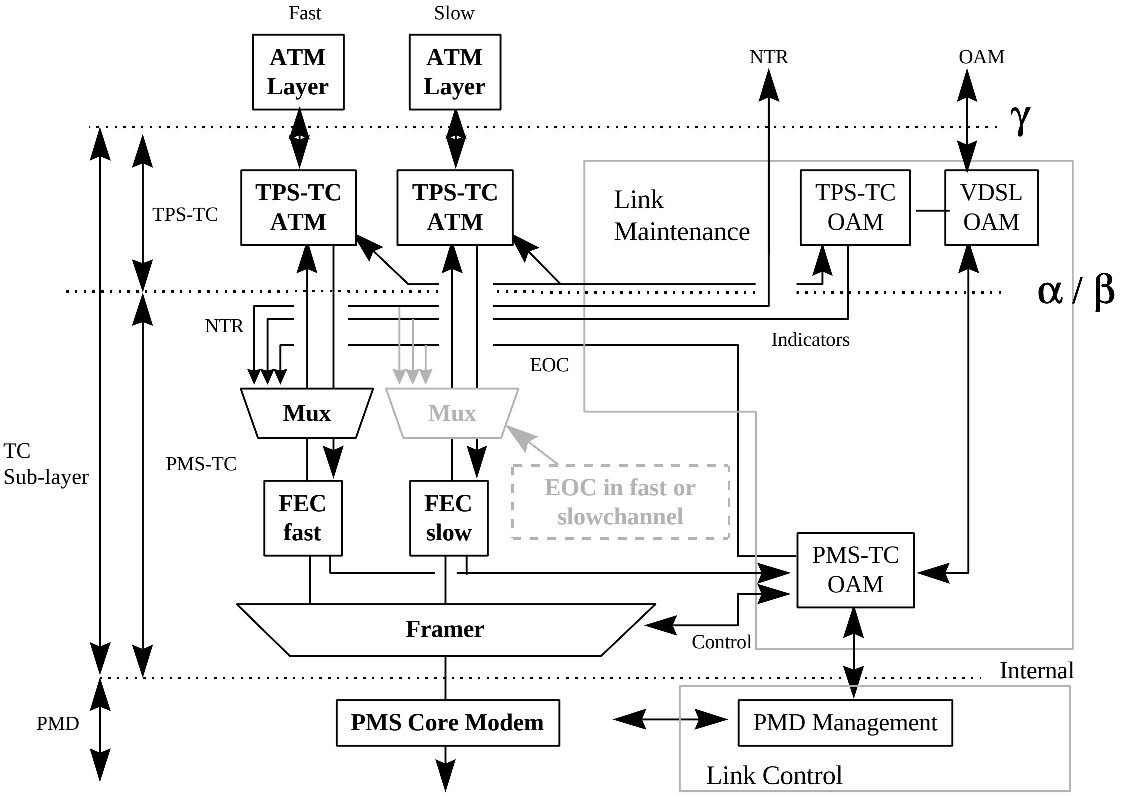


Figure 8: VDSL functional reference model applied to SDH

2.1.6 VDSL reference model for ATM transport

Figure 9 shows the VDSL functional reference model as applied to the ATM application.



NOTE 1: It is not compulsory to implement both the fast and slow channels. Single channels with programmable latency are equally acceptable.

NOTE 2 : The EOC shall support the transport of indicator states to support the status and performance monitoring of the VDSL PMD layer.

Figure 9 : VDSL functional reference model applied to ATM

3 Transport capacity capabilities

Systems complying with this specification shall be capable of supporting both symmetric and asymmetric transmission between the ONU and the customer premise. Specifically, a compliant system shall support at least the downstream-to-upstream payload bit rate ratios given in Table 2. The exact downstream and upstream payload bit rates supported on a particular line will depend on the loop and noise conditions; rate adaptivity at start-up in steps of 64N kbps (where N is TBD) is required. Tables 3 and 4 give examples of asymmetric and symmetric payload bit rate combinations that compliant modems will be capable of supporting, subject to loop and noise conditions.

Table 2. Required downstream-to-upstream payload bit rate combinations

8:1

6:1

4:1

3:1

2:1

1:1

Table 3. Asymmetric VDSL payload bit rate combinations

Downstream (kbps)	**Upstream (kbps)**
50 x 1024	6.25 x 1024
24 x 1024	6 x 1024
24 x 1024	4 x 1024
12 x 1024	6 x 1024
12 x 1024	4 x 1024
12 x 1024	2 x 1024
6 x 1024	2 x 1024

Table 4. Symmetric VDSL payload bit rates

Downstream and Upstream (kbps)
24 x 1024
12 x 1024
6 x 1024

3.1 Transport of SDH data

For further study.

3.2 Transport of ATM data

A VDSL system shall support ATM transport, at least in a single latency mode.

For ATM systems the channelization of different payloads is embedded within the ATM data stream using different Virtual Paths and/or Virtual Channels. Hence, the basic requirements for ATM are for at least one VDSL channel downstream and at least one VDSL upstream channel.

The need for dual latency for ATM services depends on the service/application profile. One of the three different "latency classes" may be used:

- Single latency, not necessarily the same for each direction of transmission;
- Dual latency downstream, single latency upstream;
- Dual latency both upstream and downstream.

Additional ATM aspects of the specification are given in Section 5.

3.3 Transport of Network Timing Reference

Some services require that a reference clock be available in the higher layers of the protocol stack (that is, above the physical layer); this is used to guarantee end-to-end synchronization of transmit and receive sides. Examples are Voice and Telephony Over ATM (VTOA) and Desktop Video Conferencing (DVC).

To support the distribution of a timing reference over the network, the VDSL system shall transport an 8 kHz timing marker as the network timing reference (NTR). This 8 kHz timing marker may be used for voice/video playback at the decoder (D/A converter) in DVC and VTOA applications. The 8 kHz timing marker is input to the VTU-C as part of the interface at the V reference point.

For ATM mode, provision of NTR transport capability by the VTU-C is mandatory; the network operator may choose not to use the NTR.

4 Physical Medium-Dependent (PMD) Sublayer Specification

This section overviews the PMD sublayer of the SDMT specification. Two duplexing schemes are accommodated: time-division duplexing (TDD) and frequency-division duplexing (FDD). Section 4.1 explains the TDD SDMT implementation, and Section 4.2 describes the specific FDD implementation called Zipper. Sections 4.3through 4.6are common to both the TDD and Zipper specifications.

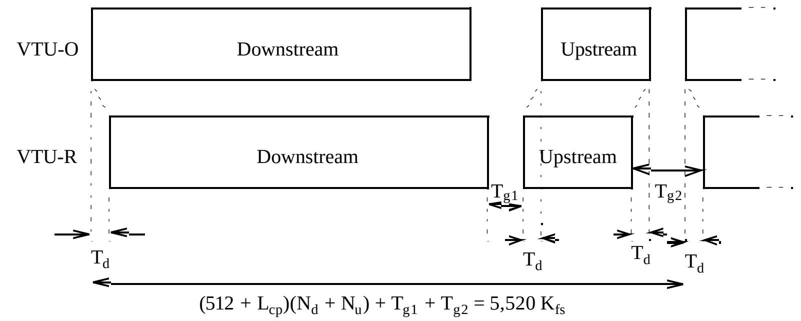
4.1 TDD Specification

4.1.1 Overview

One system specified in this document uses a time-division duplexed implementation of synchronized discrete multitone (SDMT) to transport data over the VDSL line. This section overviews the technique; upcoming sections detail specific system parameters.

In the time-division duplexed (TDD) implementation of discrete multitone (DMT) a transceiver may either transmit or receive DMT signals at any given time. The system uses a superframe structure to coordinate which symbols in the data path are used for downstream and upstream transmission. To prevent lines co-located at the ONU (or local exchange) from injecting near-end crosstalk (NEXT) into each other, all VTU-O and VTU-R transmissions are synchronized at the ONU to a common superframe structure to ensure all transmissions in each direction coincide. Synchronization may be achieved in any number of ways and does not necessarily require use of a common clock. Contribution T1E1.4/96-247 describes the add/delete method, which is one way to synchronize superframes without requiring a common clock.

A superframe is a set of successive DMT symbols. Each superframe is composed of two types of symbols, downstream and upstream, and silent intervals whose durations may or may not be integer multiples of a symbol period. Downstream symbol periods are used by the VTU-O to transmit data to the VTU-R; upstream symbol periods are used by the VTU-R to transmit data to the VTU-O. The sets of downstream and upstream symbols are separated by silent periods that allow the channel echo response to decay sufficiently before reception in the opposite direction begins. Figure 10 illustrates an asymmetric superframe structure.



T_d = propagation delay of transmission path, in units of samples at $K_{fs}f_s$ Hz
T_{g1}, T_{g2} = guard times, in units of samples at $K_{fs}f_s$ Hz
L_{cp} = length in samples of cyclic prefix
N_d = number of symbols allocated for downstream transmission
N_u = number of symbols allocated for upstream transmission
K_{fs} = sampling frequency factor (1, 2, or 4)

Figure 10: Asymmetric TDD superframe structure

Asymmetric transmission is supported when the number of downstream symbol periods exceeds the number of upstream symbol periods. When equal numbers of symbols are allocated to both the upstream and downstream directions, symmetric transmission is supported.

During downstream symbol periods, the bitstream is encoded by the VTU-O transmitter into a set of quadrature amplitude modulated (QAM) subsymbols, where each QAM subsymbol represents a number of bits determined by the signal-to-noise ratio (SNR) of its associated subchannel, the desired overall error probability, and the target bit rate. The set of subsymbols is then input as a block to a complex-to-real inverse discrete Fourier transform (IDFT). Following the IDFT, a cyclic prefix is prepended to the output samples to eliminate intersymbol interference, and the result is converted from digital to analog format and applied to the channel. At the VTU-R receiver, after analog-to-digital conversion, the cyclic prefix is stripped, and the samples are transformed back to the frequency domain by a DFT. Each output value is then scaled by a single complex number to compensate for the magnitude and phase of each subchannel's frequency response, and a memoryless detector decodes the resulting symbols. The set of complex numbers, one per subchannel, is called the frequency-domain equalizer (FEQ). Figure 11 shows a block diagram of a DMT transmitter and receiver pair, assuming a noiseless channel.

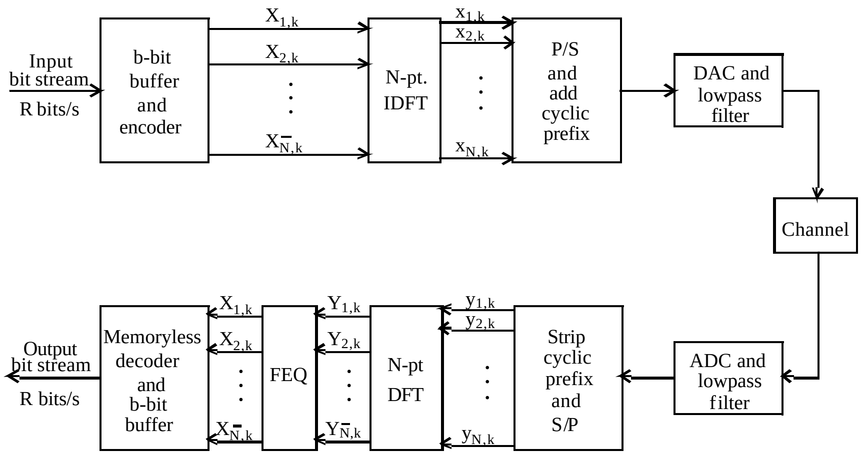


Figure 11: DMT transmitter/receiver pair

In steady-state, the subchannel SNRs are monitored in a data driven manner by the VTU-R during downstream symbol periods, and the bit distribution is modified as necessary at the VTU-O to maintain near-optimal system performance. Upon detecting degradation in one or more subchannel SNRs, the VTU-R computes a modified bit distribution that better achieves the desired error performance. Depending on the SNR of a degraded subchannel, some or all of its bits may be moved via a bit swap algorithm to one or more other subchannels that can support additional bits. The bit distribution change is reported to the VTU-O, where it is implemented. Details about bit swapping can be found in Section 4.5.2.

During upstream symbol periods, the roles of the VTU-O and VTU-R are reversed, but the operation is the same.

4.1.2 TDD VTU functional characteristics

Because the proposed system is DMT-based and operates in a time-division duplexed (TDD) fashion, a number of functions are common to both the VTU-O and VTU-R. This section describes these functions. Requirements specific to the VTU-O and VTU-R are described in Sections 4.1.3 and 4.1.4, respectively.

4.1.2.1 Discrete multitone modulation

4.1.2.1.1 Sampling rate

To enable support of a wide range of loop conditions and data rate requirements, compliant modems shall support up to three sampling rates. Some services, typically lower bit rate services, shall be supported using a sampling rate of f_s = 11.04 MHz. Other services shall be supported by increasing the sampling rate to $2f_s$ (22.08 MHz) or $4f_s$ (44.16 MHz) while maintaining the number of subchannels into which the bandwidth is partitioned. (See Section P.TDD.2.1.2.) Support of the $2f_s$ sampling rate is mandatory. The appropriate sampling rate and data rate combination is determined during initialization, and either the VTU-O or VTU-R may reject any optional sampling rate.

For ease of notation in this specification, parameters specific to the f_s, $2f_s$, and $4f_s$ systems are written as $X\ (Y,\ Z)$, where X is the value appropriate for the system with sampling rate f_s, and Y and Z are the values appropriate for the $2f_s$ and $4f_s$ systems, respectively. For additional notational convenience, sampling rates shall sometimes be expressed in this specification as $K_{fs}f_s$, where the value of K_{fs} may be 1, 2, or 4. K_{fs} shall be referred to as the sampling rate factor.

4.1.2.1.2 Subchannels

The frequency range from zero to 5.52 (11.04, 22.08) MHz shall be partitioned into 256 subchannels. The frequency spacing between carriers is 21.5625 (43.125, 86.25) kHz.

4.1.2.1.3 Data subchannels

Transmission may occur on up to 255 subchannels, although those subchannels overlapping the POTS and ISDN bands and the restricted amateur radio frequency bands shall not be used in the default configuration. The lowest subchannel available to support data transmission will be dependent upon the choice of sampling rate and on the POTS/ISDN splitter design and shall be configurable by the network operator via the network management software.

4.1.2.1.4 Pilot

The subchannel at f = TBD MHz shall be reserved for a pilot irrespective of sampling rate. The data modulated onto the pilot is TBD.

4.1.2.1.5 Nyquist frequency

The subchannel centered at the Nyquist frequency (subchannel 256) shall not be used for data.

4.1.2.1.6 Modulation by the inverse discrete Fourier transform (IDFT)

The encoder generates 255 complex values Z_i, plus zeros at dc and Nyquist because the subchannels centered at 0 and Nyquist are not used. To generate real, time-domain values x_k using a complex-to-real IDFT, the set of frequency-domain values Z_i is augmented to generate a new vector Z'. The vector Z' is Hermitian, meaning its real part is even and its imaginary part is odd. That is,

$$Z_i' = \text{conj}\,(Z_{512-i}), \qquad i = 257 \text{ to } 511$$

The vector *Z'* is then transformed to the time domain by an inverse discrete Fourier transform (IDFT). The modulating transform defines the relationship between the 512 real, time-domain values x_k and the 512 complex numbers Z_i':

$$x_k = \sum_{i=0}^{511} Z_i' \exp\left(\frac{j\pi ki}{256}\right), \qquad k = 0 \text{ to } 511$$

4.1.2.1.7 Cyclic prefix

The last L_{cp} samples (where L_{cp} can be any number less than or equal to 64) of the IDFT output shall be prepended to the block of 512 time-domain samples x_k and read out to the digital-to-analog converter (DAC) in sequence. That is, the subscripts *k* of the DAC samples in the sequence are $(512 - L_{cp})$,...,511,0,1,...511.

4.1.2.2 Superframes

The VTU-O shall group together 5,520 K_{fs} consecutive samples as a superframe, where K_{fs} is the sampling frequency factor as defined previously. A symbol is composed of 512 time-domain samples preceded by a cyclic prefix of length L_{cp}. Superframes are denoted as N_d-Q-N_u-Q, where N_d is the number of symbols allocated for downstream transmission, N_u is the number of symbols allocated for upstream transmission, and the Qs represent two silent periods. The durations of the silent periods, in samples, are T_{g1} and T_{g2}, where the values of T_{g1} and T_{g2} are dependent on the point on the line at which the channel activity is observed. (T_{g1} and T_{g2} at the VTU-O does not equal T_{g1} and T_{g2} at the VTU-R, but the sum of T_{g1} and T_{g2} is the same at all locations on the line.) The values of L_{cp}, N_d, N_u, T_{g1} and T_{g2} must be chosen to satisfy the relation

$$(512 + L_{cp})(N_d + N_u) + T_{g1} + T_{g2} = 5{,}520\ K_{fs}.$$

For a given K_{fs}, N_d and N_u are chosen to satisfy the downstream-to-upstream bit rate ratio requirements. The sum of the silent period durations is then determined by the choice of L_{cp}. Table 5 details example superframe structures to support downstream:upstream bit rate ratios of 8:1, 2:1, and 1:1 for the three possible K_{fs} values.

Table 5. Examples of superframe structures for 8:1, 2:1, and 1:1 downstream-to-upstream data rate ratios

Sampling rate factor K_{fs}	Downstream:Upstream bit rate ratio	Superframe structure N_d-Q-N_u-Q
1	8:1	8-Q-1-Q
	2:1	6-Q-3-Q
	1:1	4-Q-4-Q or 5-Q-5-Q
2	8:1	16-Q-2-Q
	2:1	12-Q-6-Q
	1:1	9-Q-9-Q
4	8:1	32-Q-4-Q
	2:1	24-Q-12-Q
	1:1	18-Q-18-Q or 19-Q-19-Q

Table 5 gives example superframe structures, but the structure for a particular connection will depend on a number of factors, including the choice of L_{cp}. However, the duration of a superframe shall always be 500 µs, or 5,520K_{fs} samples, irrespective of sampling frequency. The superframe frequency is thus always 2 kHz.

4.1.2.3 Synchronization

4.1.2.3.1 Loop timing

To enable coordinated upstream and downstream transmissions, when a common clock is available all VTU-Os and VTU-Rs that share a cable shall be synchronized to this common clock. If used, a master clock signal shall be broadcast downstream from the VTU-O. During all phases of communication, each VTU-R shall loop time its local sampling clock to the master clock, which ensures that all VTU-Rs transmit with respect to the same clock signal. The locking of the sampling clock to the superframe clock can be done either by an analog tuning of the sampling clock or by digital interpolation in either the time or frequency domain.

4.1.2.3.2 Methods to ensure superframe synchronization

The 2 kHz superframe clock, which is available at all VTU-Os, shall be derived from a reference clock (for example, GPS). It shall be guaranteed that the superframe clock is phase-synchronous in all VTU-Os in a shared cable with a TBD maximum phase error tolerance. It is the responsibility of the operator to provide this clock to the ONU backpanel. An example of clock broadcast is shown in Figure 12. The jitter, wander, and duty cycle of the frame clock are TBD.

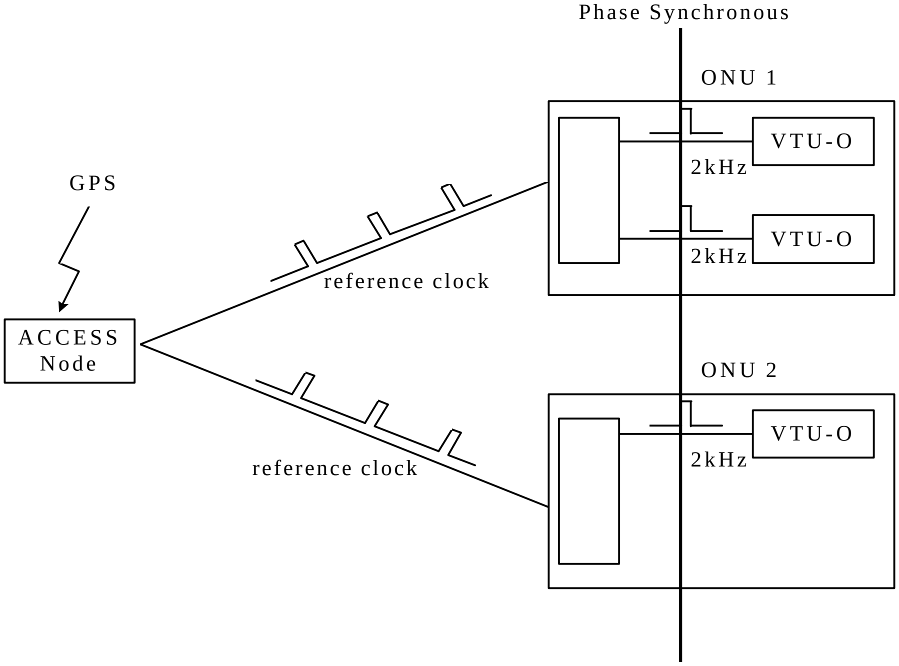


Figure 12: Example of synchronization strategy for generating the 2 kHz superframe clock

The downstream time slots of all VTU-Os in the same binder shall be synchronized to the rising edge of the 2 kHz superframe clock. The synchronization error shall be measured at the U_1-O interface (on the line after the analog filters). The method of measuring the error is TBD. The maximum tolerable synchronization error is TBD.

4.1.3 Functional characteristics specific to the VTU-O

This section describes the procedure to adjust the VTU-O transmit power level, if necessary. The α interface is also described here.

4.1.4 Functional characteristics specific to the VTU-R

This section is the complement to Section 4.1.3 and includes a discussion of power cut-back at the VTU-R. The β interface is also defined here.

4.1.4.1 VTU-R ranging

For further study.

4.2 Zipper (FDD) Specification

4.2.1 Overview

The specified system uses discrete multi-tone modulation based on the Zipper duplexing scheme to transport data over the transmission channel. This section overviews the technique; the following sections detail specific system parameters.

Zipper is a frequency-division duplexed (FDD) implementation of DMT with the following characteristics:

1. The Zipper duplexing scheme implies that the frequency band from dc to the Nyquist frequency is divided into a set of 2048 DMT subcarriers. Each subcarrier is exclusively chosen to be used for either the upstream or the downstream direction.
2. Pulse shaping of the DMT frame is performed prior to transmission for reduction of the out of band power of the DMT signal. A time window is applied on the sampled DMT symbol at the receiver to obtain high spectral containment of interfering signals.
3. Two different modes of operation are offered by Zipper: synchronous mode and asynchronous mode. Common for the two modes is that the transmitters at the VTU-O and at the VTU-R on each copper wire pair transmit DMT symbols simultaneously with a common frame clock. In the synchronous mode all transmitters in a cable binder group are synchronized with a global common clock. In the asynchronous mode synchronization is only needed on a line-by-line basis between a VTU-O and its associated VTU-R.
4. When operating in synchronous mode, the cyclic extension of the symbols must be dimensioned for the maximum propagation delay of all the lines in the cable binder. This is to ensure the orthogonality between the signal and all the noise sources originating from DMT signals in the opposite direction (see Figure 13). Further, the size of the cyclic extension is minimized by applying timing-advance (TA).

Figure 13 depicts how two VDSL systems sharing the same cable binder are affected by line attenuation, echoes and cross-talk.

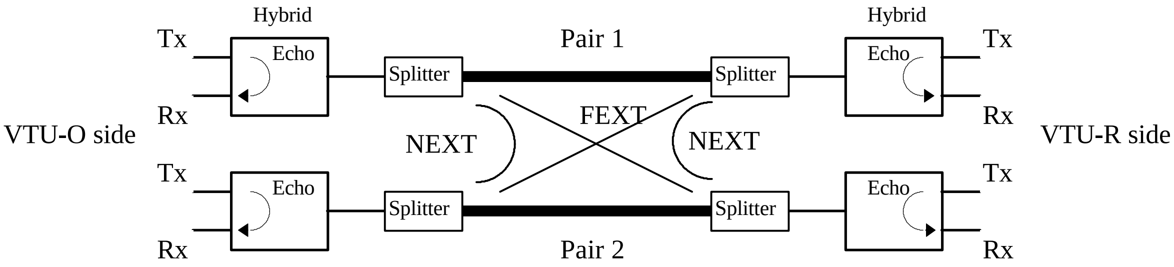


Figure 13: Disturbing signals that affect the orthogonality of a Zipper DMT-VDSL system

4.2.1.1 Synchronous Zipper mode

In the synchronous mode all transmitters at the VTU-O and VTU-R operating in the same cable binder are synchronized to a common frame clock. The Zipper scheme implies that every carrier, in the total set of carriers in the DMT signal, is chosen to be used exclusively for either the upstream or the downstream direction. When all transmitters are time-synchronized, the near-end cross-talk (NEXT) and near-end echoes injected in the received signal are orthogonal to the desired signal. To ensure the orthogonality between the signal and all the noise sources originating from DMT signals in the opposite direction, the cyclic extension of the symbols must be dimensioned for the maximum propagation delay of all the channels in the cable binder. For the dimensioning of the cyclic extension, the timing-advance is important to lower the required length.

When timing-advance is used, all transceivers start the transmission of each frame at the same time. There are three types of signals that affect the length of the cyclic extension in each frame: the received signal; the NEXT signal; and the echo signal due to imperfect balance of the hybrid and impedance discontinuities in the line. Figure 14 illustrates this concept.

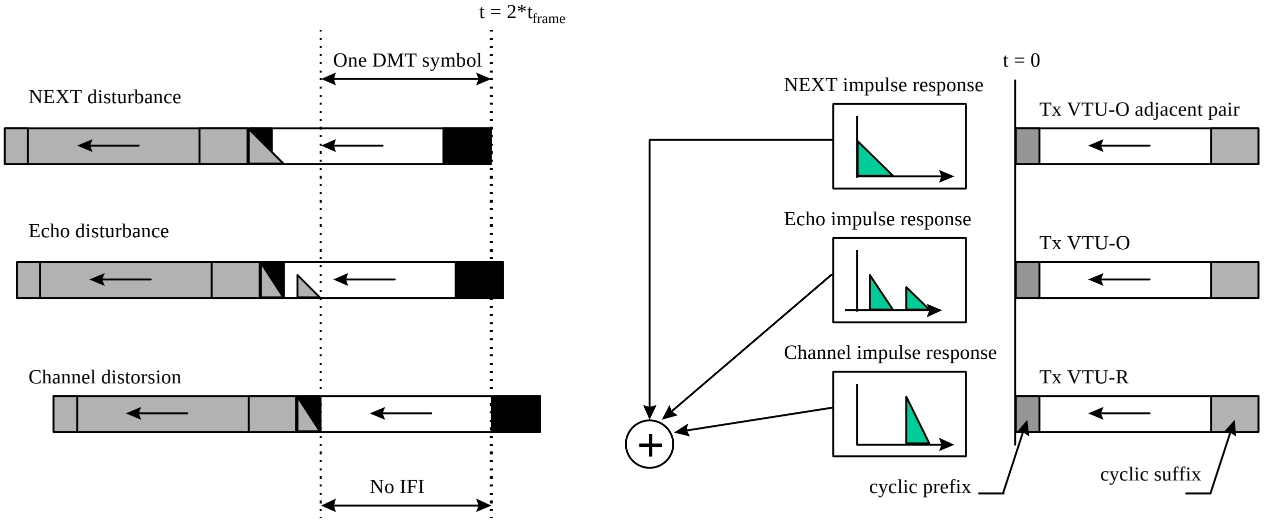


Figure 14: Sampling at the VTU-O side of received frame disturbed by frames from near-end transmitters

The orthogonality between the received desired signal and the disturbance is preserved if each sampled DMT symbol (the part that is fed to the DFT) is disturbed by no more than one single frame from each one of the near-end transmitters. As a consequence, the cyclic extension has to be dimensioned to cover all impulse responses of the lines, the echoes and the NEXT. The management of capacity split between upstream and downstream is performed by assigning the individual carriers to either direction. As an example, if fully symmetric services are desired, even carrier indexes can be assigned for the upstream direction and odd for the downstream direction. For an asymmetric 8:1 split each ninth carrier can be assigned for the upstream and the rest for the downstream. However, for the sake of spectral compatibility with other existing and future systems operating in the same cable binder, alternative carrier assignments grouping the carriers should be considered.

4.2.1.2 Asynchronous Zipper mode

In the asynchronous mode no global clock synchronization need to be performed between transceivers operating in the same cable binder. Synchronization is done on a line-by line basis only, synchronizing a VTU-R with its associated VTU-O. When Zipper operates asynchronously the non-orthogonal NEXT will be suppressed by the pulse shaping and by the windowing (see Sections 4.2.2.1.6 and 4.2.2.1.7, respectively). To exploit the NEXT reduction, the upstream and downstream carriers should be grouped in larger blocks, that is, larger and fewer upstream and downstream frequency bands. This is in contrast with the synchronized mode where a change of direction can be done with every subcarrier. Synchronization and timing-advance are still needed within each separate pair to maintain orthogonality to the self-echoes that otherwise would be a severe disturbance. In the asynchronous mode the cyclic extension can be dimensioned individually for each line according to its propagation delay and impulse responses. The asynchronous mode has a small performance penalty compared to the synchronous mode but is intended for situations where global clock synchronization cannot be provided or is undesirable. The penalty associated with the asynchronous mode is slightly lower performance on long cables (in comparison with the synchronous mode) and lower flexibility in the frequency allocation for upstream and downstream bands. The latter is however unlikely to be a bottleneck in practice. Contribution T1E1.4/98-041 describes synchronous versus asynchronous mode in more detail.

4.2.1.3 Transmission and reception

The transmission and reception of symbols is performed simultaneously at both ends by the VTU-O and by the VTU-R. For downstream transmission the bitstream is encoded by the VTU-O transmitter into a set of quadrature amplitude modulated (QAM) sub-symbols, where each QAM sub-symbol represents a number of bits determined by: the signal-to-noise ratio (SNR) of its associated downstream subchannel; the desired overall error probability; and the target bit rate. The set of sub-symbols is then input as a block to a complex-to-real inverse discrete Fourier transform (IDFT). Following the IDFT, a cyclic prefix is prepended to the output samples to eliminate intersymbol interference, and a cyclic suffix is appended to the output samples to maintain orthogonality between the desired signal and near-end distorting signals. The result is converted from digital to analog format and applied to the channel. At the VTU-R receiver, an analog-to-digital conversion takes place, the cyclic prefix and suffix are stripped, and the samples are transformed back by a DFT. Each output value is then scaled by a single complex number to compensate for the magnitude and the phase of each downstream subchannel's frequency response, and a detector decodes the resulting symbols. The scaling and phase rotation, one per downstream subchannel, is called frequency-domain equalization (FEQ). Figure 15 shows a block diagram of a Zipper DMT transmitter and receiver pair, assuming a noiseless channel.

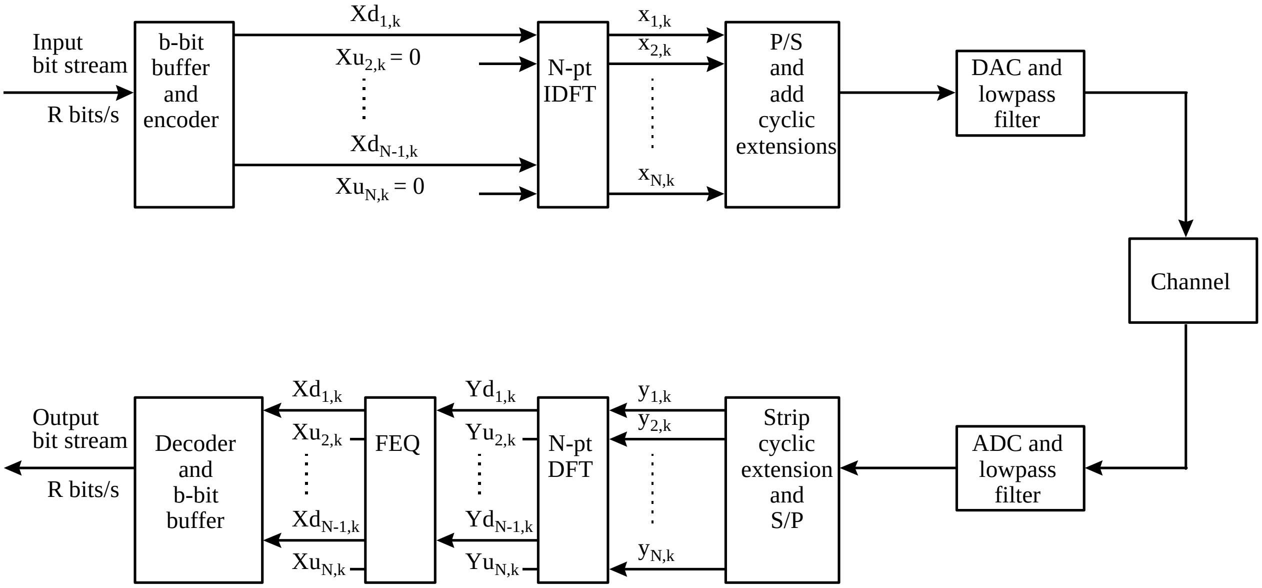


Figure 15: Zipper DMT transmitter/receiver pair for downstream transmission, configured such that every other carrier is used to support downstream transmission; remaining carriers are used to support upstream transmission. Upstream carriers are italicized.

In steady-state, the subchannel SNRs are monitored in a data-driven manner by the VTU-R for the downstream, and the bit distribution is modified as necessary at the VTU-O to maintain system performance. Upon detecting degradation in one or more of the subchannel SNRs, the VTU-R computes a modified bit distribution that better achieves the desired error performance. Depending on the SNR of a degraded subchannel, some or all of its bits may be moved via a bit-swap algorithm to one or more other subchannels that can support additional bits. The bit distribution change is reported to the VTU-O, where it is implemented. Details about bit swapping can be found in Section 4.5.2.

For upstream transmission, the roles of the VTU-O and VTU-R are reversed, that is, transmission and reception are performed on the upstream set of subchannels and the operations described above are the same.

4.2.2 Zipper VTU functional characteristics

Because the proposed system is DMT-based and operates in a Zipper duplexed fashion, a number of functions are common to both the VTU-O and VTU-R. This section describes these functions.

4.2.2.1 Discrete multi-tone modulation

4.2.2.1.1 Nyquist frequency

The Nyquist frequency shall be 11.04 MHz.

4.2.2.1.2 Subchannels

The frequency range from zero to 11.04 MHz shall be partitioned into 2048 subchannels. The Nyquist carrier (subchannel 2048), or equivalently, the dc carrier (subchannel 0) shall not be used for data.

4.2.2.1.3 Data subchannels

Transmission may take place on up to 2047 subcarriers, although those subcarriers overlapping the amateur radio frequency bands and the POTS band, or the ISDN band, shall not be used in the default configuration. The lowest subchannel available to support data transmission will dependent on the POTS/ISDN splitter design and shall be configurable by the network operator via the network management software.

4.2.2.1.4 Frame format

The frame format of Zipper consists of two parts: the DMT symbol and the cyclic extension. Orthogonality is maintained between the received signal and disturbing DMT signals transmitted in the opposite direction if they are sufficiently aligned in time. This requirement is fulfilled by the use of a cyclic extension of the DMT symbol and the use of timing-advance (TA). For ease of description the cyclic extension is divided into a cyclic prefix (CP) and a cyclic suffix (CS) part, where the suffix part is greater than the propagation delay of the channel and the prefix part is greater than the guard time needed to eliminate intersymbol interference. A fixed number of extra samples is added to both the prefix and suffix parts dedicated for the pulse shaping at the transmitter and for the windowing at the receiver (see Sections 4.2.2.1.6 and 4.2.2.1.7, respectively). The Zipper frame format is shown in Figure 16.

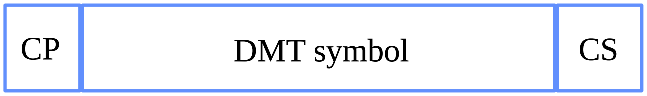


Figure 16: Frame format of Zipper

4.2.2.1.5 Cyclic extension

When timing-advance is used all the transmitters start transmitting at the same time. The suffix part of the cyclic extension is required to maintain orthogonality between up and downstream channels along the wire line. To fulfill the orthogonality requirement at the receiver, the cyclic extension (prefix + suffix) also has to cover the impulse responses of the NEXT and echo signals. Finally, the samples required for the pulse shaping in the transmitter and the windowing in the receiver have to be added to the prefix and the suffix. Denote the 4096 sample IDFT output with x_k. The first L_{cs} samples (where L_{cs} can be any number less than or equal to TBD) of x_k shall be appended to the block of 4096 time-domain samples. The last L_{cp} samples (where L_{cp} can be any number less than or equal to TBD) of x_k shall be prepended to the same block. The pulse shaping is applied to the outermost $\beta/2$ samples at both ends. The frame of samples is then read out to the digital-to-analog converter (DAC) in sequence. That is, the subscripts k of the DAC samples in the sequence are $(4096-L_{cp}),\ldots,4095,0,1,\ldots,4095,0,1,\ldots,(L_{cs}-1)$, with outermost $\beta/2$ samples on each side multiplied by the pulse shaping window.

The length of the cyclic extension ($L_{cp} + L_{cs}$), the number of samples to be affected by the pulse-shaping (β), and the number of samples used for the receiver windowing (μ), are all programmable entities set by the network operator.

4.2.2.1.6 Pulse shaping of the frame at the transmitter

Pulse shaping of the frame is performed at the transmitter to reduce the frequency-domain sidelobes of the DMT signal and thus the out-of-band power. To preserve orthogonality and to avoid inter-carrier interference, the pulse shaping is only applied to extra samples in the cyclic extension added to the frame for this purpose. The frame is extended cyclically with β/2 samples at each end prior to pulse shaping. These β/2 samples at each edge of the DMT frame are shaped with a raised cosine window. However, any two consecutive DMT-frames are transmitted with β/2 samples overlap, that is, the last β/2 samples of every symbol are added to the first β/2 samples of the following symbol, as shown in Figure 17. By this procedure the average transmitted power on the line is kept constant and the efficiency loss of introducing pulse shaping is halved.

The number of samples β to be used for pulse shaping is a programmable entity set by the network operator. The default setting of β shall be 140 samples. Thus, as a default 140 samples are added to the DMT frame, 70 of which are put on each side and shaped with a raised cosine. But, because of the overlap between symbols, the DMT-frame rate is decreased only as if the symbol length were increased by 70 samples.

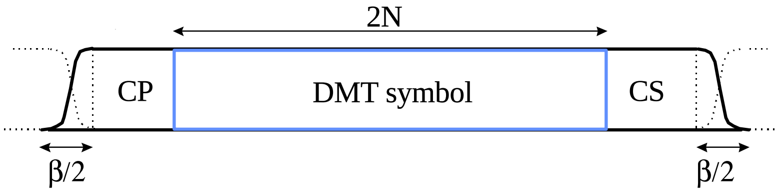


Figure 17: Pulse shaping of the Zipper frame prior to transmission

4.2.2.1.7 Windowing of the DMT symbol at the receiver

To obtain higher spectral containment of interfering signals, a time windowing operation shall be performed at the receiver. When the cyclic extension of the DMT symbol was dimensioned, μ samples were added for the purpose of this receiver windowing. The windowing is performed by first multiplying μ samples at the beginning and μ samples at the end of the 2N+μ block of samples. Then the outermost μ/2 samples from each end are added to their respective corresponding samples at the opposite end of the 2N remaining block of samples (c+a and b+d in Figure 18). To maintain orthogonality a symmetrical window is required. A raised cosine window shall be used.

The number of samples μ to be used for receiver windowing is a programmable entity set by the network operator. The default setting of μ shall be 70 samples. Thus, as a default 70 samples are added to the DMT frame, 35 of which are put on each end. But, at each end 70 samples are multiplied by the time window and shaped with a raised cosine.

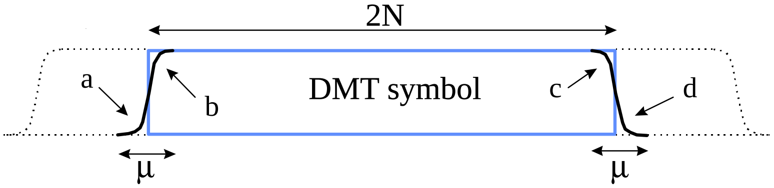


Figure 18: Windowing of the DMT symbol at the receiver

4.2.2.1.8 Timing advance

In order to maximize the duplex efficiency, timing-advance shall be used so that a VTU-O transmitter and its VTU-R transmitter start transmitting each DMT frame at the same time. For operation in synchronous mode, the timing advance is to make all VTU-O and VTU-R in the same binder group start transmission of DMT frames simultaneously, that is, to have a common frame clock. For operation in asynchronous mode, the timing advance is to make a VTU-O/VTU-R pair start their transmission of frames in opposite directions at the same time.

When operating in synchronous mode, a proper timing advance makes the NEXT become orthogonal to the desired signal with a minimum cyclic extension of the DMT symbol.

4.2.2.1.9 Modulation by the inverse Fourier transform (IDFT)

The encoder generates 2048 complex values Z_i, plus zeros at dc and Nyquist because the subchannels centered at 0 and Nyquist are not used. To generate real, time-domain values x_k using a complex-to-real IDFT, the set of frequency-domain values Z_i is augmented to generate a new vector Z'. The vector Z' is Hermitian, meaning its real part is even and its imaginary part is odd. That is,

$$Z_i' = \text{conj}\,(Z_{4096-i}), \qquad i = 2049 \text{ to } 4095$$

The vector Z_i' is then transformed to the time domain by an inverse discrete Fourier transform (IDFT). The modulating transform defines the relationship between the 4096 real, time-domain values x_k and the 4096 complex numbers Z_i':

$$x_k = \sum_{i=0}^{4095} Z_i' \exp\left(\frac{jpki}{2048}\right), \qquad k = 0 \text{ to } 4095$$

4.2.2.2 Synchronous Zipper mode

The defining characteristic of the synchronous mode of operation for Zipper is that all the VTU-O and VTU-R transceivers on the same cable binder have a common DMT frame clock, and thus start the transmission of DMT frames at the same time. This can, for example, be achieved by distributing the frame clock between all the VTU-Os and then letting each VTU-O synchronize its VTU-R. As the lengths of the individual lines in a cable binder in general are different and all VTU-R (and VTU-O) start transmitting at the same time, it is important that the size of the cyclic suffix corresponds to the propagation delay of the longest line. Then all NEXT become orthogonal to the desired signal.

When operating in synchronous mode there is no other restriction on carrier assignment for the upstream or downstream than that any subchannel should be used in no more than one direction in the same cable binder. Change of transmission direction can be done for every subchannel if so desired.

4.2.2.3 Asynchronous Zipper mode

The defining characteristic of the asynchronous mode of operation for Zipper is that only the VTU-O and VTU-R transceivers on the same line have a common DMT frame clock. No synchronization with transceivers operating on other lines is necessary. Compared to the synchronous mode of operation, the asynchronous mode has, in general, a performance penalty. For some cable binders the average line capacity may actually increase, but there is always a penalty for the capacity on the longest lines. The asynchronous mode is intended for situations where binder-by-binder frame synchronization is problematic to maintain or otherwise unfeasible.

In the asynchronous mode the cyclic extension can be set individually for each line, as opposed to being matched to the longest line as in the synchronous mode. Timing advance is still to be used, but on a line-by-line basis and negotiated between a VTU-O and its VTU-R. Synchronization between VTU-O transceivers is no longer necessary. The cyclic extension for each line can be preset upon installation or determined after measuring the channel during the cold start phase.

When operating in asynchronous mode the same restriction on carrier assignment as in the synchronous mode applies; in other words, any particular subchannel may be used only for either upstream or downstream in the same cable binder. In addition, change of transmission direction implies a performance penalty as non-orthogonal NEXT arises in the subchannels closest in frequency to where the change of transmission direction occurs. This may not be true if the change of direction takes place where nothing is transmitted, for example, in conjunction with the amateur radio bands. The subchannels should be assigned to the upstream or downstream in spectrally compact and, preferably, wide blocks. For the asynchronous mode it is imperative that pulse shaping at the transmitter and windowing at the receiver takes place. This reduces the spectral spreading of the non-orthogonal NEXT. The default setting of the pulse shaping and windowing should be sufficient for successful asynchronous mode operation.

4.2.2.4 Management of line rate and symmetry ratio by carrier assignment

When operating in synchronous mode all carriers in a Zipper duplex scheme can be regarded as independent of each other. This provides a large number of carrier configurations for symmetry ratios and transport classes that can be set up for the system as long as the same carrier is not used for both the upstream and the downstream in the same cable binder.

The carrier assignment according to line rate and symmetry ratio is a network operator controlled programmable feature. The carrier assignment should be optimized depending on the required services and the network topology. Contribution T1E1.4/97-138 describes a carrier allocation that is feasible in a central office VDSL installation.

4.2.2.5 Configurations for spectral compatibility

Zipper can be spectrally compatible with other frequency-division duplexed xDSL systems due to the inherent flexibility in assigning individual subcarriers for either upstream or downstream. Spectral compatibility can be achieved with almost no performance loss when pulse shaping at the transmitter and windowing at the receiver takes place as described, respectively in Sections 4.2.2.1.6 and 4.2.2.1.7.

Spectral compatibility with ADSL is maintained when the carriers in Zipper are configured so that only FEXT is introduced between the two systems. In a central office based VDSL installation no further adaptation in the transmit power need to be made for the sake of ADSL compatibility. In a FTTCab scenario where the ADSL equipment is installed in the central office and the VDSL equipment is installed in the cabinet, the VDSL transceivers may transmit at lower power [TBD] on a set [TBD] of spectrally overlapping carriers in order to not exceed the ADSL FEXT.

Zipper is spectrally compatible with single carrier FDD-VDSL systems when the subcarrier configuration is set to avoid NEXT between the two systems.

A detailed carrier assignment scheme for spectral compatibility is subject to further study.

4.2.2.6 Synchronization

4.2.2.6.1 Loop timing

The loop timing differs between the synchronous mode and the asynchronous mode. To enable coordinated frame transmission in the synchronous mode, all VTU-Os within the same cable binder use a common frame start time. Each VTU-R receiver synchronizes to this frame start time using the received data stream. In order to synchronize the frame start time of all VTU-R and VTU-O transmitters, an offset called timing-advance (TA), individual to each VTU-R, is subtracted from the received frame start time. The result is used as the VTU-R's individual transmitter frame start time. The TA should be equal to the propagation delay from the VTU-O to the VTU-R.

In the asynchronous mode no coordination between different VTU-Os is necessary. The timing-advance is set on a line-by-line basis between each VTU-O and VTU-R according to the principles described above. The method to implement TA is vendor-discretionary.

4.2.2.6.2 Methods to ensure frame synchronization

TBD.

4.2.3 On-line adaptation and reconfiguration

TBD.

4.3 Constellation encoder

An algorithmic constellation encoder shall be used to construct subchannel constellations with a maximum number of bits equal to 11 and a minimum number of bits equal to 1. For a given subchannel, the encoder shall select an odd-integer point (X,Y) from the square-grid constellation based on the b bits $\{v_{b-1}, v_{b-2},...,v_1,v_0\}$. For convenience of description, these b bits are identified with an integer label whose binary representation is $(v_{b-1}, v_{b-2},...,v_1,v_0)$. For example, for b=2, the four constellation points are labeled 0, 1, 2, and 3 corresponding to (v_1,v_0) = (0,0), (0,1), (1,0), and (1,1), respectively.

4.3.1 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 $\{v_{b-1}, v_{b-2},...,v_1,v_0\}$ as follows. X and Y are the odd integers with twos-compliment binary representations $(v_{b-1}, v_{b-3}, ..., v_1, 1)$ and $(v_{b-2}, v_{b-4}, ..., v_0, 1)$, respectively. The most significant bits (MSBs), v_{b-1} and v_{b-2}, are the sign bits for X and Y, respectively. Figure 19 shows example constellations for b = 2 and b = 4.

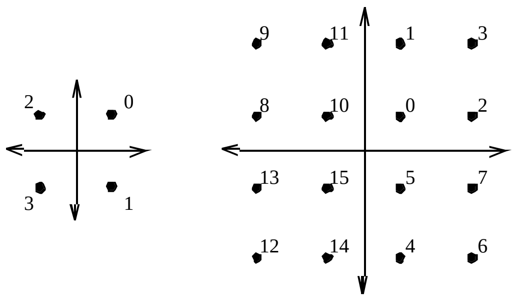


Figure 19: Constellation labels for b = 2 and b = 4

The 4-bit constellation can be obtained from the 2-bit constellation by replacing each label n by the 2x2 block of labels:

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

The same procedure can be used to construct the larger even-bit constellations recursively.

The constellations obtained for even values of b are square in shape.

4.3.2 Odd values of *b*, *b* = 1 or *b* = 3

Figure 20 shows the constellations for the cases b = 1 and b = 3.

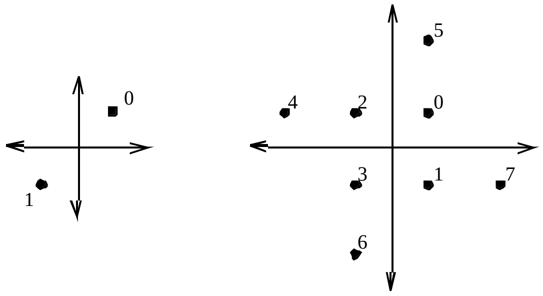


Figure 20: Constellation labels for b = 1 and b = 3

4.3.3 Odd values of *b*, *b* > 3

If b is odd and greater than 3, the 2 MSBs of X and the 2 MSBs of Y are determined by the 5 MSBs of the b bits. Let $c = (b+1)/2$, then X and Y have the twos-compliment binary representations $(X_c, X_{c-1}, v_{b-4}, v_{b-6},...,v_3, v_1, 1)$ and $(Y_c, Y_{c-1}, v_{b-5}, v_{b-7}, v_{b-9},...,v_2, v_0, 1)$, 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 $v_{b-1}, v_{b-2},...,v_{b-5}$ is shown in Table 6.

Table 6. Determining the top two bits of X and Y

$\boldsymbol{v}_{b-1}, \boldsymbol{v}_{b-2},\ldots,\boldsymbol{v}_{b-5}$	$\boldsymbol{X}_c, \boldsymbol{X}_{c-1}$	$\boldsymbol{Y}_c, \boldsymbol{Y}_{c-1}$
0 0 0 0 0	0 0	0 0
0 0 0 0 1	0 0	0 0
0 0 0 1 0	0 0	0 0
0 0 0 1 1	0 0	0 0
0 0 1 0 0	0 0	1 1
0 0 1 0 1	0 0	1 1
0 0 1 1 0	0 0	1 1
0 0 1 1 1	0 0	1 1
0 1 0 0 0	1 1	0 0
0 1 0 0 1	1 1	0 0
0 1 0 1 0	1 1	0 0
0 1 0 1 1	1 1	0 0
0 1 1 0 0	1 1	1 1
0 1 1 0 1	1 1	1 1
0 1 1 1 0	1 1	1 1
0 1 1 1 1	1 1	1 1
1 0 0 0 0	0 1	0 0
1 0 0 0 1	0 1	0 0
1 0 0 1 0	1 0	0 0
1 0 0 1 1	1 0	0 0
1 0 1 0 0	0 0	0 1
1 0 1 0 1	0 0	1 0
1 0 1 1 0	0 0	0 1
1 0 1 1 1	0 0	1 0
1 1 0 0 0	1 1	0 1
1 1 0 0 1	1 1	1 0
1 1 0 1 0	1 1	0 1
1 1 0 1 1	1 1	1 0
1 1 1 0 0	0 1	1 1
1 1 1 0 1	0 1	1 1
1 1 1 1 0	1 0	1 1
1 1 1 1 1	1 0	1 1

Figure 21 shows the constellation for the case $b = 5$.

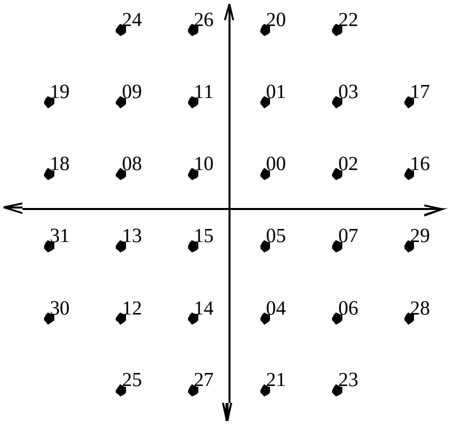


Figure 21: Constellation labels for $b = 5$

The 7-bit constellation shall be obtained from the 5-bit constellation by replacing each label n by the 2 x 2 block of labels:

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

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

4.3.4 Gain scaling

A gain adjuster g_i shall be used to effect a frequency-variable transmit power spectral density (PSD). It consists of a fine gain adjustment with a range from approximately 0.75 to 1.33 (that is, dB), which may be used to equalize the expected error rates for all the subchannels. Each point (X_i, Y_i), or complex number $Z_i = X_i + jY_i$, output from the encoder is multiplied by g_i: $Z_i' = g_i Z_i$.

Other uses of gain scaling are for further study.

4.3.5 Transmitter dynamic range

4.3.5.1 Noise/Distortion floor

The signal-to-noise-plus-distortion (SINAD) ratio of the transmitted signal in a given subchannel is defined as the ratio of the rms value of the full-amplitude tone in that subchannel to the rms sum of all the non-tone signals in the f_o-kHz frequency band centered on the subchannel center frequency, where f_o is 21.5625 (43.125, 86.25) kHz. The SINAD is characterized for each subchannel used for transmission: SINAD_i represents the SINAD available on the transmitted signal in the ith subchannel.

Over the transmission frequency band, the SINAD of the transmitter in any subchannel shall be no less than ($3 N_{downi} + 20$) dB, where N_{downi} is defined as the size of the constellation (in bits) to be used on subchannel i. The minimum transmitter SINAD shall be at least 38 dB (corresponding to an N_{downi} of 6) for any subchannel.

4.3.6 Transmitter spectral response

Figure 22 shows a representative spectral response mask for the transmitted signal. The passband is defined as the frequency range over which the modem transmits. The low frequency stop band is defined as the POTS/ISDN band; the high frequency stop band is defined as frequencies greater than 11.04 (22.08, TBD) MHz. The exact value of X, the upper edge of the low frequency stop band, is dependent on the choice of POTS/ISDN splitter but will likely be 200-400 kHz. The TBD frequency for the $4f_s$ system's high frequency stop band lower edge is under study.

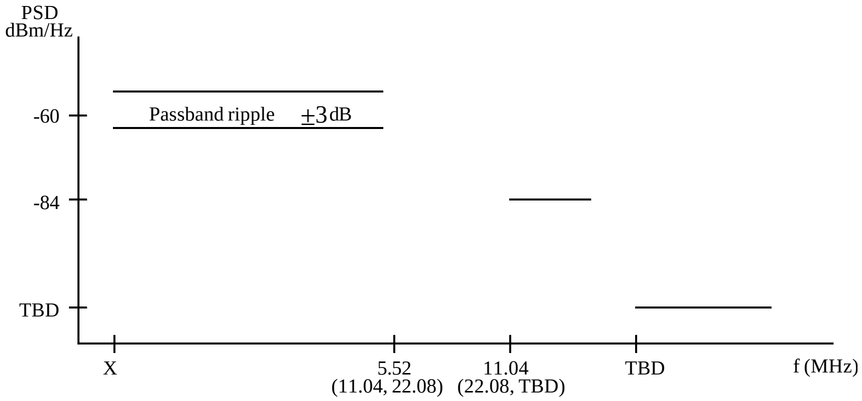


Figure 22: VTU transmit PSD mask

4.3.6.1 Passband response

The pass band ripple shall be no greater than ±3 dB, and the group delay variation over the pass band shall not exceed 5 µs.

4.3.6.2 Low frequency stop band rejection

The low frequency stop band rejection is driven by the POTS/ISDN requirements given in Section 10.

4.3.6.3 High frequency stop band rejection

The high frequency stop band rejection shall be at least TBD dB below the spectral density of the -60 dBm/Hz passband mask.

4.3.7 Transmit power spectral density and aggregate power level

4.3.7.1 Egress

In the default mode, emissions from both the VTU-O and VTU-R shall be controlled by constraining the transmitted PSD in frequency bands allocated in the over-the-air spectrum for amateur radio transmissions to levels no higher than -80 dBm/Hz. The bands to which the -80 dBm/Hz requirement applies are detailed in Table 7.

Table 7. International amateur radio bands

Start frequency (MHz)	End frequency (MHz)
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	29.100

An optional mode enables subchannels within one or more of the amateur radio bands. This optional mode, which can be invoked only by the network operator via the network management interface, improves VDSL performance when emissions into the amateur radio bands are not of concern.

4.3.7.2 Power spectral density of all signals

The VDSL transmit PSD in the band from 200 kHz to 5.52 (11.04, 22.08) MHz shall not exceed -60 dBm/Hz (subject to the 3 dB ripple requirement specified in Section 4.3.6.1) for a total power of not greater than 7.42 (10.43, 13.44) dBm. Levels lower than -60 dBm/Hz on some carriers are discretionary, except in the amateur radio bands, where the levels defined in Section 4.3.7.1 shall not be exceeded under normal circumstances. The PSD and total power may, however, be changed in either of the following circumstances:

(a) Power cut-back: Use of power cut-back in the remote transmitter is necessary on short lines to reduce crosstalk into upstream symbols transmitted on longer lines. The level to which the power should be cut back is TBD. Power cut-back at the VTU-O may also be necessary on short lines.

(b) The bit and gain tables computed during initialization may eliminate some of the subchannels and finely adjust (within ± 2.5 dB range, as specified in Section 4.3.4) the levels of others in order to equalize expected error rates on each of the subchannels.

Avoidance of the amateur radio bands (as described in Section 4.3.7.1) is mandatory; support of an option to enable transmission in one or more amateur radio bands is discretionary. In this optional configuration, the PSD levels on all subchannels shall not exceed -60 dBm/Hz except within the limits defined by (b) above.

The VDSL PSD in the POTS and ISDN bands shall conform to requirements that are TBD, in accordance with Section 10.

4.4 Initialization

4.4.1 Signature negotiation

Modems shall be characterized by signals called signatures. A signature specifies a set of modulation and duplexing parameters that a modem can accommodate. All VTU-Os and VTU-Rs shall be required to accommodate a minimal set of signatures; support of additional signatures is discretionary, and either the VTU-O or VTU-R can reject any signature it is unable to accommodate outside the minimal set.

During the initialization process, the VTU-O and VTU-R negotiate a signature to establish modulation parameters and capabilities. Based on the outcome of the negotiation, they complete and appropriate initialization procedure.

Specific signatures (for example, for TDD and Zipper systems) are TBD.

4.4.2 Activation and deactivation

Activation and deactivation may be commanded by network management, or result from autonomous action caused by transmission anomalies. Additionally, where call-state information is available, activation may be linked to broadband call-state transitions. Such linkage is not applicable to SDH applications, and is not currently supported by ATM level standards. Methods may however be developed to enable the transmission performance advantages for VDSL to be exploited by ATM applications.

4.4.2.1 Activation/deactivation definitions

On first installation or on demand of the network operator, the start-up of a VDSL transceiver might be subject to an installation procedure under control of the network operator in order to check the spectral compatibility of the transceiver. (NOTE: Such test procedure is for further study.)

Following a successful first installation, the activation procedures shall start. Four activation procedures shall be supported. The four mandatory activation procedures (Cold-Start, Normal-Start, Resume-on-Error, and Warm-Start) are defined below:

Cold-Start: Cold-Start applies when power is first applied to the transceiver after intrusive maintenance or if there have been significant changes in line characteristics (for example, due to thermal effects). The Cold-Start also applies when transmission rates and other transmission parameters (such as noise margin, spectral masks, class of service, etc.) are altered. The duration of a Cold-Start shall be less than 30 seconds.

Normal-Start: This start applies when both transceivers start from the Power-Down state. Power-Down is reached after a transceiver has had its AC power removed on purpose via the Power-Down procedure, typically forced by the customer. Normal-start applies only if there have been few or no changes in line characteristics. This procedure may also apply when there is an accidental AC removal or failure at the customer, provided the transceiver can store all necessary data and parameters to avoid the Cold-Start. The duration of the Normal-Start procedure shall be less than 5 seconds.

Resume-on-Error: Resume-on-Error is the start-up process that applies to transceivers that lose synchronization during steady-state transmission, such as after a large impulse hit or an interruption longer than the specified micro-interruption. Resume-on-Error applies only if there have been no changes in line characteristics, and if the clock-frequency recovery circuits can still predict the sample timing. Events leading to loss of synchronization are longer than a micro-interruption (>10 ms) but limited to a TBD maximum value, related to the loss of frequency locking. Completion of the Resume-on-Error procedure shall require less than 300 ms.

Warm-Resume: Warm-Resume is the start-up process that applies to transceivers that have achieved synchronization and have subsequently responded to a deactivation request. Warm-resume is the usual method of activating the VDSL transmission system on receipt of a first incoming or outgoing broadband call request. Warm-Resume can only be initiated after a deactivation procedure, such as the Power-Saving state, which keeps both LT and NT VDSL transceivers in a power-saving sleeping mode. A Warm-Resume shall take place in less than 100 ms.

Following completion of one of the activation states, steady-state transmission is supported:

Steady-state transmission: A transceiver supporting Steady-state transmission has completed all start-up processes, including full clock and frame synchronization. In addition, Steady-state implies that DSP filter adaptations have been performed.

In addition to the four activation procedures, a deactivation procedure and its corresponding final state plus a power-down procedure and its corresponding state shall be supported:

Deactivation: Deactivation is the process that places the VDSL transceiver into a power-saving state to save ONU power and reduce unwanted RF emissions. Included in this process is the confirmation towards UNI and the network side that the VDSL transmission is terminated. Deactivation assumes the termination of all broadband traffic.

Deactivated Power-Saving state: This state is required to permit the digital transmission system to be placed in a low power consumption mode when no calls are in progress. The NT and LT consume less power but are capable of detecting a wake up signal from the network side and/or from the UNI and executing a Warm-Resume. When enabled by the Network Management System, this state may be entered automatically after a programmable time after the last broadband call. During the Deactivated Power-Saving state the transceivers could continue some (modulation dependent) form of synchronization on some of the following levels: clock-sync, frame-sync, equalizer checking and trimming, etc.

Power-Down procedure: The Power-Down procedure is the process by which a pair of fully operational transceivers transition to the Power-Down state. It is a guided procedure used, for example, when the customer wants to turn off the transceiver AC power, or when the LT cannot accommodate to the Power-Saving deactivation. To enable use of the Normal-Start activation procedure later, VDSL transceivers engaged in the Power-Down procedure may store transmission related data, such as equalizer states, line characteristics, and service related parameters.

Power-Down state: Power-Down state corresponds to the VTU’s state following full removal of power at the NT or LT, or the state at the LT when the Power-Saving deactivated state cannot used and VDSL transmission must be halted, such as for maintenance (hardware and/or software).

An additional, optional dynamic power-saving state is also defined. Support of this state requires support of a fifth activation procedure:

Dynamic Power Save state: The optional Dynamic Power Save State is intended to reduce the overall power consumption of the VDSL LT transceiver, and to reduce the crosstalk level and RF egress from the VDSL system. It may be used when ATM or some other application links are active but not consuming the full bandwidth of the VDSL link. The Dynamic Power Save state alternates with Steady-state transmission. No loss of application data shall be tolerated when the VDSL transceiver alternates between Steady-state transmission and Dynamic Power Save state. Support of the Dyamic Power Save state implies support of the Hot-Resume.

Hot-Resume: Hot-Resume is the implied immediate power-ON procedure to resume transmission whenever the VDSL transceiver alternates between Steady-state and the optional Dynamic Power Save state.

Figure 23 illustrates the various required and optional activation, steady-state, and deactivation states and procedures.

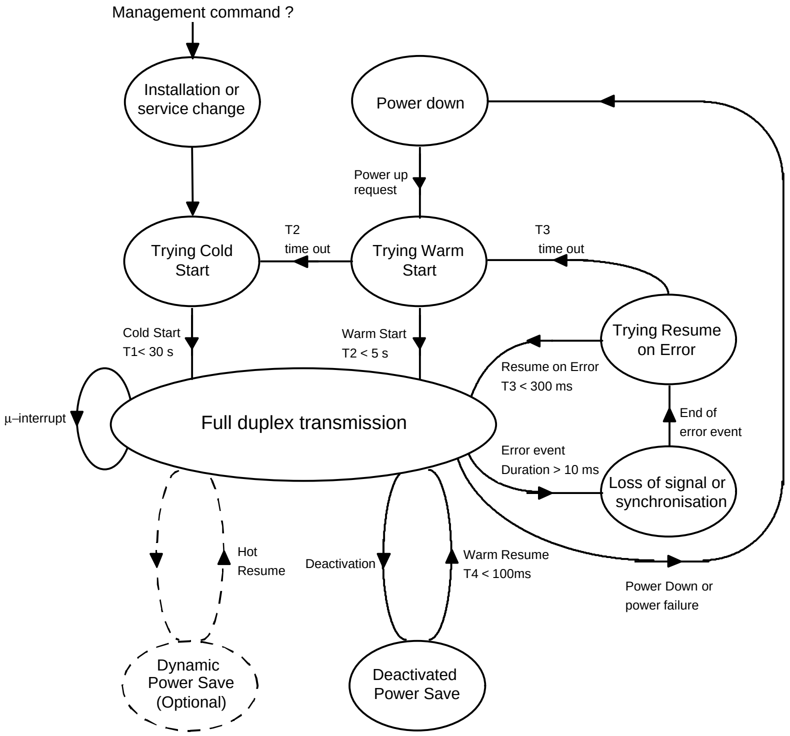


Figure 23: State and timing diagram

A metric is defined to quantify the performance when establishing a VDSL link:

Delay to service start-up: The delay to service start-up is the time from when Activation is requested or power is applied until the broadband dial tone is issued toward the UNI. The VDSL system must have achieved Steady-state transmission before the broadband dial tone (or equivalent) is issued.

4.4.3 Activation and acknowledgment - VTU-R

4.4.4 Activation and acknowledgment - VTU-O

4.4.5 Transceiver training - VTU-O

4.4.6 Transceiver training - VTU-R

4.4.7 Channel analysis - VTU-O

4.4.8 Channel analysis - VTU-R

4.4.9 Exchange - VTU-O

Exchange of both FEC and interleaver parameters occurs here.

4.4.10 Exchange - VTU-R

Exchange of both FEC and interleaver parameters occurs here.

4.5 On-line adaptation and reconfiguration

4.5.1 The VDSL overhead control (VOC) channel

A VDSL overhead control channel shall be included to support overhead functions. The raw VOC channel is specified at any 16*V* kbps. The mechanism used to support the VOC channel is described in detail in Section 5.1.5.

4.5.1.1 VOC protocol

All VOC messages shall be transmitted 5 consecutive times to improve the probability they are received and decoded properly. A transceiver unit shall only act on a VOC message if it has received three identical messages in a time period spanning 5 of that particular message. When a receiving unit detects an unrecognizable command, no action shall be taken by the receiving unit. The transmitting unit (the originating unit of the VOC command) is responsible for any time-outs and local recovery schemes when no acknowledgment to its request has been detected during a reasonable period of time. Recovery schemes may be proprietary to vendors of VDSL transceivers.

4.5.2 High-level on-line adaptation - Bit swapping

Bit swapping enables a VDSL system to change the number of bits assigned to a subchannel, or change the transmit energy of a subcarrier without interrupting the data flow.

Either VTU may initiate a bit swap; the swapping procedures in the upstream and downstream directions are independent and may take place during the same set of superframes.

4.5.2.1 Bit swap channel

Bit swaps are conducted using the VOC channel, described in Section 4.5.1. Consequently, all bit swap messages shall be repeated five consecutive times over the VOC channel.

4.5.2.2 Bit swap coordination

Bit swapping is conducted with respect to synchronized counters at the VTU-O and VTU-R. The counters are started and incremented as follows:

1. The VTU-O and VTU-R transmitters shall start their counters immediately after transitioning from initialization to steady-state operation;
2. Each transmitter shall increment its counter after each superframe;
3. Correspondingly, each receiver shall start its counter immediately after transitioning from initialization to steady-state, and then increment it after receiving each superframe.

Synchronization of the corresponding transmitter and receiver superframe counters is maintained by the superframe structure. Any form of restart that requires a transition from initialization to steady-state shall reset the counter.

4.5.2.3 Bit swap request

Upon detecting a degradation in one or more subchannel SNR, the receiver shall initiate a bit swap by sending a bit swap request back to the transmitter via the VOC channel. This request tells the transmitter which subchannels are to be modified. The bit swap request message contains the following:

- a VOC message header consisting of 8 binary ones to indicate the ensuing bit swap request;
- four message fields, each of which consists of an eight-bit command followed by a related eight-bit subchannel index. Valid eight-bit commands for the bit swap message shall be as shown in Table 8. The eight-bit subchannel index is counted from low to high frequencies with the lowest frequency subcarrier assigned the number zero.

Table 8. Bit swap request commands

Value	Interpretation
00000000	Do nothing.
00000001	Increase the allocated number of bits by one.
00000010	Decrease the allocated number of bits by one.
00000011	Change the transmitted power by the factor +1 dB.
00000100	Change the transmitted power by the factor +2 dB.
00000101	Change the transmitted power by the factor +3 dB.
00000110	Change the transmitted power by the factor -1 dB.
00000111	Change the transmitted power by the factor -2 dB.
00001xxx	Reserved for vendor-specific commands.

The bit swap request message (that is, the header plus the four message fields, a total of nine bytes) is transmitted five consecutive times. Thus, transmission of each bit swap request requires 45 superframes or 22.5 ms.

4.5.2.4 Bit swap acknowledge

After a VTU has received three identical bit swap request messages within the span of five message times, the transmitter shall act on the request. The transmitter shall first send a bit swap acknowledge, which contains the following:

- a VOC message header containing 8 binary ones, indicating receipt of the request message;
- one message field that consists of eight binary ones followed by the eight-bit superframe counter number, which indicates when the bit swap is to take place. Specifically, the new bit and/or transmit energy table(s) shall take effect starting from the first symbol of the VDSL superframe specified by the superframe counter number. In other words, if the bit swap superframe counter number contained in the bit swap acknowledge message is *n*, then the new table(s) shall take effect starting from the first applicable symbol of the *n*th superframe.

Transmission of the bit swap acknowledge, which is composed of three bytes, requires 15 superframes or 7.5 ms.

4.5.2.5 Bit swap - Receiver

The receiver shall act on a bit swap request when it has received three identical bit swap acknowledge messages within the span of 15 superframes. The receiver shall then wait until the superframe counter equals the value specified in the bit swap acknowledge. Then, beginning with the first symbol in the next superframe, the receiver shall:

- change the bit assignment of the appropriate subchannels, and perform tone re-ordering based on the new subchannel bit assignment;

- update applicable receiver parameters of the appropriate subchannels to account for any changes in their transmitted energy.

4.5.2.6 Bit swap - Transmitter

After transmitting the bit swap acknowledge, the transmitter shall wait until the superframe counter equals the value specified in the bit swap acknowledge. Then, beginning with the first symbol in the next superframe, the transmitter shall:

- change the bit assignment of the appropriate subchannels and perform tone re-ordering based on the new subchannel bit assignment;
- change the transmit energy in the appropriate subchannels by the desired factors.

4.6 Dynamic rate adaptation

Dynamic rate adaptation is not allowed.

5 Transmission Convergence (TC) Sublayer Specification

5.1 PMS-TC functions

5.1.1 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 so that descrambling can occur without requiring a particular alignment with the scrambled sequence. Denoting a message byte at time n as $m(n)$ and the output of the scrambler as $x(n)$, the scrambler is represented by the equation

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

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

5.1.2 Forward error correction

A standard byte-oriented Reed-Solomon code shall be used for protection against random and burst errors. Comprised of R=16 redundant check bytes $c_0, c_1, ..., c_{R-2}, c_{R-1}$ appended to K message bytes $m_0, m_1, ..., m_{K-2}, m_{K-1}$, a Reed-Solomon code has N = K + R bytes. K is a programmable parameter with value up to 239.

Specific Reed-Solomon parameters are TBD.

5.1.3 Interleaving

Interleaving shall be used to protect against bursts of errors by spreading the errors over a number of Reed-Solomon code words. A TBD method of interleaving shall be used to reduce latency and memory requirements. Two interleaving modes shall be available: fast and slow. Both modes protect against frequency-localized impulse noise, but slightly greater protection is offered by the slow mode at the cost of additional delay. The interleave depth is programmable, with a maximum interleave depth of 64 codewords when the number of bytes per codeword (N) equals 255. For smaller values of N, the interleave depth can grow nearly proportionately.

Latency is a function of the data rate and burst error correction capability. For data rates greater than or equal to 13 Mbps, the latency between the α and β interfaces shall not exceed 10 ms in slow mode and 1.25 ms in fast mode. At lower data rates there is a trade-off between higher latency and decreased burst error correction ability. Typically, however, at lower data rates there are either fewer byte errors, or they persist over a fewer number of symbols. For applications with latency requirements stricter than the fast mode allows, interleaving can be turned off.

Specific interleaving parameters are TBD.

5.1.4 Framing of the fast channel

The fast channel shall contain data bytes coming from the TPS-TC layer and dummy bytes to fill in the frame. Insertion of EOC bytes and the number of EOC bytes per frame are TBD. The check bytes of the RS codewords shall be computed on this aggregate of payload bytes.

An integer number of RS codewords shall be embedded in one DMT frame. Figure 24 depicts the structure of one DMT frame. For a requested payload rate of 64*B* kbps, one DMT frame contains *S* RS codewords, whose payload is composed of 4*B* bytes and *D*1 stuffing bytes. Other bytes added to the frame are TBD. The number of codewords per frame (*S*), the codeword length (*K*), and the number of stuffing bytes *D*1 are given by

$$S = \left\lceil \frac{4B + TBD}{K_{\max}} \right\rceil$$

$$K = \left\lceil \frac{4B + TBD}{S} \right\rceil$$

$$D1 = SK - (4B + TBD)$$

where K_{max}, whose value is TBD, is a parameter that limits the codeword length.

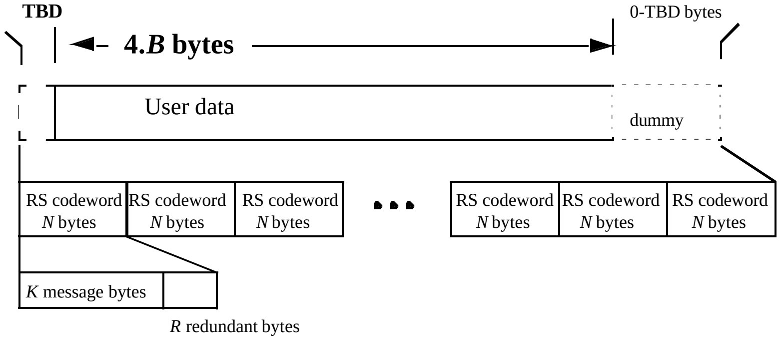


Figure 24: Framing of the fast channel

The *D*1 last bytes of the last RS codeword's payload are the dummy bytes.

Because one DMT symbol contains an integer number of fast bytes, and *SN* does not have to be a multiple of the number of symbols per frame, it is necessary to foresee a second source of stuffing bytes to fill in the DMT frame at the PMD level. These bytes are inserted in the last DMT symbol of the frame and are not used to compute the RS check bytes. Note: These bytes are not represented in Figure 24.

5.1.5 Framing of the fast and interleaved data just before mapping into constellation points, after RS encoding and interleaving

After data from the interleaved and optional fast paths have passed through the RS encoder and the interleaver and have been multiplexed together, bytes for the VOC channel and additional post-multiplexor dummy bytes are included. Post-multiplexor dummy bytes may be needed when the number of bytes to be transmitted in each superframe does not divide the number of symbols in a superframe evenly. The addition of these dummy bytes allows each DMT symbol to carry the same number of bytes.

The addition of *V* VOC bytes and post-multiplexor dummy bytes is illustrated in Figure2.3. VOC bytes *i* and *i+1* are separated by I_{i+1} bytes of multiplexed and encoded data; the first VOC byte comes after I_0 bytes of multiplexed and encoded data. The number of VOC bytes depends on the required bandwidth of the VOC channel. Typically there will be a multiple of two VOC bytes to allow VOC messages to be sent over redundant paths. The values of I_k should be chosen so that VOC bytes are separated in time and frequency. These values are exchanged between the

VTU-O and VTU-R during initialization.

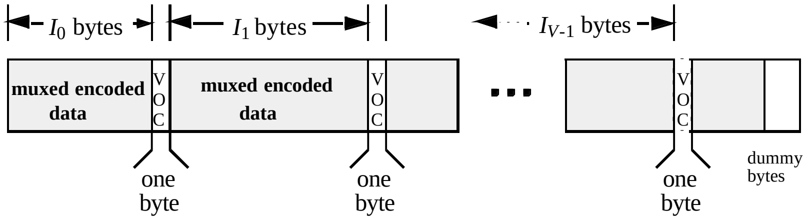


Figure 25: Addition of VOC and post-interleaver dummy bytes

The values of *I* and *D*2, the number of post-multiplexor dummy bytes, are chosen to separate VOC bytes in time and frequency and to guarantee that each symbol carries the same number of bytes. We denote the total number of RS coded bytes per TDD frame equal to P_{total}. This is the sum of the contributions from the fast and interleaved paths and is given by

$$P_{total} = P_i + P_f$$

where P_{i} and P_{f} are the number of RS encoded bytes from the interleaved and fast paths.

For two VOC bytes, for example, I_0 can equal 0 and I_1 can equal P_{total}. This way, the first VOC byte comes in the first DMT symbol at the lowest frequencies and the second VOC bytes comes in the last VOC bytes in the highest frequencies. This effectively interleaves the VOC bytes.

If the number of bytes in each DMT symbol is constrained to be the same, the number of bytes in each symbol is given by

$$BytesPerSymbol = \left\lceil \frac{P_{total} + V}{T} \right\rceil$$

where *T* is the number of active (transmit or receive) symbols per TDD superframe.

The number of post multiplexor dummy bytes, if all symbols carry the same number of bytes, is given by

$$D2 = BytesPerSymbol \cdot T - (P_{total} + V).$$

The number of dummy bytes, D2, will never exceed *T*-1 and represents a small amount of overhead, at most less than one byte per DMT symbol.

5.2 STM-specific TC functions

For further study.

5.3 ATM-specific TC functions

5.3.1 Idle cell insertion

Idle cells shall be inserted in the transmit direction for cell rate decoupling. Idle cells are identified by the standardized pattern for the cell header given in ITU-T I.432.

NOTE: This specification is written on the assumption that idle cells will be discarded by a remote TPS-TC ATM sublayer

5.3.2 Header error control generation

The header error control (HEC) byte shall be generated in the transmit direction as described in ITU-T I.432, including the recommended modulo 2 addition (XOR) of the pattern 0101010101 to the HEC bits.

The generator polynomial coefficient set used and the HEC sequence generation procedure shall be in accordance with ITU-T I.432.

5.3.3 Cell payload scrambling

Scrambling of the cell payload field shall be used in the transmit direction to improve the security and robustness of the HEC cell delineation mechanism. In addition, it randomizes the data in the information field, for possible improvement of the transmission performance. The self-synchronizing scrambler polynomial and procedures defined in [ITU-T I.432] shall be implemented.

NOTE: This specification is written on the assumption that the cell payload will be descrambled by a remote TPS-TC ATM sublayer.

5.3.4 Bit timing and ordering

When interfacing ATM data bytes to the fast or slow subchannels provided by the PMS-TC sublayer, the most significant bit (msb) shall be sent first. The fast or slow subchannel data rate shall be kbit/s, with bit timing derived from the downstream modem clock.

5.3.5 Cell delineation

The cell delineation function permits the identification of cell boundaries in the payload. It uses the HEC field in the cell header.

Cell delineation shall be performed using a coding law checking the header error control HEC field in the cell header according to the algorithm described in ITU-T I.432. The ATM cell delineation state machine is shown in Figure 26.

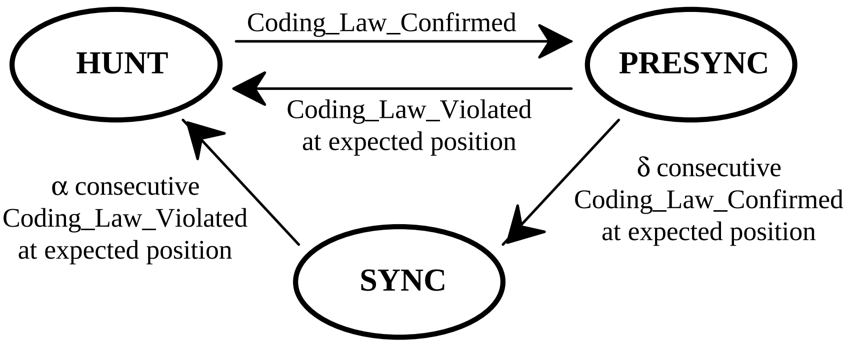


Figure 26: ATM cell delineation state machine

With reference to ITU-T I.432, no recommendation is made for the values of α and δ, as the choice of these values is not considered to affect interoperability. However, it should be noted that the use of the values suggested in ITU-T I.432 ($\alpha = 7$, $\delta = 6$) may be inappropriate due to the particular transmission characteristics of VDSL.

5.3.6 Header Error Control Verification

The header error control covers the entire cell header. The code used for this function is capable of either:

- single bit error correction
- multiple bit error detection

Error detection shall be implemented as defined in ITU-TI.432 with the exception that any HEC error shall be considered as a multiple bit error, and therefore HEC error correction shall not be performed.

6 Operations and maintenance

6.1 Detection of correctable block errors

6.2 Detection of non-correctable block errors

6.3 Monitoring synchronization status

6.4 Monitoring received signal power

7 Electrical specifications

7.1 dc characteristics

All requirements in this document shall be met in the presence of all POTS loop currents from 0 mA to 100 mA. Splitters shall pass POTS tip-to-ring dc voltages of 0 V to 105 V and ringing signals of 40 V to 150 V Rms at any frequency from 15.3 Hz to 68 Hz with a dc component in the range from 0 V to 105 V.

ISDN-specific requirements are TBD.

The dc resistance from tip-to-ring at the PSTN interface with the U_2-O interface shorted, or at the POTS interface with the U_2-R interface shorted, shall be less than or equal to 25 ohms. The dc resistance from tip to ground and from ring to ground at the PSTN interface with the U_2-O interface open, or at the POTS interface with the U_2-R interface open shall be greater than or equal to 5 megohms.

7.2 Voice-band characteristics

7.2.1 Metallic (differential mode)

A common test setup shall be used for measurement of the voice-band insertion loss, attenuation distortion, delay distortion, return loss, and noise and distortion. All measurements shall be performed between TBD interfaces with a variety of TBD reference loops.

7.2.1.1 Insertion loss

For each of the test loops and using the TBD test set-up, the insertion loss from TBD to TBD shall be measured with and without the VTU-O and VTU-R connected to the test loop. The impedance of the test equipment at the TBD interface shall be TBD ohms, and the impedance at the POTS interface shall be TBD ohms.

The increase in insertion loss at TBD Hz on any of the test loops, due to the addition of the splitters shall be less than or equal to TBD dB.

7.2.1.2 Attenuation distortion

The variation of insertion loss with frequency of the combination of both POTS splitters shall be measured using the TBD test setup. The impedance of the test equipment at the PSTN interface shall be TBD ohms, and the impedance of the test equipment at the POTS interface shall be TBD ohms. The added attenuation distortion of the combined POTS splitters relative to loss at TBD Hz measured using each of the test loops identified shall be not more than TBD dB at any frequency between TBD Hz and TBD Hz.

7.2.1.3 Delay distortion

The delay distortion of the POTS splitters shall be measured using the TBD test setup. The increase in envelope delay distortion between TBD Hz and TBD Hz caused by the two POTS splitters in each of the test loops shall be less than TBD seconds.

7.2.1.4 Return loss

TBD.

7.2.1.5 Noise and distortion

TBD.

7.2.2 Longitudinal (common mode)

TBD.

7.2.2.1 Longitudinal output voltage

TBD.

7.2.2.2 Longitudinal balance

TBD.

7.3 VDSL band

7.3.1 Return loss

At the TBD reference points the nominal impedance in the VDSL band shall be TBD ohms. The return loss defined from TBD to TBD and relative to TBD ohms in the frequency range from TBD to TBD Hz shall be TBD.

7.3.2 Longitudinal balance

TBD.

7.4 VDSL noise interference into POTS/ISDN circuits

7.4.1 Steady state noise - POTS

The idle channel noise on the POTS circuit shall not exceed 18 dBrnC at either the POTS or the PSTN interfaces with the VDSL system installed whether operating or not operating.

The power at any single frequency less than TBD kHz as measured by test equipment with a bandwidth of TBD kHz shall not exceed the greater of TBD dBrn or TBD below the measured idle channel noise.

7.4.2 Impulse noise - POTS

During initialization and operation of the VDSL system, with no holding tone applied to the circuit under test, there shall be no more than fifteen counts in fifteen minutes at a threshold of TBD dBrnC at either the PSTN or the POTS interface.

During initialization and operation of the VDSL system, with a TBD dBrn0 holding tone at TBD Hz applied to the circuit under test, there shall be no more than fifteen counts in fifteen minutes at a threshold of TBD dBrnCO at either the PSTN or the POTS interface.

These impulse noise requirements shall be met with each of the specified VDSL test loops with the VDSL system forced to re-initialize once per minute during the test interval.

7.4.3 Steady state noise - ISDN

The idle channel noise on the ISDN circuit shall not exceed 18 dBrnC at either ISDN interface with the VDSL system installed whether operating or not operating.

The power at any single frequency less than TBD kHz as measured by test equipment with a bandwidth of TBD kHz shall not exceed the greater of TBD dBrn or TBD below the measured idle channel noise.

7.4.4 Impulse noise - ISDN

During initialization and operation of the VDSL system, with no holding tone applied to the circuit under test, there shall be no more than fifteen counts in fifteen minutes at a threshold of TBD dBrnC at either ISDN interface.

During initialization and operation of the VDSL system, with a TBD dBrn0 holding tone at TBD Hz applied to the circuit under test, there shall be no more than fifteen counts in fifteen minutes at a threshold of TBD dBrnCO at either ISDN interface.

These impulse noise requirements shall be met with each of the specified VDSL test loops with the VDSL system forced to re-initialize once per minute during the test interval.

8 Mechanical specifications

8.1 Wiring polarity integrity

VDSL operation shall be independent of the polarity of the pair of wires connecting the VTU-O and VTU-R.

8.2 Connector

8.3 Temperature

The VTU-O shall always meet temperature range specifications for outdoor operation. The VTU-R shall meet mechanical specifications determined by its deployment location (indoors or outdoors). VTU-Rs configured to reside within the subscriber premise are required to meet less stringent environmental specifications.

Both VTU-O units and VTU-R units configured for deployment outside the subscriber premise shall meet all functional requirements and criteria with an ambient temperature from -40^o C with no solar load to +52^o C with maximum solar load, maximum power dissipation, and a relative humidity between 5% and 95%. Maximum solar load is defined as a total short-wave radiation of 70 W/ft^2 on the entire top and 50% of the total side surface area of the enclosure. Compliance with the upper temperature limit shall be shown by testing either:

1. a fully-configured outdoor system in a chamber with no solar load and an ambient temperature of +70^o C, or
2. a partially-configured outdoor system in a chamber with no solar load and an ambient temperature of +85^o C.

VTU-Rs configured for deployment inside the customer premise shall meet all functional requirements and criteria with an ambient temperature from -10^o C to +52^o C with maximum power dissipation and a relative humidity between 5% and 95%. Compliance with the upper temperature limit shall be shown by testing a fully-configured indoor VTU-R with an outdoor VTU-O in a chamber with an ambient temperature of 70^o C.

8.4 Altitude

The VDSL system shall meet all functional requirements and criteria when installed at altitudes from 200 feet (60 meters) below mean seal level to 13,000 feet (4 km) above mean sea level.

8.5 Transportation and storage requirements

The VDSL system shall meet the transportation and storage criteria, R4-3, R4-4, and R4-5 defined in [20].

9 Testing

The methods in this section test VDSL system transmission performance. These laboratory methods evaluate a system's ability to minimize digital bit errors caused by interference from:

crosstalk coupling from other systems;
background noise;

impulse noise;
POTS/ISDN signaling.

These potential sources of impairment are simulated in a laboratory set-up that includes test loops, test sets, and interference injection equipment, as well as the test system itself. Figure 27 shows the general arrangement for testing.

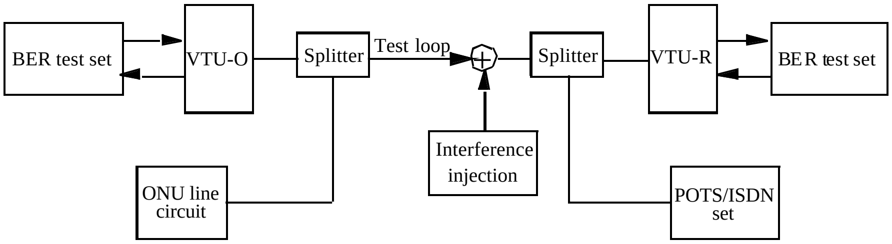


Figure 27: Overview of test setup

The crosstalk and impulse noise interfering signals are simulations that are derived from a consideration of real loop conditions and measurements. The test procedure is to inject the interference into the test loops and measure the effect on system performance by a bit error test run simultaneously on the system information channels.

For crosstalk tests, an initial, or reference, power level for the interference represents the expected worst case. If the interference power can be increased without exceeding a specified error threshold, the system has a positive performance margin. Performance margin, expressed in dB, is the difference between the interference level at which the error threshold is reached and the reference (or 0 dB) level.

The specified error threshold with crosstalk interference is a BER or 10^{-7}; the minimum performance margin is 6 dB.

In the case of impulse noise, an increasing interference level is similarly applied up to the error threshold, and the estimated performance is computed from this information. Because the impulse noise characteristics of the loop plant are not completely understood, the estimation method is based on measured data from several sites. The estimated number of error-causing impulses is compared to a 0.14% errored-seconds (ES) criterion. The test procedure makes separate determinations of crosstalk margins and impulse error thresholds, although a background crosstalk interference is applied during impulse tests.

The digital channel BER measurement shall be made while including impairments such as POTS/ISDN signaling interference and crosstalk from other twisted-pair lines. Test shall be performed using signaling and alerting activities done with an electro-mechanical telephone set and either ONU lines or an ONU simulator.

9.1 Test loops

TBD.

9.2 Impairments and their simulation in testing

9.2.1 Crosstalk

Crosstalk spectral compatibility is tested using simulations of the interference caused by coupling from other transmission systems sharing the same cable.

9.2.2 Impulse noise

TBD.

10 VDSL - POTS/ISDN splitter functional characteristics

TBD. Issues include whether the splitter is mandatory, and, if so, whether one splitter must accomplish splitting for both POTS and ISDN.