International Telecommunication Union

ITU-T
TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

G.993.5
Amendment 2
(12/2017)

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

Digital sections and digital line system – Metallic access networks

Self-FEXT cancellation (vectoring) for use with VDSL2 transceivers
Amendment 2

Recommendation ITU-T G.993.5 (2015) – Amendment 2

ITU-T G-SERIES RECOMMENDATIONS

TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

INTERNATIONAL TELEPHONE CONNECTIONS AND CIRCUITS	G.100–G.199
GENERAL CHARACTERISTICS COMMON TO ALL ANALOGUE CARRIER-TRANSMISSION SYSTEMS	G.200–G.299
INDIVIDUAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON METALLIC LINES	G.300–G.399
GENERAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON RADIO-RELAY OR SATELLITE LINKS AND INTERCONNECTION WITH METALLIC LINES	G.400–G.449
COORDINATION OF RADIOTELEPHONY AND LINE TELEPHONY	G.450–G.499
TRANSMISSION MEDIA AND OPTICAL SYSTEMS CHARACTERISTICS	G.600–G.699
DIGITAL TERMINAL EQUIPMENTS	G.700–G.799
DIGITAL NETWORKS	G.800–G.899
DIGITAL SECTIONS AND DIGITAL LINE SYSTEM	G.900–G.999
General	G.900–G.909
Parameters for optical fibre cable systems	G.910–G.919
Digital sections at hierarchical bit rates based on a bit rate of 2048 kbit/s	G.920–G.929
Digital line transmission systems on cable at non-hierarchical bit rates	G.930–G.939
Digital line systems provided by FDM transmission bearers	G.940–G.949
Digital line systems	G.950–G.959
Digital section and digital transmission systems for customer access to ISDN	G.960–G.969
Optical fibre submarine cable systems	G.970–G.979
Optical line systems for local and access networks	G.980–G.989
Metallic access networks	**G.990–G.999**
MULTIMEDIA QUALITY OF SERVICE AND PERFORMANCE – GENERIC AND USER-RELATED ASPECTS	G.1000–G.1999
TRANSMISSION MEDIA CHARACTERISTICS	G.6000–G.6999
DATA OVER TRANSPORT – GENERIC ASPECTS	G.7000–G.7999
PACKET OVER TRANSPORT ASPECTS	G.8000–G.8999
ACCESS NETWORKS	G.9000–G.9999

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

Recommendation ITU-T G.993.5

Self-FEXT cancellation (vectoring) for use with VDSL2 transceivers

Amendment 2

Summary

Vectoring is a transmission method that employs the coordination of line signals for reduction of crosstalk levels and improvement of performance. The degree of improvement depends on the channel characteristics. Vectoring may be for a single user or for multiple users' benefit.

Recommendation ITU-T G.993.5 is specifically limited to the self-far-end crosstalk (self-FEXT) cancellation in the downstream and upstream directions. It defines a single method of self-FEXT cancellation, in which FEXT generated by a group of near-end transceivers and interfering with the far-end transceivers of that same group is cancelled. This cancellation takes place between very high-bit-rate digital subscriber line 2 (VDSL2) transceivers, not necessarily of the same profile. This Recommendation is intended to be implemented in conjunction with Recommendation ITU-T G.993.2.

ITU-T G.993.5 (2015) consolidates ITU-T G.993.5 (2010) with all its amendments and corrigenda.

Amendment 1 defines the following new functionality: Transceiver O-DEACTIVATING state.

Amendment 2 adds Annex A: Mitigating strong FEXT; and Annex B: Vectored Long Reach VDSL2.

History

Edition	Recommendation	Approval	Study Group	Unique ID[*]
1.0	ITU-T G.993.5	2010-04-22	15	11.1002/1000/10414
1.1	ITU-T G.993.5 (2010) Cor. 1	2011-06-22	15	11.1002/1000/11128
1.2	ITU-T G.993.5 (2010) Amd. 1	2011-12-16	15	11.1002/1000/11396
1.3	ITU-T G.993.5 (2010) Cor. 2	2012-06-13	15	11.1002/1000/11643
1.4	ITU-T G.993.5 (2010) Amd. 2	2012-10-29	15	11.1002/1000/11796
1.5	ITU-T G.993.5 (2010) Amd. 3	2013-04-22	15	11.1002/1000/11889
1.6	ITU-T G.993.5 (2010) Amd. 4	2013-08-29	15	11.1002/1000/11993
1.7	ITU-T G.993.5 (2010) Amd. 5	2014-04-04	15	11.1002/1000/12095
2.0	ITU-T G.993.5	2015-01-13	15	11.1002/1000/12372
2.1	ITU-T G.993.5 (2015) Cor. 1	2016-11-13	15	11.1002/1000/13089
2.2	ITU-T G.993.5 (2015) Amd. 1	2016-12-22	15	11.1002/1000/13121
2.3	ITU-T G.993.5 (2015) Amd. 2	2017-12-07	15	11.1002/1000/13307

_____

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

FOREWORD

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

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

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

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

NOTE

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

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

INTELLECTUAL PROPERTY RIGHTS

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

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

Table of Contents

Recommendation ITU-T G.993.5

Self-FEXT cancellation (vectoring) for use with VDSL2 transceivers

Amendment 2

Editorial note: This is a complete-text publication that includes ITU-T G.993.5 (2015) plus its Amendment 1 (2016), Corrigendum 1 (2016) and Amendment 2 (2017). Annexes A and B, introduced by Amendment 2, are not shown in revision marks for readability purposes.

1 Scope

Vectoring is a transmission method that employs the coordination of line signals for reduction of crosstalk levels and improvement of performance. The degree of improvement depends on the channel characteristics. Vectoring may be for a single user or for multiple users' benefit.

This Recommendation is specifically limited to the self-far-end crosstalk (self-FEXT) cancellation in the downstream and upstream directions. This Recommendation defines a single method of self-FEXT cancellation, in which far-end crosstalk (FEXT) generated by a group of near-end transceivers and interfering with the far-end transceivers of that same group is cancelled. This cancellation takes place between very high-bit-rate digital subscriber line 2 (VDSL2) transceivers, not necessarily of the same profile. This Recommendation is intended to be implemented in conjunction with [ITU-T G.993.2]. Multi-pair digital subscriber line (DSL) bonding ([b-ITU-T G.998.1], [b-ITU-T G.998.2] and [b-ITU-T G.998.3]) may be implemented in conjunction with vectoring.

The techniques described in this Recommendation provide means of reducing self-FEXT generated by the transceivers in a multi-pair cable or cable binder. Self-FEXT cancellation techniques are particularly beneficial with short cable lengths (< 1 km) and limited near-end crosstalk (NEXT), background noise, and FEXT from systems which are not a part of the vectored group (alien noise). The level of non-self-FEXT noise sources relative to that of self-FEXT sources determines the degree to which self-FEXT reduction can improve performance. Another significant factor is the degree to which the self-FEXT cancelling system has access to the disturbing pairs of the cable. Maximum gains are achieved when the self-FEXT cancelling system has access to all of the pairs of a cable carrying broadband signals. For multi-binder cables, significant gains are possible when the self-FEXT cancelling system has access to all of the pairs of the binder group(s) in which it is deployed and has the ability to cancel at least the majority of dominant self-FEXT disturbers within the binder. When multiple self-FEXT cancelling systems are deployed in a multi-binder cable without binder management, gains may be significantly reduced.

2 References

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

[ITU-T G.993.2]   Recommendation ITU-T G.993.2 (2006), *Very high speed digital subscriber line transceivers 2 (VDSL2).*

[ITU-T G.994.1]	Recommendation ITU-T G.994.1 (2007), *Handshake procedures for digital subscriber line transceivers*, plus Amd. 5 (2010).
[ITU-T G.997.1]	Recommendation ITU-T G.997.1 (2009), *Physical layer management for digital subscriber line transceivers*, plus Amd. 1 (2010).
[ITU-T G.998.4]	Recommendation ITU-T G.998.4 (2010), *Improved impulse noise protection for DSL transceivers*.
[IEEE 802.3]	IEEE 802.3 (2008), *IEEE Standard for Information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements Part 3: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications*.

3 Definitions

3.1 Terms defined elsewhere

This Recommendation adopts the definitions of [ITU-T G.993.2].

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

3.2.1 backchannel: The channel through which the VTU-R sends clipped error samples to the vectoring control entity (VCE). The backchannel may be implemented as part of the eoc or as part of the Ethernet data stream from the VTU-R to the VTU-O.

3.2.2 ceiling: Rounding to the nearest higher integer, denoted as $\lceil x \rceil$.

3.2.3 channel matrix: For a particular line in a group of lines, the channel matrix characterizes the FEXT couplings on each subcarrier frequency between the line and all other lines in the group.

3.2.4 clipped error sample: A (B_max+1)-bit 2's complement representation of a normalized error sample through multiplying each component by 2^{N_max-1}, flooring and clipping to the $[-2^{B\_max}, 2^{B\_max} - 1]$ interval (with N_max a fixed value, and B_max a value controlled by the VCE).

3.2.5 expected throughput (ETR): see clause 3.2 of [ITU-T G.998.4].

3.2.6 flag tones: All subcarriers of a sync symbol with indices equal to $10n+1$ or $10n+7$, with n an integer value. Flag tones are used to signal OLR transitions during Showtime.

3.2.7 flooring: Rounding to the nearest lower integer, denoted as $\lfloor x \rfloor$.

3.2.8 normalized error sample: The complex error measured by the VTU-R, being the distance between the received signal vector and the decision constellation point referred to the input of the constellation descrambler, expressed in units equal to half the distance between two adjacent constellation points.

3.2.9 pilot sequence: A binary sequence set by the VCE. When the pilot sequence is transmitted during initialization and in Showtime, each bit of the pilot sequence determines whether the VTU-O (downstream pilot sequence) or the VTU-R (upstream pilot sequence), respectively, modulates ZEROS on all probe tones or ONES on all probe tones of a particular sync symbol.

3.2.10 probe tones: All subcarriers of a sync symbol with indices equal to $10n$, $10n+2$, $10n+3$, $10n+4$, $10n+5$, $10n+6$, $10n+8$, or $10n+9$, with n an integer value. Probe tones are used for transmission of pilot sequences.

3.2.11 Syncflag: A sync symbol in which the sync frame bits modulated on the flag tones are inverted relative to the sync frame modulated by the most recently transmitted sync symbol (i.e., if

the previous sync frame was all ZEROs modulated on the flag tones, the Syncflag would correspond to a sync frame of all ONEs modulated on the flag tones, and vice versa). The Syncflag is used to signal online reconfiguration transitions.

3.2.12 vectored group: The set of lines over which transmission from the access node (AN) is eligible to be coordinated by pre-compensation (downstream vectoring), or over which reception at the AN is eligible to be coordinated by post-compensation (upstream vectoring), or both. Depending on the configuration of the vectored group, downstream vectoring, upstream vectoring, both or none may be enabled.

3.2.13 vectoring: The coordinated transmission and/or coordinated reception of signals of multiple DSL transceivers using techniques to mitigate the adverse effects of crosstalk to improve performance.

4   Abbreviations and acronyms

This Recommendation adopts the abbreviations defined in [ITU-T G.993.2]. In addition, this Recommendation uses the following abbreviations:

ACTATP	Actual Aggregate Transmit Power
AFE	Analogue Front End
AN	Access Node
AN-MIB	Access Node Management Information Base
ATP	Aggregate Transmit Power
BDR	Backchannel Data Rate
CO	Central Office
CO-MBI	Central Office-Management Information Base
CO-side	End of the line nearer to the Central Office
CP	Customer Premises
CP-side	End of the line nearer to the Customer Premises
DMT	Discrete Multi-Tone
DSE	Disorderly Shutdown Event
DSL	Digital Subscriber Line
EC	Echo Canceller
eoc	Embedded Operation Channel
ERB	Error Report Block
ETR	Expected Throughput
FEXT	Far-end crosstalk
FTU	Fast Transceiver Unit
FTU-O	FTU at the Optical network unit
HDLC	High-Level Data Link Control
IDFT	Inverse Discrete Fourier Transform
L2+	Ethernet Layer 2 and above
ME	Management Entity (or Mean Error)

MIMO	Multiple Input Multiple Output
NEXT	Near-end crosstalk
NDR	Net Data Rate
NMS	Network Management System
NOMATPds	Nominal Aggregate Transmit Power in downstream
NOMATPus	Nominal Aggregate Transmit Power in upstream
NT	Network Termination
PCB	Power Cut-Back
PDF	Probability Density Function
PDM	Physical Medium Dependent
PSD	Power Spectral Density
QAM	Quadrature Amplitude Modulation
OLR	On-Line Reconfiguration
ONU	Optical Network Unit
QLN	Quiet Line Noise
RT	Remote Terminal
RTX	Retransmission
SC	Segment Code
SNR	Signal-to-Noise Ratio
SOC	Special Operations Channel
SOS	Save Our Showtime
SRA	Seamless Rate Adaptation
SSC	Sync Symbol Counter
TA	Timing Advance
TEQ	Time Domain Equalizers
TID	TIGAV identification number
TIGAV	Transmitter Initiated Gain Adjustment for VDSL2
UPBO	Upstream Power Back Off
VBB	Vectored Band Block
VCE	Vectoring Control Entity
VDSL2	Very high-bit-rate Digital Subscriber Line 2
VDSL2-LR	Long Reach mode for Vectored VDSL2
VME	VDSL2 Management Entity
VTU	Very high-speed digital subscriber line Transceiver Unit
VTU-O	VTU at the ONU (or central office, exchange, cabinet, etc., i.e., operator end of the loop)
VTU-R	VTU at the Remote site (i.e., subscriber end of the loop)

XTU-C   X digital subscriber line Transceiver Unit at the Central office

XTU-R   X digital subscriber line Transceiver Unit at the Remote end

5   Reference models

5.1   General

A reference model for a vectored system is illustrated in Figure 5-1. In a vectored system, the access node (AN), located at a central office (CO) or remote terminal (RT) or other location, transmits to and receives from a number of network terminations (NTs). The common element of all forms of vectoring is coordinated transmission (downstream vectoring) or coordinated reception (upstream vectoring) of signals from lines in the vectored group at the AN. Thus, the signals may be represented as a vector where each component is the signal on one of the lines. This coordination is made possible through an interface between a very high-speed digital subscriber line transceiver unit (VTU) at the ONU (VTU-O) (here called VTU-O-1) and all other VTU-Os (here called VTU-O-n, $n=2…N$, where N denotes the number of lines in the vectored group), which is here called ε-1-n to indicate that the coordination takes place between line 1 and line n.

Coordinated management of the lines is performed by the network management system (NMS), passing management information to the management entity (ME) through the Q-interface (see clause 11). Both the NMS and the ME are defined in [ITU-T G.997.1]. Inside the AN, the ME further conveys the management information for a particular line (over an interface here called ε-m) to the vectoring control entities (VCEs) of the vectoring group that line belongs to. Each VCE controls a single vectored group, and controls VTU-O-n (connected to line n in the vectored group) over an interface here called ε-c-n. Pre-coder data are exchanged between VTU-O-$n1$ and VTU-O-$n2$ over an interface here called ε-$n1$-$n2$.

Figure 5-1 shows the reference model for a vectored system (only line 1 out of a vectored group of N lines is shown). The PHY blocks represent the physical layer of the AN interface towards the network and of the NT interface towards the customer premises (CP). These blocks are shown for completeness of the data flow but are out of scope of this Recommendation. The Ethernet layer 2 and above (L2+) blocks represent the Ethernet Layer 2 and above functionalities contained in the AN and NT. These blocks are shown for completeness of the data flow but are out of scope of this Recommendation, except for the encapsulation (at NT) and decapsulation (at AN) of the backchannel (see clause 7.4.1).
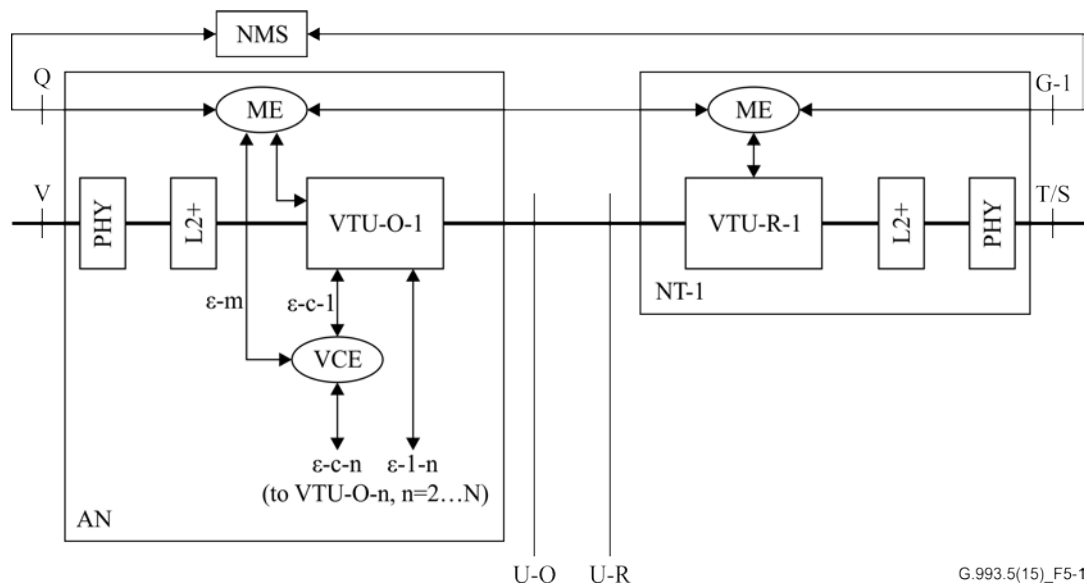
Figure 5-1 – Reference model for a vectored system (shown for line 1 in a vectored group of *N* lines)

Using [b-ITU-T G.998.1], [b-ITU-T G.998.2] and [b-ITU-T G.998.3], data rates can be increased by deploying multiple lines to the same customer premises – a technique known as bonding.

NOTE – Vectoring is not another name for bonding; bonding may be used with or without vectoring. The use of vectoring over bonded lines is often defined as bonded vectoring or as multiple input multiple output (MIMO) DSL.

The focus of this Recommendation is the use of vectoring over lines that are not bonded, although it does not preclude the use of vectoring over bonded lines.

A vectored VDSL2 system improves its performance from the use of joint signal processing in the downstream direction (coordinated transmission), or from the use of joint signal processing in the upstream direction (coordinated reception) which allows cancelling of self-FEXT (i.e., FEXT generated by the lines of the vectored group). The noise sources which are external to the group of vectored pairs in the vectored system (for example, alien crosstalk from lines operated by another service provider, interference from AM broadcast channels or interference from amateur radio ("HAM") transmitters above the AM broadcast band) reduce the benefits of FEXT cancellation and reduce the performance enhancement provided by a vectored system.

5.2 Downstream vectoring

For relatively short lines and high-bandwidth systems such as VDSL, self-FEXT is the limiting factor for downstream data rates. This Recommendation defines multi-line pre-coding at the AN to mitigate FEXT in the downstream direction, based on "pre-subtraction" or "pre-compensation" of the FEXT, while meeting transmitted power constraints. To accommodate for such pre-coding, the ITU-T G.993.2 physical medium dependent (PMD) layer is modified as shown in Figure 5-2 (adapted from Figure 10-1 of [ITU-T G.993.2], with differences shown shaded). Figure 5-2 shows the VTU-O functional model for line 1 out of a vectored group of *N* lines. For each line in the vectored group, the PMD sublayer includes an $N \times 1$ pre-coder. Over the vectored group, the *N* pre-coders for each of the *N* lines constitute the FEXT cancellation pre-coder shown in Figure 6-1.

NOTE – The pre-coder may or may not be implemented in the same physical device as the other functional blocks shown in Figure 5-2.
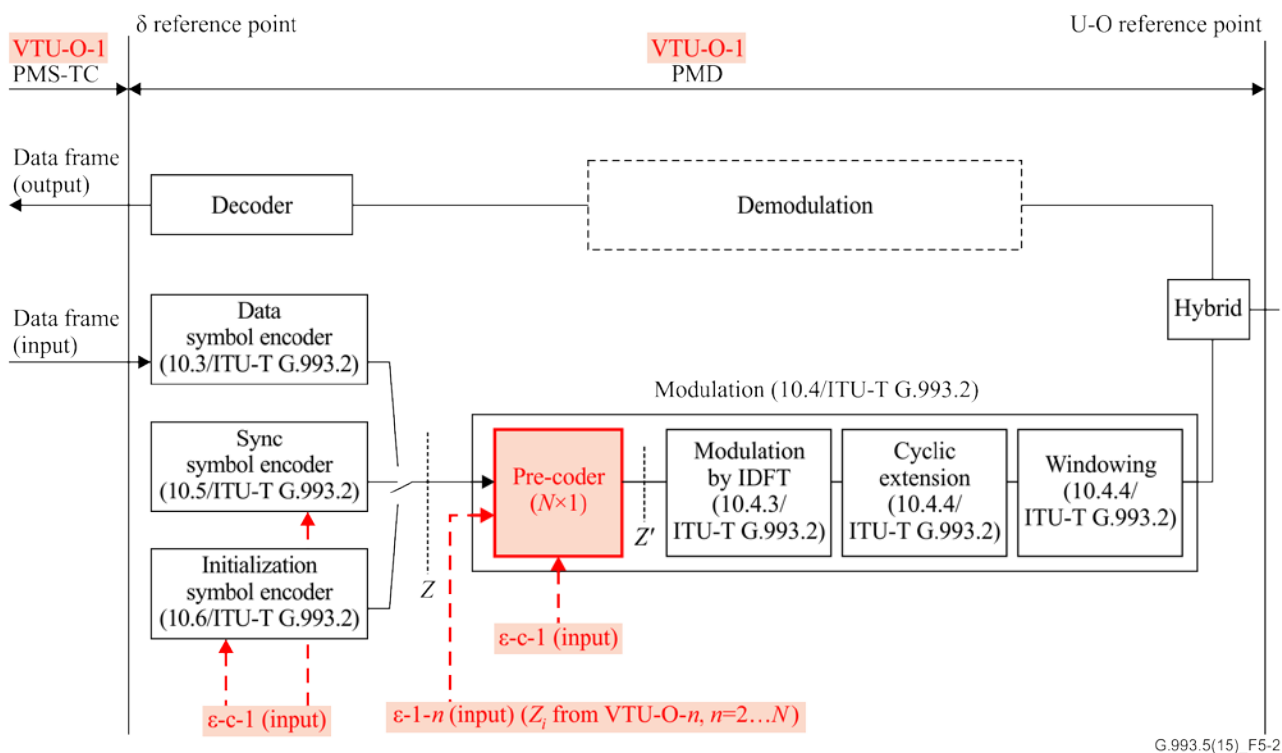
Figure 5-2 – VTU-O functional model of PMD sub-layer using $N{\times}1$ pre-coder for downstream vectoring (shown for line 1 in vectored group of N lines)

The VTU at the remote site (VTU-R) functional model of PMD sublayers is as shown in Figure 10-1 of [ITU-T G.993.2], with an addition of vectoring-related control signals applied to the sync symbol encoder and initialization symbol encoder to provide pilot sequence modulation on sync symbols, similar to those shown in Figure 5-2 (see clauses 10.3 and 10.4).

5.3   Upstream vectoring

Upstream vectoring is mainly a receiver function at the end of the line nearer to the central office (CO-side), and therefore its implementation is vendor discretionary. This Recommendation only defines the VTU-R transmitter requirements to facilitate upstream FEXT cancellation at the CO-side (e.g., transmission of upstream pilot sequence with timing and content under VCE control).

6   CO-side requirements in a vectored group

This clause describes the CO-side steady-state behaviour to support operation of an N-pair vectored group.

6.1   General

Figure 6-1 shows the functional model for the inclusion of downstream FEXT cancellation pre-coding at the AN for all lines in the vectored group, as a generalization of Figure 5-2 from a signal processing perspective. The model shows only the portion of an array of the downstream symbol encoders (which represent the data, sync or initialization symbol encoders shown in Figure 5-2) and the modulation by the inverse discrete Fourier transform (IDFT) functional blocks of the VTU-Os, with the FEXT cancellation pre-coder inserted between the symbol encoders and the modulation by the IDFT blocks.

The VCE of the vectored group learns and manages the channel matrix per vectored subcarrier, which reflects the channel characteristics of the managed group of lines. In the functional model in

Figure 6-1, the channel matrix for each vectored subcarrier is of size $N \times N$ where N is the number of lines in the vectored group.

From the channel matrix, a FEXT pre-coder matrix may be derived and used to compensate the FEXT from each line in the vectored group. In the functional model in Figure 6-1, this is shown by a matrix of FEXT cancellation pre-coders per vectored subcarrier of size $N \times N$. This FEXT cancellation pre-coding matrix may be "sparse" (see Note). Knowing the transmit symbols on each disturbing channel, the pre-coder pre-compensates the actual transmit symbol such that at the far-end receiver input, the crosstalk is significantly reduced.

NOTE – In typical cases, several of the pre-coder coefficients may be set to 0 for implementation reasons, or because the crosstalk coefficients are negligibly small.

The channel matrix and the resulting FEXT cancellation pre-coder matrix are assumed to be entirely managed inside the AN. An information exchange between the VTU-O and VTU-R is required in each vectored line to learn, track, and maintain the channel matrix and associated FEXT cancellation pre-coder matrix (see backchannel definition in clause 7 and initialization in clause 10). The actual algorithms for processing this information to obtain the channel matrix and to generate the FEXT cancellation pre-coder are vendor discretionary. Depending on the implementation, it may be possible for the VCE to directly determine the FEXT cancellation pre-coder matrix and only have an implicit learning of the channel matrix.
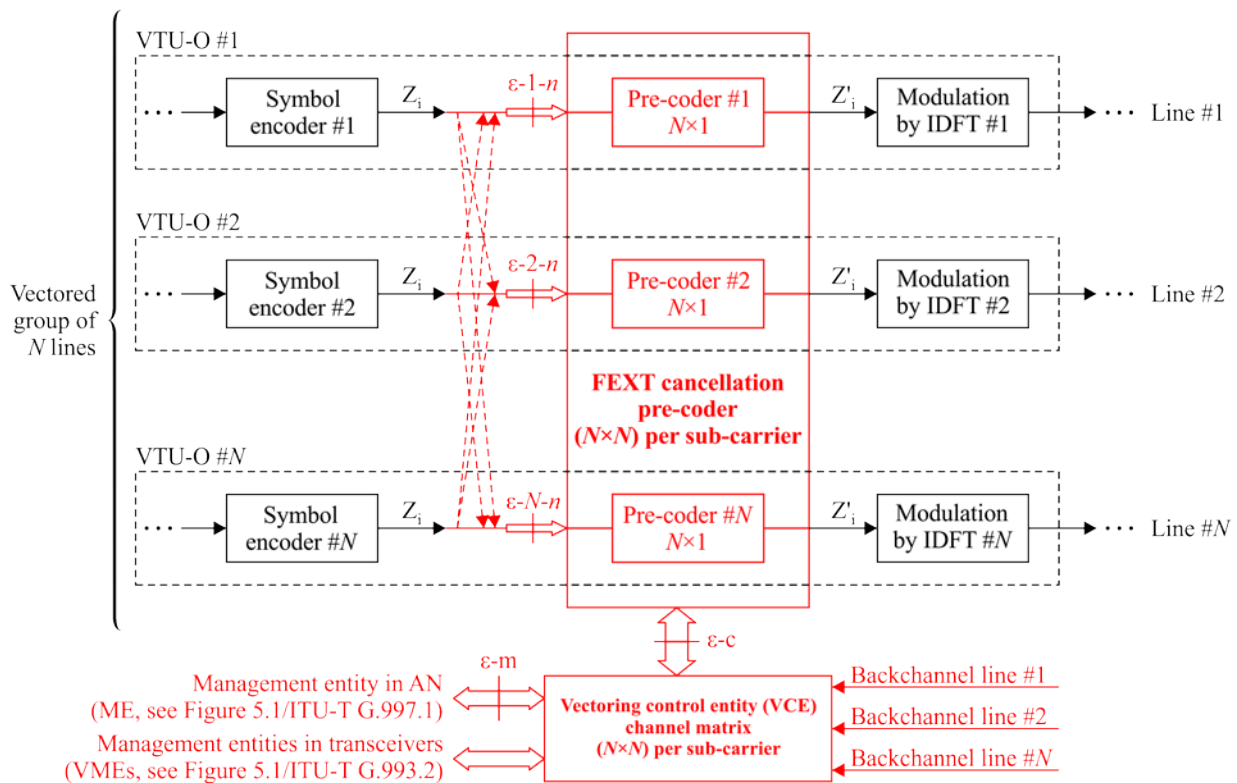
Figure 6-1 – Vectored group functional model of PMD sub-layer using $N \times N$ pre-coder for downstream vectoring

The VTU-O shall support downstream vectoring (see clause 6.2) and may support upstream vectoring (see clause 6.3).

The VTU-O shall support seamless rate adaptation ((SRA), on-line reconfiguration (OLR) Type 3) in the downstream and upstream direction, including mandatory support within SRA of:

– dynamic interleaver reconfiguration (change of D_p);

– framing reconfiguration (change of T_p, G_p and B_{p0})

as defined in clause 13.1 of [ITU-T G.993.2].

If ITU-T G.998.4 is enabled in a particular direction, the VTU-O shall also support seamless rate adaptation (SRA, OLR Type 5) in this same direction, including mandatory support within SRA of all configurations specified in clause C.3.2 of [ITU-T G.998.4].

6.2 Downstream vectoring requirements for the VTU-O

The VTU-O shall comply with [ITU-T G.993.2], with the exceptions and additional requirements contained in this Recommendation.

In order to enable the VCE to fulfil the tasks described in clause 6.1, the VTU-O shall support the requirements in this clause and the following clauses.

6.2.1 Synchronous mode

Under VCE control, all VTU-Os in the vectored group shall use the same subcarrier spacing and symbol rate, and shall start transmission of discrete multi-tone (DMT) symbols at the same time on all of the lines in the vectored group. The transmit symbol clocks shall be phase-synchronous at all VTU-Os in the vectored group with a 1 µs maximum phase error tolerance at the U-O2 reference point (defined in Figure 5-4 of [ITU-T G.993.2]).

6.2.2 Sync symbol position

The VTU-O shall have the capability to transmit sync symbols as defined in clause 10.2 of [ITU-T G.993.2]. The downstream sync symbol time positions are determined by the VCE. The VCE may configure all VTU-Os in the vectored group to transmit downstream sync symbols at the same time positions or use different time positions for one or more VTU-Os in the vectored group.

The VTU-O shall keep a downstream sync symbol counter (SSC) (MODULO N_SSC), counting continuously during Showtime. The value *N_SSC* shall be selected by the VCE and transmitted during initialization to the VTU-R in O-SIGNATURE (see clause 10.3.2.1). The counter value of the first downstream sync symbol transmitted after entering Showtime shall be set by the VCE and transmitted to VTU-R in the field First SSC of the Error Feedback command (see Table 8-3).

NOTE – This setting at the start of Showtime synchronizes the downstream sync symbol counter with the VTU-R (see clause 7.3.3).

6.2.3 Modulation of a pilot sequence

The VTU-O shall have the capability to modulate a VCE-specified downstream pilot sequence on all probe tones of the downstream sync symbols during initialization (see e.g., clause 10.3.3.1) and on all probe tones (see clause 3.2.10) of the downstream sync symbols during Showtime. The downstream pilot sequence is vendor discretionary, determined by the VCE, and is a binary string of length *Npilot_ds* (with bits indexed from 0 to *Npilot_ds – 1*, and the bit with index 0 transmitted first). If the "pilot sequence length multiple of 4" is enabled (see clause 10.2), then valid values of *Npilot_ds* are all multiples of 4 in the range from 8 to 512. Otherwise, the valid values of *Npilot_ds* shall be all powers of 2 in the range from 8 to 512. The pilot sequence shall be cyclically repeated after *Npilot_ds* bits, except the case where the downstream pilot sequence is changed by the VCE. The downstream pilot sequence bits may be changed by the VCE at any time without notification to the VTU-R, while maintaining the length of the pilot sequence. During initialization, the VTU-O may modulate on all flag tones of the downstream sync symbols either the downstream pilot sequence (the same as modulated on the probe tones), or an all ONEs sequence.

In Showtime, the first downstream sync symbol position shall be as defined in clause 10.6. Each sync symbol shall modulate a pilot sequence, which may be frequency independent or frequency dependent.

The modulation of a frequency independent pilot sequence on the probe tones of sync symbols is defined as whether the sync frame bits modulated onto the probe tones are set to all ZEROs (if the pilot sequence bit is ZERO) or set to all ONEs (if the pilot sequence bit is ONE) (i.e., a 1-bit control per sync symbol).

The modulation of a frequency dependent pilot sequence on a probe tone of sync symbols is defined as whether the sync frame bits modulated onto the probe tone shall be set to either 00 (if the pilot sequence bit for that probe tone is ZERO) or set to 11 (if the pilot sequence bit for that probe tone is ONE). Over the tones of a particular sync symbol, the pilot sequence bit shall have a periodicity of 10 tones (considering both probe and flag tones).

The sync frame bits modulated on the flag tones (see clause 3.2.6) shall be used for the transmission of a Syncflag as defined in clause 10.5.3 of [ITU-T G.993.2]. The sync frame shall be modulated onto a sync symbol as defined in clause 10.5 of [ITU-T G.993.2] (including the quadrant scrambling of all MEDLEY subcarriers, regardless of being a flag or probe tone).

6.2.4 Pre-coding

A VTU-O, when enabled for downstream vectoring, shall support FEXT cancellation pre-coding, as shown in Figure 5-2 and Figure 6-1. The pre-coding coefficients for each individual VTU-O (see clause 6.1) shall be under VCE control.

6.2.5 Transceiver states and transceiver state diagram (replaces clause 12.1.2 of ITU-T G.993.2)

NOTE 1 – This clause replaces clause 12.1.2 of [ITU-T G.993.2] as applicable to the VTU-O. Transceiver states and transceiver state diagram requirements as applicable to the VTU-R are unchanged.

State diagrams are given in Figure 6-2 for the VTU-O and in Figure 12-3 of [ITU-T G.993.2] for the VTU-R. States are indicated by ovals, with the name of the state given within the oval. The states are defined in Table 6-1 for the VTU-O and in Table 12-2 of [ITU-T G.993.2] for the VTU-R. Transitions between states are indicated by arrows, with the event causing the transition listed next to the arrow. All states are mandatory.

A variety of "host controller" commands (events preceded by "c:_" and "r:_") are shown in either state diagram to provide example events and transitions between states. The way in which these events are implemented is left to the vendor.

In the state diagram for the VTU-O, an O-IDLE state is intended to establish a quiet mode, that is necessary to allow to discontinue service or to perform certain tests (e.g., as defined in [ITU-T G.996.2]).

In the state diagram for the VTU-R, a self-test function is desirable, but it may be a vendor/customer option to define when self-test occurs (e.g., always at power-up or only under VTU-O control), and which transition to take after successfully completing self-test (e.g., enter R-IDLE, or enter R-SILENT).

IDLE is the state where the VTU is provisioned through a management interface for the service desired by the operator. In this state, the VTU does not transmit any signal. A VTU that receives a higher layer signal to activate (c:_L0_request for VTU-O or r:_L0_request for VTU-R) shall use the initialization procedure defined in clause 12.3 to transition the link from the L3 to the L0 state. A VTU that detects the signals of the initialization procedure at the U reference point, if enabled, shall respond by using the initialization procedure. If disabled, the VTU shall remain in the IDLE state.

The link transitions to the L0 state once the initialization procedure has completed successfully and both VTUs are in the SHOWTIME state. A VTU-O shall return to the O-SILENT state upon a

guided power management (c:_L3_request, see clause 11.2.3.9), or upon a re-initialization triggered by Re-Initialization Policy (see clause 12.1.4). A VTU-R shall return to the R-SILENT state upon a guided power management (r:_L3_request, see clause 11.2.3.9), or upon a re-initialization triggered by Re-Initialization Policy (see clause 12.1.4). With the former, a VTU-R shall set AUTO_init=OFF to disable autonomous proceeding to the R-INIT/HS state. With the latter, a VTU-R shall set AUTO_init=ON to enable autonomous proceeding to the R-INIT/HS state.

The receiving VTU shall transition from the SHOWTIME state upon Persistent LOS and/or LOF failure (see clause 12.1.4). This implies that if no high_BER-hs or high_BER-fs events cause the receiving VTU to transition state earlier, then the persistency of the LOS and/or LOF failure allows the transmitting VTU to detect the LOS or LOF failure condition through the indicator bits, before the receiving VTU transitions state.

NOTE 2 – High_BER-fs event relates to fast start-up, which is for further study (see clause 12.5).

The receiving VTU shall also transition state upon a high_BER event (see clause 12.1.4). This event relates to near-end and/or far-end performance primitives and performance counters for which thresholds may be configured through the CO-MIB as to declare a high_BER event upon threshold crossing.

A VTU-O shall either enter the O-SILENT state via the O-DEACTIVATING state, upon a guided power management (c:_L3_request), or upon a re-initialization triggered by Re-Initialization Policy.

NOTE 3 – Setting the duration of O-DEACTIVATING (vendor discretionary) to zero implements an immediate transition from O-SHOWTIME to O-SILENT.

When the VTU-O transitions from the O-SHOWTIME state to the O-DEACTIVATING state followed by transition to the O-SILENT state, the VTU-R detects a Persistent LOS Failure. Upon detection, the VTU-R shall transition to the R-SILENT state followed by the R-INIT/HS state and shall start transmitting R-TONES-REQ within a maximum of 6 s after the VTU-O transitioning to the O-SILENT state.

When the VTU-O transitions from the O-INIT/TRAIN state to the O-DEACTIVATING state followed by transition to the O-SILENT state, , the VTU-R detects a failure in the training. Upon detecting a failure in the training, the FTU-R shall transition to the R-SILENT state followed by transition to the R-INIT/HS state.

NOTE 4 – The direct transition from the O-INIT/TRAIN state to the O-SILENT state is shown in Figure 6-2 as a transition via the O-DEACTIVATING state, the duration of which is vendor discretionary and may be zero DMT symbols.

When the VTU-R transitions from the R-SHOWTIME state to the R-SILENT state, the VTU-O detects a Persistent LOS Failure. Upon detection, the VTU-O shall transition to the O-DEACTIVATING state followed by transition to the O-SILENT state, either followed by waiting to receive R-TONES-REQ (VTU-R initiated HS) or followed by the O-INIT/HS state (VTU-O initiated HS).

NOTE 5 – While the VTU-O is in the O-DEACTIVATING state, the VCE may update the FEXT cancellation coefficients among the showtime lines.
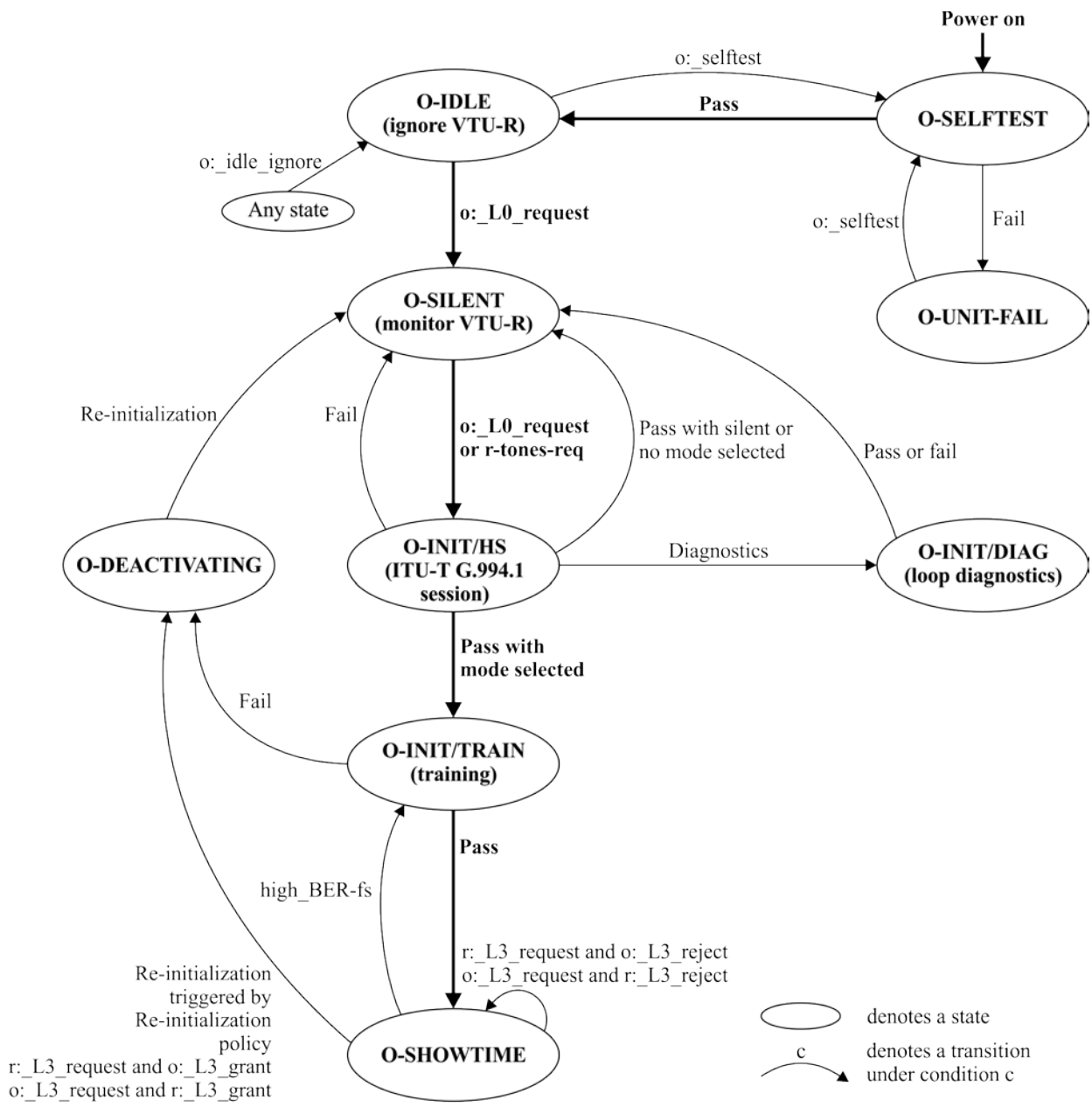
Figure 6-2 – State diagram for the VTU-O

Table 6-1 – VTU-O state definitions

State name	Description
O-SELFTEST (mandatory)	• Temporary state entered after power-up in which the VTU performs a self-test; • Transmitter off (QUIET at U-O interface); • Receiver off (no response to R-TONES-REQ signal); • No response to host control channel; • If self-test pass then transition to O-IDLE; • If self-test fail then transition to O-UNIT-FAIL.
O-UNIT-FAIL (mandatory)	• Steady state entered after an unsuccessful VTU self-test; • Transmitter off (QUIET at U-O interface); • Receiver off (no response to R-TONES-REQ signal); • Monitor host control channel if possible (allows the host controller to retrieve self-test results).
O-IDLE (mandatory)	• Steady state entered after successful self-test; • Transmitter off (QUIET at U-O interface); • Receiver off (no response to R-TONES-REQ signal); • Monitor host control channel.
O-SILENT (mandatory)	• Steady state defined in [ITU-T G.994.1], entered upon host controller command; • Transmitter off (QUIET at U-O interface); • Receiver on (monitor for R-TONES-REQ signal, if detected, transition to O-INIT/HS state); • Monitor host control channel.
O-INIT/HS (mandatory)	• Temporary state entered to perform ITU-T G.994.1 phase of initialization; • Transmitter on (start with transmitting C-TONES signal); • Receiver on (start with monitoring for R-SILENT0 signal); • Monitor host control channel; • If silent period or no mode selected then transition to O-SILENT1; • If loop diagnostics mode then transition to O-INIT/DIAG; • If operating mode selected then transition to O-INIT/TRAIN.
O-INIT/TRAIN (mandatory)	• Temporary state entered to perform other phases of initialization; • Transmitter on (start with O-P-QUIET1); • Receiver on (start with monitoring for R-P-QUIET1); • If init pass then transition to O-SHOWTIME; • If init fail then transition to O-DEACTIVATING; • Monitor host control channel.
O-INIT/DIAG (mandatory)	• Temporary state entered to perform other phases of initialization in loop diagnostics mode; • Transmitter on (start with O-P-QUIET1); • Receiver on (start with monitoring for R-P-QUIET1); • Transition to O-SILENT; • Monitor host control channel.

Table 6-1 – VTU-O state definitions

State name	Description
O-SHOWTIME (mandatory)	• Steady state in which one or more bearer channels are active; • On-line reconfigurations occur within this state; • Upon conditions satisfying the Re-Initialization Policy ($RIpolicy_n$) then transition to O-DEACTIVATING; • If link transition to L3 state is granted, then transition to O-DEACTIVATING; • Monitor host control channel.
O-DEACTIVATING (mandatory)	• Temporary state entered upon line transition to L3 state. The duration of this state is vendor discretionary and may be zero; • Transmitter is on: VTU-O shall not transmit the direct signal (i.e, Zi=0 for all sub-carriers) while it may transmit the pre-compensation signal Zi' in downstream; • Receiver may be on: VTU-O may receive signals in upstream to support upstream FEXT cancellation; • VCE may update the downstream and upstream FEXT cancellation coefficients; • Controlled by the VCE, the VTU-O transitions to the O-SILENT state.

6.3 Upstream vectoring requirements for the VTU-O

The implementation at the CO-side is vendor discretionary, apart from the required ability to convey sync symbol timing and upstream vectoring control parameters from the VCE to the end of the line nearer to the customer premises (CP-side). These requirements are defined in clause 10 and apply to each VTU-O member of a vectored group.

The VTU-O shall comply with [ITU-T G.993.2], with the exceptions and additional requirements contained in this Recommendation.

During initialization, each VTU-O in a vectored group shall have the capability to transmit a time marker to the VTU-R to indicate which symbols are at a time position that coincides with Showtime sync symbols on active lines. The modulation method of such time marker on such symbols is defined in clause 10.3.3.5.

The VTU-O shall have the capability to convey the control parameters of the upstream vectored group defined in clause 7 and clause 10 from the VCE to the CP-side.

If upstream vectoring is enabled, the VTU-O shall support operation also in the case when not all probe tones of the upstream sync symbol have the same sign, but the sign pattern over the tones of the sync symbol has a periodicity of 10 tones (considering both probe and flag tones).

6.4 Requirements for the VCE

The VCE shall support downstream vectoring.

The VCE shall include the capability to be controlled by the ME over the ε-m interface (shown in Figure 5-1) to use *B_min*=0 (see Table 7-1 for the definition and Table 7-2 for valid values of *B_min*).

7 CP-side requirements in a vectored group

This clause describes the CP-side steady-state behaviour as part of an N-pair vectored group.

7.1 General

The VTU-R shall send clipped error samples (defined in clause 7.2.1) to the VCE of the vectored group, through the backchannel (defined in clauses 7.2.2 through 7.2.4). The VTU-R shall support Layer 2 Ethernet encapsulation (defined in clause 7.4.1) and shall support embedded operation channel (eoc) encapsulation (defined in clause 7.4.2) of the backchannel information. The VCE shall select the encapsulation method to be used, and communicate this setting to the VTU-R during initialization (see clause 10.5.2.1). The set encapsulation method shall be kept unchanged during Showtime.

Figure 7-1 shows the reference model for the Layer 2 encapsulated backchannel information flow. Within the NT, the clipped error samples are first sent from the VTU-R to the L2+ functional block (streamBC.indicate primitive), where they are encapsulated into the Layer 2 transport protocol (defined in clause 7.4.1) and further multiplexed into one of the upstream Ethernet (or Ethernet over ATM) data streams (stream(n).confirm, see Annex K of [ITU-T G.993.2]). At the AN, the Layer 2 encapsulation is terminated in the L2+ functional block and the clipped error samples are delivered to the VCE (streamBC.indicate primitive).
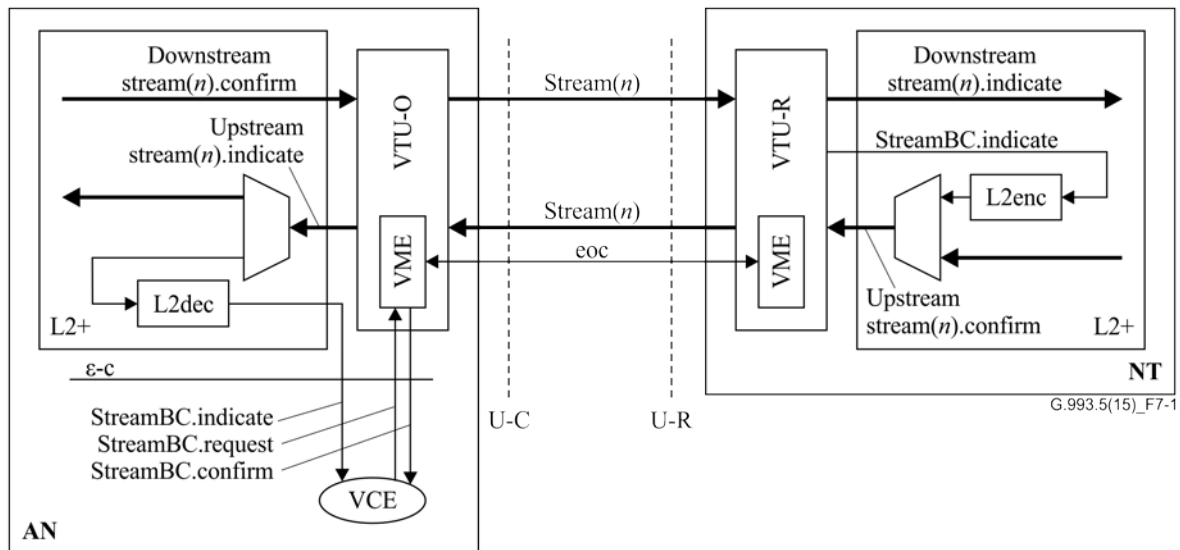
Figure 7-1 – Reference model for the Layer 2 encapsulated backchannel information flow

Figure 7-2 shows the reference model for the eoc encapsulated backchannel information flow. Within the VTU-R, the clipped error samples are sent to the VDSL2 management entity (VME), where they are encapsulated into an eoc message, as defined in clause 8.1. At the VDSL2 management entity (VME, see clause 11.2 of [ITU-T G.993.2]) of the VTU-O, the eoc encapsulation is terminated and the clipped error samples are delivered to the VCE (streamBC.indicate primitive).
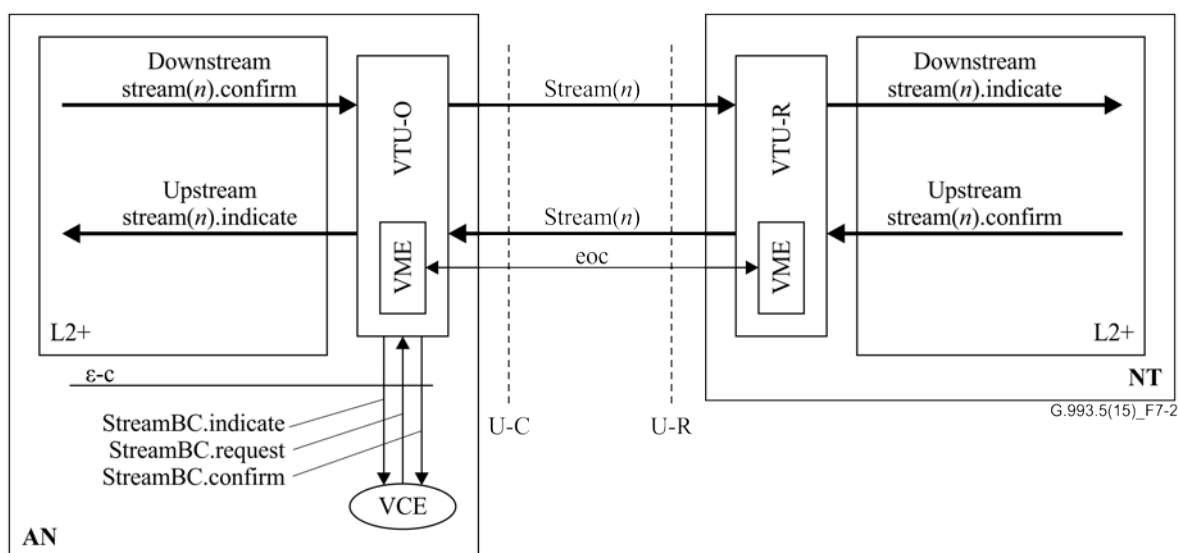
Figure 7-2 – Reference model for the eoc encapsulated backchannel information flow

Regardless of the backchannel encapsulation method, the VCE communicates with the VTU-O VME to set the backchannel control parameters (defined in Table 7-1), e.g., for which subcarriers the VTU-R shall send clipped error samples through the backchannel (streamBC.request primitive). The VTU-O VME uses eoc commands (defined in clause 8.1) to communicate these backchannel control parameters to the VTU-R VME and delivers the information received from VTU-R VME eoc responses back to the VCE (streamBC.confirm primitive).

The VTU-R shall support seamless rate adaptation (SRA, OLR Type 3) in the downstream and upstream direction, including mandatory support within SRA of:

– dynamic interleaver reconfiguration (change of D_p);

– framing reconfiguration (change of T_p, G_p and B_{p0}).

as defined in clause 13.1 of [ITU-T G.993.2], titled "Types of on-line reconfiguration".

If ITU-T G.998.4 is enabled in a particular direction, the VTU-R shall also support seamless rate adaptation (SRA, OLR Type 5) in this same direction, including mandatory support within SRA of all configurations specified in clause C.3.2 of [ITU-T G.998.4].

7.2 Downstream vectoring requirements for the VTU-R

The VTU-R shall comply with [ITU-T G.993.2], with the exceptions and additional requirements contained in this Recommendation.

This Recommendation defines that all probe tones of a sync symbol, both during initialization and during Showtime, may have the same sign (i.e., if a frequency independent pilot sequence is modulated, see clause 6.2.3) or may not have the same sign (i.e., if frequency dependent pilot sequence is modulated, see clause 6.2.3). The VTU-R shall support reception and all related functionalities required for computing error signals also in case when not all probe tones of the sync symbol have the same sign, but the sign pattern over the tones of the downstream sync symbol has a periodicity of 10 tones (considering both probe and flag tones).

7.2.1 Definition of normalized error sample

The VTU-R converts the received time domain signal into frequency domain samples, resulting in a complex value Z for each of the received subcarriers. The subsequent constellation de-mapper associates each of these complex values Z with a constellation point, represented by a value $\hat{C}$. Figure 7-3 shows the computation of a normalized error sample E for a particular subcarrier in a

particular sync symbol. The normalized error sample represents the error between the received complex data sample Z normalized to the 4-quadrature amplitude modulation (QAM) constellation point and the corresponding decision constellation point $\hat{C}$ associated with the received sync symbol in a VTU-R and referred to the input of the constellation descrambler. For illustration, in Figure 7-3, the received normalized complex data sample Z is shown to occur within the constellation boundary of the decision constellation point $\hat{C} = (+1, +1)$.

For each of the subcarriers, the complex normalized error sample E is defined as $E = Z - \hat{C}$, where E is the complex error defined as $E = e\_x + j \times e\_y$ with real component e_x and imaginary component e_y, and Z is the received normalized data sample defined as $Z = z\_x + j \times z\_y$ with real component z_x and imaginary component z_y, and $\hat{C}$ is the decision constellation point associated with the received data sample Z, defined as $\hat{C} = \hat{c}\_x + j \times \hat{c}\_y$ with real component $\hat{c}\_x$ and imaginary component $\hat{c}\_y$ (with $\hat{c}\_x = \pm 1$ and $\hat{c}\_y = \pm 1$).
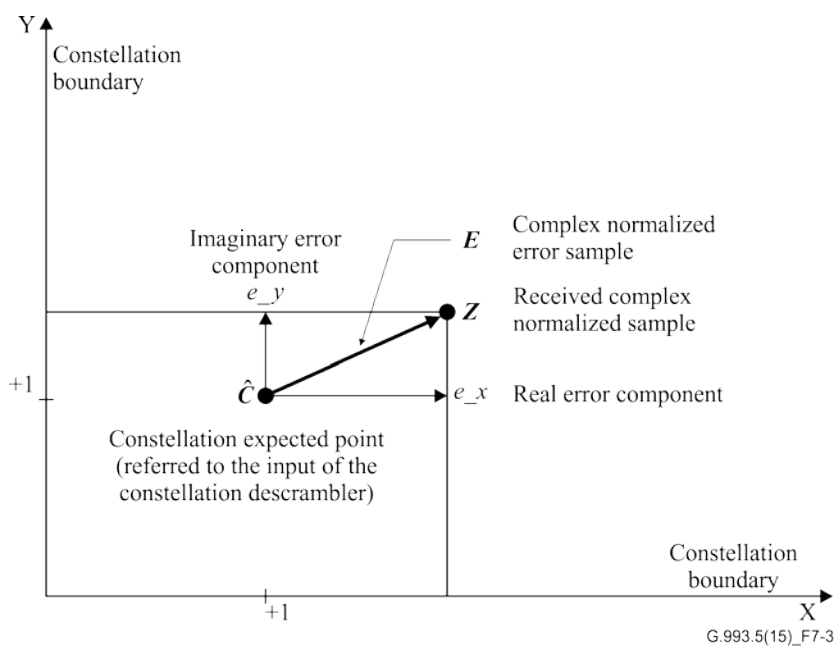
Figure 7-3 – Definition of the normalized error sample E

The real and imaginary components of each normalized error sample E are clipped and quantized to integer values for the clipped error sample components q_x and q_y respectively, as follows:

$$q\_x = \max\left(-2^{B-\max}, \min\left(\left\lfloor e\_x \times 2^{N-\max-1} \right\rfloor, 2^{B-\max} - 1\right)\right)$$
$$q\_y = \max\left(-2^{B-\max}, \min\left(\left\lfloor e\_y \times 2^{N-\max-1} \right\rfloor, 2^{B-\max} - 1\right)\right)$$

where $Q = q\_x + j \times q\_y$ represents the clipped error sample and *N_max* represents the VTU-R's maximum quantization depth of normalized error samples and shall be set to 12, and *B_max* represents the upper bound of the bit index for reporting clipped error sample components q_x and q_y (*B_max* < *N_max*, with *B_max* configured by the VCE, see Tables 7-1 and 7-2).

The values of both clipped error sample components q_x and q_y shall be represented using the two's-complement representation of *B_max*+1 bits. The format of the clipped error sample for reporting over the backchannel is defined in clause 7.2.2. The particular subcarriers on which

clipped error samples shall be reported during initialization and Showtime shall be configured as described in clauses 10.4.2.1, and in clause 8.1, respectively.

7.2.2 Reporting of clipped error samples

The VTU-R shall send clipped error samples (defined in clause 7.2.1) to the VTU-O through the backchannel established between the VTU-O and the VTU-R in each line of the vectored group, as defined in clause 7.4.1 (Layer 2 backchannel) or in clause 8.1 (eoc backchannel) or in clause 10 (special operations channel (SOC) backchannel). The VTU-O conveys the received clipped error samples to the VCE of the vectored group.

7.2.2.1 Control parameters for clipped error sample reporting

The VCE communicates to the VTU-O a set of control parameters for clipped error sample reporting defined in Table 7-1.

Table 7-1 – Control parameters of clipped error samples

Parameter name	Definition
Vectored bands	The downstream frequency bands for which the VTU-R shall send clipped error samples for the subcarriers through the backchannel.
	The vectored downstream bands shall be defined by indices of the lowest frequency and the highest frequency subcarriers.
	N_band denotes the number of vectored bands configured. No more than eight bands shall be configured (i.e., $N\_band \leq 8$). The configured bands shall be identified by their numbers: $vb = 0, 1, 2, 3, 4, 5, 6, 7$ assigned in the ascending order of subcarrier indices associated with the band.
	$N\_carrier(vb)$ denotes the number of subcarriers in frequency band number vb, i.e., the index of the last subcarrier minus the index of the first subcarrier plus one.
	The index of the first (lowest frequency) subcarrier of each vectored downstream band shall be an even value.
	Each of the vectored downstream bands shall be assigned within the boundaries of a single ITU-T G.993.2 standard downstream band (as exchanged during the ITU-T G.994.1 phase) and possibly having more than one vectored band per such standard downstream band. The vectored bands shall not overlap one another.
F_sub	The sub-sampling factor to be applied to the vectored bands.
	For every vectored downstream band, the clipped error sample of the subcarrier with the smallest index shall be transmitted first, followed by the clipped error sample of every F_subth subcarrier within the vectored band.
	Configured by the VCE for each vectored downstream band separately.
F_block	The block size (number of subcarriers) for grouping of clipped error samples.
	Configured by the VCE. The same block size configuration shall be used for all vectored downstream bands (see Table 8-4).
B_min	Lower bound of the bit index for reporting of a clipped error sample component (see clause 7.2.2.2).
	Configured by the VCE for each vectored downstream band separately.
B_max	Upper bound of the bit index for reporting of a clipped error sample component (see clause 7.2.1).
	Configured by the VCE for each vectored downstream band separately.

Table 7-1 – Control parameters of clipped error samples

Parameter name	Definition
L_w	Maximum number of bits for reporting of a clipped error sample component. Configured by the VCE for each vectored downstream band separately. If L_w is set to 0 for a particular vectored downstream band, then that band shall not be reported. L_w shall be set to a non-zero value for at least one vectored downstream band.
padding	Indicates whether or not the VTU-R shall pad clipped error samples through sign extension or zero padding to maintain using L_w bits for reporting of a clipped error sample component if $S < L\_w - 1$ (see clause 7.2.2.2). Configured by the VCE. The same padding configuration shall be used in all vectored downstream bands. If padding is enabled, then B_min shall be set to 0.

Table 7-2 defines the optional and mandatory values for the clipped error samples control parameters. In particular, it defines the valid values for the VCE to configure and the mandatory values for the VTU-R to support. The VTU-O shall support all valid values for VCE to configure. The VTU-R shall indicate during initialization its capabilities to support optional values, and the VCE shall select the values accordingly (see clause 10).

Table 7-2 – Values of backchannel control parameters

Parameter	Valid values for VCE	Mandatory values for VTU-R to support
F_sub	1, 2, 4, 8, 16, 32 and 64	2, 4, 8, 16, 32 and 64
F_block	1, 32, and $\left\lceil \dfrac{N\_carrier}{F\_sub} \right\rceil$	1 and $\left\lceil \dfrac{N\_carrier}{F\_sub} \right\rceil$
B_min	0, … , 11	All valid values
B_max	B_min, … , 11	All valid values
L_w	0, 1, … , min(8, $B\_max - B\_min + 1$)	0, 1, … , 8
padding	1 (enable); 0 (disable) with $F\_block = 32$; 0 (disable) with $F\_block = \left\lceil \dfrac{N\_carrier}{F\_sub} \right\rceil$	1 (enable); 0 (disable) with $F\_block = \left\lceil \dfrac{N\_carrier}{F\_sub} \right\rceil$

For each vectored downstream band assigned by the VTU-O for clipped error sample reporting, the VTU-R shall report the clipped error samples for all subcarriers with indices $X = X\_L + n \times F\_sub$, where n gets all integer values 0, 1, 2, … for which $X\_L \leq X \leq X\_H$ and with X_L and X_H respectively, the indices of the lowest frequency and the highest frequency subcarriers of the vectored downstream band. Clipped error samples of other subcarriers shall not be reported.

On the subcarriers that are not used for transmission ($b_i = 0$, and $g_i = 0$) but assigned for clipped error sample reporting, the VTU-R shall report a dummy error sample. The value of this dummy error sample is vendor discretionary, but shall comply with error sample control parameters and shall not impact reports on other subcarriers.

NOTE – It is the responsibility of the VTU-O and/or the VCE to identify and drop clipped error samples for subcarriers that are not intended for channel estimation.

7.2.2.2 Grouping of clipped error samples

The VTU-R shall group clipped error samples into blocks. Valid block sizes for the parameter *F_block* are defined in Table 7-2. For each block, the VTU-R shall calculate parameters *B_M* and *B_L*. The parameters *B_M* and *B_L* represent the highest and the lowest bit indices of the reported clipped error sample, with the assumption that bit index is counted from the LSB to the MSB, starting from 0.

Figure 7-4 depicts the example of *F_block*=1, *B_min*=2, *B_max*=10, *L_w*=4, and *padding*=0. Two registers each (*B_max*+*L_w*) bits wide contain a clipped error sample component in the bits labelled from *B_max* (clipped error sample MSB) down to 0 (clipped error sample LSB), while the $L\_w - 1 = 3$ remaining bits of each register are set to 0 and labelled with a negative bit index –1 down to $1 - L\_w = -3$. For each component in the block, only the $B\_M - B\_L + 1$ bits with indices from *B_M* down to *B_L* inclusive are included in the error report block (ERB) format defined in clause 7.2.3.1. Parameters *B_M* and *B_L* shall be computed for each block as described below. The VTU-R shall examine all clipped error sample components in each block and determine for each component *ec* (*ec* = 1 to 2×*F_block*) a data-dependent scale parameter s_{ec}, defined to be the sign bit index of the shortest 2's complement representation of the component.

For example, as depicted in Figure 7-4, the first clipped error sample component, having the 11-bit 2's complement representation 11110010101, has shortest representation 10010101 and hence its scale is $s_1 = 7$. Likewise, the second component 00000010010 has shortest representation 010010 and hence its scale is $s_2 = 5$.

The VTU-R then computes for each block a data-dependent block scale parameter $S = \max_{ec}(s_{ec})$, where the maximization index *ec* runs over all 2×*F_block* clipped error sample components in the block.

For example, as depicted in Figure 7-4, *F_block* = 1 and the block scale parameter *S* is the maximum of s_1 and s_2, hence $S = 7$.

If *padding* = 0, then for each block in the given vectored band, the VTU-R shall set

$$B\_M = \max(S, B\_\min), \quad B\_L = \max(B\_M - L\_w + 1, B\_\min) \tag{7-1}$$

If *padding* = 1, then for each block in all the vectored bands, the VTU-R shall set

either $B\_M = \max(S, L\_w\text{-}1)$ (sign extension) or $B\_M = S$ (zero padding);

and

$$B\_L = B\_M - L\_w + 1 \text{ (with bits set to 0 for bit indices} < 0). \tag{7-2}$$

The parameters *B_M* and *B_L* shall always satisfy the relations $B\_L \le B\_M$ and $0 \le B\_M \le B\_max$.
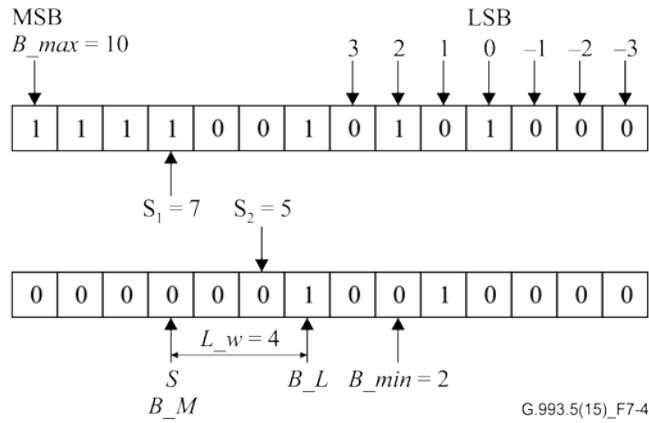
**Figure 7-4 – Example of two registers, each representing a
clipped error sample component**

Figure 7-5 depicts an example of the reported bits (shown shaded) for a block of clipped error samples for different padding types, with $F\_block=1$, $B\_min=1$, $B\_max=7$, $L\_w=5$.
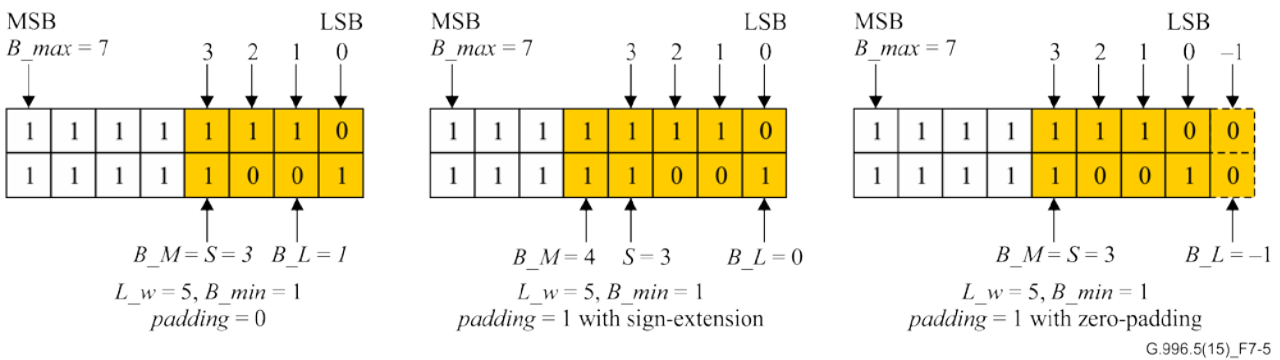
**Figure 7-5 – Example of reported bits for a block of clipped
error samples for different padding types**

For the assigned value of F_block, the block consists of clipped error samples reported for F_block subsequent subcarriers from those assigned for reporting in the vectored downstream band. The subcarriers shall be assigned to blocks starting from the lowest frequency subcarrier of the vectored band, subsequently, in ascending order, F_block subcarriers in each block. The number of blocks in the vectored band vb can be computed as:

$$N\_block(vb) = \left\lceil \frac{\left\lceil \dfrac{N\_carrier(vb)}{F\_sub(vb)} \right\rceil}{F\_block} \right\rceil$$

The blocks shall be identified by their numbers: $eb = 0$ to $N\_block(vb) - 1$, assigned in the ascending order of subcarrier indices associated with the block. The last components of the last block that do not belong to the subcarriers of the vectored downstream band (if any) shall be set to dummy values that represent the value of zero.

7.2.3 Backchannel format

For each sync symbol, an integer number of octets shall be sent through the backchannel.

The number of bytes per symbol needed to report the clipped error samples depends on the values configured by the VCE for the backchannel control parameters (see clause 7.2.2). Blocks of clipped error samples (error blocks) of the vectored downstream bands are mapped into the ERB.

Each ERB is associated with a particular symbol of the O-P-VECTOR 2-1 signal (see clause 10.4.3.7). The ERB has a single format that is further encapsulated into:

– Ethernet format (for an L2-based backchannel); or

– eoc format (for an eoc-based backchannel); or

– SOC format (for an SOC-based backchannel).

The sync symbol associated with the ERB is identified by the value of its sync symbol counter (for an L2 or an eoc backchannel during Showtime) or by the timing of the report (for an SOC backchannel during initialization).

7.2.3.1 Format of the ERB

The format of the ERB is presented in Figure 7-6. The ERB starts from an 8-bit ERB_ID field, followed by up to eight vectored band blocks (VBBs) fields. The VTU-R may set the MSB of the ERB_ID field to '1' to indicate that the clipped error samples in the ERB are potentially corrupted (e.g., due to impulse noise, or RFI). Otherwise, the VTU-R shall set the MSB of the ERB_ID field to '0'. The seven LSB of the ERB_ID field shall be set to 0 and are reserved for ITU-T. The number of bytes in the ERB (N_ERB) is the sum of the number of bytes in each of the VBBs, plus one byte for the ERB_ID field. The concatenation of VBBs in an ERB shall be in the ascending order of the vectored band numbers, i.e., starting from the vectored band associated with lowest subcarrier indices. Some vectored bands may not be reported on request of the VCE (i.e., the ERB shall not contain a VBB for the vectored bands for which VCE configures $L\_w=0$).

G.993.5(15)_F7-6
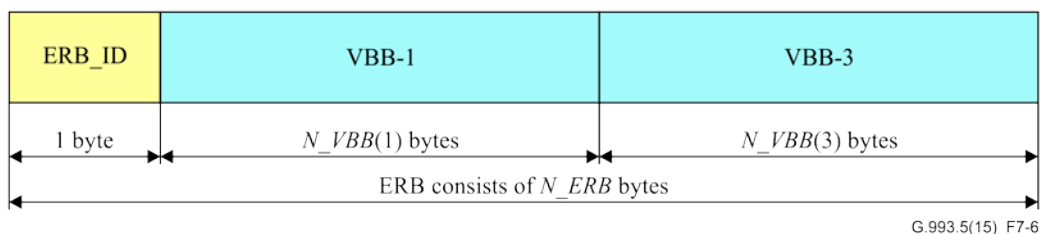
Figure 7-6 – ERB format (in case only vectored bands 1 and 3 are requested by the VCE)

The format of the VBB is presented in Figure 7-7. Each VBB starts from an 8-bit VBB_ID field, followed by a VBB_Aux field, followed by concatenated error blocks, and ends with a pad of 0, 2, 4 or 6 bits to fit the length of the VBB to an integer number of bytes (odd number of padding bits is not applicable). The three MSBs of the VBB_ID field shall include the number of the vectored band (000 for VBB-0, 001 for VBB-1, … up to 111 for VBB-7). The five LSBs of the VBB_ID field shall be set to '0' and be reserved for ITU-T. The error blocks shall be concatenated in a VBB in ascending order: the first block inside the vectored band is the one that contains clipped error samples for subcarriers with lowest indices and shall be transmitted first.

F_block = ⌈N_carried/F_sub⌉

F_block = 32

F_block = 1
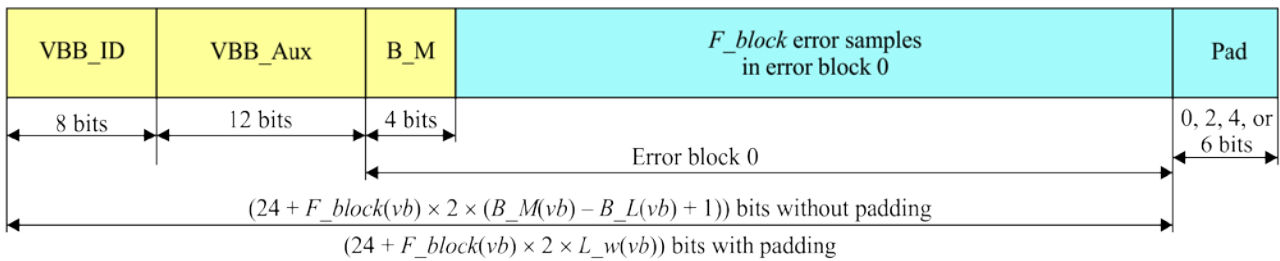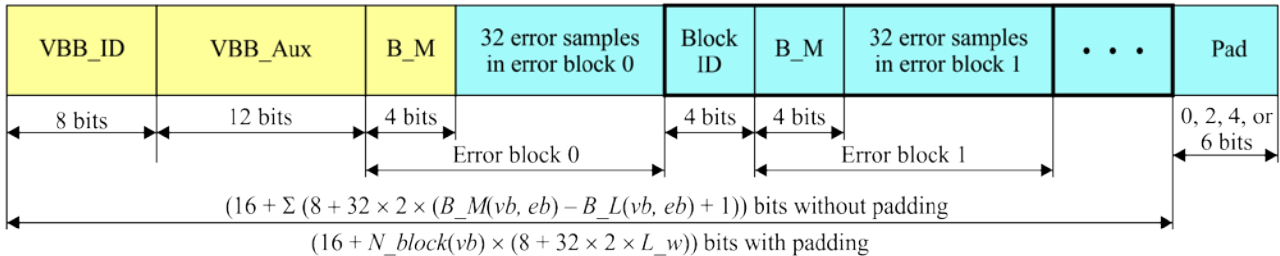
Padding is mandatory with *F_block* = 1
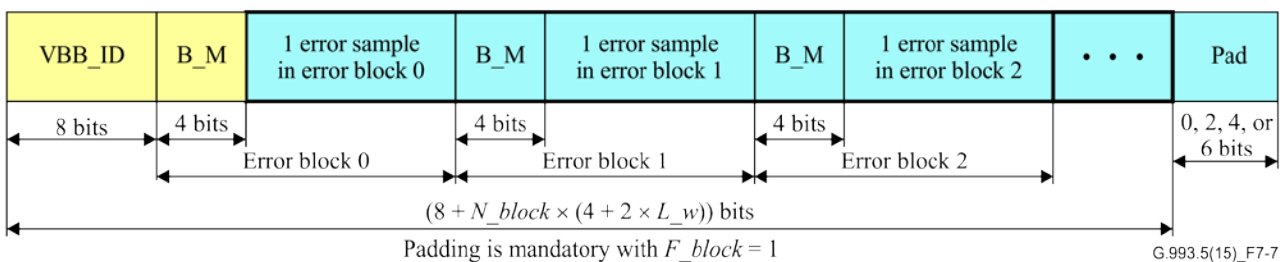
G.993.5(15)_F7-7

Figure 7-7 – VBB format depending on *F_block*

The format of the error block is defined in clause 7.2.3.2.

In case *F_block* = 32, a Block_ID shall be pre-pended to each error block, starting with error block number 1. A Block_ID shall not be inserted just before error block 0. The Block_ID shall be 4 bits long, and shall represent modulo 16 the number of the error block it precedes as an unsigned integer, with the assumption that the first block in the vectored band has the number 0.

In case *F_block* = 1 or $\left\lceil \dfrac{N\_carrier}{F\_sub} \right\rceil$, a Block_ID shall not be inserted.

NOTE 1 – The VCE can identify VBB in the received ERB by its VBB_ID and then compute the number of error blocks, *N_block(vb)*, in the VBB-*vb* as described in clause 7.2.2.2, since all the backchannel control parameters are known at the CO-side. The length of the error block is computed using the parameters (*B_M*, *B_L*) of the clipped error sample and the block size *F_block*. The first reported sample of the first error block in the vectored band is for the subcarrier with index *X_L* (which is always even).

NOTE 2 – With *F_block* = 32, the end of each error block is byte aligned. No padding bits are added at the end of the VBB.

The VBB_Aux field shall be used to communicate the mean error value using the format defined in Table 7-3. The mean error (*ME*) for vectored band *vb* shall be computed as:

$$ME(vb) = \sum_{n=0}^{\left\lceil \frac{N\_carrier(vb)}{F\_sub(vb)} \right\rceil - 1} \left(\left| e\_x\left(X\_L(vb) + n \times F\_sub(vb)\right) \right| + \left| e\_y\left(X\_L(vb) + n \times F\_sub(vb)\right) \right| \right)$$

where $e\_x(sc)$ and $e\_y(sc)$ are real and imaginary components of the normalized error estimated on subcarrier sc (see Figure 7-3).

The clipped and quantized value of $ME(vb)$ shall be represented as:

$$MEq(vb) = \min\left(\left\lfloor ME(vb) \times 2^{ME\_N\_max-1} \right\rfloor, 2^{ME\_B\_max} - 1\right)$$

where $ME\_N\_max = 12$ and $ME\_B\_max = 22$.

The value of the MEq shall be reported using a 4-bit exponent and an 8-bit mantissa, in the similar way as for the clipped error sample components. The VTU-R shall compute the scale ME_S as the index of the most significant bit of the MEq that is not a sign extension bit. The mantissa shall consist of the 8 bits with indices ME_B_M down to ME_B_L. The values of ME_B_M and ME_B_L shall be computed at the VTU-R as:

$$ME\_B\_M = \max(ME\_S, 7), \text{ and}$$

$$ME\_B\_L = ME\_B\_M - 7$$

Table 7-3 – Format of the VBB_Aux field

Parameter	Bit numbers	Description
ME_EXP	[11:8]	4-bit value of *ME_B_L*
ME_MANT	[7:0]	8-bit mantissa of the *MEq*

7.2.3.2 Format of the error block

The representation for an error block containing *F_block* clipped error samples ($2 \times F\_block$ clipped error sample components of *F_block* subcarriers) shall include a *B_M* field (4 bits), and an error field (variable length), see Figure 7-8. The error field includes *F_block* sub-fields, each carrying a complex clipped error sample of a subcarrier which is assigned for reporting during the backchannel configuration (see clause 7.2.2).

For each clipped error sample component, the compressed representation, as defined in clause 7.2.2.2, includes only those bits of the clipped error sample component with indices *B_L* through *B_M*, using the convention that the MSB of the compressed representation of the component has index *B_max* and the least significant bit (LSB) of the compressed representation of the component has index *B_min*. Accordingly, the total number of bits in the error field of a block of clipped error samples in compressed representation shall be $2 \times F\_block \times (B\_M - B\_L + 1)$.

The *B_M* fields shall include parameter *B_M* represented as a 4-bit unsigned integer, in the range from 0 to 15.

NOTE – The parameter *B_L* is not reported as it can be calculated by the VCE from the clipped error sample control parameters (see equations 7-1 and 7-2) and the value of the reported *B_M* parameter.

The format of the error block is presented in Figure 7-8. All parameters and clipped error samples shall be mapped with the MSB at the left side so that the MSB is transmitted first (i.e., the first transmitted bit is the MSB of the *B_M* field).

Clipped error samples in the error field shall be mapped in ascending order of subcarrier index from left to right. For each clipped error sample, the *q_x* (real) component shall be mapped left from the *q_y* (imaginary) component.
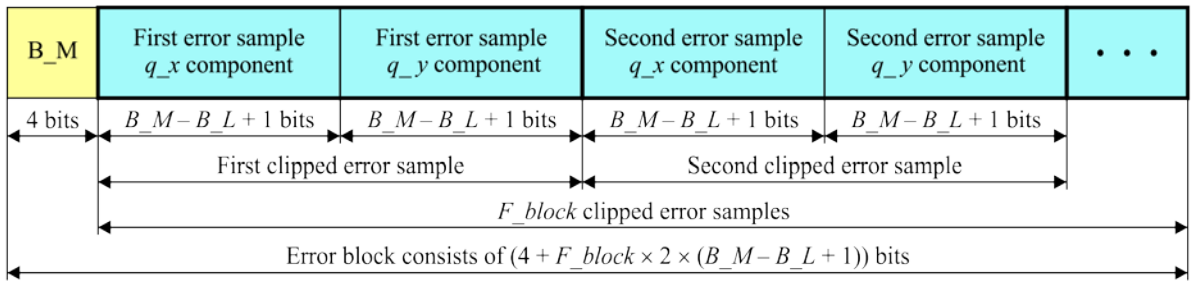
G.993.5(15)_F7-8

Figure 7-8 – Format of an error block

7.2.3.3 Backchannel data rate (informative)

In case $F\_block = \left\lceil \dfrac{N\_carrier}{F\_sub} \right\rceil$, the number of bytes in the VBB-*vb*, following from Figures 7-6, 7-7 and 7-8 is:

$$N\_VBB(vb) = \left\lceil \frac{24 + F\_block(vb) \times 2 \times (B\_M(vb) - B\_L(vb) + 1)}{8} \right\rceil$$

where *B_M(vb)* represents the *B_M* parameter for the vectored band number *vb*, and *B_L(vb)* represents the *B_L* parameter for the vectored band *vb*.

Note that in general this value is not fixed, but may be different from one error report to the next, depending on the exact values of the clipped error samples. If padding (see Table 7-1) is used, on the other hand, the number of bytes in the VBB-*vb* only depends on the clipped error sample control parameters and not on the values of the clipped error sample values:

$$N\_VBB(vb) = \left\lceil \frac{24 + F\_block(vb) \times 2 \times L\_w(vb)}{8} \right\rceil$$

In case $F\_block = 32$, the number of bytes in the VBB-*vb*, following from Figures 7-6 and 7-8 is:

$$N\_VBB(vb) = 2 + \sum_{eb=0}^{N\_block(vb)-1} (1 + 8 \times (B\_M(vb,eb) - B\_L(vb,eb) + 1))$$

where *B_M(vb,eb)* represents the *B_M* parameter for the error block number *eb* of vectored band number *vb*, *B_L(vb,eb)* represents the *B_L* parameter for the error block number *eb* of vectored band *vb*.

Note that in general this value is not fixed, but may be different from one error report to the next, depending on the exact values of the clipped error samples. If padding (see Table 7-1) is used, the number of bytes in the VBB-*vb* only depends on the clipped error sample control parameters and not on the values of the clipped error sample values:

$$N\_VBB(vb) = 2 + N\_block(vb) \times (1 + 8 \times L\_w(vb))$$

In case $F\_block = 1$, padding is used and the number of bytes in the VBB-*vb* only depends on the clipped error sample control parameters and not on the values of the clipped error sample values:

$$N\_VBB(vb) = \left\lceil \frac{8 + N\_block(vb) \times (4 + 2 \times L\_w(vb))}{8} \right\rceil$$

The *N_ERB* can be calculated as:

$$N\_ERB = 1 + \sum_{vb=0}^{N\_band-1} report(vb) \times N\_VBB(vb)$$

where *report(vb)* =1 if the VBB-*vb* is included in the ERB (i.e., *L_w* > 0 for band number *vb*), and *report(vb)* = 0 if the VBB-*vb* is not included in the ERB (i.e., *L_w* = 0 for band number *vb*).

The backchannel data rate (BDR) for transmission of the error report block for each sync symbol is:

$$BDR = 8 \times N\_ERB \times \left(f_{DMT}/257\right)$$

where f_{DMT} is the symbol rate (in symbols/s) defined in clause 10.4.4 of [ITU-T G.993.2].

The BDR is not defined when padding is not used. In that case, *N_ERB* varies from error report to error report.

7.2.4   Identification of the ERB during Showtime

At each of the sync symbol counts indicated by the VTU-O, the VTU-R shall transmit a single ERB. With each ERB, the VTU-R shall also transmit the downstream sync symbol count (as defined in clause 7.3.2) as identification of the downstream sync symbol the ERB corresponds to. The VTU-O shall indicate such sync symbol counts using the following time identification control parameters:

–   the error sample update period (*m*);

–   the error sample shift period (*z*).

The error sample update period gets value of *m* if the error sample has to be reported on every *m*-th sync symbol, i.e., on the sync symbol positions with sync symbol counts *SSC* = *m*×*P*+*k*, where *P* is any integer in the range from 0 to $\lfloor(N\_SSC-1-k)/m\rfloor$, and *k* is the offset, which is an integer in the range from 0 to *m*–1. Which is an integer in the range from 0 to *m*–1. After the SSC counter wraps around at the value of *N_SSC*-1, the next sync symbol count at which ERB shall be reported is SSC = *k* (this count is obtained by setting *P*=0).

The VTU-R shall set *k*=0 for the first report after the VTU-O's Error Feedback request. This report shall be sent for the first available sync symbol with SSC count that is a multiple of *m* after reception of the ERB request (see clause 8.1). If *z* > 0, the VTU-R shall increase *k* by 1 after each error sample shift period of *z* reports, wrapping around *k* at *m*-1.

If *m* = 1, the VTU-R shall report on each sync symbol. The error sample update period value of *m* = 0 is special and shall be used to indicate that the VTU-R shall stop error sample reporting. The non-zero error sample shift period *z* is valid only for *m* > 1. The error sample shift period value of *z* = 0 shall be used if no error sample shift is to be done and if *m*=1.

NOTE 1 – The parameters *m* and *z* should be selected such that the error samples are reported at least once for all the bits of the pilot sequence after a certain time.

NOTE 2 – For example, with *N_SSC* = 1024, *m* = 3, and the first report sent at SSC = 6, the reports are on the following sync symbol counts:

  m = 3 and *z* = 0 then *SSC* = 6, 9, …, 1020, 1023, 0, 3, 6, 9, …

  m = 3 and *z* = 128 then *SSC* = 6, 9, …, 128×3, 129×3, 130×3+1, 131×3+1, … 257×3+1, 258×3+2, 259×3+2,…. 340×3+2, 2, 5, ….44×3+2, 45×3, 46×3, 47×3, …

The values for the time identification control parameters are defined in Table 7-4.

Table 7-4 – Values of time identification control parameters

Parameter	Valid values for VCE	Mandatory values for VTU-R to support
m	0, 1, 2, …, 63, 64	All valid values
z	If $m > 1$: 0, 2, …, 254, 255, 256 If $m \leq 1$: 0	All valid values

7.3 Upstream vectoring requirements for the VTU-R

The VTU-R shall comply with [ITU-T G.993.2], with the exceptions and additional requirements contained in this Recommendation.

In order to enable the VCE to fulfil the tasks described in clause 6.1, the VTU-R shall support the requirements in the following clauses.

7.3.1 Symbol alignment

Under VCE control, all VTU-Rs in the vectored group shall use the same subcarrier spacing and symbol rate.

NOTE – The VCE may control the alignment of symbols from different lines of the vectored group at the U-O2 reference point (defined in Figure 5-4 of [ITU-T G.993.2]) by adjusting the timing advance (TA) of these lines during initialization (see clause 10).

7.3.2 Sync symbol position

The VTU-R shall have the capability to transmit sync symbols as defined in clause 10.2 of [ITU-T G.993.2]. The VTU-R shall transmit sync symbols at time positions assigned by the VCE and communicated to the VTU-R during initialization. The time position of upstream sync symbols is defined by an offset between upstream and downstream sync symbol positions.

The offset between the upstream and downstream sync symbol time positions is set by the VCE and sent to the VTU-R in the O-SIGNATURE message.

The VCE may configure all VTU-Rs in the vectored group to transmit upstream sync symbols at the same time positions or at different time positions for one or more VTU-Rs in the vectored group.

The VTU-R shall keep a downstream sync symbol counter (MODULO N_SSC), counting continuously over Showtime. The counter value of the first downstream sync symbol transmitted in Showtime shall be set by the VTU-R to the value of the field First SSC of the first received Error Feedback command (see Table 8-3). Before receiving the first Error Feedback command, the value of the downstream sync symbol counter for the first downstream sync symbol transmitted in Showtime is vendor discretionary.

NOTE – This setting at the start of Showtime synchronizes the downstream sync symbol counter with the VTU-O/VCE (see clause 6.2.2).

7.3.3 Modulation of pilot sequence

The VTU-R shall have the capability to modulate a VCE-specified upstream pilot sequence on all subcarriers of the upstream sync symbols during initialization (see clause 10.3.4.1) and on the probe tones (see clause 3.2.10) of the upstream sync symbols during Showtime. The upstream pilot sequence is vendor discretionary, determined by the VCE, with length *Npilot_us* and sent to the VTU-R at initialization in the O-SIGNATURE message. Pilot sequence bits are indexed from 0 to *Npilot_us* – 1. The bit with index 0 shall be transmitted first, followed by the bit with index 1, up to bit with index *Npilot_us* – 1. If the "pilot sequence length multiple of 4" is enabled (see

clause 10.2), then valid values of *Npilot_us* are all multiples of 4 in the range from 8 to 512. Otherwise, the valid values of *Npilot_us* shall be all powers of 2 in the range from 8 to 512. The pilot sequence shall be cyclically repeated after *Npilot_u*s bits, except for the case where the upstream pilot sequence is changed by the VCE through the procedure defined in clause 8.2.

The time position of the upstream pilot sequence is determined by the VCE and communicated to VTU-R during the initialization by special markers (see clause 10.3.3.5). Subcarriers of upstream sync symbols shall be modulated by the upstream pilot sequence bits corresponding to the time position of the upstream pilot sequence.

In Showtime, the first upstream sync symbol position shall be as defined in clause 10.6.

The modulation of a pilot sequence on the probe tones (see clause 3.2.10) of sync symbols is defined as whether the sync frame bits modulated onto the probe tones are set to either 00 (if the pilot sequence bit is ZERO) or set to 11 (if the pilot sequence bit is ONE). Over the tones of a particular sync symbol, the pilot sequence bit shall have a periodicity of 10 tones (considering both probe and flag tones).

If upstream frequency dependent pilot sequence (upstream FDPS) is enabled through ITU-T G.994.1, then eight pilot sequences with indices from 0 to 7 are defined. The pilot sequences #(0,1,2,3,4,5,6,7) shall be modulated onto tone indices $10n+(0,2,3,4,5,6,8,9)$ respectively. All eight pilot sequences shall have the same length *Npilot_us*. All pilot sequences shall start at the same sync symbol position.

The sync frame bits modulated on the flag tones (see clause 3.2.6) shall be used for the transmission of a Syncflag as defined in clause 10.5.3 of [ITU-T G.993.2]. The sync frame shall be modulated onto a sync symbol as defined in clause 10.5 of [ITU-T G.993.2] (including the quadrant scrambling of all MEDLEY subcarriers, regardless of it being a flag or a probe tone).

7.4 Requirements for the NT system

The NT (see Figure 5-1) shall support downstream vectoring.

7.4.1 Layer 2 Ethernet encapsulation of the backchannel data

If the VCE selects to use this encapsulation type, the backchannel data shall be encapsulated as defined in this clause.

Within the NT, the clipped error samples are first sent from the VTU-R to the L2+ functional block, where they are encapsulated into the Layer 2 transport protocol and multiplexed into one of the upstream Ethernet (or Ethernet over ATM) data streams.

Ethernet encapsulation is based on [IEEE 802.3] and shall be as described in this clause.

The Layer 2 Ethernet frame encapsulation shall consist of the following fields:
–   Destination MAC address shall be MAC address of the VCE;
–   Source MAC address shall be the MAC address of the VTU-R;
–   Length field (as per the IEEE 802.3 MAC frame format [IEEE 802.3]);
–   LLC PDU header coding for SNAP protocol (3 bytes, AA-AA-03);
–   SNAP PDU header containing a 3-octet ITU OUI 00-19-A7 + 2-octet Protocol ID of ITU subtype 00-03 for a PRIVATE protocol;
–   Protocol payload data (Line_ID, Sync Symbol Count, Segment Code and Backchannel Data);
–   Padding (only for the last segment and as per the IEEE 802.3 MAC frame format [IEEE 802.3]);
–   Standard Ethernet 4-byte FCS (as per the IEEE 802.3 Ethernet frame FCS [IEEE 802.3]).

The VCE MAC Address field shall contain the VCE MAC Address as configured by the VCE through O-PMS, see clause 10.5.2.1. The protocol payload data shall contain the Line_ID (as configured by the VCE through O-PMS, see clause 10.5.2.1), the Sync Symbol Count (as defined in clause 7.2.4), the Segment Code (as defined in [ITU-T G.993.2]) and the backchannel data ERB (as defined in clause 7.2.3). The Length field shall equal the length of the protocol payload data, increased with the 8-byte LLC SNAP header length, and shall not exceed 1024+8=1032. If the protocol payload data exceeds 1024 bytes, the backchannel data ERB shall be segmented as defined in clause 11.2.3.1 of [ITU-T G.993.2]. For protocol payload data lengths shorter than or equal to 1024 bytes, the backchannel data ERB may also be segmented. If segmented, each segment of the backchannel data ERB shall be Layer 2 Ethernet encapsulated as shown in Figure 7-9, with the number of segments per backchannel data ERB not exceeding 16.

The format of the Ethernet encapsulated backchannel data ERB is shown in Figure 7-9.
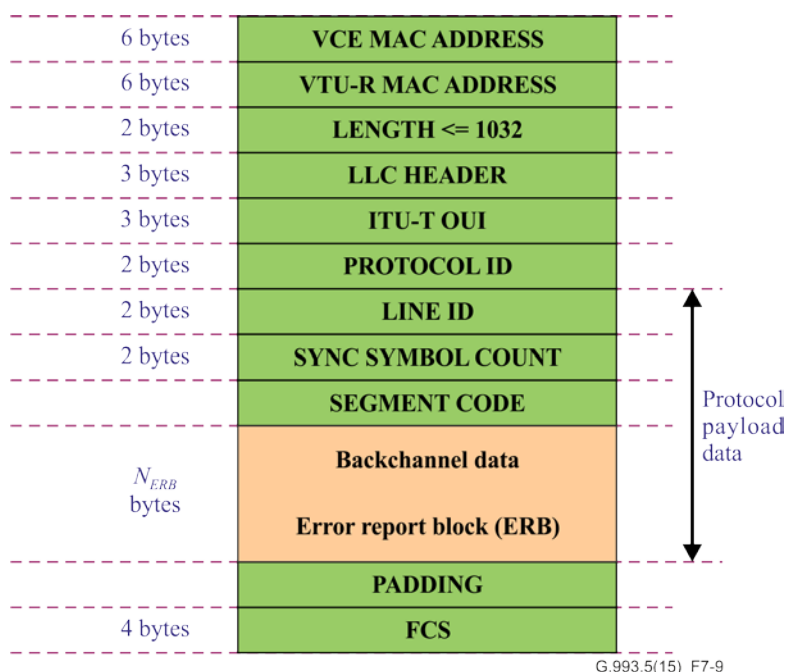
Figure 7-9 – Format of the Ethernet encapsulation of backchannel data message

7.4.2   eoc encapsulation of the backchannel data

If the VCE selects to use this encapsulation type, the backchannel data shall be communicated using the eoc protocol described in clause 8.1.

8   Vectoring-specific eoc messages

The VTU-O and VTU-R VME shall use the eoc commands and responses defined in this clause to support vectoring. For vectoring-related eoc commands and responses, both the VTU-O and VTU-R shall use the standard eoc protocol for message communication defined in clause 11.2.2 of [ITU-T G.993.2] and the protocol for commands and responses defined in clause 11.2.3 of [ITU-T G.993.2], except for the protocol for the Error Feedback command and responses, which shall be as defined in clause 8.1.

The list of additional eoc commands to facilitate operation of vectored lines is presented in Table 8-1 (high priority) and Table 8-2 (normal priority).

Table 8-1 – High priority commands and responses

Command type and assigned value	Direction of command	Command content	Response content
Error Feedback 0001 1000$_2$	From VTU-O to VTU-R	Request for error samples for the given vectored band and with the given format	eoc encapsulated error samples and associated parameters, ACK or NACK

Table 8-2 – Normal priority commands and responses

Command type and assigned value	Direction of command	Command content	Response content
Pilot sequence update 0001 0001$_2$	From VTU-O to VTU-R	Request to update upstream pilot sequence	Acknowledgement

8.1 eoc messages for backchannel configuration

The VTU-O VME shall use the Error Feedback command and responses for obtaining clipped error samples from the VTU-R VME and for updates of backchannel control parameters. The command (request for clipped error samples) may be initiated only by the VTU-O and shall use the format shown in Table 8-3; the VTU-R shall respond with clipped error samples for the requested subcarriers in the requested format, or with ACK (if error samples are communicated over L2-based backchannel), or with NACK. The NACK provides a rejection code describing the reason of the request denial. Prior to sending the NACK, the VTU-R VME shall suspend sending clipped error samples until it receives a new Error Feedback command with a valid set of backchannel and error report control parameters. The VTU-R shall use the format of the response message as described in Table 8-6 or Table 8-7. The rejection codes shall be as described in Table 8-8.

The first octet of the command and the response shall be the assigned value of the Error Feedback command type, as shown in Table 8-1. The second and subsequent octets shall be as shown in Table 8-3 for the command and in Table 8-6 or Table 8-7 for responses. The communicated data octets shall be mapped using the generic format described in clause 11.2.3.1 of [ITU-T G.993.2].

The VTU-O sends an Error Feedback command to request the VTU-R to start sending clipped error samples with particular parameters. The command indicates:

– the error sample update period (m);

– the error sample shift period (z);

– the range of subcarrier indices to be covered in the report (defined by vectored downstream bands);

– the error report control parameters (F_sub, F_block, B_min, B_max, L_w, etc.).

Upon reception of the command, the VTU-R shall either start sending clipped error samples (Error Feedback data messages as defined in Table 8-6 for the eoc backchannel, and in Table 8-7 for the L2 backchannel) or respond with a NACK (as defined in Table 8-8). The first Error Feedback data message is an ACK that the Error Feedback command was admitted. More Error Feedback data messages may be transmitted if necessary (either as subsequent eoc messages or as L2 Ethernet packets). Transmissions of Error Feedback data messages shall be triggered by every error sample update sync symbol counts requested in the Error Feedback command (update period and shift period). If the update period is more than 1, the VTU-R shall update error samples at the exact sync symbol counts indicated by the VTU-O.

Error Feedback data messages shall not be acknowledged. If the Error Feedback data message exceeds 1024 bytes, it shall be segmented as defined in clause 11.2.3.1 of [ITU-T G.993.2] with the maximum number of segments not to exceed 16; segments shall be sent without waiting for IACK. The VTU-R shall not retransmit Error Feedback data messages or their segments. If the VTU-O does not receive the response (ACK), it may send another Error Feedback command, possibly with different control parameters. The VTU-R shall continue sending Error Feedback data messages while waiting for Syncflag after an OLR command. If in the time period allocated to send a particular Error Feedback data message the eoc channel is busy with another high-priority message (e.g., OLR command), the VTU-R shall drop this Error Feedback data message and continue with the next Error Feedback data message.

At the start of Showtime, the VTU-R shall not send clipped error samples until it receives an Error Feedback command with a valid set of backchannel and error report control parameters. To start communication of clipped error samples, the VTU-O shall send a backchannel configuration eoc command within the first second of Showtime. To stop communication of clipped error samples, the VTU-O shall send an Error Feedback command that carries a special backchannel configuration (i.e., error sample update period m=0, see Table 8-3). Upon reception of the command, the VTU-R shall first stop sending Error Feedback data messages and subsequently respond with NACK.

Table 8-3 – Error Feedback command transmitted by the VTU-O

Name	Length (octets)	Octet number	Content
Error Feedback request	$9 + 5 \times N\_band$ ($N\_band \leq 8$)	2	01_{16} (Note 1)
		3 to 4	First SSC (see clause 6.2.2, clause 7.3.2 and Note 6)
		5	Error sample update period (m) (see clause 7.2.4 and Note 2)
		6 to 7	Error sample shift period (z) (see clause 7.2.4 and Note 3)
		8 to $8 + 3 \times N\_band$	Vectored bands descriptor (see Table 12-18 of [ITU-T G.993.2], Note 4)
		$9 + 3 \times N\_band$ to $9 + 5 \times N\_band$	Error report configuration descriptor (Note 5)
NOTE 1 – All other values are reserved by ITU-T.			
NOTE 2 – The error sample update period (m) shall be represented as an unsigned integer.			
NOTE 3 – The error sample shift period (z) shall be represented as an unsigned integer.			
NOTE 4 – The value of N_band is defined as octet 1 of the ITU-T G.993.2 band descriptor			
NOTE 5 – This descriptor defines N_band sets of clipped error sample reporting parameters defined in clause 7.2.2 for each downstream vectored band (2 octets per band). It shall use the format defined in Table 8-4.			
NOTE 6 – The value of the First SSC shall be the same for all error feedback commands after entering Showtime.			

Table 8-4 – Error report configuration descriptor

Parameter	Bit	Octet number	Description
N_band	[7:4]	0	The number of configured vectored bands in the range from 1 to 8 represented as an unsigned integer
padding	3		As defined in clause 7.2.2.
Reserved by ITU-T	2		Shall be set to 0_2.
F_block	[1:0]		Block size, encoded as (see Note): $00_2 - F\_block = \left\lceil \dfrac{N\_carrier}{F\_sub} \right\rceil$ $01_2 - F\_block = 1$ $10_2 - F\_block = 32$ 11_2 – Reserved for use by ITU-T
Parameters for vectored band 1		1-2	See Table 8-5
. . . . . .		…..	
Parameters for vectored band *N_band*		$2 \times N\_band - 1$ to $2 \times N\_band$	See Table 8-5
NOTE – If encoded 01_2 or 10_2, then *F_block* has the same value for all vectored bands. If encoded 00_2, then *F_block* may have a different value for each vectored band depending on the number of subcarriers *(N_carrier)* and subsampling *(F_sub)*.			

Table 8-5 – Vectored band control parameters

Parameter	Bits	Octet number	Description
F_sub	[7:4]	0	Sub-sampling rate *F_sub* as defined in clause 7.2.2, with $\log_2(F\_sub)$ represented as unsigned integer.
L_w	[3:0]		Length of the clipped error sample in compressed representation as defined in clause 7.2.2, with *L_w* represented as an unsigned integer.
B_min	[7:4]	1	Parameter *B_min* as defined in clause 7.2.2, with *B_min* represented as an unsigned integer.
B_max	[3:0]		Parameter *B_max* as defined in clause 7.2.2, with *B_max* represented as an unsigned integer.

Table 8-6 – Error Feedback response transmitted by the VTU-R for eoc backchannel

Name	Length (Octets)	Octet number	Content
Error Feedback data/ACK	$5 + N_{ERB}$	2	80_{16} (see Note 1)
		3-4	Sync symbol count (SSC) represented as unsigned integer in the range as defined in clause 7.3.2 (see Note 2).
		5	Segment code (SC), represented as defined in clause 11.2.3.3 of [ITU-T G.993.2].
		6 to $5 + N_{ERB}$	Backchannel data, represented with N_{ERB} octets as defined in clause 7.2.3 (see Note 3).
NACK	3	2	81_{16} (see Note 1)
		3	1 octet for reason code (see Table 8-8)
NOTE 1 – All other values for this octet are reserved by ITU-T.			
NOTE 2 – This field identifies the downstream sync symbol for which clipped error samples are reported.			
NOTE 3 – This field shall carry the ERB using the format described in clause 7.2.3.			

Table 8-7 – Error Feedback response transmitted by the VTU-R for L2 backchannel

Name	Length (Octets)	Octet number	Content
ACK	6	2	80_{16} (see Note 1)
		3-4	Both octet shall be set to 00_{16}
		5	Octet shall be set to 11000000_2 (see Note 2)
		6	Octet shall be set to 00_{16} (see Note 3).
NACK	3	2	81_{16} (see Note 1)
		3	1 octet for reason code (see Table 8-8)
NOTE 1 – All other values for this octet are reserved by ITU-T.			
NOTE 2 – This value corresponds with the segment code of a non-segmented eoc message as defined in clause 11.2.3.3 of [ITU-T G.993.2].			
NOTE 3 – This field shall serve as ACK indicating that the backchannel configuration required by Error Feedback command was accepted.			

Table 8-8 – NACK reason codes

Value	Definition
01_{16}	Invalid set of error sample parameters or clipped error sample report format.
02_{16}	VTU-R stops sending error reports on the VCE's request.
NOTE – All other reason codes are reserved by ITU-T.	

8.2 Pilot sequence update command and response

The VTU-O VME shall use the pilot sequence update command and response to force an update of the upstream pilot sequence(s) and communicate the updated pilot sequence(s) for the vectored line (see clause 7.3.3) to the VTU-R VME. Separate commands are defined for updating a single pilot sequence (in case upstream FDPS is disabled through ITU-T G.994.1) and for updating eight upstream pilot sequences (in case upstream FDPS is enabled through ITU-T G.994.1). These commands are shown in Table 8-9, and may be initiated only by the VTU-O; the VTU-R shall respond with the ACK, using the format shown in Table 8-10.

The first octet of the command shall be the assigned value of the pilot sequence update command type, as shown in Table 8-2. The second and subsequent octets shall be as shown in Tables 8-9 for commands and in Table 8-10 for responses. The data octets shall be mapped using the format described in clause 11.2.3.1 of [ITU-T G.993.2].

Using the pilot sequence update message, the VCE may update the upstream pilot sequence(s).

The command message length depends on the length of the upstream pilot sequence ($Npilot\_us$ bits, see clause 7.3.3). Only the upstream pilot sequence bits may be changed during Showtime. The newly assigned upstream pilot sequence length shall be the same as the length of the upstream pilot sequence that was set at initialization.

The command message bytes shall be defined as shown in Table 8-9.

Table 8-9 – Pilot sequence update commands transmitted by the VTU-O

Name	Length (Octets)	Octet number	Content
Pilot sequence configuration (FDPS disabled through ITU-T G.994.1)	$3 + Npilot\_us/8$	2	01_{16} for change of upstream pilot sequence with upstream FDPS disabled through ITU-T G.994.1 (see Note)
		3	01_{16} if interruption of current upstream pilot sequence is not allowed; 02_{16} if interruption of current upstream pilot sequence is allowed (see Note)
		4 to $3 + \lceil Npilot\_us/8 \rceil$	Upstream pilot sequence bits, coded as defined for field #4 in Table 10-7.
Pilot sequence configuration (FDPS enabled through ITU-T G.994.1)	$11 + (Naips + 1)$ $\times \lceil Npilot\_us/8 \rceil$	2	02_{16} for change of upstream pilot sequences with upstream FDPS enabled through ITU-T G.994.1 (see Note)
		3	01_{16} if interruption of current upstream pilot sequence is not allowed; 02_{16} if interruption of current upstream pilot sequence is allowed (see Note)
		4 to $3 + \lceil Npilot\_us/8 \rceil$	Upstream pilot sequence bits, coded as defined for field #4 in Table 10-7.
		$4 + \lceil Npilot\_us/8 \rceil$ to $11 + (Naips + 1)$ $\times \lceil Npilot\_us/8 \rceil$	The upstream FDPS descriptor as defined in Table 10-9.
NOTE – All other values for this octet are reserved by ITU-T.			

The third octet of the pilot sequence update command defines the time at which the upstream pilot sequence change shall occur:

– If interruption of the current upstream pilot sequence is not allowed (value 01_{16}), the upstream pilot sequence change shall be applied starting from the next sync symbol position after the end of the current upstream pilot sequence, i.e., after the sync symbol that modulates the last bit of the old upstream pilot sequence, the next sync symbol shall modulate the first bit of the new upstream pilot sequence.

– If interruption of the current upstream pilot sequence is allowed (value 02_{16}), the upstream pilot sequence change may occur at any sync symbol position, i.e., after the sync symbol that modulates bit i of old upstream pilot sequence, the next sync symbol shall modulate bit i+1 of the new upstream pilot sequence.

The only allowed response from the VTU-R is to acknowledge the correct reception of the command, as shown in Table 8-10.

Table 8-10 – Pilot sequence update response transmitted by the VTU-R

Name	Length (Octets)	Octet number	Content
ACK	2	2	80_{16} (see Note)
NACK	3	2	81_{16} (see Note)
		3	1 octet for reason code (see Table 8-11)
NOTE – All other values for this octet are reserved by ITU-T.			

Table 8-11 – NACK reason codes

Value	Definition
01_{16}	Invalid set of parameters.
NOTE – All other reason codes are reserved by ITU-T.	

If the pilot sequence update command updates the upstream pilot sequence(s), the VTU-R shall apply the change only after sending the ACK message. If interruption of the current pilot sequence(s) is allowed, the update should occur as soon as possible, and shall occur within 200 ms after sending the ACK message.

The timing diagram of the pilot sequence eoc command and response is shown in Figure 8-1.
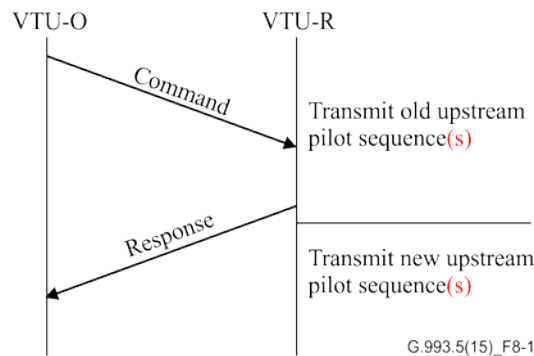
Figure 8-1 – Timing diagram of the pilot sequence update command and response

8.3 Power management commands and responses

The same power management commands and responses shall be used as defined in clause 11.2.3.9 of [ITU-T G.993.2]. The orderly shutdown procedures described in clauses 11.2.3.9.1 and 11.2.3.9.2 of [ITU-T G.993.2] shall be modified as defined in this clause.

8.3.1 L3 Request by VTU-R (replaces clause 11.2.3.9.1 of [ITU-T G.993.2])

Upon receipt of the L3 Request command, the responding VTU-O shall send either the Grant or Reject response. The proposed link state shall be formatted as 03_{16} for the L3 link state. If any other link state is received, the Reject response shall be sent with the reason code 02_{16}.

The VTU-O may reject a request to move to link state L3 using reason code 01_{16} because it is temporarily busy, or reject it using code 03_{16} because it has local knowledge that the L3 state is not desired at this time.

When the VTU-R receives the Grant response, the VTU-R shall transition from the R-SHOWTIME state to R-SILENT (see Figure 12-3). Upon entering the R-SILENT state, the VTU-R shall not yet change the input impedance as seen from the line at the U-R2 reference point.

When the VTU-O detects that the VTU-R has stopped transmission (because the VTU-R transitioned to the R-SILENT state), the VTU-O shall transition from the O-SHOWTIME state to the O-DEACTIVATING state.

Controlled by the VCE, the VTU-O shall transition from the O-DEACTIVATING state to the O-SILENT state.

When the VTU-R detects that the VTU-O has stopped transmission (because the VTU-O transitioned to the O-DEACTIVATING state or the O-SILENT state), the VTU-R may change the characteristics of the transmission path. However, for the sake of vectoring stability of the vectored group, the VTU-R should maintain approximately the input impedance as seen from the line at the U-R2 reference point.

8.3.2 L3 Request by VTU-O (replaces clause 11.2.3.9.2 of [ITU-T G.993.2])

Upon receipt of the L3 Request command, the responding VTU-R shall send either the Grant or Reject response. The proposed link state shall be formatted as 03_{16} for the L3 link state. If any other link state is received, the Reject response shall be sent with the reason code 02_{16}.

The VTU-R may reject a request to move to link state L3 using reason code 01_{16} because it is temporarily too busy, or reject it using code 03_{16} because it has local knowledge that the L3 state is not desired at this time.

When the VTU-O receives the Grant response, the VTU-O shall transition from the O-SHOWTIME state to the O-DEACTIVATING state. In the O-DEACTIVATING state, the VTU-O shall not yet change the input impedance as seen from the line at the U-O2 reference point.

Controlled by the VCE, the VTU-O shall transition from the O-DEACTIVATING state to the O-SILENT state. Upon entering the O-SILENT state, the VTU-O shall still not change the input impedance as seen from the line at the U-O2 reference point.

When the VTU-R detects that the VTU-O has stopped transmission (because the VTU-O transitioned to the O-DEACTIVATING state or the O-SILENT state), the VTU-R shall transition from the R-SHOWTIME state to the R-SILENT state.

When the VTU-O detects that the VTU-R has stopped transmission (because the VTU-R transitioned to the R-SILENT state), the VTU-O may change the characteristics of the transmission path. However, for the sake of vectoring stability of the vectored group, the VTU-O should maintain approximately the input impedance as seen from the line at the U-O2 reference point.

9 Activation and deactivation of pairs in a vectored group

The activation of a line in a vectored group is achieved through the initialization procedure defined in clause 10.

The deactivation of a line from the vectored system also requires an orderly procedure. If the line to be deactivated is used in upstream or downstream FEXT cancellation, then the performance of the vectoring system may suffer from an abrupt disconnection. The procedures for an "Orderly shutdown event" and for a "Disorderly shutdown event" are described in this clause.

9.1 Orderly shutdown event

The orderly shutdown event shall consist of a power management transition to line state L3. The related power management commands and responses are defined in clause 8.3.

9.2 Disorderly shutdown event

Upon detection of a near-end *los* defect, (see clause 11.3.1.3 of [ITU-T G.993.2]), the VTU-O shall transition from the O-SHOWTIME state to the O-DEACTIVATING state.

Controlled by the VCE, the VTU-O shall transition from the O-DEACTIVATING state to the O-SILENT state.

NOTE – If errors on the other lines in the vectored group are acceptable, an additional and/or alternative technique to the switching-off of the transmit signal, is fast update of the coefficients. This may be effectuated as follows. When a disorderly shutdown event (DSE) or other disorderly event is detected on a line, the VTU-Os of the other lines should send error feedback requests preferably using robust eoc channel to their VTU-Rs. The VTU-Rs should then provide the requested error samples to the respective VTU-Os in the vectoring feedback channel. Upon receiving the error samples, it is sufficient that the VCE estimates only the changed channel coefficients, i.e., the channel coefficients associated with the line subject to DSE, in order to update an estimate of the full channel. This can be performed using error samples corresponding to a few sync symbols only. Then, the VCE uses the updated channel estimate comprising the estimated changed channel coefficients and the unchanged channel coefficients to update the pre-coder. The duration of the period of errors, before the pre-coder is updated using such a fast update mechanism, has an approximate length of a few superframes, and therefore may avoid the other lines to retrain due to the DSE.

10 Initialization of a vectored group

This clause defines the initialization of a vectored group.

10.1 Overview

The initialization procedure described in this clause is based on ITU-T G.993.2 initialization with addition of steps for FEXT channel estimation. The final mode of vectored operation (i.e., downstream and upstream vectoring, or downstream only vectoring) is determined during the ITU-T G.994.1 Phase of initialization.

Figure 10-1 provides an overview of the initialization procedure for both upstream and downstream directions. For this Recommendation, the ITU-T G.993.2 initialization phases are adopted with some modifications to the SOC messages and addition of initialization signals for FEXT channel estimation. The initialization signals added to the ITU-T G.993.2 Channel Discovery phase and Training phase are highlighted in Figure 10-1.

If several lines are initialized simultaneously, the initialization procedures of these lines have to be aligned in time, so that all lines pass the vectoring-related phases simultaneously (see clauses 10.3.3.6 and 10.4.3.9).
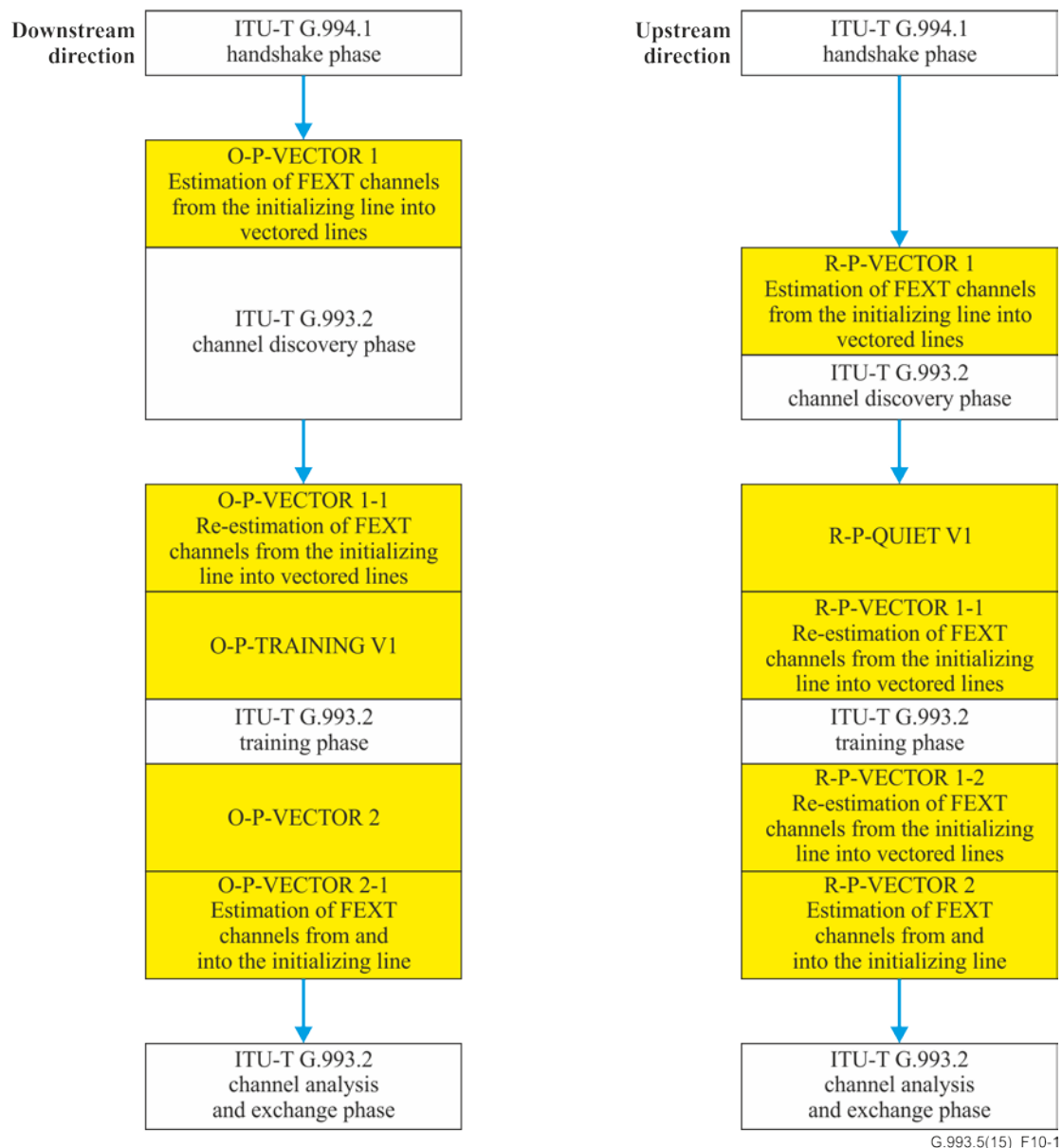
Figure 10-1 – ITU-T G.993.5 initialization overview

In the downstream direction, at the beginning of the Channel Discovery phase, the VTU-O of the initializing line transmits O-P-VECTOR 1 signal which comprises only sync symbols modulated by the pilot sequence and which is aligned with sync symbols of vectored lines, see Figure 10-2. The O-P-VECTOR 1 signal allows the VCE to estimate FEXT channels from the initializing lines into the vectored lines. The VCE estimates these FEXT channels based on the reported clipped error samples from the VTU-Rs of the vectored lines and enables the pre-coding in the VTU-Os of these vectored lines to cancel FEXT from the initializing lines into these vectored lines during the remainder of the initialization of the initializing lines.

At the beginning of the Training phase, the initializing VTU-O will transmit O-P-VECTOR 1-1 signal, which is the same as O-P-VECTOR 1 and allows the VCE to update the downstream FEXT channel estimates from the initializing lines into the vectored lines, prior to transitioning into the ITU-T G.993.2 Training phase.

After the ITU-T G.993.2 Training phase, the VTU-O transmits the O-P-VECTOR 2 signal, followed by the O-P-VECTOR 2-1 signal, which both comprise sync symbols modulated by the pilot sequence and regular symbols carrying the SOC, see Figure 10-3. During the transmission of O-P-VECTOR 2-1, the VCE estimates FEXT channels from all vectored lines into each initializing

line and vice versa. Finally, at the end of the transmission of O-P-VECTOR 2-1, the whole FEXT channel matrix, including FEXT coefficients from the initializing line into the vectored lines and FEXT coefficients from the vectored lines into each initializing line, is estimated by the VCE. At this point the initialization process is complete and the initializing lines may be included in the pre-coding operation. After O-P-VECTOR 2-1 transmission is complete, the VTU-O of the initializing line enters the Channel Analysis and Exchange phase for estimation of the signal-to-noise ratio (SNR) and determination of the bit loading to be used during Showtime.

In the upstream direction, in order to avoid excessive FEXT into vectored lines, the VTU-R of an initializing line, after detection of the O-SIGNATURE message in the Channel Discovery phase, starts transmitting an R-P-VECTOR 1 signal, which has the same format as O-P-VECTOR 1, see Figure 10-2. During transmission of the R-P-VECTOR 1, the VCE estimates the FEXT channels from the initializing lines into all vectored lines, and enables the VTU-Os of the vectored lines to cancel FEXT from the initializing lines during the remainder of the initialization of the initializing lines. The time position of the upstream sync symbols and the upstream pilot sequence are assigned by the VCE and are indicated to the VTU-R in the O-SIGNATURE message and by special markers added to the O-P-CHANNEL DISCOVERY V1 signal.

Furthermore, other optional parameters may be added to the O-P-SIGNATURE message for upstream transmit power reduction during the initial upstream phase (R-P-VECTOR 1). The upstream transmit power reduction can be used to reduce the crosstalk of the R-P-VECTOR 1 signals into non-vectored lines operating in the same binder and provides a flat attenuation of the upstream transmit PSD of R-P-VECTOR 1 in addition to the standard upstream power back-off as defined in [ITU-T G.993.2].

NOTE 1 – Parameters *a, b* that determine the limiting upstream PSD mask (UPBOMASK, see clause 7.2.1.3.2.2 of [ITU-T G.993.2]) are provided by the operator via the CO-MIB as specified in [ITU-T G.997.1]. The operator may provision or allow for default values of a, b that are different from those geographic region specific values defined in [ITU-T G.993.2] (e.g., Annexes A.2.3, B.3, and C.2.1.4), and thus allow higher upstream PSDs, since upstream FEXT is reduced through crosstalk cancellation. After UPBO has been applied (during the initialization), the VTU-R may further adjust its transmit PSD (while it remains below the UPBOMASK) during the Showtime by request from the VTU-O, via SRA, as per clause 7.2.1.3.1 of [ITU-T G.993.2], to improve upstream performance (under control of the VCE). The operator may also adjust the applied parameters *a, b* via a new initialization.

At the beginning of the Training phase, the initializing VTU-R will transmit the R-P-VECTOR 1-1 signal, which is the same as R-P-VECTOR 1 and allows the VCE to update the upstream FEXT channel estimates from the initializing lines into the vectored lines, prior to transitioning into the ITU-T G.993.2 Training phase. The VTU-O transmits the O-P-TRAINING V1 signal as a time fill signal while the VTU-R transmits R-P-VECTOR 1-1.

The initial value of timing advance is assigned by the VTU-O and is communicated in O-SIGNATURE, based on the provisional knowledge on the length of the line. If the timing advance is further re-adjusted during the Training phase, then the FEXT channel estimate in the upstream direction will be updated at the end of the Training phase to account for any resulting change in the FEXT channel (signal R-P-VECTOR 1-2 in Figure 10-1). The VTU-O transmits the O-P-VECTOR 2 signal as a time fill signal while the VTU-R transmits R-P-VECTOR 1-2.

At the end of the Training phase, the VTU-R transmits R-P-VECTOR 2, which comprises sync symbols modulated by the pilot sequence and regular symbols carrying the SOC. During the transmission of R-P-VECTOR 2, the VCE estimates the FEXT channels from all vectored lines into the initializing lines and vice versa. Finally, at the end of the R-P-VECTOR 2 transmission, the whole FEXT channel matrix, including FEXT coefficients from the initializing lines into the vectored lines and FEXT coefficients from vectored lines into the initializing lines, are estimated by the VCE. At this point the initialization process is complete and the initializing lines become active members of the vectored group. After R-P-VECTOR 2 transmission is complete, the VTU-R enters

the Channel Analysis and Exchange phase for estimation of the SNR and determination of the bit loading to be used during Showtime.

During the transmission of R-P-VECTOR 2, the SOC parameters may be set to provide higher speed SOC, necessary to convey clipped error samples from the VTU-R to the VTU-O. Since both VTU-O and VTU-R already passed the Training phase, the number of repetitions in the SOC may be reduced (similarly to [ITU-T G.993.2] during the Channel Analysis and Exchange phase). This will provide a fast backchannel which is necessary for quick estimation of FEXT channels from vectored lines into the initializing line.

Figures 10-2 and 10-3 show how positions of sync symbols modulated by pilot sequences are aligned during the initialization signals O-P-VECTOR and R-P-VECTOR; the downstream sync symbols of all lines are synchronized in time and upstream sync symbols of all lines are synchronized in time. A time shift between upstream and downstream sync symbols of one or more symbols is set during initialization (see clause 10.3.2.1).

NOTE 2 – In some implementations, the transmit path of an initializing VTU may change during the Channel Discovery phase. The update of the downstream and upstream FEXT channel allows to capture any related change of the FEXT generated into the vectored lines. Any changes in the transmit path of the analogue front end (AFE) prior to the transmission of O-P-VECTOR 1-1 or R-P-VECTOR 1-1 may increase FEXT generated by the initializing line into vectored lines from the moment of the change until the start of O-P-VECTOR 1-1 or R-P-VECTOR 1-1. Therefore, implementations should minimize the modifications in AFE during the Channel Discovery phase.
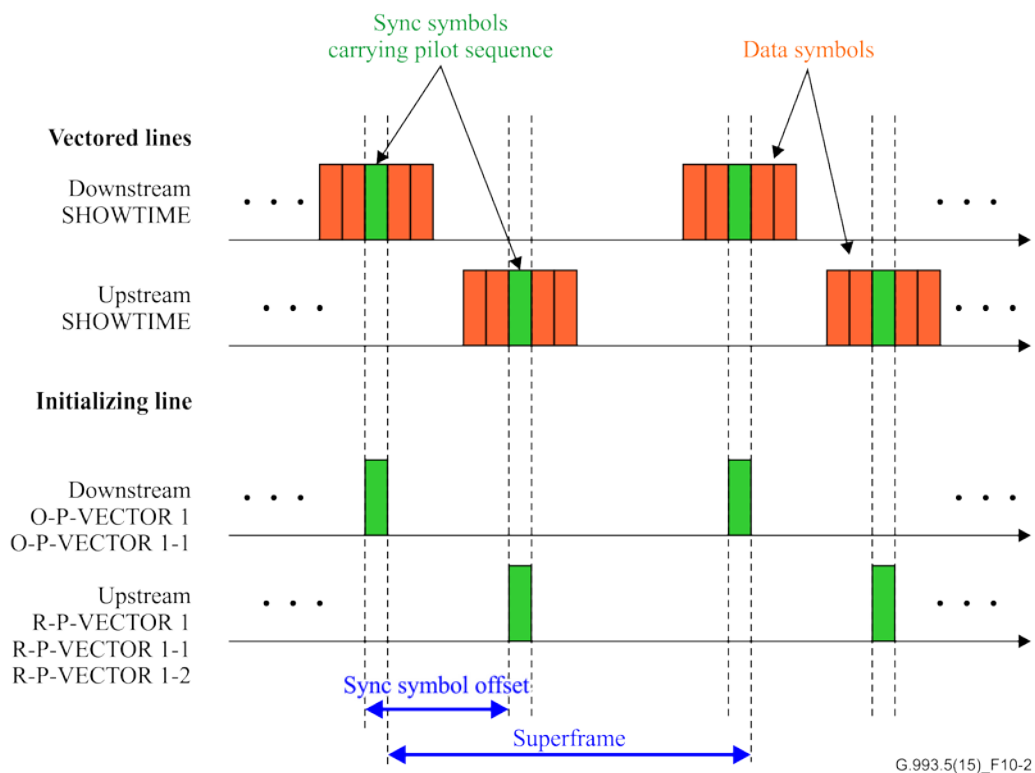
**Figure 10-2 – Signal timing in the upstream and downstream directions
(signals O-P-VECTOR 1 and R-P-VECTOR 1)**
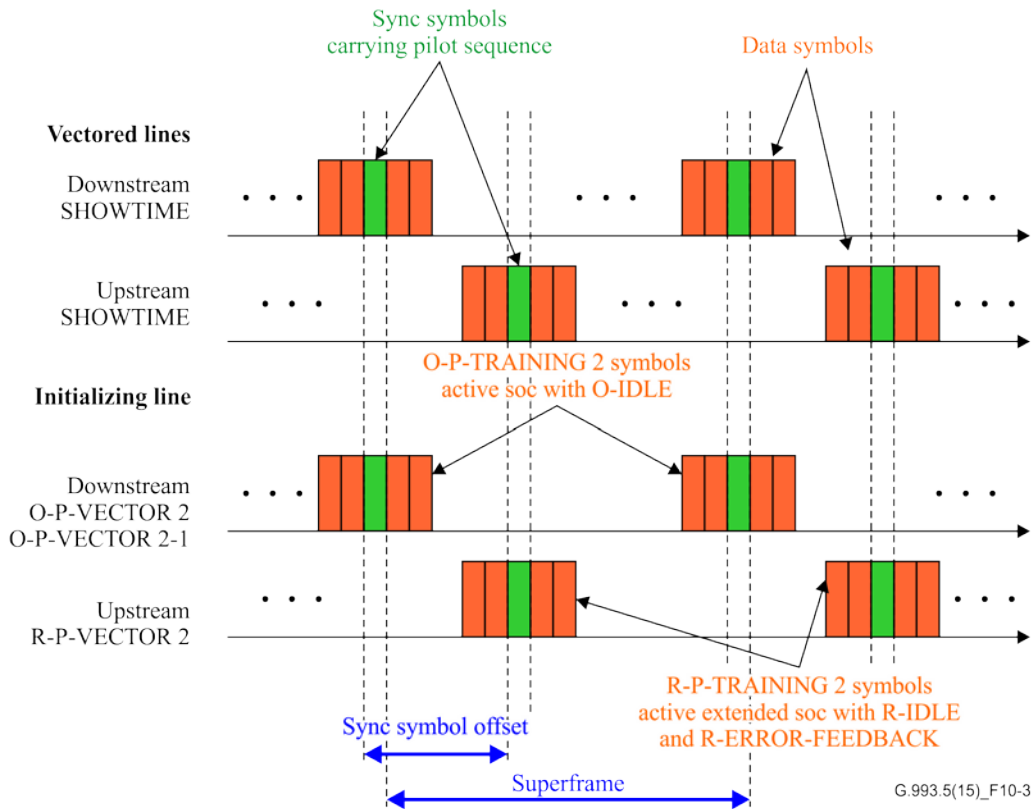
Figure 10-3 – Signal timing in the upstream and downstream directions (signals O-P-VECTOR 2 and R-P-VECTOR 2)

In the following, various phases of the initialization procedure are discussed in more detail.

10.2   ITU-T G.994.1 Handshake phase

The initialization procedure starts with the ITU-T G.994.1 Handshake phase. During this phase, the VTU-O and the VTU-R shall exchange their enabled vectoring capabilities in addition to the parameters communicated in a regular Handshake phase of [ITU-T G.993.2]. The VTU-O shall support downstream vectoring and may support upstream vectoring. The VTU-R shall support downstream vectoring and shall support upstream vectoring. Based on these capabilities, the final mode of vectored operation (i.e., downstream and upstream vectoring, or downstream only vectoring) is determined during the ITU-T G.994.1 phase of initialization (see Tables 11.68.0.1 and 11.68.10 of [ITU-T G.994.1] and Tables 7-a/b/c/d).

Before transmission of the MS message, the VTU-O shall verify whether all of the following conditions are TRUE (Note 1):

–   the CO-MIB parameter VECTORMODE_ENABLE bit 0 is set to 0;

–   the Annex X "ITU-T G 993.5-friendly ITU-T G.993.2 operation in the downstream direction" NPar(2) bit is set to ZERO in the CL message or in the CLR message;

–   the Annex Y "Full ITU-T G.993.5-friendly ITU-T G.993.2 operation" NPar(2) bit is set to ZERO in the CL message or in the CLR message;

–   the "ITU-T G.993.5" SPar(2) bit is set to ZERO in the CL message or in the CLR message.

If all of the above conditions are TRUE, then the VTU-O shall ensure that the "ITU-T G.993.2" SPar(1) bit is set to ZERO in the last transmitted MS message before the ITU-T G.994.1 cleardown procedure (Note 2). Otherwise, the operating mode shall be negotiated solely based on the VTU-O and VTU-R enabled capabilities indicated in the CL and CLR message respectively, as defined in Annex X of [ITU-T G.993.2], Annex Y of [ITU-T G.993.2], and in this clause.

NOTE 1 – The verification of these conditions is for the VTU-O to ensure that the line will not initialize in "ITU-T G.993.2 mode with neither Annex X nor Annex Y enabled" if this mode is not allowed in the CO-MIB.

NOTE 2 – This may require the use of the ITU-T G.994.1 extended transaction A:B as defined in Table 14 of [ITU-T G.994.1].

The VCE shall force the VTU-O to set the subcarrier spacing and symbol rate in the initializing line to the same value as used in the other vectored lines.

NOTE 3 – The same symbol rate between all lines of the vectored group is achieved by setting the same ratio between the IDFT size and CE length in samples for upstream and downstream.

NOTE 4 – During the Handshake phase, the VTU-O selects the value of CE based on the supported values indicated by the VTU-O and the VTU-R. Only the value CE=$5\times N/32$ (where $2\times N$ is the IDFT size) is mandatory. In the absence of other information about the CE capabilities of the VTU-R, this will be the only value that is guaranteed to be supported by a new initializing line.

Table 10-1 – VTU-O CL message SPar(2) and NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bit
ITU-T G.993.5	This bit shall be set to ONE, if and only if the VTU-O supports ITU-T G.993.5 and ITU-T G.993.5 is allowed via the CO-MIB (i.e., VECTORMODE_ENABLE bit 3 set to 1, see clause 7.3.1.13.9 of [ITU-T G.997.1]).
ITU-T G.994.1 NPar(3) Bit	**Definition of NPar(3) bits**
Downstream vectoring	This bit shall be set to ONE, indicating the VTU-O supports downstream vectoring.
Upstream vectoring	If set to ONE, this bit indicates the VTU-O supports upstream vectoring. If set to ZERO, this bit indicates the VTU-O does not support upstream vectoring.
Pilot sequence length multiple of 4	If set to ONE, this bit indicates the VTU-O supports pilot sequence lengths that are a multiple of 4. If set to ZERO, this bit indicates the VTU-O only supports pilot sequence lengths that are a power of 2.
Upstream FDPS	If set to ONE, this bit indicates the VTU-O supports upstream FDPS. If set to ZERO, this bit indicates the VTU-O does not support upstream FDPS.
8192 superframes duration for O-P-VECTOR 1	If set to ONE, this bit indicates the VTU-O supports extending of O-P-VECTOR 1 duration to 8192 superframes. If set to ZERO, this bit indicates the VTU-O does not support extending of O-P-VECTOR 1 duration to 8192 superframes.
Use of O-P-VECTOR 1 flag tones only	If set to ONE, this bit indicates the VTU-O supports the use of O-P-VECTOR 1 flag tones only (see clause 10.3.3.1). If set to ZERO, this bit indicates that the VTU-O does not support use of O-P-VECTOR 1 flag tones only. If bit "8192 superframes duration for O-P-VECTOR 1" is set to ZERO, then bit "Use of O-P-VECTOR 1 flag tones" shall also be set to ZERO.

Table 10-2 – VTU-O MS message SPar(2) and NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bits
ITU-T G.993.5	This bit shall be set to ONE if, and only if, it was set to ONE in both the last previous CL message and the last previous CLR message. If set to ONE, this bit indicates that both VTUs shall enter ITU-T G.993.5 initialization.
ITU-T G.994.1 NPar(3) Bit	**Definition of NPar(3) bits**
Downstream vectoring	This bit shall be set to ONE, indicating downstream vectoring.
Upstream vectoring	This bit shall be set to ONE if, and only if, it was set to ONE in both the last previous CL message and the last previous CLR message. If set to ONE, this bit indicates upstream vectoring is enabled. If set to ZERO, this bit indicates upstream vectoring is disabled.
Pilot sequence length multiple of 4	This bit shall be set to ONE if, and only if, it was set to ONE in both the last previous CL message and the last previous CLR message. If set to ONE, this bit indicates that "pilot sequence length multiple of 4" is enabled. If set to ZERO, this bit indicates only pilot sequence lengths that are a power of 2 are enabled.
Upstream FDPS	This bit shall be set to ONE if, and only if, it was set to ONE in both the last previous CL message and the last previous CLR message. If set to ONE, this bit indicates that upstream FDPS is enabled. If set to ZERO, this bit indicates that upstream FDPS is disabled.
8192 superframes duration for O-P-VECTOR 1	This bit shall be set to ONE if, and only if, it was set to ONE in both the last previous CL message and the last previous CLR message. If set to ONE, this bit indicates that "8192 superframes duration for O-P-VECTOR 1" is enabled. If set to ZERO, this bit indicates that "8192 superframes duration for O-P-VECTOR 1" is disabled.
Use of O-P-VECTOR 1 flag tones only	This bit shall be set to ONE if, and only if, it was set to ONE in both the last previous CL message and the last previous CLR message. If set to ONE, this bit indicates that "Use of O-P-VECTOR 1 flag tones only" is enabled. If set to ZERO, this bit indicates that "Use of O-P-VECTOR 1 flag tones only" is disabled.

Table 10-3 – VTU-R CLR message SPar(2) and NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bits
ITU-T G.993.5	This bit shall be set to ONE, if and only if the VTU-R supports ITU-T G.993.5.
ITU-T G.994.1 NPar(3) Bit	**Definition of NPar(3) bits**
Downstream vectoring	This bit shall be set to ONE, indicating the VTU-R supports downstream vectoring.
Upstream vectoring	This bit shall be set to ONE, indicating the VTU-R supports upstream vectoring.
Pilot sequence length multiple of 4	If set to ONE, this bit indicates the VTU-R supports pilot sequence lengths that are a multiple of 4. If set to ZERO, this bit indicates the VTU-R only supports pilot sequence lengths that are a power of 2.
Upstream FDPS	If set to ONE, this bit indicates the VTU-R supports upstream FDPS. If set to ZERO, this bit indicates the VTU-R does not support upstream FDPS.
8192 superframes duration for O-P-VECTOR 1	If set to ONE, this bit indicates the VTU-R supports extending of O-P-VECTOR 1 duration to 8192 superframes. If set to ZERO, this bit indicates the VTU-R does not support extending of O-P-VECTOR 1 duration to 8 192 superframes.
Use of O-P-VECTOR 1 flag tones only	If set to ONE, this bit indicates the VTU-R supports the use of O-P-VECTOR 1 flag tones only (see clause 10.3.3.1). If set to ZERO, this bit indicates that the VTU-R does not support use of O-P-VECTOR 1 flag tones only. If bit "8192 superframes duration for O-P-VECTOR 1" is set to ZERO, then bit "Use of O-P-VECTOR 1 flag tones" shall also be set to ZERO.

Table 10-4 – VTU-R MS message SPar(2) and NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bits
ITU-T G.993.5	This bit shall be set to ONE if, and only if, it was set to ONE in both the last previous CL message and the last previous CLR message. If set to ONE, this bit indicates that both VTUs shall enter ITU-T G.993.5 initialization.
ITU-T G.994.1 NPar(3) Bit	**Definition of NPar(3) bits**
Downstream vectoring	This bit shall be set to ONE, indicating downstream vectoring.
Upstream vectoring	This bit shall be set to ONE if, and only if, it was set to ONE in both the last previous CL message and the last previous CLR message. If set to ONE, this bit indicates upstream vectoring is enabled. If set to ZERO, this bit indicates upstream vectoring is disabled.
Pilot sequence length multiple of 4	This bit shall be set to ONE if, and only if, it was set to ONE in both the last previous CL message and the last previous CLR message. If set to ONE, this bit indicates that "pilot sequence length multiple of 4" is enabled. If set to ZERO, this bit indicates only pilot sequence lengths that are a power of 2 are enabled.

Table 10-4 – VTU-R MS message SPar(2) and NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bits
Upstream FDPS	This bit shall be set to ONE if, and only if, it was set to ONE in both the last previous CL message and the last previous CLR message. If set to ONE, this bit indicates that upstream FDPS is enabled. If set to ZERO, this bit indicates that upstream FDPS is disabled.
8192 superframes duration for O-P-VECTOR 1	This bit shall be set to ONE if, and only if, it was set to ONE in both the last previous CL message and the last previous CLR message. If set to ONE, this bit indicates that "8192 superframes duration for O-P-VECTOR 1" is enabled. If set to ZERO, this bit indicates that "8192 superframes duration for O-P-VECTOR 1" is disabled.
Use of O-P-VECTOR 1 flag tones only	This bit shall be set to ONE if, and only if, it was set to ONE in both the last previous CL message and the last previous CLR message. If set to ONE, this bit indicates that "Use of O-P-VECTOR 1 flag tones only" is enabled. If set to ZERO, this bit indicates that "Use of O-P-VECTOR 1 flag tones only" is disabled.

10.2.1 Avoidance of false initialization in crosstalk environment

The functionality defined in this clause prevents one VTU-O from establishing communication with two VTU-Rs. Such communication would lead to two VTU-Rs sending the same upstream pilot sequence, with potential negative impact on the VCE learning the upstream channel matrix.

Support of this functionality is optional for the VTU-O and is optional for the VTU-R. If supported, the functionality shall be implemented as defined in this clause.

In the ITU-T G.994.1 identification field, two parameters are defined for the exchange of transceiver IDs (see [ITU-T G.994.1] Table 9.14, Tables 9.14.1.x, and Tables 9.14.2.x):

– network side transceiver ID SPar(2) with associated 30-bit NPar(3) parameter;

– remote side transceiver ID SPar(2) with associated 30-bit NPar(3) parameter.

The network side transceiver ID is the VTU-O ID. The VTU-O ID shall be generated by the VTU-O.

The remote side transceiver ID is the VTU-R ID. The VTU-R ID shall be generated by the VTU-R.

The 30 bit VTU ID shall consist of two parts:

– a first part (the MSBs) derived from the serial number and vendor ID;

– a second part (the LSBs) using a random number generator.

The first part has length 16 bits and shall be calculated as the 16-bit high-level data link control (HDLC) frame check sequence (FCS), as specified in clause 6.4.3 of [ITU-T G.997.1], of the VTU vendor ID and the VTU serial number.

The FCS shall be calculated over all bits of the VTU vendor ID followed by the VTU serial number.

The FCS shall be calculated starting with bit 1 (LSB) of octet 1. The octets shall following each other in ascending numerical order. Within an octet, the bits shall follow each other in ascending numerical order.

The register used to calculate the CRC shall be initialized to the value FFFF_{16}.

The VTU vendor ID shall consist of the T.35 country code (2 octets) followed by the provider code (4 octets), as indicated in the Vendor ID information block during the ITU-T G.994.1 Handshake phase of initialization (see Table 7 of [ITU-T G.994.1]).

NOTE – This is excluding the "Vendor-specific information" of the Vendor ID information block.

The VTU-O serial number shall be the G.997.1 X digital subscriber line transceiver unit at the central office (XTU-C) serial number (see clause 7.4.7 of [ITU-T G.997.1]).

The VTU-R serial number shall be the equipment serial number that is part of the G.997.1 X digital subscriber line transceiver unit at the remote end (XTU-R) serial number (see clause 7.4.8 of [ITU-T G.997.1]).

NOTE – This is excluding the equipment model and the equipment firmware version that are also part of the G.997.1 XTU-R serial number.

The second part has length 14 bits and shall be generated by the VTU by means of a vendor discretionary random number generator. The randomly generated number shall change from one ITU-T G.994.1 session to the next.

If a transceiver sends any of the messages listed in Table 10-5, that message shall include the transceiver IDs as listed in Table 10-5. The "M" denotes "mandatory", the "CO" denotes "conditionally optional", and the "CM" denotes "conditionally mandatory", with the condition being that the far-end transceiver ID is included if and only if it has been received in a previous message during the same ITU-T G.994.1 session.

Table 10-5 – Transceiver IDs included in ITU-T G.994.1 and initialization messages

	VTU-O ID	**VTU-R ID**
CLR	–	M
CL	M	CO
MP	CM	M
MS from VTU-O	M	CM
MS from VTU-R	CM	M
O-SIGNATURE	–	CM

If the VTU-R receives a CL or MS message that contains a VTU-R ID different from the VTU-R ID sent in the CLR message, then the VTU-R shall respond with a NAK-CD message followed by the ITU-T G.994.1 session cleardown procedure specified in clause 11.3 of [ITU-T G.994.1].

If the VTU-O receives an MP or MS message that contains a VTU-O ID different from the VTU-O ID sent in the CL message, then the VTU-O shall respond with a NAK-CD message followed by the ITU-T G.994.1 session cleardown procedure specified in clause 11.3 of [ITU-T G.994.1].

If the VTU-R receives an O-SIGNATURE message that contains a VTU-R ID different from the VTU-R ID sent in the CLR message, then the VTU-R shall return to the R-SILENT state.

If the VTU-R receives an O-SIGNATURE message that contains a VTU-R ID equal to the VTU-R ID sent in the CLR message, then communication has been be established only among transceivers with acknowledged transceiver IDs, and initialization shall proceed as defined in clause 10.3.

NOTE 1 – The VTU-R transceiver ID is included in O-SIGNATURE to avoid false detection in the case a VTU-O decides to interrupt the communication during O-P-VECTOR-1.

NOTE 2 – Even if communication has been be established only among transceivers with acknowledged transceiver IDs, the resulting communication may be over a crosstalk path (i.e., not the direct path). If this should occur, the integrity of the upstream channel matrix is not compromised during the R-P-VECTOR 1 phase of channel discovery, since the VCE will see unique upstream pilot sequences on each initializing line.

The VTU-O shall ensure that the ITU-T G.994.1 message sequence allows both the VTU-O and the VTU-R to get acknowledgement of their transceiver ID during the ITU-T G.994.1 session. Table 10-6 lists examples of such ITU-T G.994.1 message sequences.

Table 10-6 – Examples of ITU-T G.994.1 transaction sequences

Example nr	ITU-T G.994.1 message sequence
1	Transaction C: CLR → CL → ACK(1); Transaction D: MP → MS → ACK(1).
2	Transaction C: CLR → CL → ACK(1); Extended transaction A:B: MS → REQ-MR → MR → MS → ACK(1).
3	Transaction C: CLR → CL (including the VTU-R ID) → ACK(1); Transaction A: MS → ACK(1).
4	Transaction C: CLR → CL (including the VTU-R ID) → ACK(1); Transaction B: MR → MS → ACK(1).

10.3 Channel Discovery phase

10.3.1 Overview

The Handshake phase shall be followed by the Channel Discovery phase. If both downstream and upstream vectoring are disabled after the ITU-T G.994.1 phase, then all vectoring-related parts of the initialization shall be skipped and the Channel Discovery phase shall be performed as defined in [ITU-T G.993.2].

If downstream vectoring or upstream vectoring is enabled, then the Channel Discovery phase is a modified version of the ITU-T G.993.2 Channel Discovery phase. Figures 10-4 and 10-5 highlight the signals added and the signals/messages modified in the ITU-T G.993.2 Channel Discovery phase for ITU-T G.993.5 transceivers. Non-highlighted signals and messages shall be as defined in [ITU-T G.993.2].
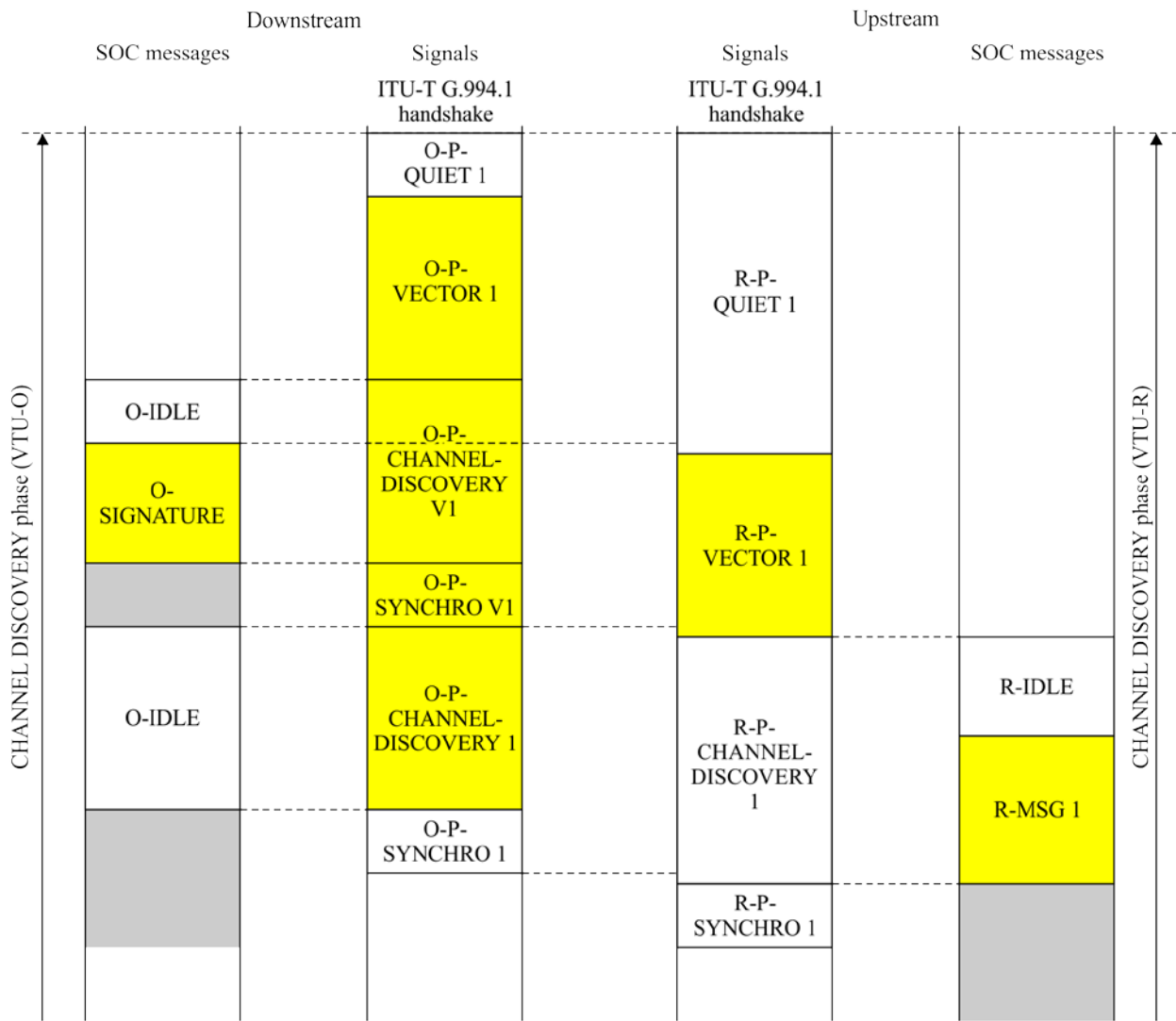
Figure 10-4 – Early stages of the Channel Discovery phase
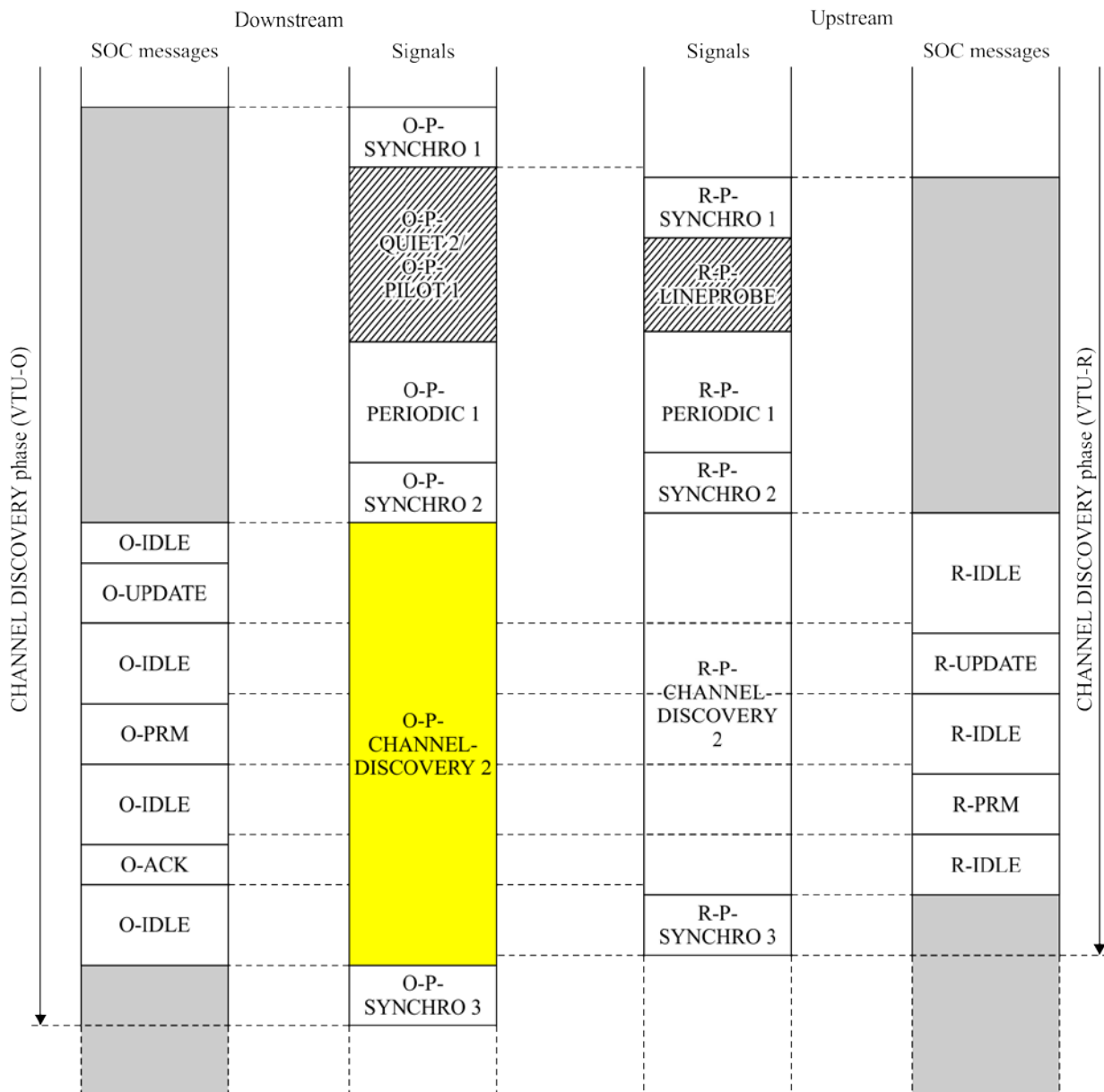
Figure 10-5 – Last stages of the Channel Discovery phase

10.3.2 Modified SOC messages sent during Channel Discovery phase

10.3.2.1 O-SIGNATURE

The O-SIGNATURE message which is transmitted during O-P-CHANNEL DISCOVERY V1 and O-P-CHANNEL DISCOVERY 1 contains an ITU-T G.993.5 parameter field A and an ITU-T G.993.5 parameter field B. The ITU-T G.993.5 parameter field A is of variable length and contains several parameters needed for the FEXT cancellation operation, as shown in Table 10-7. The ITU-T G.993.5 parameter field B includes parameters needed to define the upstream FDPS, as shown in Table 10-9.

Table 10-7 – ITU-T G.993.5 parameter field A in message O-SIGNATURE

Field	Content of field	Format
1	ITU-T G.993.5 parameter field A length	1 byte
2	Vectored downstream bands	Bands descriptor
3	Upstream pilot sequence length	2 bytes
4	Upstream pilot sequence	$\lceil Npilot\_us/8 \rceil$ bytes
5	Upstream sync symbol offset	1 bytes
6	Upstream R-P-VECTOR 1 PSD cutback	1 bytes
7	Downstream sync symbol counter modulo value (*N_SSC*)	2 bytes
8	VCE vendor ID and version number	10 bytes
9	VTU-R ID	4 bytes

Field #1, "ITU-T G.993.5 parameter field A length", indicates the length of the ITU-T G.993.5 parameter field A in bytes, excluding the ITU-T G.993.5 parameter field A length field. All fields shown in Table 10-7 shall be included in the ITU-T G.993.5 parameter field A in the O-SIGNATURE message. The field shall be represented as an unsigned integer.

Field #2, "Vectored downstream bands", defines frequency bands that are allocated by the VCE for vectoring in the downstream direction. This field shall be formatted as "Bands descriptor" (see Table 12-18 of [ITU-T G.993.2]). No more than eight bands shall be specified. The subcarrier indices that define band edges shall comply with the requirements in clause 7.2.2.

Field #3, "Upstream pilot sequence length", defines the length of the upstream pilot sequence (*Npilot_us*, see clause 7.3.3) in bits. If the "pilot sequence length multiple of 4" is enabled (see clause 10.2), then valid values are all multiples of 4 in the range from 8 to 512. Otherwise, valid values are powers of 2 in the range from 8 to 512. The field shall be represented as an unsigned integer representing the length of the sequence.

Field #4, "Upstream pilot sequence", defines the pilot sequence allocated by the VCE to be modulated on the sync symbols contained in the R-P-VECTOR signals. The format is a binary string of length *Npilot_us* bits (see clause 7.3.3), with the first bit of the pilot sequence (bit index 0) mapped to the LSB of the first byte in this field and the last bit of the pilot sequence (bit index Npilot_us – 1) mapped on the MSB of the last byte of the field. The length of the field shall be derived from field #3 as $\lceil Npilot\_us/8 \rceil$. If *Npilot_us* is not a multiple of 8 then the last octet of this field shall have the 4 MSBs set to 0.

Field #5, "Upstream sync symbol offset", defines the time offset set by the VCE (expressed as a number of symbols) between the downstream sync symbol and the upstream sync symbol. The field shall be represented as an integer in 2's complement representation with valid range from –127 to +127, except 0, where negative offset indicates that the upstream sync symbols are delayed relatively to the downstream sync symbols.

NOTE – The value of 0 is excluded from the valid range of offsets between sync symbols in upstream and downstream directions on the U-interface because it may influence vendor specific processing done on the sync symbols due to reduced randomness of the echo signal.

Field #6, "Upstream R-P-VECTOR 1 PSD cutback", defines a flat attenuation set by the VCE for the upstream transmit PSD of R-P-VECTOR 1 in addition to the upstream power back-off. It is coded in steps of 0.1 dB in a 0 dB to 25.5 dB range. The field shall be represented as an unsigned integer in the 0 (0 dB) to 255 (25.5 dB) range.

Field #7 "Downstream sync symbol counter modulo value (N_SSC)", defines the modulo value to be used for maintaining the downstream sync symbols counter during Showtime. If the "pilot

sequence length multiple of 4" is enabled (see clause 10.2), then this field is coded as an unsigned integer representing the value of N_SSC, with a single valid value being the lowest $(2n \times Npilot\_ds) \geq 1024$, where n is an integer. Otherwise, it is coded as an unsigned integer with a single valid value if N_SSC equal to 1024.

NOTE – If N_SSC is an integer multiple of the downstream pilot sequence length, then the pilot sequence bit index may be derived from the downstream sync symbol counter through a modulo operation.

Field #8 "VCE vendor ID and version number" defines the VCE vendor ID and version number. It consists of 10 bytes, with definition and format as depicted in Table 10-8.

Field #9 "VTU-R ID", contains the 30-bit transceiver ID of the VTU-R (with the two MSBs of this field set to 00_2). If the VTU-O has received the VTU-R ID during the last previous ITU-T G.994.1 session, then this field shall contain that VTU-R ID, otherwise this field shall be set to 00000000_{16}.

Table 10-8 – VCE Vendor ID information block (10 bytes)

ITU-T T.35 country code (2 bytes – Note 1)
Provider code (vendor identification) (4 bytes – Note 2)
Vendor specific version number (4 bytes)
NOTE 1 – If the bits in the first octet are not all set to binary ONE, the bits in the second octet shall be set to binary ZERO by the transmitter and ignored by the receiver. The only purpose of the country code is to identify the country of registry of the provider code. NOTE 2 – Specification of the coding and order of transmission of this field is the responsibility of the regional standards body allocating the provider code. See Appendix II of [ITU-T G.994.1] for provider code contact information.

Table 10-9 – ITU-T G.993.5 parameter field B in message O-SIGNATURE

Field	Content of field	Format
1	ITU-T G.993.5 parameter field B length	2 bytes
2	Upstream FDPS	Upstream FDPS descriptor

Field #1, "ITU-T G.993.5 parameter field B length", indicates the length of the ITU-T G.993.5 parameter field B in bytes, excluding the ITU-T G.993.5 parameter field B length field. If none of the fields following field #1 is included in the ITU-T G.993.5 parameter field B, then the ITU-T G.993.5 parameter field B shall be two bytes long with value 0000_{16}. The field shall be represented as an unsigned integer.

Field #2, "Upstream FDPS", defines the additional independent pilot sequences allocated by the VCE and how the upstream pilot sequences to be modulated on the sync symbols contained in the R-P-VECTOR signals are derived. This field shall be formatted as "upstream FDPS descriptor" (see Table 10-10). If upstream FDPS is disabled through ITU-T G.994.1, then the upstream FDPS descriptor shall not be included in the ITU-T G.993.5 parameter field B.

Table 10-10 – Upstream FDPS descriptor

Field	Content of field	Format
1	Index of the associated independent pilot sequence	3 bytes
2	Sign of the sequence relatively to the associated independent sequence	1 byte
3	Cyclical shift of the sequence relative to the associated independent sequence	3 bytes
4	Number of additional independent pilot sequences (*Naips*)	1 byte
5	Bits of independent pilot sequence #1	$\lceil Npilot\_us/8 \rceil$ bytes
	…	…
	Bits of independent pilot sequence #*Naips*	$\lceil Npilot\_us/8 \rceil$ bytes

Field #1, "Index of the associated independent pilot sequence", is a 24-bit field divided into eight 3-bit subfields. The first subfield (in the 3 LSB) represents the index of the independent pilot sequence to be the pilot sequence #0, the eighth subfield (in the 3 MSB) represents the index of the independent pilot sequence to be the pilot sequence #7. The index shall be represented as a 3-bit unsigned integer.

Field #2, "Sign of the sequence relatively to the associated independent pilot sequence", is an 8-bit bitmap, where a 0 indicates that the pilot sequence with the given index has the same sign as the associated independent pilot sequence and a 1 indicates that it has an inverted sign relative to the associated independent pilot sequence. The LSB indicates whether the sign inversion shall be applied to pilot sequence #0, the MSB indicates whether the sign inversion shall be applied to pilot sequence #7.

Field #3, "Cyclical shift of the sequence relative to the associated independent pilot sequence", is a 24-bit field divided into eight 3-bit subfields. The first subfield (in the 3 LSB) represents the cyclic shift of pilot sequence #0 relative to the associated independent pilot sequence, the eighth subfield (in the 3 MSB) represents the cyclic shift of pilot sequence #7 relative to the associated independent pilot sequence. The value of the subfield is the actual cyclic shift (*CyS*) represented as unsigned integer with values 0 to 7, where:

Pilot sequence bit [*i*] =

Associated independent pilot sequence bit [(*i* + *CyS* × *Npilot_us* / 8) MOD *Npilot_us*].

If *Npilot_us* is an odd multiple of 4, then the value of *CyS* shall be even.

Field #4, "Number of additional independent pilot sequences (*Naips*)" is a 1-byte field field representing the number of additional independent pilot sequences included in the Upstream FDPS descriptor. Valid *Naips* values are 0 to 7.

Field #5, "Bits of additional independent pilot sequences", defines the bits of the *Naips* additional independent pilot sequences (i.e., independent pilot sequence #1 to independent pilot sequence #*Naips*) allocated by the VCE to be modulated on the upstream sync symbols. Each sequence is *Npilot_us* bits long (see clause 7.3.3). Each sequence is mapped into $\lceil Npilot\_us/8 \rceil$ bytes as defined for field #4 in Table 10-7 (the last byte can be incomplete). The total length of the field shall be $Naips \times \lceil Npilot\_us/8 \rceil$ bytes. Bits of the independent pilot sequence #0 are communicated in the "Upstream pilot sequence" field #4 of the ITU-T G.993.5 parameter field A.

10.3.2.2   R-MSG1

The R-MSG1 message (defined in Table 12-24 of [ITU-T G.993.2]), which is transmitted during R-P-CHANNEL DISCOVERY 1, contains an ITU-T G.993.5 parameter field. The ITU-T G.993.5

parameter field contains several parameters needed for FEXT cancellation operation, as shown in Table 10-11.

Table 10-11 – ITU-T G.993.5 parameter field in message R-MSG1

Field	Field name	Format
1	ITU-T G.993.5 parameter field length	1 byte
2	Maximum number of FEXT estimation symbols per superframe	1 byte
3	Support of optional backchannel control parameters	Parameters descriptor

Field #1, "ITU-T G.993.5 parameter field length", indicates the length of the vectoring descriptor field in bytes, excluding the ITU-T G.993.5 parameter field length field. All fields shown in Table 10-11 shall be included in the R-MSG1 message. The field shall be represented as an unsigned integer.

Field #2, "Maximum number of FEXT estimation symbols per superframe", defines the maximum number ($Kmax$) of symbols in the superframe for which the VTU-R supports error sample reporting (see clause 10.4.2.1). The field shall be formatted as an unsigned integer with valid $Kmax$ values = 1, 2, 4, 6, and 8. The VTU-R shall support the value $Kmax = 1$. Other values of $Kmax$ are optional.

Field #3, "Support of optional backchannel control parameters", indicate the optional values of control parameters supported by the VTU-R, as described in Table 10-12.

Table 10-12 – Optional backchannel control parameters descriptor

Bit	Description
0	Set to 1 if $F\_block = 32$ with $padding = 0$ is supported and 0 otherwise.
1	Set to 1 if $F\_block = 32$ with $padding = 1$ is supported and 0 otherwise.
2	Set to 1 if $F\_sub = 1$ is supported and 0 otherwise.
3	Set to 1 if $L\_w = 9$ is supported and 0 otherwise.
4	Set to 1 if $L\_w = 10$ is supported and 0 otherwise.
5	Set to 1 if $L\_w = 11$ is supported and 0 otherwise.
6	Set to 1 if $L\_w = 12$ is supported and 0 otherwise.
7	Reserved by ITU-T and shall be set to 0.

10.3.3 Vectoring-specific VTU-O signals transmitted during the Channel Discovery phase

10.3.3.1 O-P-VECTOR 1

The O-P-QUIET 1 signal shall be followed by the O-P-VECTOR 1 signal.

The O-P-VECTOR 1 signal shall consist of sync symbols and quiet symbols only. sync symbols shall be transmitted at each downstream sync symbol position (as defined in clause 6.2.3). Quiet symbols shall be transmitted at all other symbol positions (see Figure 10-2).

The O-P-VECTOR 1 sync symbols shall be generated as described in clause 10.5 of [ITU-T G.993.2]. These sync symbols shall modulate a pilot sequence. The pilot sequence is a repetitive sequence, as defined in clause 6.2.3, assigned to the initializing line by the VCE. Each probe tone of a sync symbol from the SUPPORTEDCARRIERSds set with a pilot sequence bit equal to ZERO shall modulate a 00 constellation point, and with a pilot sequence bit equal to ONE shall modulate a 11 constellation point. The 00 and 11 constellation points shall be per the 4-QAM constellation defined in clause 10.3.3.2.1 of [ITU-T G.993.2]. The constellation points on

subcarriers shall then be rotated by the quadrant scrambler defined in clause 12.3.6.2 of [ITU-T G.993.2].

If the bit "8192 superframes duration for O-P-VECTOR 1" is disabled in the ITU-T G.994.1 phase (see clause 10.2), then for sync symbols, the transmit PSD of all subcarriers shall be equal to CDPSDds.

If the bit "8192 superframes duration for O-P-VECTOR 1" is enabled and the bit "Use of O-P-VECTOR 1 flag tones only" is disabled in the ITU-T G.994.1 phase (see clause 10.2), then for sync symbols, the transmit PSD of all subcarriers shall be equal to CDPSDds.

If both the bit "8192 superframes duration for O-P-VECTOR 1" and the bit "Use of O-P-VECTOR 1 flag tones only" are enabled in the ITU-T G.994.1 phase (see clause 10.2), then for sync symbols, the transmit PSD of all subcarriers shall be equal to CDPSDds, except that for the first N sync symbols, the transmit power of all probe tones shall be 0 (with N a value determined by the VCE, in the range from 0 to 2048 sync symbols).

NOTE 1 – A way to identify the value of N is described in Appendix II.

The duration of O-P-VECTOR 1 is vendor discretionary, but shall be minimum 4×257 symbols and maximum $M \times 1024 \times 257$ symbols. Valid values for M are 1 and 8. Support of $M = 1$ is mandatory for the VTU-O and the VTU-R. Support of $M = 8$ is optional for both the VTU-O and the VTU-R. If the bit "8192 superframes duration for O-P-VECTOR 1" is enabled in the [ITU-T G.994.1] phase (see clause 10.2), then $M = 8$. Otherwise, $M = 1$.

NOTE 2 – The O-P-VECTOR 1 signal should be shortened by the VCE to accelerate full system start-up.

NOTE 3 – Appendix II provides examples of VCE control of the initialization process in the activation of multiple lines in the vectored group. Clause II.2 describes such VCE control using the "8192 superframes duration for O-P-VECTOR 1" capability in handling two groups of lines. Clause II.3 describes such VCE control using handshake capabilities.

During transmission of the O-P-VECTOR 1 signal, the SOC is in its inactive state.

During transmission of the O-P-VECTOR 1 signal, the VCE estimates the downstream FEXT channels from the initializing lines into the vectored lines based on the reported clipped error samples from the VTU-Rs of the vectored lines. From this point on, FEXT cancellation matrices are established in the VTU-Os for all vectored lines in the downstream direction and FEXT from the initializing line into vectored lines is cancelled.

The O-P-VECTOR 1 signal shall be followed by the O-P-CHANNEL DISCOVERY V1 signal, which determines the actual duration of O-P-VECTOR 1. The start time of O-P-CHANNEL DISCOVERY V1 transmission is determined by the VCE.

10.3.3.2   O-P-CHANNEL DISCOVERY V1

The O-P-CHANNEL DISCOVERY V1 signal shall be identical to the O-P-CHANNEL DISCOVERY 1 signal defined in clause 12.3.3.3.1 of [ITU-T G.993.2], with the addition of markers to indicate the downstream sync symbol positions and upstream pilot sequence positions (as defined in clause 10.3.3.5).

The addition of markers consists of modulating on all symbols the subcarriers with index $10n+9$ with constellation point 00 or 11, as defined in clause 10.3.3.5.

During transmission of O-P-CHANNEL DISCOVERY V1, the SOC is in its active state, sending O-IDLE for a period of at least 1500 symbols and no more than 2000 symbols and followed by the O-SIGNATURE message, as defined in clause 12.3.3.2.1 of [ITU-T G.992.3] and clause 10.3.2.1. The O-SIGNATURE shall be sent in auto-repeat mode, the same as O-SIGNATURE in [ITU-T G.993.2].

The O-P-CHANNEL DISCOVERY V1 signal shall be followed by the O-P-SYNCHRO V1 signal, which determines the actual duration of the O-P-CHANNEL DISCOVERY V1. The start time of O-P-SYNCHRO V1 transmission is determined by the VCE.

10.3.3.3   O-P-SYNCHRO V1

The O-P-SYNCHRO V1 signal shall be identical to the O-P-SYNCHRO 1 signal defined in clause 12.3.3.3.1 of [ITU-T G.993.2].

During transmission of O-P-SYNCHRO V1, the SOC is in its inactive state.

With the VTU-O transmitting the O-P-SYNCHRO V1 signal, the VCE notifies the VTU-R that the upstream FEXT channel estimation is completed, and that the VTU-R shall end the transmission of R-P-VECTOR 1. The VTU-O shall transmit O-P-SYNCHRO V1 only after VCE detects that R-P-VECTOR 1 is transmitted during at least 4 x 257 symbols.

The O-P-SYNCHRO V1 signal shall be followed by the O-P-CHANNEL DISCOVERY 1 signal.

10.3.3.4   O-P-CHANNEL DISCOVERY 1 and O-P-CHANNEL DISCOVERY 2

These signals shall be identical to the O-P-CHANNEL DISCOVERY 1 and O-P-CHANNEL DISCOVERY 2 signals defined in clause 12.3.3.3.1 of [ITU-T G.993.2], respectively, with the addition of markers to indicate the downstream sync symbol positions and upstream pilot sequence position (as defined in clause 10.3.3.5). The pattern of markers shall be continued taking into account all downstream sync symbol positions from the beginning of O-P-CHANNEL DISCOVERY V1.

NOTE – It is beneficial if O-P-SYNCHRO 1 and O-P-SYNCHRO 3 signals are not transmitted at downstream sync symbol positions.

During the O-P-CHANNEL DISCOVERY 1, the VTU-O shall transmit O-IDLE; the transmission shall start after the last symbol of O-P-SYNCHRO V1.

10.3.3.5   Downstream sync symbol and upstream pilot sequence markers

To indicate the time position of the downstream sync symbols and the required by VCE time position of the upstream sync symbols and upstream pilot sequence, the VTU-O shall modulate the subset of subcarriers with indices $10n+9$ with either the constellation point (00) or the constellation point (11) of the 4-QAM constellation, before the quadrant scrambler. All those subcarriers shall be modulated with the same information per symbol, i.e., either 00 or 11. Symbols whose subcarriers are modulated with either 00 or 11 are further noted in this clause as either ZERO or ONE symbols, respectively. A sequence of ZERO and ONE symbols forms a pattern that is used to indicate time positions of the sync symbol and pilot sequence.

Figure 10-6 shows the symbol modulation pattern. The time position of a downstream sync symbol shall be indicated by eight consecutive ONE symbols, starting at the time position of the downstream sync symbol of the vectored lines. The VTU-R shall derive the time position of the upstream sync symbol from the indicated time position of the downstream sync symbol by applying the offset between upstream and downstream sync symbols, which is communicated to the VTU-R in O-SIGNATURE.

The time position of the upstream pilot sequence shall be indicated by a 20-symbol pattern following the eight consecutive ONEs pattern, see Figure 10-6. This pattern of ONE and ZERO symbols shall represent the bit index of the upstream pilot sequence that modulates subcarriers of the upstream sync symbol associated (through the value of the offset) with this downstream sync symbol that precedes the mentioned 20-symbol pattern (as shown in Figure 10-6).

The bit index of the upstream pilot sequence shall be represented as an unsigned integer, and each bit of this integer is represented by two consecutive symbols of the pattern, with symbols 7 and 8 in Figure 10-6 representing the LSB. A bit value 0 shall be represented by a ZERO symbol followed

by a ONE symbol. A bit value 1 shall be represented by a ONE symbol followed by a ZERO symbol. All the symbols after the 20-symbol pattern shall be ZERO symbols until the time position of the next downstream sync symbol.

NOTE – With this technique, the upstream sync symbol time position can be detected by looking for the pattern of eight consecutive ONEs and the bit index in the pilot sequence by decoding the 20 following symbols. This allows a quick detection of the time position of the upstream pilot sequence. The 10-bit pattern decoded from the 20 following symbols indicates the bit index in the upstream pilot sequence associated with the detected upstream sync symbol.
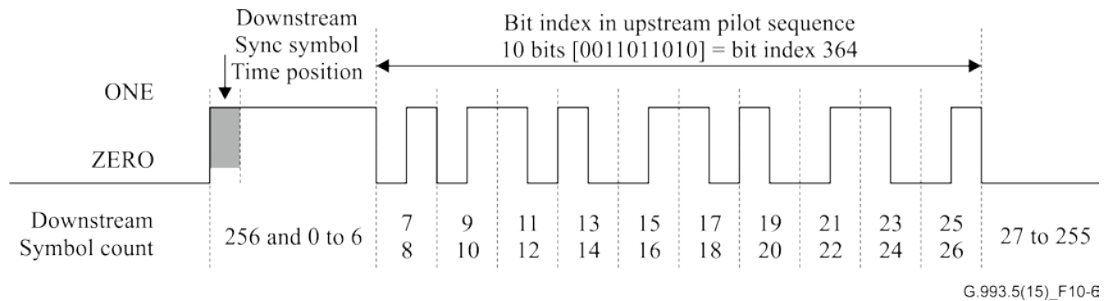
Figure 10-6 – Pattern modulated on subcarriers $10n+9$ following the sync symbol position of the vectored lines

10.3.3.6 Initialization of multiple initializing lines

When the VCE initializes multiple lines:

– The downstream crosstalk channels from the initializing lines into the active lines of the vector group should be estimated simultaneously by insuring that O-P-VECTOR 1 signals are sent on all initialization lines during the estimation. This can be done by controlling the end and the start of O-P-VECTOR 1 in each line.

– The upstream crosstalk channels between the initializing lines and the active lines of the vector group should be estimated simultaneously by insuring that R-P-VECTOR 1 signals are sent on all initialization lines during the estimation. This can be done by controlling the end of R-P-VECTOR 1 with the O-P-SYNCHRO V1 signal in each line.

10.3.4 Vectoring specific VTU-R signals transmitted during Channel Discovery phase

10.3.4.1 R-P-VECTOR 1

The VTU-R shall transmit R-P-QUIET signal until it correctly receives the O-SIGNATURE message.

Upon receiving the O-SIGNATURE message, the VTU-R shall transmit R-P-VECTOR 1.

The VTU-R shall identify the downstream Sync symbols positions and derive the upstream sync symbol positions, by detecting the sync symbol markers on the O-P-CHANNEL DISCOVERY V1 signal.

The R-P-VECTOR 1 shall consist of sync symbols and quiet symbols only. Sync symbols shall be transmitted at each upstream sync symbol position (as defined in clause 7.3.2). Upstream sync symbol positions shall be the downstream sync symbol positions (as indicated by the markers on the O-P-CHANNEL DISCOVERY V1 signal), advanced or delayed by the upstream sync symbol offset (contained in the O-SIGNATURE message). Quiet symbols shall be transmitted at all other time positions (see Figure 10-2).

The R-P-VECTOR 1 sync symbols shall be generated as described in clause 10.4.4 of [ITU-T G.993.2]. These sync symbols shall modulate a pilot sequence. The transmission of sync symbols shall start from the sync symbol that carries the first identified reference point of the

upstream pilot sequence. The timing of reference points of the pilot sequence is indicated by the markers in the O-P-CHANNEL DISCOVERY V1 signal, as described in clause 10.3.3.5.

The pilot sequence is a repetitive sequence, as defined in clause 6.2.3, assigned to the initializing line by the VCE and communicated to the VTU-R in the O-SIGNATURE message. Each probe tone of a sync symbol from the SUPPORTEDCARRIERSus set with a pilot sequence bit equal to ZERO shall modulate a 00 constellation point, and with a pilot sequence bit equal to ONE shall modulate a 11 constellation point (the SUPPORTEDCARRIERSus set is also indicated in the O-SIGNATURE message). The 00 and 11 constellation points shall be per the 4-QAM constellation defined in clause 10.3.3.2.1 of [ITU-T G.993.2]. The constellation points on subcarriers shall then be rotated by the quadrant scrambler defined in clause 12.3.6.2 of [ITU-T G.993.2].

The transmit PSD of all subcarriers shall be equal to CDPSDus and shall follow the upstream PSD limit imposed by the VTU-O as indicated in the O-SIGNATURE message.

During transmission of R-P-VECTOR 1, the SOC is in its inactive state.

During R-P-VECTOR 1, the VCE estimates the upstream FEXT channels from the initializing lines into the vectored lines. From this point on, FEXT cancellation matrices are established in the VTU-Os for all vectored lines in the upstream direction and FEXT from the initializing lines into vectored lines is cancelled.

The duration of R-P-VECTOR 1 is determined by the VTU-O. The VTU-R shall end the transmission of the R-P-VECTOR 1 signal within 64 symbols after the last symbol of the O-P-SYNCHRO V1 signal. The duration of the R-P-VECTOR 1 shall not exceed 1024×257 symbols.

The R-P-VECTOR 1 signal shall be followed by the R-P-CHANNEL DISCOVERY 1 signal.

10.4 Training phase

10.4.1 Overview

The Channel Discovery phase is followed by the Training phase. If both downstream and upstream vectoring are disabled after the ITU-T G.994.1 Phase, then all vectoring-related parts shall be skipped and the Training phase shall be as defined in [ITU-T G.993.2].

If downstream vectoring or upstream vectoring is enabled, then the Training phase shall be modified relative to the ITU-T G.993.2 Training phase as defined in this clause.

Figure 10-7 and Figure 10-8 highlight the signals added and the signals/messages modified in the ITU-T G.993.2 Training phase for ITU-T G.993.5 transceivers. Non-highlighted signals and messages shall be as defined in [ITU-T G.993.2].
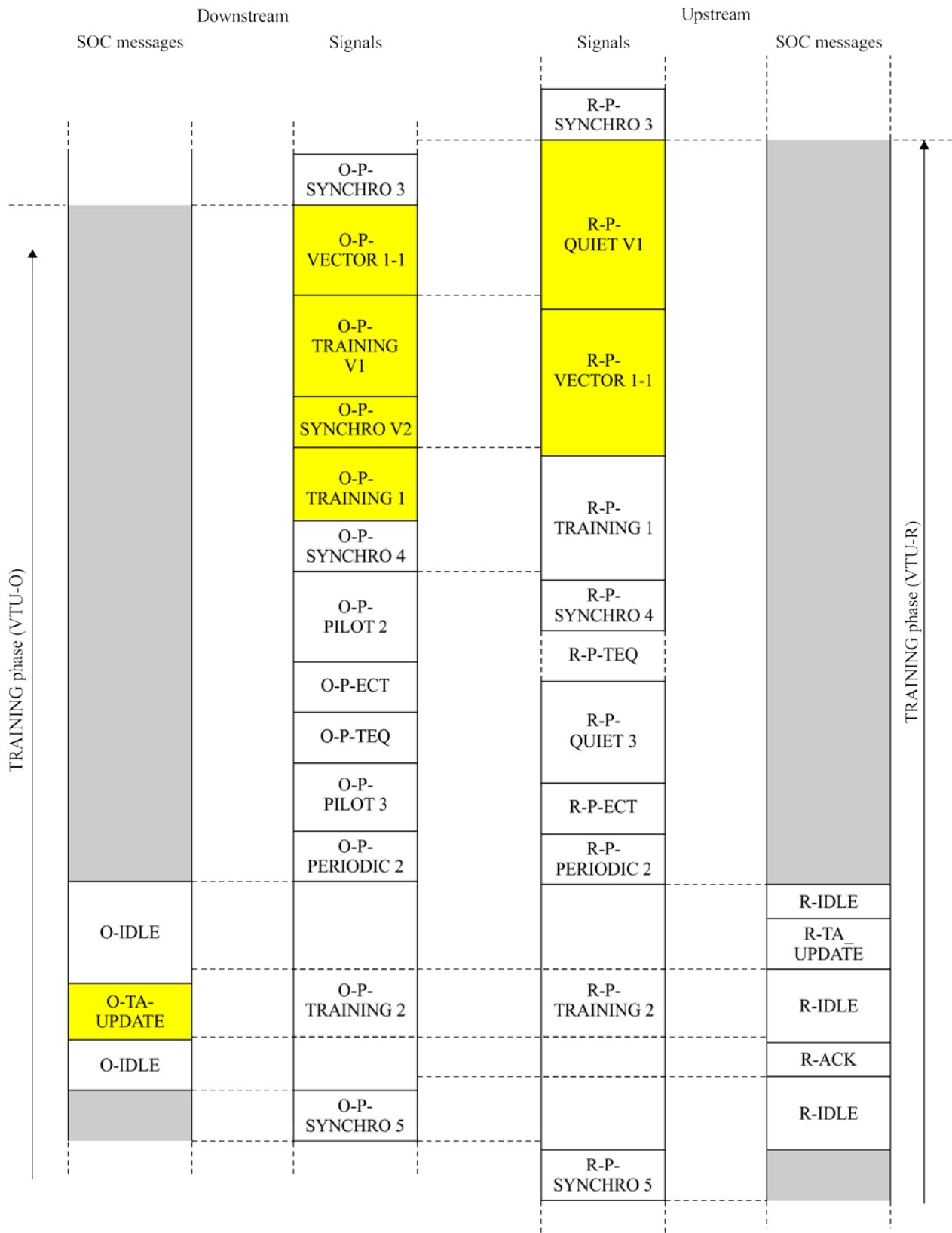
Figure 10-7 – Early stages of the Training phase
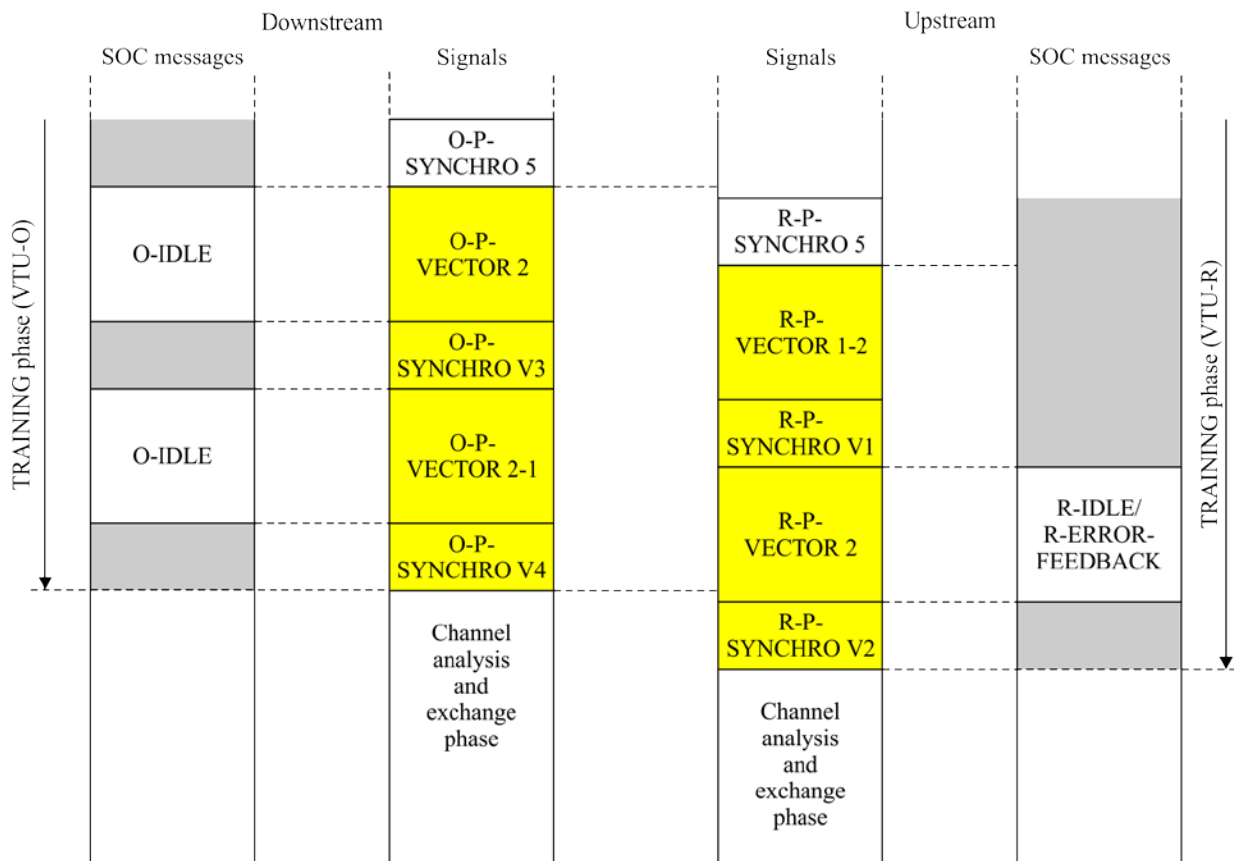
Figure 10-8 – Last stages of the Training phase

10.4.2 Modified SOC messages sent during the Training phase

10.4.2.1 O-TA_UPDATE

The O-TA_UPDATE message (defined in Table 12-32 of [ITU-T G.993.2]) which is transmitted during O-P-TRAINING 2 contains an ITU-T G.993.5 parameter field. The ITU-T G.993.5 parameter field contains several parameters needed for FEXT cancellation operation, as shown in Table 10-13.

Table 10-13 – Parameter field in message O-TA_UPDATE

Field	Field name	Format
1	ITU-T G.993.5 parameter field length	1 byte
2	Error report control parameters	Error report configuration descriptor
3	SOC repetition factor (1/R)	1 byte
4	FEXT estimation symbols per superframe	1 byte

Field #1, "ITU-T G.993.5 parameter field length", indicates the length of the ITU-T G.993.5 parameter field in bytes, excluding the ITU-T G.993.5 parameter field length field. All fields shown in Table 10-13 shall be included in the O-TA_UPDATE message. The field shall be represented as an unsigned integer.

Field #2, "error report control parameters", defines the control parameters for each of the vectored bands indicated in O-SIGNATURE. The control parameters are defined in Table 7-1 and valid values are defined in Table 7-2. The values defined in this field may include optional values indicated by the VTU-R in R-MSG1. Table 8-4 defines the mapping of the control parameters into the Error Report configuration descriptor. The VTU-O shall select control parameters so that in conjunction with the selected SOC repetition rate, the expected duration of the ERROR_FEEDBACK message will not exceed the limits defined in clause 10.4.2.2.

Field #3, "SOC Repetition Factor", defines the SOC repetition factor, $1/R$, as set by the VCE. The valid $1/R$ values are all multiples of 10 in the [10, 120] range. This corresponds to the number of bits per symbol ($N\_bits\_per\_symbol$) of the SOC being a multiple of 16 in the [16, 192] range. The field shall be represented as an unsigned integer.

Field #4, "FEXT estimation symbols per superframe", defines the number of symbols (K) in the superframe for which a clipped error sample shall be reported. The clipped error samples shall be reported in a format defined by Field #2. The field shall be formatted as an unsigned integer with valid values K=1, 2, 4, 6, and 8. The value of K shall not exceed the VTU-R capability ($Kmax$) indicated in the R-MSG1 message. Clause 10.4.2.2 defines the symbol positions for which clipped error samples shall be reported for different values of K.

The O-TA_UPDATE message may indicate a correction to the timing advance (TA) value. If the TA value contained in the O-TA_UPDATE message is different from the TA value previously used by the VTU-R, then the TA value shall be updated starting with the first symbol following R-P-SYNCHRO 5.

NOTE – This requirement is different from the way the TA value is updated in [ITU-T G.993.2].

10.4.2.2   R-ERROR-FEEDBACK

During transmission of R-P-VECTOR 2, the VTU-R shall report back to the VTU-O the clipped error samples through the SOC using R-ERROR-FEEDBACK messages (see Figure 10-8). The SOC message code for this message shall be $8B_{16}$. The VTU-O shall not acknowledge any of R-ERROR-FEEDBACK messages and the VTU-R shall not re-transmit any of them.

The R-ERROR-FEEDBACK messages shall be alternated with R-IDLE. Figure 10-9 shows the timeline of R-IDLE and the R-ERROR-FEEDBACK message for subsequent symbols on which the clipped error samples are reported. The sequence shall start from R-IDLE. Both R-IDLE and the R-ERROR-FEEDBACK message shall use the extended SOC channel with settings as described in clause 10.4.4.4. The rest of R-IDLE parameters shall be the same as for R-IDLE defined in clause 12.2.4 of [ITU-T G.993.2]: it shall consist of HDLC flag $7E_{16}$ sent repeatedly.

The first R-IDLE transmission (after completion of R-P-VECTOR 1-2) allows the receiver in the VTU-O to adjust to the extended SOC channel and shall be at least 16 symbols long. The duration of the other R-IDLE transmissions (denoted as t_{IDLE} in Figure 10-9) shall be set by the VTU-R so that the VTU-R can complete the R-ERROR-FEEDBACK message during the time which is less than the time period between two adjacent symbols on which the clipped error samples have to be reported. Each time period t_{IDLE} shall be at least two symbols long. Transmission of R-ERROR-FEEDBACK message shall start at the time t_{START} that shall be inside the transmission window (see Figure 10-9). The transmission window starts three symbol periods (i.e., $3 / f_{DMT}$) after the start of the symbol on which the clipped error samples are reported. The transmission window ends W_max symbol periods (i.e., W_max / f_{DMT}) after the start of the symbol on which the clipped error samples are reported. The maximum value of t_{IDLE} depends on the length of the R-ERROR-FEEDBACK message. The total of the value of t_{IDLE} and the duration of the transmission of the R-ERROR-FEEDBACK message shall not exceed the time-limit that will prevent the VTU-R to start transmission of the next R-ERROR-FEEDBACK message inside the next transmission window.
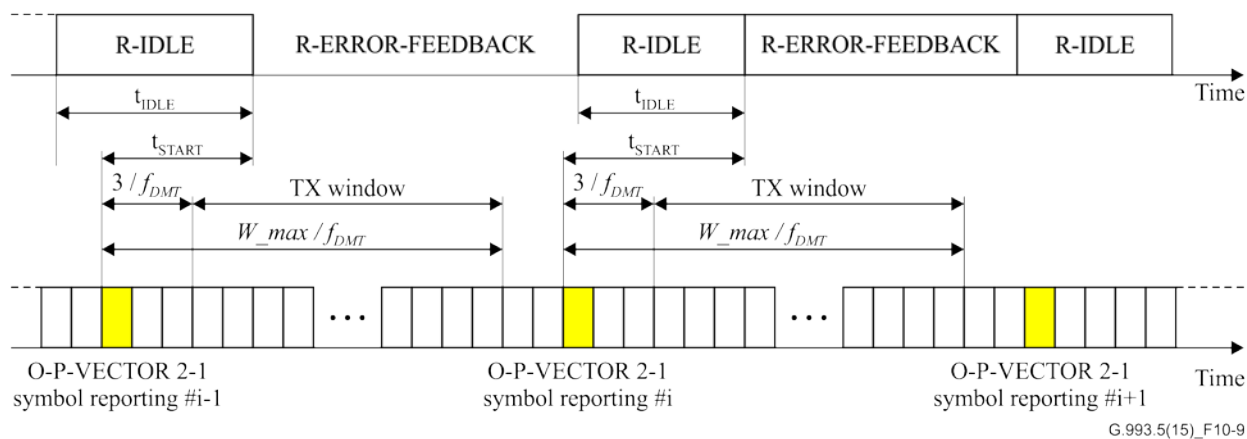
Figure 10-9 – Timeline of R-ERROR-FEEDBACK messages

Through the O-TA_UPDATE message, the VCE indicates how many FEXT estimation symbols per superframe (i.e., the value of K determined by the O-TA_UPDATE message) the clipped error samples shall be reported. For the given value of K (assigned by O-TA_UPDATE), the VTU-R shall report clipped error samples for all the O-P-VECTOR 2-1 symbols of each downstream superframe with symbol count $i(k) = (k+1) \times \lfloor 256/K \rfloor$, where $k = 0, 1, 2, \ldots, K–1$. The value of W_max for the given value of K shall be computed as $W\_max = \lfloor 257/K \rfloor - 2$.

NOTE 1 – If K=1, the VTU-R reports clipped error samples on the O-P-VECTOR 2-1 downstream sync symbols only.

The number of bytes used to report the clipped error samples in a single R-ERROR-FEEDBACK message depends on the backchannel control parameters indicated in the O-TA_UPDATE message. The total number of bytes to be transmitted is equal to the number of bytes in the ERB, N_ERB, plus 3 (see Table 10-14).

If the size of the R-ERROR_FEEDBACK message is larger than the maximum allowed segment size, the message shall be segmented as defined in clause 12.2.6 of [ITU-T G.993.2] for AR mode, with the number of segments not to exceed 15. All segments except the last one shall be set to be of the maximum allowed segment size.

NOTE 2 – Minimum gaps between segments reduce the overhead of error feedback transmission and thus save bandwidth of the backchannel.

The number of symbols required to communicate this number of bytes can be calculated as:

$$N\_symbol = \left\lceil \frac{8 \times (N\_ERB + 3 + N\_OH)}{N\_bits\_per\_symbol} \right\rceil = \left\lceil 5 \times \frac{N\_ERB + 3 + N\_OH}{1/R} \right\rceil$$

where N_OH is the SOC encapsulation overhead, equal to 6 octets plus the statistical overhead due to byte stuffing, as specified in [ITU-T G.997.1]. If the R-ERROR-FEEDBACK message is segmented, the N_OH (per segment) shall be multiplied by the number of segments.

NOTE 3 – The 0.1% worst case statistical overhead due to byte stuffing for a message with randomized content that is longer than 512 bytes is not expected to be more than 3% and goes down for longer messages.

NOTE 4 – When padding is not used, N_ERB will depend on the actual values of the error samples. In that case, the number of bytes per symbol should be calculated based on the worst-case assumption of the resolution needed for the error samples.

The VCE shall configure the SOC bit rate, such that the value of N_symbol (including the statistical overhead due to byte stuffing) does not exceed $(\lfloor 257/K \rfloor - 2)$ symbols (with K the number of symbols per superframe on which clipped error samples are reported, as indicated in the O-TA_UPDATE message). The VTU-R shall terminate transmission of the R-ERROR-

FEEDBACK message if its duration (due to unexpectedly high SOC overhead) will prevent the VTU-R to start transmission of the next R-ERROR-FEEDBACK message inside the next transmission window.

The message R-ERROR_FEEDBACK shall have the structure shown in Table 10-14.

Table 10-14 – Description of message R-ERROR_FEEDBACK

	Field name	Format
1	Message descriptor	Message code
2	Sync symbol count	2 bytes
3	Error report block	N_ERB bytes

Field #1, "Message descriptor", is a unique one-byte code that identifies the message. It shall be coded $8B_{16}$.

Field #2, "Sync symbol count", contains the sync symbol count modulo 1024 of the last received downstream sync symbol and the sequence number $k = 0, …, K – 1$ of the report in the superframe. The VTU-R shall count sync symbols starting from the first downstream sync symbol after it receives O-P-SYNCHRO V3 (this sync symbol shall have count 0) through transmission of O-P-VECTOR 2-1.

The four MSBs of the 2-byte field shall represent the sequence number k of the report as an unsigned integer in the range from 0 to $K–1$. The ten LSBs shall represent the sync symbol count as an unsigned integer in the range from 0 to 1023. The bits 10 and 11 are reserved by ITU-T and shall be set to 0.

NOTE 5 – If the ERB is reported for a sync symbol, the "sync symbol count" field has the four MSBs set to $K – 1$ and the ten LSBs set to the count of the sync symbol for which the ERB is reported.

Field #3, "Error report block", contains the real and imaginary parts of the clipped error samples associated with the subcarriers of the indicated vectored band(s). If only a single band is reported in the R-ERROR-FEEDBACK message, then the N_{ERB} shall be calculated (see clause 7.2.3.3) as if L_w=0 for the other bands. The format is defined in clause 7.2.3.

10.4.3 Vectoring specific VTU-O signals transmitted during the Training phase

10.4.3.1 O-P-VECTOR 1-1

The O-P-SYNCHRO 3 signal shall be followed by the O-P-VECTOR 1-1 signal.

The O-P-VECTOR 1-1 signal shall be identical to the O-P-VECTOR 1 signal, except that the PSD shall be equal to MREFPSDds.

The duration of O-P-VECTOR 1-1 is vendor discretionary, but shall be minimum 4×257 symbols and maximum 1024×257 symbols.

During transmission of O-P-VECTOR 1-1, the SOC is in its inactive state.

The O-P-VECTOR 1-1 signal allows the downstream FEXT channel re-estimation from the initializing line into the vectored lines. This re-estimation is to capture changes in the FEXT channels caused by possible modifications of the VTU-O AFE configurations during the Channel Discovery phase.

The O-P-VECTOR 1-1 signal shall be followed by the O-P-TRAINING V1 signal, which determines the actual duration of O-P-VECTOR 1-1.

10.4.3.2 O-P-TRAINING V1

The O-P-TRAINING V1 signal shall be identical to the O-P-TRAINING 1 signal defined in clause 12.3.4.3.1.1 of [ITU-T G.993.2], with the addition of markers to indicate the downstream sync symbol positions and upstream pilot sequence position. Markers shall be added as defined in clause 10.3.3.5. The pattern of markers shall be continued taking into account all downstream sync symbol positions from the beginning of the O-P-CHANNEL DISCOVERY V1 signal.

During the transmission of O-P-TRAINING V1, the SOC is in its inactive state.

The O-P-TRAINING V1 signal shall be followed by the O-P-SYNCHRO-V2 signal, which determines the actual duration of the O-P-TRAINING V1.

10.4.3.3 O-P-SYNCHRO V2

The O-P-SYNCHRO V2 signal shall be identical to the O-P-SYNCHRO 4 signal described in clause 12.3.4.3.1 of [ITU-T G.993.2].

During transmission of O-P-SYNCHRO V2, the SOC is in its inactive state.

With the VTU-O transmitting the O-P-SYNCHRO V2 signal, the VCE notifies the VTU-R that the upstream FEXT channel re-estimation from the initializing lines into other vectored lines is completed, and that the VTU-R shall stop transmission of the R-P-VECTOR 1-1 signal.

The VTU-O shall transmit O-P-SYNCHRO V2 only after the VCE detects the R-P-VECTOR 1-1 signal transmitted during at least 4×257 symbols.

The O-P-SYNCHRO V2 signal shall be followed by the O-P-TRAINING 1 signal.

10.4.3.4 O-P-TRAINING 1 and O-P-TRAINING 2

These signals shall be identical to the O-P-TRAINING 1 and O-P-TRAINING 2 signals defined in clause 12.3.4.3.1 of [ITU-T G.993.2], respectively, with the addition of markers to indicate the downstream sync symbol positions and upstream pilot sequence positions (as defined in clause 10.3.3.5). The pattern of markers shall be continued taking into account all downstream sync symbol positions from the beginning of O-P-CHANNEL DISCOVERY V1.

NOTE – It is beneficial if O-P-SYNCHRO 4 and O-P-SYNCHRO 5 signals are not transmitted at downstream sync symbol positions.

10.4.3.5 O-P-VECTOR 2

The O-P-VECTOR 2 signal shall follow the O-P-SYNCHRO 5 signal.

At sync symbol positions, the O-P-VECTOR 2 signal shall contain sync symbols, modulated as defined for the O-P-VECTOR 1 signal. At other symbol positions, the SOC channel shall be modulated using one byte per symbol mapping, as defined for the O-P-TRAINING 2 signal in [ITU-T G.993.2].

During the sync symbols, the SOC is in the inactive state. During the other symbols, the SOC is in the active state, and the VTU-O shall transmit O-IDLE.

The minimum duration of O-P-VECTOR 2 is 128 symbols.

The O-P-VECTOR 2 signal shall be followed by the O-P-SYNCHRO V3 signal, which determines the actual duration of O-P-VECTOR 2.

The VTU-O shall transmit O-P-SYNCHRO V3 at least 70 symbols prior to transmission of the sync symbol (to avoid ambiguity in sync symbol count at the VTU-R).

10.4.3.6 O-P-SYNCHRO V3

The O-P-SYNCHRO V3 signal shall be identical to the O-P-SYNCHRO 5 signal, as defined in clause 12.3.4.3.1.9 of [ITU T G.993.2].

During transmission of O-P-SYNCHRO V3, the SOC is in its inactive state.

With the VTU-O transmitting the O-P-SYNCHRO-V3 signal, the VCE notifies the VTU-R that the upstream FEXT channel re-estimation from the initializing line into other vectored lines is completed, and that the VTU-R shall stop transmission of the R-P-VECTOR 1-2 signal. The VTU-O shall transmit O-P-SYNCHRO V3 only after the VCE detects the R-P-VECTOR 1-2 signal transmitted during at least 4×257 symbols.

The O-P-SYNCHRO V3 signal shall be followed by the O-P-VECTOR 2-1 signal.

10.4.3.7   O-P-VECTOR 2-1

The O-P-VECTOR 2-1 signal shall be identical to the O-P-VECTOR 2 signal.

During the sync symbols, the SOC is in the inactive state. During the other symbols, the SOC is in the active state, and the VTU-O shall transmit O-IDLE.

Transmission of O-P-VECTOR 2-1 enables the VCE to estimate the downstream FEXT channels from the vectored lines into the initializing line, and to update the estimates of the downstream FEXT channels from the initializing lines into the vectored lines.

The duration of O-P-VECTOR 2-1 is vendor discretionary, but shall be minimum 257 symbols and maximum 1024×257 symbols.

The O-P-VECTOR 2-1 signal shall be followed by the O-P-SYNCHRO V4 signal, which determines the actual duration of the O-P-VECTOR 2-1.

10.4.3.8   O-P-SYNCHRO V4

The O-P-SYNCHRO V4 signal shall be identical to the O-P-SYNCHRO V3 signal, as defined in clause 10.4.3.6.

During transmission of the O-P-SYNCHRO V4 signal, the SOC is in its inactive state.

With the VTU-O transmitting the O-P-SYNCHRO-V4 signal, the VCE notifies the VTU-R that the downstream FEXT channel estimation from the other vectored lines into the initializing lines is completed, and that the VTU-R shall stop transmission of the R-P-VECTOR 2 signal.

The Training phase is completed at this point, and the VTU-O shall transition into the Channel Analysis and Exchange phase, see Figure 10-8.

10.4.3.9   Initialization of multiple initializing lines

When the VCE initializes multiple lines:

–   The downstream crosstalk channel from the initializing lines into the active lines of the vector group should be estimated simultaneously by insuring that O-P-VECTOR 1-1 signals are sent on all initialization lines during the estimation. This can be done by controlling the start and the end of O-P-VECTOR 1-1 in each line.

–   The upstream crosstalk channel between the initializing lines and the active lines of the vector group should be estimated simultaneously by insuring that R-P-VECTOR 1-1 signals are sent on all initialization lines during the estimation. This can be done by controlling the end of R-P-VECTOR 1-1 with the O-P-SYNCHRO V2 signal in each line.

–   The upstream crosstalk channels between the initializing lines and the active lines of the vector group should be estimated simultaneously by insuring that R-P-VECTOR 1-2 signals are sent on all initialization lines during the estimation. This can be done by controlling the end of R-P-VECTOR 1-2 with the O-P-SYNCHRO V3 signal in each line.

– The downstream crosstalk channel from the active lines into the initializing lines of the vector group should be estimated simultaneously by insuring that O-P-VECTOR 2-1 signals are sent on all initialization lines during the estimation. This can be done by controlling the end of O-P-VECTOR 2-1 with the O-P-SYNCHRO V4 signal in each line.

10.4.4 Vectoring specific VTU-R signals transmitted during the Training phase

10.4.4.1 R-P-QUIET V1

The R-P-SYNCHRO 3 signal shall be followed by the R-P-QUIET V1 signal.

The R-P-QUIET V1 signal shall be identical to the R-P-QUIET 2 signal.

During the R-P-QUIET V1 signal, the SOC is in its inactive state.

The duration of R-P-QUIET V1 signal is controlled by the VTU-O. The VTU-R shall end the transmission of R-P-QUIET V1 upon detection of the O-P-TRAINING V1 signal, and start transmission of R-P-VECTOR 1-1 signal.

10.4.4.2 R-P-VECTOR 1-1

The R-P-VECTOR 1-1 signal shall be identical to the R-P-VECTOR 1 signal, except its PSD shall be equal to MREFPSDus.

During transmission of R-P-VECTOR 1-1, the SOC is in its inactive state.

The VTU-R should use the timing advance value calculated in the Channel Discovery phase to ensure that the sync symbols of the initializing line are aligned at the VTU-O with the sync symbols of vectored lines.

The R-P-VECTOR 1-1 signal allows the upstream FEXT channel re-estimation between the initializing line and the vectored lines. This re-estimation is to capture changes in the FEXT channels caused by possible modifications of the VTU-O AFE configurations during the Channel Discovery phase.

The duration of R-P-VECTOR 1-1 signal is controlled by the VTU-O. Within 64 symbols after the last symbol of the O-P-SYNCHRO V2 signal, the VTU-R shall end the transmission of the R-P-VECTOR 1-1. The duration of R-P-VECTOR 1-1 shall not exceed 1024×257 symbols.

The R-P-VECTOR 1-1 signal shall be followed by the R-P-TRAINING 1 signal.

10.4.4.3 R-P-VECTOR 1-2

The R-P-VECTOR 1-2 signal shall follow the R-P-SYNCHRO 5 signal. The R-P-VECTOR 1-2 signal shall be identical to the R-P-VECTOR 1-1 signal.

During transmission of R-P-VECTOR 1-2, the SOC is in its inactive state.

The R-P-VECTOR 1-2 signal allows the upstream FEXT channel re-estimation between the initializing line and the vectored lines. This re-estimation is to capture changes in the FEXT channels caused by possible modifications of the timing advance during the Training phase.

The duration of R-P-VECTOR 1-2 signal is controlled by the VTU-O. Within 64 symbols after the last symbol of the O-P-SYNCHRO V3 signal, the VTU-R shall end the transmission of the R-P-VECTOR 1-2 signal. The duration of R-P-VECTOR 1-2 shall not exceed 1024×257 symbols.

The R-P-VECTOR 1-2 signal shall be followed by the R-P-SYNCHRO V1 signal.

10.4.4.4 R-P-SYNCHRO V1

The R-P-SYNCHRO V1 signal shall be identical to the R-P-SYNCHRO 5 signal, as defined in clause 12.3.4.3.2.9 of [ITU T G.993.2].

During transmission of the R-P-SYNCHRO V1 signal, the SOC is in its inactive state.

The R-P-SYNCHRO V1 signal shall be followed by R-P-VECTOR 2 signal.

10.4.4.5   R-P-VECTOR 2

At sync symbol positions, the R-P-VECTOR 2 signal shall contain sync symbols, modulated as defined for the R-P-VECTOR 1 signal. At other symbol positions, the symbols shall be modulated as for the R-P-TRAINING 2 signal, with the extended SOC channel being established.

Transmission of R-P-VECTOR 2 enables the VCE to estimate upstream FEXT channels from the vectored lines into the initializing line, and update the estimates of the upstream FEXT from the initializing lines into the vectored lines.

During the sync symbols, the SOC is in the inactive state. During the other symbols, the SOC is in the active state, and the VTU-R shall transmit R-IDLE or the R-ERROR-FEEDBACK message.

The duration of R-P-VECTOR 2 signal is controlled by the VTU-O. Within 64 symbols after the last symbol of the O-P-SYNCHRO V4 signal, the VTU-R shall end the transmission of the R-P-VECTOR 2 signal.

The R-P-VECTOR 2 signal shall be followed by the R-P-SYNCHRO V2 signal.

To establish the extended SOC, the R-P-VECTOR 2 symbols with active SOC shall be modulated with bit mapping as defined in Table 10-15, with the number of bits per symbol calculated as:

$$N_{bitspersymbol} = \frac{16}{10 \cdot R}$$

with $1/R$ an integer multiple of 10 in the [10, 120] range, as indicated in the O-TA_UPDATE message.

Table 10-15 – Bit mapping for R-P-VECTOR 2

Subcarrier index	Constellation point
5, 10, 15,..., 5n, ...	00
1, $1/R$+1, $2/R$+1, ..., n/R + 1, ...	SOC message bits 0 and 1
2, $1/R$+2, $2/R$+2, ..., n/R + 2, ...	SOC message bits 2 and 3
...	...
$10k+m$, $1/R$+$10k+m$, $2/R$+$10k+m$, ..., n/R+$10k+m$, ... with $k = 0, 1, 2, ...,\ \dfrac{1}{10 \cdot R} - 1$ and $m = 1, 2, 3, 4, 6, 7, 8, 9$	SOC message bits $16k+f(m)$ and $16k+f(m)+1$ with $f(m) = \begin{cases} 2m-2 & \text{if } m=1,2,3,4 \\ 2m-4 & \text{if } m=6,7,8,9 \end{cases}$
...	...
$1/R$–1, $2/R$–1, $3/R$–1, ..., $n + 1/R$–1, ...	SOC message bits $\dfrac{16}{10 \cdot R} - 2$ and $\dfrac{16}{10 \cdot R} - 1$

NOTE – In [ITU-T G.993.2], the SOC bit mapping allows 16 bits per symbol. For faster reporting of clipped error samples, the VCE may increase the SOC bit mapping in steps of 16 bits per symbol, from 16 bits up to 192 bits per symbol, by reducing the number of repetitions of these bits within each symbol. For operation at 4000 symbols/s, this increases the SOC bit rate in steps of 64 kbit/s, from 64 kbit/s (as in [ITU-T G.993.2]) up to 768 kbit/s. For operation at 8000 symbols/s, this increases the SOC bit rate in steps of 128 kbit/s, from 128 kbit/s (as in [ITU-T G.993.2]) up to 1536 kbit/s.

10.4.4.6   R-P-SYNCHRO V2

The R-P-SYNCHRO V2 signal shall be identical to the R-P-SYNCHRO V1 signal.

During transmission of the R-P-SYNCHRO V2 signal, the SOC is in its inactive state.

The Training phase is completed at this point, and VTU-R shall transition into the Channel Analysis and Exchange phase, see Figure 10-8.

10.5 Channel Analysis and Exchange phase

10.5.1 Overview

The Channel Analysis and Exchange phase does not require any changes with respect to [ITU-T G.993.2], other than the ITU-T G.993.5 parameter field defined for the O-PMS message.

10.5.2 Modified SOC messages sent during Channel Analysis and Exchange phase

10.5.2.1 O-PMS

The O-PMS message (defined in Table 12-46 of [ITU T G.993.2]) which is transmitted during O-P-MEDLEY contains an ITU-T G.993.5 parameter field. The ITU-T G.993.5 parameter field contains several parameters needed for FEXT cancellation operation as shown in Table 10-16.

Table 10-16 – ITU-T G.993.5 parameter field in message O-PMS

Field	Field name	Format
1	ITU-T G.993.5 parameter field length	1 byte
2	Showtime backchannel encapsulation	1 byte
3	Layer 2 VCE MAC address	6 bytes
4	Layer 2 Line_ID	2 bytes

Field #1, "ITU-T G.993.5 parameter field length", indicates the length of the ITU-T G.993.5 parameter field in bytes, excluding the ITU-T G.993.5 parameter field length field. All fields shown in Table 10-16 shall be included in the O-PMS message. The field shall be represented as an unsigned integer.

Field #2, "Showtime backchannel encapsulation", defines whether the Showtime backchannel is encapsulated into eoc messages or into Layer 2 Ethernet packets. The field shall be set to 00_{16} for eoc encapsulation and shall be set to 01_{16} for Layer 2 Ethernet encapsulation. Other values are reserved for ITU-T.

Field #3, "Layer 2 VCE MAC Address", defines the VCE MAC Address to be used by the NT as MAC destination address in case Layer 2 Ethernet encapsulation is used. The field shall be set to all 00_{16} bytes in case eoc encapsulation is used.

Field #4, "Layer 2 Line_ID", defines the Line_ID to be used by the NT in case Layer 2 Ethernet encapsulation is used. The Line_ID shall be inserted as the first two bytes of the Ethernet packet payload (see Figure 7-9). The field shall be set to 0000_{16} in case eoc encapsulation is used.

10.6 Transition from initialization to Showtime

The last symbol of O-P-SYNCHRO 6 shall be transmitted at a downstream sync symbol position, such that the first symbol of Showtime is a data symbol transmitted at downstream symbol count 0.

The first DMT symbol following O-P-SYNCHRO 6 of the Channel Analysis and Exchange phase shall be the first downstream symbol of Showtime. The PMD, PMS-TC and TPS-TC parameter settings negotiated during the Channel Analysis and Exchange phase shall be applied starting from the first symbol of Showtime.

The last symbol of R-P-SYNCHRO 6 shall be transmitted at an upstream sync symbol position, such that the first symbol of Showtime is a data symbol transmitted at upstream symbol count 0.

The first DMT symbol following R-P-SYNCHRO 6 shall be the first upstream symbol of Showtime. The PMD, PMS-TC and TPS-TC parameter settings negotiated during the Channel Analysis and Exchange phase shall be applied starting from the first symbol of Showtime.

The last symbol of R-P-SYNCHRO 6 shall be transmitted at least 15 and no more than 15+64+257 symbols after transmission of the last symbol of O-P-SYNCHRO 6.

The downstream sync symbol positions and the downstream pilot sequence shall be continued from initialization into Showtime. Each downstream sync symbol in Showtime shall be modulated by the downstream pilot sequence (see clause 6.2.3).

The upstream sync symbol positions and the upstream pilot sequence shall be continued from initialization into Showtime. Each upstream sync symbol in Showtime shall be modulated by the upstream pilot sequence (see clause 7.3.3).

10.7   Loop diagnostic mode procedures

10.7.1 Overview

The loop diagnostic mode procedure described in this clause is based on the initialization as described in clause 10.1 through 10.6, with addition of steps specific for loop diagnostic mode, and without sending R-ERROR-FEEDBACK messages.

If the loop diagnostic mode codepoint in the MS message is set (see clauses 12.3.2.1.2 and 12.3.2.2.2 of [ITU-T G.993.2]), then the loop diagnostic mode shall be entered after completion of the ITU-T G.994.1 Handshake phase. Loop diagnostic mode shall be entered upon request by either VTU. Both VTUs shall support the loop diagnostic mode.

The sequence of stages in the loop diagnostic mode shall be the same as for initialization (defined in clauses 10.1 through 10.6) up to the Channel Analysis and Exchange phase, where the test parameters listed in Table 12-64 of [ITU-T G.993.2] and defined in clause 11.4.1 of [ITU-T G.993.2] are exchanged. However, the test parameters for the quiet line noise (QLN) and the channel characteristics function (Hlog) shall be measured and exchanged during the Channel Discovery phase, as described in clause 12.4.3 of [ITU-T G.993.2].

The time-outs specified in clause 12.3.1 of [ITU-T G.993.2] do not apply to loop diagnostic mode. Time-out values are for further study.

10.7.1.1   SOC message mapping during loop diagnostic mode

See clause 12.4.1.1of [ITU-T G.993.2].

10.7.2 Channel discovery and training phases of loop diagnostic mode

10.7.2.1   SOC messages exchanged during the channel discovery and training phases of loop diagnostic mode

The SOC messages for the Channel Discovery phase and the Training phase of the loop diagnostic mode shall be the same as for the initialization procedure described in clauses 10.3 and 10.4, respectively, except for O-PRM, R-PRM, R-MSG1 and O-TA_UPDATE.

10.7.2.1.1 O-PRM & R-PRM

The test parameters for the QLN and the channel characteristics function, Hlog, shall be measured and exchanged during the Channel Discovery phase in the O-PRM-LD and R-PRM-LD messages described in clause 12.4.2.1 of [ITU-T G.993.2], which replace O-PRM and R-PRM.

NOTE – Field #13 and field #14 in O-PRM and R-PRM contain the ITU-T G.998.4 parameter field and the ITU-T G.993.5 parameter field. While field #13 and field #14 in O-PRM-LD and R-PRM-LD contain QLN and Hlog.

10.7.2.1.2 R-MSG1 (supplements clause 10.3.2.2)

Field #2, "maximum number of FEXT estimation symbols per superframe", defines the maximum number (*Kmax*) of symbols in the superframe for which the VTU-R supports error sample reporting. The field shall be formatted as an unsigned integer with value *Kmax* = 0.

Field #3, "support of optional backchannel control parameters", indicate the optional values of control parameters supported by the VTU-R. The field shall be formatted as an unsigned integer with value 00_{16}.

NOTE – This text is identical to Annex Y, clause Y.10.3.2.2 of [ITU-T G.993.2].

10.7.2.1.3 O-TA_UPDATE (supplements clause 10.4.2.1)

Field #2, "error report control parameters", defines the control parameters for each of the vectored bands indicated in O-SIGNATURE. The VTU-R shall ignore the error report control parameters.

Field #3, "SOC Repetition Factor", defines the SOC repetition factor, 1/R, as set by the VCE. The VTU R shall ignore this field.

Field #4, "FEXT estimation symbols per superframe", defines the number of symbols (*K*) in the superframe for which a clipped error sample shall be reported. The field shall be formatted as an unsigned integer with value *K* = 0.

NOTE – This text is identical to clause Y.10.4.2.1, Annex Y of [ITU-T G.993.2], except for field #3.

10.7.2.2 Signals transmitted during the channel discovery and training phases

The signals transmitted during the channel discovery and training phases are the same as defined in clauses 10.3 and 10.4 for initialization, with the following exceptions:

– the SOC message mapping shall be as defined in clause 12.4.1.1 of [ITU-T G.993.2];

– the duration of O-P-QUIET 1 shall be at least 8192 symbols but not longer than 16384 symbols;

– R-P-VECTOR 2 definition.

10.7.2.2.1 R-P-VECTOR 2 (replaces clause 10.4.4.5)

At sync symbol positions, the R-P-VECTOR 2 signal shall contain sync symbols, modulated as defined for the R-P-VECTOR 1 signal. At other symbol positions, the symbols shall be modulated as for the R-P-TRAINING 2 signal, with the SOC message mapping as defined in clause 12.4.1.1 of [ITU-T G.993.2].

Transmission of R-P-VECTOR 2 enables the VCE to estimate upstream FEXT channels from the vectored lines into the initializing line, and update the estimates of the upstream FEXT from the initializing lines into the vectored lines.

During the sync symbols, the SOC is in the inactive state. During the other symbols, the SOC is in the active state, and the VTU-R shall transmit the R-IDLE message.

The duration of R-P-VECTOR 2 signal is controlled by the VTU-O. Within 64 symbols after the last symbol of the O-P-SYNCHRO V4 signal, the VTU-R shall end the transmission of the R-P-VECTOR 2 signal.

The R-P-VECTOR 2 signal shall be followed by the R-P-SYNCHRO V2 signal.

NOTE 1 – The R-P-VECTOR 2 signal in loop diagnostic mode is identical to the R-P-VECTOR 2 signal defined in clause 10.4.4.5 for initialization, without extended SOC and with the VTU-R transmitting R-IDLE messages instead of R-ERROR-FEEDBACK messages.

NOTE 2 – This text is identical to clause Y.10.4.4.5, Annex Y of [ITU-T G.993.2], except for the SOC message mapping.

10.7.3 Channel Analysis and Exchange phase of loop diagnostic mode

The Channel Analysis and Exchange phase of loop diagnostic mode in ITU-T G.993.5 does not require any changes in comparison to loop diagnostic mode in [ITU-T G.993.2].

11 Configuration and test parameters

This Recommendation defines configuration parameters and test parameters that shall be accessible through the access node management information base (AN-MIB). The configuration parameters are defined in clause 11.1. The test parameters are defined in clause 11.2. Configuration parameters and test parameters are defined in [ITU-T G.997.1] as management objects accessible over the Q-interface.

11.1 Configuration parameters

11.1.1 FEXT cancellation enable/disable

This configuration parameter shall be defined for each line in a group of vectored lines. It enables or disables FEXT cancellation from all the other vectored lines into a line in the vectored group. If FEXT cancellation is disabled for a line, then no FEXT cancellation shall occur from any other line in the vectored group into that line.

This configuration parameter shall be defined independently for the upstream and downstream directions.

11.1.2 FEXT cancellation not required frequency bands

This configuration parameter shall be an array of pairs of subcarrier indices. Each pair represents the start and stop subcarrier index of a frequency band in which FEXT cancellation is not required. Up to eight frequency bands may be configured.

The same configuration shall be applied for all lines in the vectored group.

This configuration parameter shall be defined independently for the upstream and downstream directions.

11.1.3 Target NDR/target ETR

Both the target net data rate (target NDR) configuration parameter and the target expected throughput (target ETR) configuration parameter shall be defined for each line in a group of vectored lines. These configuration parameters assist a VCE to decide on allocating vectored AN resources among the lines in a vectored group for FEXT cancellation. Because of limited resources, the vectored AN may be unable to mitigate all the FEXT sources into every single line in the vectored group. Therefore, The VCE may choose to limit the number of crosstalk sources to cancel for each vectored line.

11.1.3.1 Target NDR

For each line, the target NDR configuration parameter should be set to the expected NDR achievable for the line when all lines in the vectored group are active and operating without ITU-T G.998.4 retransmission, or alternatively, it may be set to a special value indicating that no target NDR is configured by the operator.

If the target NDR is configured by the operator and ITU-T G.998.4 retransmission is not selected during initialization for the applicable direction, the VCE should allocate sufficient resources in such a way that the NDR is higher than or equal to the target NDR. If at initialization time, the NDR is below the target NDR but above the minimum NDR (*net_min*, see Annex K of [ITU-T G.993.2]), the VTU shall still transition to Showtime.

This configuration parameter shall be defined independently for the upstream and downstream directions.

This configuration parameter corresponds with the ITU-T G.997.1 parameter TARGET_NDR (see clause 7.3.2.20.2 of [ITU-T G.997.1]) in the AN-MIB.

11.1.3.2 Target ETR

For each line, the target ETR configuration parameter should be set to the expected ETR achievable for the line when all lines in the vectored group are active and operating with ITU-T G.998.4 retransmission, or alternatively, it may be set to a special value indicating that no target ETR is configured by the operator.

If the target ETR is configured by the operator and ITU-T G.998.4 retransmission is selected during initialization for the applicable direction, the VCE should allocate sufficient resources in such a way that the ETR is higher than or equal to the target ETR. If at initialization time, the ETR is below the target ETR but above minimum ETR (*ETR_min*, see clause 7 of [ITU-T G.998.4]), the VTU shall still transition to Showtime.

This configuration parameter shall be defined independently for the upstream and downstream directions.

This configuration parameter corresponds with the ITU-T G.997.1 parameter TARGET_ETR (see clause 7.3.2.20.1 of [ITU-T G.997.1]) in the AN-MIB.

11.1.4 Line priorities

This configuration parameter assists a VCE to decide on allocating vectored AN resources among the lines in a vectored group for FEXT cancellation. Because of limited resources, the vectored AN may be unable to mitigate all the FEXT sources into every single line in the vectored group. Therefore, the VCE may choose to limit the number of crosstalk sources to cancel for each vectored line.

Compliance with line priorities configuration parameter is optional. If supported, this configuration parameter shall be defined for each line in a group of vectored lines. For compliance, a VCE should initially allocate sufficient resources in such a way that the target NDR (if ITU-T G.998.4 retransmission is not selected for the applicable direction) or target ETR (if ITU-T G.998.4 retransmission is selected for the applicable direction) is met for all the lines in a vectored group. Subsequently, the VCE should exploit the configured line priority levels to allocate the remaining resources among the lines to further improve the NDRs/ETRs.

For each line in the vectored group, the line priority is configured as either LOW or HIGH, or alternatively, it may be set to a special value indicating that no line priority is configured by the operator. The VCE should allocate more resources to a line with a line priority HIGH in order to further increase the NDR/ETR above the target NDR/target ETR (e.g., by further mitigating FEXT). The VCE should not allocate additional resources to a line with line priority HIGH if the maximum NDR (*net_max*, see Annex K of [ITU T G.993.2]) is already met on that line. If the maximum NDR condition is met for all the vectored lines with line priority HIGH, then the VCE may allocate its remaining resources to vectored lines with line priority LOW to improve the NDR/ETR above the target NDR/target ETR.

NOTE – A VCE with sufficient resources may not need to use the configured line priorities for allocating its resources and in such cases, the VCE may ignore the configured line priorities.

This configuration parameter shall be defined independently for the upstream and downstream directions.

11.1.5 Requested Xlin subcarrier group size (XLINGREQ)

This parameter represents the requested value of *XLING* (see clauses 11.2.1.2 and 11.2.2.2). The reported *XLING* value shall be the smallest supported value that is equal or greater than *XLINGREQ*.

This configuration parameter shall be defined independently for the upstream and downstream directions.

11.2 Test parameters

11.2.1 FEXT downstream coupling coefficients (Xlinpsds)

11.2.1.1 Definition of downstream FEXT coupling coefficients (Xlinpsds)

The FEXT insertion gain from line L_2 into line L_1 in the downstream direction over frequency f, $FEXT\_IG\_DS_{L1,L2}(f)$, is defined as the ratio of the received FEXT voltage into a 100-ohm load on line L_1 to the transmit voltage (into a 100-ohm load) on line L_2. If the transmit voltage on line L_2 into a 100-ohm load is $V\_REFERENCE\_O(f)$ and the received FEXT voltage on line L_1, while both ends are terminated with a 100-ohm load as shown in Figure 11-1, is $V\_FEXT\_R(f)$, then the downstream FEXT insertion gain from line L_2 into line L_1 in linear scale is given by the equation below:

$$FEXT\_IG\_DS_{L1,L2}(f) = \frac{V\_FEXT\_R(f)}{V\_REFERENCE\_O(f)}$$

The downstream FEXT coupling coefficient from line L_2 into line L_1 over the frequency f is defined as the ratio of the FEXT insertion gain from line L_2 into line L_1 to the direct channel insertion gain of line L_1 (or the channel characteristic function, H, of line L_1) as follows:

$$Xlinds_{L1,L2}(f) = \frac{FEXT\_IG\_DS_{L1,L2}(f)}{H_{L1}(f)}$$

The downstream FEXT coupling coefficient can also be represented in terms of the direct channel $V\_DIRECT\_R(f)$ received on line L_1, and the FEXT channel received voltage on line L_1 as:

$$Xlinds_{L1,L2}(f) = \frac{V\_FEXT\_R(f)}{V\_DIRECT\_R(f)}$$

where, as shown in Figure 11-2, $V\_DIRECT\_R(f)$ is the received voltage into a 100-ohm load on line L_1 when a transmitter with a transmit voltage equal to $V\_REFERENCE\_O(f)$ (into 100 ohms) is frozen in its transmitting state and is connected to the same line. As shown in Figure 11-1, $V\_FEXT\_R(f)$ is the received voltage on line L_1 when this line is terminated with a 100-ohm load on both sides and the transmitter with the same transmit voltage is connected to line L_2.

NOTE 1 – The definition is independent of the value of $V\_REFERENCE\_O(f)$. However, it should be of the same order as typical transmitting voltage values on the line.

NOTE 2 – The above definition is independent of any receiver filter as the receiver filter effects of line L_1 are included in both the numerator and the denominator and cancel out.

Figure 11-1 – Definition of downstream Xlin (FEXT channel received voltage)

Figure 11-2 – Definition of downstream Xlin (direct channel received voltage)

11.2.1.2 Reporting of downstream FEXT coupling coefficients (Xlinpsds)

Each frequency band over which the downstream FEXT coupling coefficients $Xlinpsds_{i,k}$ $(n \times \Delta f)$ are stored and reported shall be represented by a pair of (start_subcarrier_index, stop_subcarrier_index). The reported parameter $XLINBANDSds$ shall represent an array of such pairs in increasing frequency order.

NOTE – The start_subcarrier_index and stop_subcarrier_index may not coincide with the defined edges of the bandplan.

The downstream FEXT coupling coefficients $Xlinpsds_{i,k}$ $(n \times \Delta f)$, shall be stored and reported to the management entity upon request at least for all pairs of line indices (i, k) in the vectored group and subcarrier indices n for which FEXT from line k into line i is estimated or cancelled in the downstream direction over a frequency band containing the subcarrier index n and

$$n \in \bigcup_{bands} \{start\_subcarrier\_index + m \times XLINGds : m = 0 ... \lfloor (stop\_subcarrier\_index - start\_subcarrier\_index) / XLINGds \rfloor \}$$

,

where $\lfloor x \rfloor$ denotes rounding to the lower integer.

In this description, $XLINGds$ is the subcarrier group size for reporting the FEXT coupling and is restricted to powers of two, and shall be the smallest supported value that is equal to or greater than the $XLINGREQds$ value (see clause 11.1.5) and less than or equal to 64, and shall be restricted to a maximum number of 511 subcarriers being reported.

The channel characteristics function $Xlinpsds_{i,k}$ $(n \times \Delta f)$, shall be represented in linear format by a scale factor and a normalized complex number $a(n) + j \times b(n)$, where n is the subcarrier index. The scale factor $XLINSCds$ shall be coded as a 16-bit unsigned integer. Both $a(n)$ and $b(n)$ shall be coded as a 16-bit 2's-complement signed integers. The value of $Xlinpsus_{i,j}$ $(n \times \Delta f)$ shall be defined as $Xlinpsus_{i,j}$ $(n \times \Delta f) = (XLINSCds/2^{15}) \times (a(n) + j \times b(n))/2^{15}$. In order to maximize precision, the *scale* factor $XLINSCds$ shall be chosen such that $max(|a(n)|, |b(n)|)$ over all n is equal to $2^{15} - 1$.

This data format supports an $Xlin(f)$ granularity of 2^{-15} and an $Xlin(f)$ dynamic range of approximately +6 dB to –90 dB.

An $Xlinpsds_{i,j}$ $(n \times \Delta f)$ value indicated as $a(n) = b(n) = -2^{15}$ is a special value. It indicates that no measurement could be done for done from line k into line i for subcarrier n.

An *Xlinpsds_{i,j}* (n×Δf) value indicated with $a(n) \geq 0$ and $b(n) = 0$ for all reported n is another special value meaning that there is no phase information and the magnitude of *Xlinpsus_{i,j}* (n×Δf) is $(XLINSCds/2^{15}) \times (a(n))/2^{15}$.

The magnitude of *Xlinpsds_{i,k}* (n×Δf) in dB is *Xlogpsds_{i,k}* (n×Δf):

$$Xlogpsus_{i,k}\ (n \times \Delta f) = 20\log_{10}(\ |Xlinpsus_{i,k}\ (n \times \Delta f)|\ )$$

All accuracy requirements for *Xlinpsus* will be formulated in terms of magnitude only (*Xlogpsds*).

Accuracy requirements for *Xlogpsds* shall allow for *Xlogpsds* to be the logarithm of the magnitude of the elements of the Taylor first-order approximation of the inverse of the pre-coder matrix (see Figure 6-1). Other accuracy requirements for *Xlogpsds* are for further study.

11.2.2 FEXT upstream coupling coefficients (Xlinpsus)

11.2.2.1 Definition of upstream FEXT coupling coefficients (Xlinpsus)

The FEXT insertion gain from line L_2 into line L_1 in the upstream direction over the frequency f, $FEXT\_IG\_US_{L1,L2}(f)$, is defined as the ratio of the received FEXT voltage into a 100 ohm load on line L_1 to the transmit voltage (into a 100 ohm load) on line L_2. If the transmit voltage on line L_2 into a 100 ohm load is $V\_REFERENCE\_R(f)$ and the received FEXT voltage on line L_1, while both ends are terminated with 100 ohm load as is shown in Figure 11-3 is $V\_FEXT\_O(f)$ then the upstream FEXT insertion gain from line L_2 into line L_1 in linear scale is given by the equation below:

$$FEXT\_IG\_US_{L1,L2}(f) = \frac{V\_FEXT\_O(f)}{V\_REFERENCE\_R(f)}$$

The upstream FEXT coupling coefficient from line L_2 into line L_1 over the frequency f is defined as the ratio of the FEXT insertion gain from line L_2 into line L_1 to the direct channel insertion gain of line L_2 (or the channel characteristic function, H, of line L_2) as in the following:

$$Xlinus_{L1,L2}(f) = \frac{FEXT\_IG\_US_{L1,L2}(f)}{H_{L2}(f)}$$

The upstream FEXT coupling coefficient can also be represented in terms of the direct channel, $V\_DIRECT\_O(f)$ received on line L_2 and the FEXT channel received voltage on line L_1 as:

$$Xlinus_{L1,L2}(f) = \frac{V\_FEXT\_O(f)}{V\_DIRECT\_O(f)}$$

where, as shown in Figure 11-4, $V\_DIRECT\_O(f)$ is the received voltage into a 100 ohm load on line L_2 when a transmitter with a transmit voltage equal to $V\_REFERENCE\_R(f)$ (into 100 ohm) is frozen in its transmitting state and is connected to the same line. As shown in Figure 11-3, $V\_FEXT\_O(f)$ is the received voltage on line L_1 when this line is terminated with 100 ohm loads on both sides and the transmitter with the same transmit voltage is connected to line L_2.
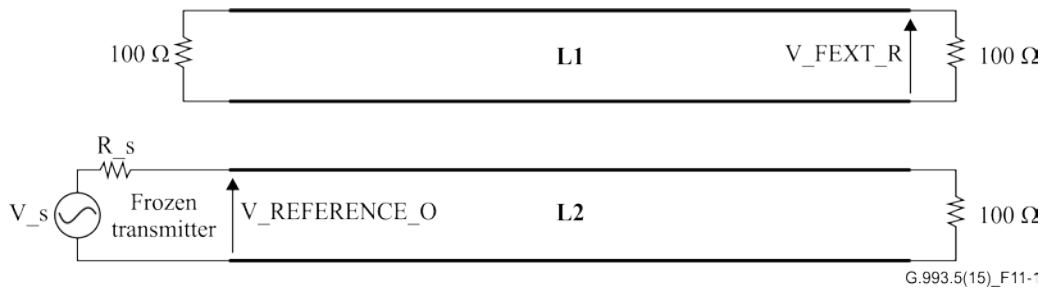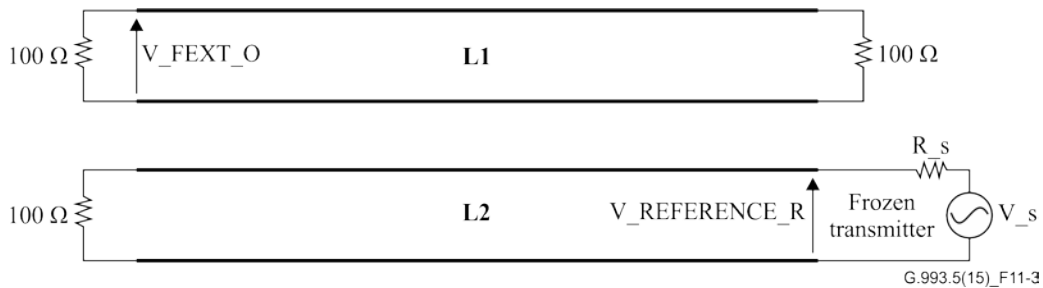
Figure 11-3 – Definition of upstream Xlin (FEXT channel received voltage)
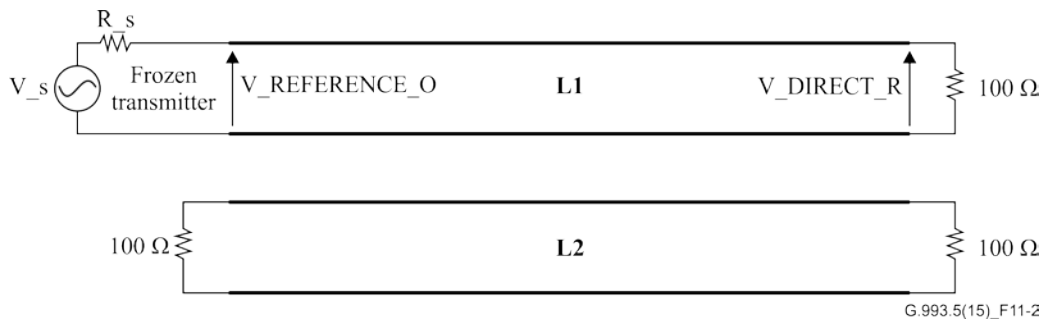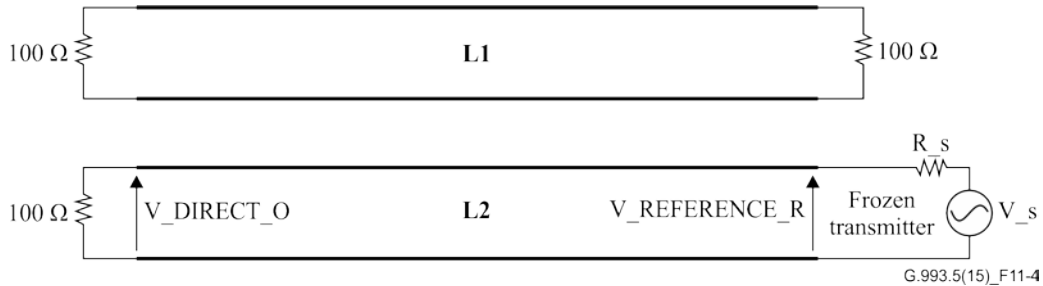

Figure 11-4 – Definition of upstream Xlin (direct channel received voltage)

11.2.2.2 Reporting of upstream FEXT coupling coefficients (Xlinpsus)

Each frequency band over which the upstream FEXT coupling coefficients $Xlinpsus_{i,k}$ ($n \times \Delta f$) are stored and reported shall be represented by a pair of (start_subcarrier_index, stop_subcarrier_index). The reported parameter *XLINBANDSus* shall represent an array of such pairs in increasing frequency order.

NOTE – The start_subcarrier_index and stop_subcarrier_index may not coincide with the defined edges of the bandplan.

The upstream FEXT coupling coefficients, $Xlinpsus_{i,k}$ ($n \times \Delta f$), shall be stored and reported to the management entity upon request at least for all pairs of line indices (i, k)in the vectored group and subcarrier indices n for which FEXT from line k into line i is estimated or cancelled in the upstream direction over a frequency band containing the subcarrier index n and

$$n \in \bigcup_{bands} \{start\_subcarrier\_index + m \times XLINGus : m = 0 ... \lfloor (stop\_subcarrier\_index - start\_subcarrier\_index) / XLINGus \rfloor \}$$,

where $\lfloor x \rfloor$ denotes rounding to the lower integer.

In this description, *XLINGus* is the subcarrier group size for reporting the FEXT coupling and is restricted to powers of two, equal to or greater than the *XLINGREQus* value (see clause 11.1.5) and less than or equal to 64, and restricted to a maximum number of 511 subcarriers being reported.

The channel characteristics function $Xlinpsus_{i,k}$ ($n \times \Delta f$), shall be represented in linear format by a scale factor and a normalized complex number $a(n) + j \times b(n)$, where n is the subcarrier index. The scale factor *XLINSCus* shall be coded as a 16-bit unsigned integer. Both $a(n)$ and $b(n)$ shall be coded as a 16-bit 2's-complement signed integers. The value of $Xlinpsus_{i,j}$ ($n \times \Delta f$) shall be defined as $Xlinpsus_{i,j}$ ($n \times \Delta f$)= ($XLINSCus/2^{15}$) $\times$ ($a(n) + j \times b(n))/2^{15}$. In order to maximize precision, the scale factor *XLINSCus* shall be chosen such that $max(|a(n)|, |b(n)|)$ over all reported n is equal to $2^{15} - 1$.

This data format supports an *Xlin(f)* granularity of 2^{-15} and an *Xlin(f)* dynamic range of approximately +6 dB to –90 dB.

An $Xlinpsus_{i,j}$ ($n \times \Delta f$) value indicated as $a(n) = b(n) = -2^{15}$ is a special value. It indicates that no measurement could be done for done from line k into line i for subcarrier n.

An *Xlinpsus$_{i,j}$ (n×Δf)* value indicated with $a(n) \geq 0$ and $b(n) = 0$ for all reported *n* is another special value meaning that there is no phase information and the magnitude of *Xlinpsus$_{i,j}$ (n×Δf)* is the magnitude of $a(n)$.

The magnitude of *Xlinpsus$_{i,k}$ (n×Δf)* in dB is *Xlogpsus$_{i,k}$ (n×Δf)*:

$$Xlogpsus_{i,k} (n×Δf) = 20\log_{10}(\ |Xlinpsus_{i,k} (n×Δf)| \ )$$

All accuracy requirements for *Xlinpsus* shall be formulated in terms of magnitude only (*Xlogpsus*) and are for further study.

Annex A

Mitigating strong FEXT

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

A.1 Introduction

This annex defines a method for mitigating strong FEXT.

This annex is an optional functionality, only applicable if the VTU is operating according to Annex Q of [ITU-T G.993.2].

The functionality defined in this annex includes:

• transmitter initiated gain adjustment for VDSL2 transceiver (TIGAV) procedure;

• use of extended error clipping threshold.

A.2 Control parameters for the minimum message overhead data rate (amends clause 9.5.4 of [ITU-T G.993.2])

For operation according to this annex, the downstream msg_{min} and the upstream msg_{min} control parameters shall be derived from the MSGMINds and MSGMINus configuration parameters (defined in the CO-MIB, see clause 7.3.1.5 of [ITU-T G.997.1]) respectively, as follows:

• for profile 35b:
  – downstream: $\max(\text{MSGMINds}, 200 \text{ kbit/s}) \le msg_{min} \le 236 \text{ kbit/s}$;
  – upstream: $\max(\text{MSGMINus}, 64 \text{ kbit/s}) \le msg_{min} \le 236 \text{ kbit/s}$;
• for profile 17a:
  – downstream: $\max(\text{MSGMINds}, 64 \text{ kbit/s}) \le msg_{min} \le 236 \text{ kbit/s}$;
  – upstream: $\max(\text{MSGMINus}, 64 \text{ kbit/s}) \le msg_{min} \le 236 \text{ kbit/s}$;

A.3 Clipped error samples

A.3.1 Definition of clipped error sample (replaces clause 3.2.4)

clipped error sample: Is a normalized error sample that is further clipped by the VTU-R with control from the VCE (see clause A.3.3).

A.3.2 Control parameters for clipped error sample reporting (amends clause 7.2.2.1)

For operation according to this annex, Table A.1 defines an additional mandatory value for the clipped error samples control parameters, in addition to the values in Table 7-2. This value is defined for the VCE to configure and for the VTU-O and VTU-R to support.

Table A.1 – Additional values of backchannel control parameters

Parameter	Additional valid value for VCE	Additional mandatory value for VTU-O and VTU-R
B_max	13	13

A.3.3 Definition of normalized error sample (amends clause 7.2.1)

For all values of *B_max*, the normalized error sample shall be as defined in clause 7.2.1.

The real and imaginary components of each normalized error sample E shall be clipped and quantized to integer values for the clipped error sample components q_x and q_y respectively, as follows:

$$\text{for } B\_max \leq 11: \quad \begin{aligned} q\_x &= \max\!\left(-2^{B-\max}, \min\!\left(\left\lfloor e\_x \times 2^{N-\max-1} \right\rfloor, 2^{B-\max}-1\right)\right) \\ q\_y &= \max\!\left(-2^{B-\max}, \min\!\left(\left\lfloor e\_y \times 2^{N-\max-1} \right\rfloor, 2^{B-\max}-1\right)\right) \end{aligned},$$

$$\text{for } B\_max = 13: \quad \begin{aligned} q\_x &= \max\!\left(-CT, \min\!\left(\left\lfloor e\_x \times 2^{N-\max-1} \right\rfloor, CT-1\right)\right) \\ q\_y &= \max\!\left(-CT, \min\!\left(\left\lfloor e\_y \times 2^{N-\max-1} \right\rfloor, CT-1\right)\right) \end{aligned},$$

where $Q = q\_x + j \times q\_y$ represents the clipped error sample and N_max represents the VTU-R's maximum quantization depth of normalized error samples and shall be set to 12, and B_max represents the upper bound of the bit index for reporting clipped error sample components q_x and q_y ($B\_max < N\_max$, with B_max configured by the VCE, see Table 7-1 and Table 7-2).

For the case $B\_max = 13$, the parameter CT represents the clipping threshold, which is a vendor discretionary value that shall be within the interval $[2^{B\_max} - 2^{(N\_max-1)}, 2^{B\_max}]$. The value of CT shall be determined by the VTU-R during initialization before sending the R-ERROR-FEEDBACK message, and shall remain identical for the remainder of initialization and the subsequent showtime (see Notes 1 and 2).

NOTE 1 – Referring to the scaling shown in Figure 7-3, the equivalent clipping intervals for e_x and e_y are:

$$\text{for } B\_max \leq 11: \quad \left[-\left(\frac{2^{B-\max}}{2^{(N-\max-1)}}\right), \left(\frac{2^{B-\max}-1}{2^{(N-\max-1)}}\right)\right], \text{ which approximately equals } [-1,1) \text{ for}$$

$B\_max = 11$;

$$\text{for } B\_max = 13: \quad \left[-\frac{CT}{2^{(N-\max-1)}}, \frac{CT-1}{2^{(N-\max-1)}}\right], \text{ with } \frac{CT}{2^{(N-\max-1)}} \text{ in the interval } [3,4], \text{ which}$$

approximately equals $[-3,3)$ for $CT = (2^{B\_max} - 2^{(N\_max-1)})$.

NOTE 2 – For $B\_max = 13$, no vendor discretionary clipping is allowed for error samples within the range of $[-(2^{B\_max} - 2^{(N\_max-1)}), (2^{B\_max} - 2^{(N\_max-1)})-1]$.

For all values of B_max, the values of both clipped error sample components q_x and q_y shall be represented using the two's-complement representation of B_max+1 bits. The format of the clipped error sample for reporting over the backchannel is defined in clause 7.2.2. The particular subcarriers on which clipped error samples shall be reported during initialization and Showtime shall be configured as described in clauses 10.4.2.1, and in clause 8.1, respectively.

A.4   OLR commands

The VTU shall support OLR commands to facilitate operation of vectored lines according to this annex, (see Table A.2).

Table A.2 – OLR commands and responses

Command type	Direction of command	Command content	Response content
OLR request type 7 (TIGAV)	From VTU-O to VTU-R	The relative gain compensation factor (r_i) and the proposed bit loading (b_i) to be applied to a set of downstream subcarriers.	TIGAV-ACK response or TIGAV-Reject response
OLR request type 8 (TIGAVRESP)	From VTU-R to VTU-O	The bit loading (b_i) to be applied to the relevant set of downstream subcarriers and framing parameters.	TIGAVRESP-ACK response or TIGAVRESP-Reject response

A.5   ITU-T G.994.1 Handshake phase (amends clause 10.2)

The functionality defined in this annex shall be negotiated during the ITU-T G.994.1 Handshake phase of initialization, using the NPar(3) codepoint defined in Table 11.68.10.1 of [ITU-T G.994.1]. The use of this codepoint in the ITU-T G.994.1 CL, CLR and MS messages is defined in Tables A.3 to A.6.

Table A.3 – VTU-O CL message NPar(3) bit definitions

ITU-T G.994.1 NPar(3) Bit	Definition of NPar(3) bits
Support of strong FEXT mitigation	If set to ONE, this bit indicates that the VTU-O supports the functionality defined in this annex. If set to ZERO, this bit indicates that the VTU-O does not support the functionality defined in this annex.

Table A.4 – VTU-O MS message NPar(3) bit definitions

ITU-T G.994.1 NPar(3) Bit	Definition of NPar(3) bits
Support of strong FEXT mitigation	This bit shall be set to ONE if, and only if, it was set to ONE in both the last previous CL message and the last previous CLR message, and a profile is selected to which this annex applies. If set to ONE, this bit indicates that the functionality defined in this annex is enabled. If set to ZERO, this bit indicates that the functionality defined in this annex is disabled.

Table A.5 – VTU-R CLR message NPar(3) bit definitions

ITU-T G.994.1 NPar(3) Bit	Definition of NPar(3) bits
Suport of strong FEXT mitigation	If set to ONE, this bit indicates that the VTU-R supports the functionality defined in this Annex. If set to ZERO, this bit indicates that the VTU-R does not support the functionality defined in this annex.

Table A.6 – VTU-R MS message NPar(3) bit definitions

ITU-T G.994.1 NPar(3) Bit	Definition of NPar(3) bits
Support of strong FEXT mitigation	This bit shall be set to ONE if, and only if, it was set to ONE in both the last previous CL message and the last previous CLR message, and a profile is selected to which this annex applies. If set to ONE, this bit indicates that the functionality defined in this annex is enabled. If set to ZERO, this bit indicates that the functionality defined in this annex is disabled.

If the ITU-T G.994.1 CLR message has the "Support of strong FEXT mitigation" Npar(3) bit set to ONE, then it shall indicate support for profile 35b and may indicate support for any other profile.

If the ITU-T G.994.1 CL message has the "Support of strong FEXT mitigation" Npar(3) bit set to ONE and the profile 35b is enabled in the CO-MIB, then it shall indicate support for profile 35b and may indicate support for any other profile.

If the ITU-T G.994.1 MS message has the "Support of strong FEXT mitigation" Npar(3) bit set to ONE, then it shall operate according to Annex Q of [ITU-T G.993.2] and select operation according to either profile 17a or profile 35b.

A.6 TIGAV functionality

The functionality associated with TIGAV procedure shall be supported by both the VTU-O and the VTU-R.

The goal of the procedure is fast accommodation of precoder changes in high crosstalk environment by indicating to the VTU-R the associated changes of compensation gain and expected changes of bit loading on relevant downstream subcarriers.

The VTU-O starts the procedure by sending a TIGAV command to the VTU-R that indicates the relative gain compensation factor (r_i) and the proposed bit loading (b_i) to be applied to the indicated set of downstream subcarriers. In response, based on the received r_i values, the VTU-R computes the actual downstream bit loading and sends it back to the VTU-O in TIGAVRESP command. Further, the VTU-O sends to the VTU-R a time marker indicating the symbol position at which the new values of r_i are applied by the VTU-R and the actual b_i values requested by the VTU-R are applied by both VTUs. The details of the message exchange are in clause A.6.2.

The VTU-R may either accept the actual bit loading to be as proposed in the TIGAV command, or request the actual bit loading to be different. In the latter case, the actual bit loading requested by the VTU-R in the TIGAVRESP shall follow the rules defined in clause A.6.1.2.

A.6.1 TIGAV and TIGAVRESP commands

The TIGAV and TIGAVRESP are OLR commands and shall be used to facilitate the TIGAV procedure. Both commands are high priority; the first octets of commands and associated responses shall be an OLR commands type defined in Table 11-2 of [ITU-T G.993.2]. The subsequent octets of the commands shall be as defined in Table A.7. The subsequent octets of the responses shall be as defined in Table A.8. The octets of all commands and responses shall be sent using the format described in clause 11.2.3.1 of [ITU-T G.993.2]. Message segmentation shall be applied as defined in clause 11.2.3.3 of [ITU-T G.993.2].

The TIGAV command shall be sent by the VTU-O only.

The TIGAVRESP command shall be sent by the VTU-R only.

The 4-bit TIGAV identification number (TID) is used to identify the particular TIGAV command. The TID shall be incremented whenever a TIGAV containing a new set of parameters is initiated by

the VTU-O and wrap around at count 1111_2, i.e., incrementing from 1111_2 to 0000_2. The VTU-R shall indicate in the TIGAVRESP command the same TID value as indicated by the VTU-O in the corresponding TIGAV command.

Table A.7 – TIGAV and TIGAVRESP commands

Name	Length (bytes)	Octet number	Content	Support
Request Type 7 (TIGAV)	variable	2	10_{16} (Note 1)	Mandatory
		3	The four MSBs represent the TID (with valid range 0 to 15, represented as unsigned integer). The four LSBs represent the number of subcarrier band parameter subfields ($1 \leq N_{scbt} \leq 15$, represented as unsigned integer).	
		variable	Subcarrier bands parameter field, includes N_{scbt} subcarrier band parameter subfields, see Table A.10.	
		variable	1 octet for Segment Code (SC)	
Request Type 8 (TIGAVRESP) (Note 2)	variable	2	11_{16} (Note 1)	Mandatory
		3-4	two octets containing the new value for L_1	
		5	one octet containing the new value for B_{10}	
		6	one octet containing the new value for M_1	
		7	one octet containing the new value for R_1	
		8	one octet containing the new value for Q	
		9	one octet containing the new value for V	
		10	one octet containing the new value for Q_{tx}	
		11	one octet containing the new value for lb	
		12	The four MSBs represent the TID (with valid range 0 to 15, represented as unsigned integer). The four LSBs represent the number of subcarrier band parameter subfields ($0 \leq N_{scbr} \leq 15$, represented as unsigned integer). $N_{scbr} = 0$: Accept the TIGAV proposed bit loading. $N_{scbr} > 0$: Response with the bit loading values requested by the VTU-R, indicated in the subcarrier bands parameter field.	
		variable	Subcarrier bands parameter field, includes N_{scbr} subcarrier band parameter subfields, (see Table A.12). If $N_{scbr}=0$, the length of this field shall be 0 bytes.	
		variable	1 octet for Segment Code (SC)	
NOTE 1 – All other values are reserved by ITU-T.				
NOTE 2 – The framing parameters in octets 3 to 11 shall be represented as defined for request type 5 in clause C.3.2 of [ITU-T G.998.4].				

The TIGAV-Reject and TIGAV-ACK, and TIGAVRESP-Reject and TIGAVRESP-ACK, are responses on TIGAV and TIGAVRESP commands, respectively (see Table A.8). The reason codes for the reject responses are defined in Table A.9.

The TIGAV-Reject and TIGAV-ACK responses shall be sent by the VTU-R only.

The TIGAVRESP-Reject and TIGAVRESP-ACK responses shall be sent by VTU-O only.

Table A.8 – TIGAV and TIGAVRESP responses

Name	Length (octets)	Octet number	Content	Support
Reject Type 7 request (TIGAV-Reject)	3	2	87_{16} (Note)	Mandatory
		3	1 octet for reason code	
ACK Type 7 request (TIGAV-ACK)	2	2	89_{16} (Note)	Mandatory
Reject Type 8 request (TIGAVRESP-Reject)	3	2	88_{16} (Note)	Mandatory
		3	1 octet for reason code	
ACK Type 8 request (TIGAVRESP-ACK)	2	2	$8A_{16}$ (Note)	Mandatory
NOTE – All other values are reserved by ITU-T.				

Table A.9 – Reason codes for TIGAV and TIGAVRESP responses

Reason	Octet value	Applicable to Reject Type 7	Applicable to Reject Type 8
Busy	01_{16} (Note)	No	Yes
Invalid parameters	02_{16} (Note)	Yes	Yes
NOTE – All other values are reserved by ITU-T.			

A.6.1.1 Parameters of the TIGAV command

The subcarrier bands parameter field in the TIGAV command includes N_{scbt} subcarrier band parameter subfields. The format of each subcarrier band parameter subfield is defined in Table A.10.

Each of the subcarrier band parameter subfields identifies one TIGAV band. A TIGAV band is delimited by its *i_start* and *i_stop* subcarrier indices:

- The *i_start* may fall on an active or on an inactive subcarrier (i.e., $g_i=0$). The *i_stop* may fall on an active or on an inactive subcarrier (i.e., $g_i=0$). There may also be inactive subcarriers within a TIGAV band.

- The *i_start* and *i_stop* determine the grid of control subcarrier indices for the "r_i" interpolation (see clause A.6.1.3) as:

    $i = i\_start + k \times F\_sub\_TIGAV$, where $k = 0, 1, 2, ... (N_r - 1)$,

    with a constraint: $i\_stop = i\_start + (N_r - 1) \times F\_sub\_TIGAV$, where N_r is an integer larger than 1, and F_sub_TIGAV is the applied *ri* sub-sampling, as defined in Table A.10.

- The *i_start* and *i_stop* indices shall satisfy:

    i_start > i_start_DSx – F_sub_TIGAV,
    i_stop < i_stop_DSx + F_sub_TIGAV,

where i_start_DSx and i_stop_DSx are respectively the minimum and the maximum subcarrier index that belong to the particular downstream passband (see clause 7.1 of [ITU-T G.993.2]).

NOTE – This allows freedom in choosing the location of TIGAV control point grid.

- The i_start and i_stop are independent from the MEDLEYds set, i.e., i_start can be smaller than, equal to, or larger than the minimum subcarrier index of MEDLEYds set and i_stop can be smaller than, equal to, or larger than the maximum subcarrier index of MEDLEYds set, respectively.

- The i_start and i_stop are independent from the vectored bands (as exchanged in the *vectored bands* field of the Error Feedback Command defined in Table 8-3).

For each particular TIGAV band n, followed by TIGAV band $n+1$ ($n = 1$ to $N_{scbt} - 1$):

- The $i\_stop(n)$ shall be less than or equal to $i\_start(n+1)$, i.e., no or one common index;

- If $i\_stop(n) = i\_start(n+1)$ (i.e., one common index), the r_i and b_i values shall satisfy following constraints: $r(i\_stop(n)) = r(i\_start(n+1))$ and $b(i\_stop(n)) = b(i\_start(n+1))$.

Both inactive and active subcarriers may exist outside the TIGAV bands. On these active subcarriers, the VTU-R shall assume an $r_i = 1$ (i.e., FEQ will not be affected by TIGAV) and shall assume no change in b_i.

TIGAV bands shall be transmitted in the ascending order of their intervals of subcarrier indices.

Table A.10 – Subcarrier band parameter subfield of the TIGAV command

Parameter	Length (byte)	Definition
Control byte	1	[c000 ffff] Control bit c = 0 indicates that this subfield contains real r_i parameters (see Note 2). Control bit c = 1 indicates that this subfield contains complex r_i parameters (see Note 2). Control bits ffff = F_sub_TIGAV for this subfield, represented as unsigned integer.
i_start	2	TIGAV band start subcarrier index (i_start), represented as a 16-bit unsigned integer.
i_stop	2	TIGAV band stop subcarrier index (i_stop), represented as a 16-bit unsigned integer.
b_i	ceil(N_b / 2) (Note 1)	This field contains N_b TIGAV b_i parameters (see Table A.11) for subcarriers with indices i_start to i_stop, in ascending order of subcarrier indices.
real r_i	$2 \times N_r$	This field is present if and only if the control bit c = 0. This field contains N_r TIGAV real r_i parameters (see Table A.13) for subcarriers with index $i\_start + k \times F\_sub\_TIGAV$, with $k = 0$ to $N_r - 1$, in ascending order of subcarrier indices.
complex r_i	$3 \times N_r$	This field is present if and only if the control bit c = 1. This field contains N_r TIGAV complex r_i parameters (see Table A.12) for subcarriers with index $i\_start + k \times F\_sub\_TIGAV$, with $k = 0$ to $N_r - 1$, in ascending order of subcarrier indices.
NOTE 1 – $N_b = i\_stop - i\_start + 1$. NOTE 2 – The bit c shall be set to the same value in all subcarrier band parameter subfields.		

The valid values for F_sub_TIGAV are 1, 4, and 8 (i.e., the r_i values may be subsampled).

Both VTU-O and VTU-R shall support all valid values for *i_start*, *i_stop*, and *F_sub_TIGAV*.

Table A.11 – The b_i parameter format in a TIGAV command

Bit	Length (bits)	Parameter (see Notes 1 and 2)	Format
3-0	4	b_i (of subcarrier k)	Unsigned integer in the [0:15] range
7-4	4	b_i (of subcarrier $k+1$)	Unsigned integer in the [0:15] range
NOTE 1 – The values of b_i for subcarriers that are in the specified range (i.e., from *i_start* to *i_stop*) but not part of the MEDLEYds set shall be included. They shall be set to zero by the transmitter and ignored by the receiver.			
NOTE 2 – If the N_b is odd, the bits 7-4 of the b_i parameter associated with the highest subcarrier index shall be set to 0000_2.			

Table A.12 – The complex r_i parameter format of the TIGAV command

Bit	Length (bits)	Content (see Notes 1 and 2)	Format
2-0	3	Exponent of r_i	E3/4
12-3	10	Mantissa of real part of r_i	M10(1Q9) signed
22-13	10	Mantissa of imaginary part of r_i	M10(1Q9) signed
23	1	Reserved by ITU-T	Bit shall be set to 0
NOTE 1 – The values of r_i for subcarriers that are in the specified range (i.e., from *i_start* to *i_stop*), but not part of the MEDLEYds set are set to a vendor discretionary non-zero value.			
NOTE 2 – The byte transmitted first shall contain bits 23(MSB) to 16(LSB). The byte transmitted second shall contain bits 15(MSB) to 8(LSB). The byte transmitted third shall contain bits 7(MSB) to 0(LSB).			

The format descriptor L **M** ML(i**Q**f) **E** LE/B designates a floating point format with total wordlength L. It has mantissa wordlength of ML bits, with the binary point just to the right of the i-th most significant bit (including the sign bit if signed integer), and f bits are allocated behind the binary point (i.e., ML=i+f). The exponent is always unsigned and has wordlength LE. The exponent has unity gain when its value equals B. Letters M, Q and E are syntax-separators.

The real and imaginary part of the complex gain r_i value shall both be formatted as 13M10(1Q9) E3/4 with a signed mantissa, and a common exponent.

A non-zero complex r_i value shall be within the valid range expressed in dB as:

$$-18 \text{ dB} < 20 \times \log10(abs(r_i)) < +18 \text{ dB},$$

where abs(x) is the modulus of a complex value x.

A special value of complex r_i is $r_i = 0$, which shall be coded with a mantissa=0 and exponent=0, for both real and imaginary part, and shall be accompanied with $b_i = 0$.

Table A.13 – The real r_i parameter format of the TIGAV command

Bit	Length (bits)	Content (see Notes 1 and 2)	Format
2-0	3	Exponent of r_i	E3/4
12-3	9	Mantissa of r_i	M9(0Q9) unsigned (see Note 3)
15-12	4	Reserved by ITU-T	Bits shall be set to 0
NOTE 1 – The values of r_i for subcarriers that are in the specified range (i.e., from i_start to i_stop), but not part of the MEDLEYds set are set to a vendor discretionary non-zero value.			
NOTE 2 – The byte transmitted first shall contain bits 15(MSB) to 8(LSB). The byte transmitted second shall contain bits 7(MSB) to 0(LSB).			
NOTE 3 – Real r_i values shall be positive values only.			

A real r_i value shall be formatted as floating point 12M9(0Q9) E3/4 unsigned.

A non-zero real r_i value shall be within the valid range expressed in dB as:

$$-18 \text{ dB} < 20 \times \log_{10}(r_i) < +18 \text{ dB}.$$

A special value of real r_i is $r_i = 0$, which shall be coded with a mantissa=0 and exponent=0, and shall be accompanied with $b_i = 0$.

NOTE – The TIGAV procedure does not change the downstream g_i-values. The changes in the transmit power of the downstream subcarriers associated with TIGAV is achieved by corresponding modification of the precoder.

A.6.1.2 Parameters controlled by the TIGAVRESP command

The subcarrier bands parameter field in TIGAVRESP command includes N_{scbr} subcarrier band parameter subfields. The format of each subcarrier band parameter subfield is defined in Table A.12.

Each of the subcarrier band parameter subfields identifies one TIGAVRESP band. The TIGAVRESP bands in the TIGAVRESP command shall follow the same requirements as defined for the TIGAV bands in the TIGAV command in clause A.6.1.1, and the following additional requirements:

1) The N_{scbt} is replaced with N_{scbr}.

2) If N_{scbr} is set to a non-zero value in TIGAVRESP command, the TIGAVRESP bands in TIGAVRESP command shall include at least all MEDLEY subcarriers addressed by the corresponding TIGAV command.

3) The b_i values requested by TIGAVRESP command for all MEDLEY subcarriers addressed by corresponding TIGAV command shall not exceed the b_i values proposed by the TIGAV command. In addition to this mandatory upper limit, the actual bit loading in the TIGAVRESP should be upper limited by the bit loading that is based on the change in the SNR expected from the new values of r_i, and might be upper limited by other factors.

4) If TIGAVRESP bands in TIGAVRESP command include more MEDLEY subcarriers than the corresponding TIGAV command, the b_i values on these additional MEDLEY subcarriers are determined solely by the VTU-R.

Table A.12 – Subcarrier band parameter subfield in a TIGAVRESP command

Parameter	Length (byte)	Definition
i_start	2	TIGAVRESP band start subcarrier index (i_start), represented as a 16-bit unsigned integer.
i_stop	2	TIGAVRESP band stop subcarrier index (i_stop), represented as a 16-bit unsigned integer.
b_i	ceil(N_b / 2) (NOTE)	This field contains N_b TIGAVRESP b_i parameters (see Table A.13) for subcarriers with indices i_start to i_stop, in ascending order of subcarrier indices.
NOTE – $N_b = i\_stop – i\_start + 1$.		

Table A.13 – The b_i parameter format in a TIGAVRESP command

Bit	Length (bits)	Parameter (see Notes 1, 2 and 3)	Format
3-0	4	b_i (of subcarrier k)	Unsigned integer in the [0:15] range
7-4	4	b_i (of subcarrier k+1)	Unsigned integer in the [0:15] range
NOTE 1 – The values of b_i for subcarriers that are in the specified range (i.e., from i_start to i_stop), but not part of the MEDLEY set, shall be included. They shall be set to zero by the transmitter and ignored by the receiver.			
NOTE 2 – The values of b_i shall be transmitted in ascending order of the subcarrier indices.			
NOTE 3 – If the N_b is odd, the bits 7-4 of the b_i parameter associated with the highest subcarrier index shall be set to 0000_2.			

A.6.1.3 Interpolation of the ri values

For each particular TIGAV band n ($n=1$ to N_{scbt}), the VTU-R should derive the r_i values on all active subcarriers between $i\_start(n)$ and $i\_stop(n)$ (both inclusive), by linear interpolation in between the r_i values at the control subcarrier indices communicated in the TIGAV message. Linear interpolation shall be on a linear scale over the r_i axis and a linear scale over the index axis.

NOTE 1 – The VCE should choose the r_i values in a TIGAV command such that the linear interpolation at the VTU-R produces the desired output values on intermediate active subcarriers. The method to define these r_i values (control points) is VCE vendor discretionary.

NOTE 2 – The i_start and i_stop are allowed to fall on an inactive subcarrier. The VCE should choose the r_i values on i_start and i_stop in a TIGAV command such that the linear interpolation at the VTU-R produces the desired output values on intermediate active subcarriers.

NOTE 3 – The inactive subcarriers included in a TIGAV are known by the VTU-R. The VTU-R does not need to calculate the interpolation on these carriers.

A.6.2 TIGAV procedure

The VTU-O shall not initiate a TIGAV if either an upstream or a downstream save our showtime (SOS) type 4 or 6 procedure is ongoing.

The exchange between VTUs in the TIGAV procedure is illustrated in Figure A.1 and defined as follows:

1)   Upon the instruction of the VCE over the ε_m interface, the VTU-O shall initiate a TIGAV procedure by sending an OLR request type 7 command. A TIGAV command may be segmented. After sending the last segment of the TIGAV command, during the following 100 ms the VTU-O shall expect to receive the TIGAV-ACK response or a TIGAV-Reject

response. The last segment of the TIGAV command may be repeated if the response times out.

   a) If the VTU-O receives an OLR request type 1, 3 and 5 during or after transmission of an OLR request type 7 and prior to receiving a response, it shall reject the OLR request type 1, 3 and 5 (see Note 1).

   b) If the VTU-O receives an SOS OLR request type 4 or 6 during the TIGAV procedure, it shall abort the TIGAV procedure immediately and respond to the OLR SOS request.

   c) The VTU-O is allowed to initiate an SOS OLR request type 4 or 6 procedure at any time after the TIGAV is initiated but not completed. The initiated SOS request shall abort the TIGAV procedure (see Notes 2 and 3).

NOTE 1 – It is expected that in the aim to speed up starting TIGAV, the VTU-O may discard any pending SRA request because the modification of transmission parameters implied by this request will anyway be overridden by TIGAV.

NOTE 2 – Termination of the TIGAV procedure due to SOS OLR request is only for the line in which the SOS request takes place; other lines in the vectored group can continue their TIGAV procedures.

NOTE 3 – Clause 11.2.2 of [ITU-T G.993.2] describes the possibility of a high priority message aborting a low priority message. This TIGAV abort by an SOS is a case when a high priority message is aborted by another high priority message, and is therefore an extension to clause 11.2.2 of [ITU-T G.993.2].

2)   After reception of the last segment of a TIGAV command, the VTU-R shall either acknowledge the TIGAV command by sending the TIGAV-ACK response (see Table A.7) or reject the TIGAV command by sending a TIGAV-Reject response with a corresponding reason code.

   a) Upon receiving the first segment of a TIGAV command, the VTU-R shall reject any pending OLR command of type 1, 3 and 5 and shall not initiate any OLR request type 1, 3 and 5 procedure until the TIGAV procedure is complete.

   b) Upon receiving an SOS OLR request type 4 or 6 from the VTU-O at any time during the TIGAV procedure, it shall abort the TIGAV procedure immediately and respond to the OLR SOS request.

   c) The VTU-R is allowed to initiate an SOS OLR request type 4 or 6 procedure at any time after the TIGAV is initiated but before the start of sending the last segment of TIGAVRESP. The changes in bit loading contained in the SOS request shall be applied to the current active bit loading table (i.e. ignoring the bit loading sent in TIGAV). This initiated SOS request shall abort the TIGAV procedure. The VTU-O shall respond to the SOS OLR request with a SYNC FLAG.

   d) The VTU-R shall not initiate an SOS OLR request type 4 or 6 procedure after the start of sending the last segment of TIGAVRESP up until the end of the TIGAV procedure.

3)   Within 300 ms after sending the TIGAV-ACK response, the VTU-R shall send a TIGAVRESP command. A TIGAVRESP command may be segmented. After sending the last segment of the TIGAVRESP command, during the following 100 ms the VTU-R shall expect receiving a TIGAVRESP-ACK response or a TIGAVRESP-Reject response. If the last segment of the TIGAVRESP command times out, the VTU-R shall repeat the last segment of the TIGAVRESP command. After sending the TIGAV-Reject response, the VTU-R shall exit the TIGAV procedure.

4)   Upon reception of the TIGAV-ACK response, the VTU-O shall expect receiving the first segment of a TIGAVRESP command. The VTU-O shall either acknowledge the last segment of the TIGAVRESP command by sending a TIGAVRESP-ACK response, or reject the TIGAVRESP command by sending a TIGAVRESP-Reject response with a corresponding reason code. After sending the TIGAVRESP-ACK response, at the time

determined by the VCE, the VTU-O shall send the TIGAV-SYNCHRO pattern. After sending the TIGAVRESP-Reject response, the VTU-O shall exit the TIGAV procedure.

NOTE 4 – The TIGAV-SYNCHRO pattern has to be sent simultaneously over all relevant lines of the vectored group. For this the VCE needs to receive the TIGAVRESP command from all lines in the vectored group prior to sending TIGAV-SYNCHRO pattern. This should be within the global TIGAV timeout.

5)   Upon reception of a TIGAV-Reject response, the VTU-O shall exit the TIGAV procedure. The VTU-O may immediately start a new TIGAV procedure by sending a new TIGAV command.

6)   Upon reception of a TIGAVRESP-Reject response, the VTU-R shall send a TIGAVRESP command again. If rejection persists, the VTU-R shall exit the TIGAV procedure.

7)   Starting from the first symbol following the TIGAV-SYNCHRO pattern, both the VTU-O and the VTU-R shall synchronously apply the relative gain compensation factor indicated in the TIGAV command and the bit loading indicated in the TIGAVRESP command. Timing of changes in framing parameters shall be as specified in clause C.4 of [ITU-T G.998.4].

8)   The procedure times out if TIGAV-SYNCHRO is not received within 4 seconds after the VTU-R sends TIGAV ACK. Upon this timeout, the VTU-R shall exit the TIGAV procedure.
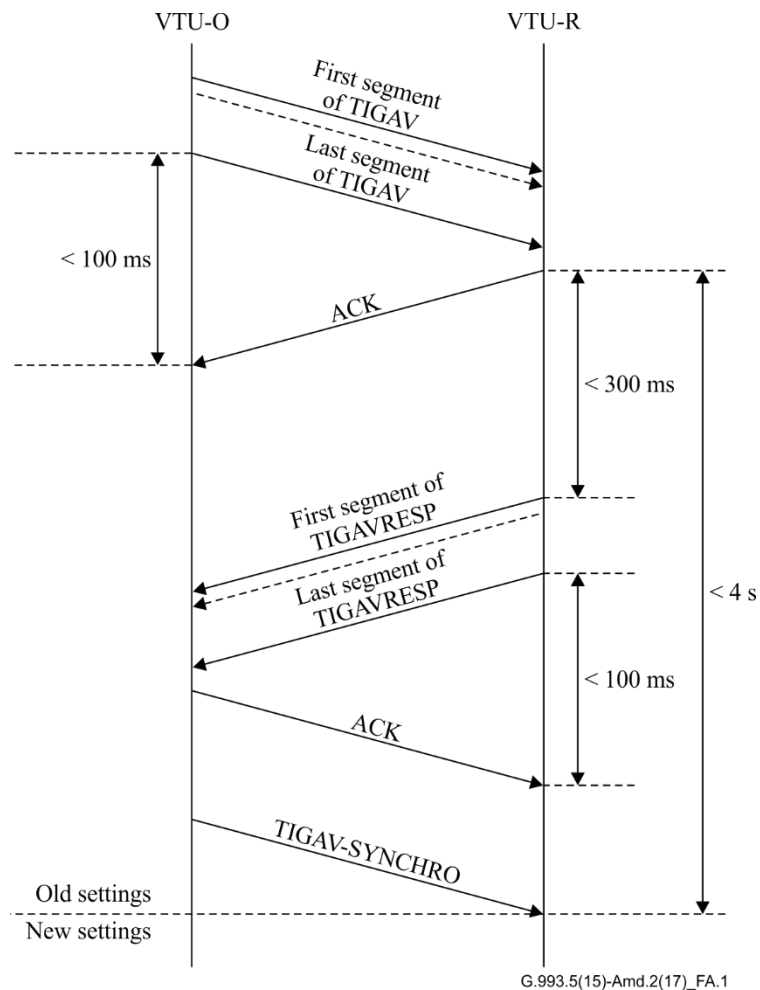

Figure A.1 – Timing diagram of TIGAV procedure

NOTE 5 – Figure A.1 does not show the case of rejecting the TIGAV command and does not show the case of rejecting the TIGAVRESP command.

A.6.2.1　Definition of TIGAV-SYNCHRO pattern

The TIGAV-SYNCHRO pattern is defined as consisting of one sync symbol with inverted flag tones (transmitted at the end of the superframe, at the sync symbol position, see Figure 10-2 of [ITU-T G.993.2]), followed by a pattern of 9 sync symbols with non-inverted flag tones (transmitted at the first 9 symbol positions in the next superframe).

The sync symbol is defined in clause 10.2 of [ITU-T G.993.2].

A.6.2.2　Implementing the TIGAV gain modification by the VTU-R

To implement the relative gain compensation factor (r_i) indicated in the TIGAV, the following rules shall apply:

- For subcarriers with $r_i \neq 0$, the VTU-R shall multiply its current settings of the gain stage in the receiver, for any subcarrier i with $g_i > 0$, by the value (r_i):

   $new\_gainstage_i = current\_gainstage_i \times r_i$

   NOTE – This scaling is to help the VTU-R to keep its receiver gain adjusted after a precoder update.

- For subcarriers with $r_i = 0$, the VTU-R shall set its receiver gain to a vendor discretionary non-zero value.

A.6.2.3　Relation TIGAV and subsequent autonomous SRA in downstream

An autonomous SRA requested by the VTU-R, subsequent to a TIGAV command, shall have bit loading values b_i that are less than or equal to the b_i values requested in the last TIGAV message preceding this SRA.

A.7　Main body amendments related to MREFPSD

A.7.1　Definitions (replaces clauses 3.31 and 3.32 of [ITU-T G.993.2])

3.31　MEDLEY reference PSD: The MEDLEY reference PSDs in the downstream and upstream directions are denoted as MREFPSDds and MREFPSDus, respectively. The MREFPSDus is the PSD of signals transmitted by a VTU-R at every frequency (i.e., in both the passband and the stopbands) during the training phase and the channel analysis and exchange phase of initialization. The MREFPSDds is the power spectral density (PSD) of signals transmitted by a VTU-O at every frequency (i.e., in both the passband and the stopbands) during the training phase only.

NOTE – In this Recommendation, including in this Annex, the MREFPSDds refers to the VTU-O TXPSD of the direct signal only, without pre-compensation signals. In [b-ITU-T G.9701], the MREFPSDds refers to the FTU-O TXPSD of the total signal at the U-interface, including pre-compensation signals.

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

A.7.2　Nominal aggregate transmit power (NOMATP) (replaces clause 10.3.4.2.1 of [ITU-T G.993.2])

NOTE – Unless otherwise specified, references in this clause refer to [ITU-T G.993.2].

The nominal aggregate transmit power in upstream (NOMATPus) shall be calculated at both the VTU-R and the VTU-O side as defined in clause 10.3.4.2.1 of [ITU-T G.993.2].

At the VTU-R side, the nominal aggregate transmit power in downstream (NOMATPds) shall be calculated as defined in clause 10.3.4.2.1 of [ITU-T G.993.2]. The g_i settings determined by the VTU-R shall be such that the value of this NOMATPds (as defined for the VTU-R) does not exceed, the CO-MIB parameter MAXNOMATPds. At the VTU-O side, the nominal aggregate transmit power in downstream (NOMATPds) is an estimate of the total amount of output power delivered by the transmit PMD function to the U-O2 reference point (defined in Figure 5-4 of [ITU-T G.993.2]) in dBm into a 100 Ohm termination impedance.

The nominal aggregate transmit power in downstream (NOMATPds) shall be computed by VTU-O, in cooperation with the VCE, according to the following equation:

$$NOMATPds = 10log_{10}(\sum_{i \in MEDLEYds} P\_Zi')$$

Where P_Z_i' is the power of the total transmitted signal at the output of the precoder for subcarrier i, referred to the U-O interface, in milliWatts assuming the network input impedance is 100 Ohms resistive (see Note 1).

NOTE 1 – In actual deployments, the network/loop input impedance may deviate from 100 Ohms resistive.

NOTE 2 – NOMATPds includes the direct signal as well as the precoder compensation signals.

The VTU-O, in cooperation with the VCE, shall ensure that the value of NOMATPds does not exceed, the CO-MIB parameter MAXNOMATPds.

NOTE 3 – The definition of NOMATPds is different at the VTU-R and VTU-O side. At the VTU-R side, the definition of NOMATPds is unchanged compared to [ITU-T G.993.2], and therefore the VTU-R g_i calculation is unchanged. At the VTU-O side, the definition of NOMATPds is changed compared to [ITU-T G.993.2].

The total amount of output power delivered by the transmit PMD function to the U-O2 reference point in dBm into a 100 Ohm termination impedance shall not deviate from the NOMATPds by more than 1 dB.

A.7.3 Frequency-domain transmit spectrum shaping (tssi) (replaces clause 10.3.4.3 of [ITU-T G.993.2])

NOTE – Unless otherwise specified, references in this clause refer to [ITU-T G.993.2].

The tss_i are intended for frequency-domain spectrum shaping, both upstream and downstream. The tss_i values are vendor discretionary and shall be in the range between 0 and 1 (linear) in steps of $\frac{1}{1024}$. The tss_i values shall be set such that the highest tss_i value across all subcarriers is 1. Smaller values of tss_i provide attenuation, and the value $tss_i = 0$ corresponds to no power transmitted on the particular subcarrier. If no frequency-domain spectrum shaping is applied, the tss_i values shall be equal to 1 for all subcarriers.

The tss_i values in dB (log_tss_i) are defined as $20 \times log_{10}(tss_i)$ and shall be converted to linear values of tss_i using the equation:

$$tss_i = \frac{Round\left(1024 \times 10^{\frac{log\_tss_i}{20}}\right)}{1024}$$

The values of tss_i for the given direction of transmission shall be determined by the transmitting VTU, and shall be defined as a set of breakpoints $\{(i_1, log\_tss_{i1}) ..., (i_n, log\_tss_{in})\}$, where i is the subcarrier index. This set shall be communicated to the receiving VTU during the channel discovery phase of the initialization using O-PRM and R-PRM messages, as described in clause 12.3.3.2. Both transmitting and receiving VTUs shall derive the tss_i values for subcarriers between the breakpoints using linear interpolation of the defined log_tss_i values over the linear

scale of subcarrier indexes. The receiving VTU shall assign tss_i values equal to tss_{i_n} for $i > i_n$, and equal to tss_{i1} for $i < i_1$.

The obtained values of tss_i are relevant only for subcarriers that are actually transmitted. The receiver shall ignore the tss_i values that are either received or obtained by interpolation for the subcarriers that are not used for transmission ($Z_i=0$, see Table 10-4).

The combined accuracy of the linear interpolation of log_tss_i values and of the conversion to linear tss_i values shall be less than one half LSB for the 10-bit representation format of the linear tss_i values. No error shall be introduced when log_tss_i equals 0 dB or is interpolated between log_tss_i values that equal 0 dB.

The transmitter of the VTU-O shall set the tss_i values such that the PSD of the transmit signal as measured in the reference impedance at the U-O2 reference point, during the training phase, shall not deviate from the values of MREFPSDds, communicated in O-PRM, by more than 1 dB (parameter "MEDLEY reference PSD", see clause 12.3.3.2).

The transmitter of the VTU-R shall set the tss_i values such that, prior to the gain adjustment (i.e., assuming $g_i =1$), the PSD of the transmit signal as measured in the reference impedance at the U interface, from the start of the training phase and for the remainder of initialization, shall not deviate from the values of MREFPSDus, communicated in R-PRM, respectively, by more than 1 dB (parameter "MEDLEY reference PSD", see clause 12.3.3.2).

Thus, tss_i settings shall take into consideration any additional spectrum shaping caused by time-domain filters and analog filters included in the transmission path between the output of the modulator and U interface.

A.7.4   General (amends clause 6.1of [ITU-T G.993.5])

…

As a part of the channel matrix or separately, the VCE shall set the precoder such that the precoder output signals (Z' values shown in Figure 6-1) shall not lead at the U-O2 reference point to violation of the MREFMASK, even with highest valid g_i values (i.e., $g_i = +2.5$ dB) for all lines in the vectored group.

A.7.5   PSD and PSD mask summary (amends clause 7.2.3 of ITU-T G.993.2)

NOTE – Unless otherwise specified, references in this clause refer to [ITU-T G.993.2].

…

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

Parameter	When determined	When communicated between VTUs (Note)	When used
MEDLEY reference PSD mask (MREFMASK)	At the end of channel discovery phase; VTU-O determines MREFMASKds, VTU-R determines MREFMASKus	Not communicated	From the beginning of training phase and thereafter during initialization and showtime
MEDLEY reference PSD downstream (MREFPSDds)	At the end of channel discovery phase; VTU-O determines MREFPSDds	MREFPSDds is sent by VTU-O to VTU-R in O-PRM	During the training phase

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

Parameter	When determined	When communicated between VTUs (Note)	When used
MEDLEY reference PSD upstream (MREFPSDus)	At the end of channel discovery phase, VTU-R determines MREFPSDus	MREFPSDus is sent by VTU-R to VTU-O in R-PRM	During the training phase and channel analysis and exchange phase
Showtime PSD	At the end of the channel analysis and exchange phase	Determined by the PSD of the channel analysis and exchange phase and the gain values (g_i) communicated during the channel analysis and exchange phase (O-PMD and R-PMD messages). Shall not exceed MREFMASK.	During showtime
NOTE – Only the minimum set of relevant parameters characterizing PSDs and PSD masks is communicated during initialization. The communication protocols and formats are described in clause 12.			

A.7.6 Channel characteristics function per subcarrier group (CCF-ps) (amends clause 11.4.1.1.1 of ITU-T G.993.2)

NOTE – Unless otherwise specified, references in this clause refer to [ITU-T G.993.2].

…

The measurement of a channel characteristics function is the result of the cascade of three functions:

• the transmitter filter characteristics function;

• the channel characteristics function; and

• the receiver filter characteristics function.

NOTE 1 – The channel characteristics function corresponds to the Hchannel(*f*) function used in the definition of the far-end crosstalk (see clause 7.4.1 of [ITU-T G.996.1]).

The objective is to provide means by which the channel characteristics can be accurately identified. Therefore, it is necessary for the receive PMD function to report an estimate of the channel characteristics. This task may prove to be a difficult one given the fact that the receive PMD function only observes the cascade of all three elements of the channel. The passband part of the reported H(*f*), which is most essential to debug possible issues with the physical loop, is not expected to significantly depend upon the receiver filter characteristics (not including receiver AGC). The receive PMD function shall therefore invert the gain (AGC) it has applied to the received signal and do a best effort attempt to remove the impact of the near-end receiver filter characteristics. The result is then a best estimate of how the receiver views the passband channel characteristics plus the transmitter filter characteristics. As the in-band portion of the spectrum is also expected not to significantly depend upon the transmitter filter characteristics, this result is considered a sufficient estimate of the channel characteristics for desired loop conditioning applications.

Two formats are defined for the channel characteristics as follows:

• Hlin(*f*): a format providing complex values on a linear scale; and

• Hlog(*f*): a format providing magnitude values on a base 10 logarithmic scale.

For Hlog(*f*), the receive PMD function shall also use the value of the PSD at the U interface of the transmit PMD function (as conveyed in messages during initialization) to remove the impact of the far-end transmit filter characteristics.

NOTE 2 – The Hlog includes the effect of the precompensation signals related to that line sent on the other lines of the vectored group which are in the L0 link state.

For Hlin(*f*), if the channel characteristics are reported over the VTU-O OAM interface (see Figure 5-3), the VTU-O shall do a best effort attempt to remove the impact of the near-end transmit filter characteristics from the channel characteristics measured at the VTU-R. If the channel characteristics are reported over the VTU-R OAM interface, the VTU-R shall do a best effort attempt to remove the impact of the near-end transmit filter characteristics from the channel characteristics measured at the VTU-O.

NOTE 3 – The Hlin includes the effect of the precompensation signals related to that line sent on the other lines of the vectored group which are in the L0 link state.

Hlin(*f*) shall be sent to the far-end VME during the loop diagnostic mode and shall be sent on request to the near-end VME during the loop diagnostic mode.

…

A.7.7 PMD Test Parameter Read commands and responses (replaces clause 11.2.3.11 of [ITU-T G.993.2])

NOTE – Revision marks in this clause show the changes relative to clause 11.2.3.11 of [ITU-T G.993.2].

Unless otherwise specified, references in this clause refer to [ITU-T G.993.2].

The PMD Test Parameter Read commands shall be used to retrieve the values of the PMD test parameters that are specified in clause 11.4.1 and maintained by the far-end VTU. The PMD Test Parameter Read commands are shown in Table 11-26, and may be initiated by either VTU. The responses shall be as shown in Table 11-27. The first octet of all PMD Test Parameter Read commands and responses shall be the assigned value for the PMD Test Parameter Read command type, as shown in Table 11-5. The subsequent octets of the commands shall be as shown in Table 11-26. The subsequent octets of the responses shall be as shown in Table 11-27. The octets shall be sent using the format described in clause 11.2.3.1.

Table 11-26 – PMD test parameter read commands sent by the requesting VTU

Name	Length (octets)	Octet number	Content	Support
Single Read	2	2	01_{16} (Note 1)	Mandatory
Next Multiple Read	2	2	03_{16} (Note 1)	Mandatory
Multiple Read	4	2	04_{16} (Note 1)	Mandatory
		3 to 4	2 octets describing the subcarrier group index	
Block Read	6	2	05_{16} (Note 1)	Mandatory
		3 to 4	2 octets describing the start subcarrier group index	
		5 to 6	2 octets describing the stop subcarrier group index	
Vector	7	2	06_{16} (Note 1)	Optional

Table 11-26 – PMD test parameter read commands sent by the requesting VTU

Name	Length (octets)	Octet number	Content	Support
Block Read		3	1 octet describing the type of test parameter to read (Note 2) 01_{16}: Channel transfer function Hlog(f) per subcarrier group 03_{16}: Quiet Line Noise PSD QLN(f) per subcarrier group 04_{16}: Signal to noise ratio SNR(f) per subcarrier group.	
		4 to 5	2 octets describing the start subcarrier group index	
		6 to 7	2 octets describing the stop subcarrier group index	
Scalar Read	3	2	07_{16} (Note 1)	Optional
		3	1 octet describing the type of scalar test parameters to be read (Note 2) 21_{16} to 28_{16}: the parameter index to read according to the ID of Table 11-28.	
SATN for G.993.5 Annex A	12	2	08_{16} (Note 1)	Mandatory
		3 to 12	Five 2-octet values of TXpower_dBm_D(m) for 5 potentially available downstream bands.	
NOTE 1 – All other values for octet number 2 are reserved by the ITU-T. NOTE 2 – All other values for octet number 3 are reserved by the ITU-T.				

Table 11-27 – PMD test parameter read responses sent by the responding VTU

Name	Length (octets)	Octet number	Content	Support
Single Read ACK	42 (Note 1)	2	81_{16} (Note 2)	Mandatory
		3 to 42	Octets for the test parameters arranged for the single read format	
Multiple Read ACK	12 (Note 1)	2	82_{16} (Note 2)	Mandatory
		3 to 12	Octets for the test parameters arranged for the multiple read format	
NACK	2	2	80_{16} (Note 2)	Mandatory
Block Read ACK	Parameter-dependent (Note 1)	2	84_{16} (Note 2)	Mandatory
		3 +	Octets for the test parameters arranged for the block read format	
Vector Block Read ACK	Parameter-dependent (Note 1)	2	86_{16} (Note 2)	Optional
		3 +	Octets for the test parameters arranged for the block read format	
Scalar Read ACK	Parameter-dependent (Note 1)	2	87_{16} (Note 2)	Optional
		3 +	Octets for the test parameters arranged for the scalar read format	

Table 11-27 – PMD test parameter read responses sent by the responding VTU

Name	Length (octets)	Octet number	Content	Support
SATN for G.993.5 Annex A ACK	12 (Note 1)	2	88₁₆ (Note 2)	Mandatory
		3 to 12	Octets for SATN arranged for the scalar read format	
NOTE 1 – Message length equals 2 octets plus the length shown in Table 11-28.				
NOTE 2 – All other values for octet number 2 are reserved by the ITU-T.				

Table 11-28 – PMD test parameter ID values and length of responses

Test parameter ID (Note 1)	Test parameter name	Length for Single Read (octets)	Length for Multiple Read (octets)	Length for Block Read or Vector Block Read (octets)	Length for Scalar Read (octets)	Support
01₁₆	Channel transfer function Hlog(f) per subcarrier group	N/A	4	2 + (stop subcarrier group index – start subcarrier group index + 1) × 2 (Note 2)	N/A	Mandatory
03₁₆	Quiet line noise PSD QLN(f) per subcarrier group	N/A	3	2 + (stop subcarrier group index − start subcarrier group index + 1) (Note 2)	N/A	Mandatory
04₁₆	Signal-to-noise ratio SNR(f) per subcarrier group	N/A	3	2 + (stop subcarrier group index − start subcarrier group index + 1) (Note 2)	N/A	Mandatory
21₁₆	Loop attenuation LATN	2 × 5	N/A	N/A	2 × 5	Mandatory
22₁₆	Signal attenuation SATN	2 × 5	N/A	N/A	2 × 5	Mandatory
23₁₆	Signal-to-noise ratio margin SNRM and SNRM-pb	2 × 6	N/A	N/A	2 × 6	Mandatory
24₁₆	Attainable net data rate ATTNDR (basic method)	4	N/A	N/A	4	Mandatory

Table 11-28 – PMD test parameter ID values and length of responses

Test parameter ID (Note 1)	Test parameter name	Length for Single Read (octets)	Length for Multiple Read (octets)	Length for Block Read or Vector Block Read (octets)	Length for Scalar Read (octets)	Support
24_{16}	Attainable net data rate ATTNDR (improved method)	8	N/A	N/A	8	Optional
25_{16}	Near-end actual aggregate transmit power ACTATP	2	N/A	N/A	2	Mandatory
26_{16}	Far-end actual aggregate transmit power ACTATP	2	N/A	N/A	2	Mandatory
27_{16}	Far-end actual impulse noise protection INP_act	N/A	N/A	N/A	2	Optional
28_{16}	Far-end actual signal-to-noise ratio margin for the robust overhead channel SNRM-ROC	N/A	N/A	N/A	2	Optional
NOTE 1 – All other Test parameter ID values are reserved by the ITU-T.						
NOTE 2 – Since the number of subcarriers, *G*, in the subcarrier group (see clause 11.4.1) may be different for QLN, Hlog, and SNR, the values of QLN, Hlog and SNR communicated by Multiple Read, Block Read, or Vector Block Read for the same subcarrier group index may correspond to different subcarrier indices. The subcarrier index for each parameter equals $G \times$ subcarrier group_index, where the value of *G* is as defined in Table 11-42 of clause 11.4.1 (for showtime) and subcarrier group index = 0 to 511.						

Upon reception of a PMD Test Parameter Read command, the responding VTU shall send the corresponding response. If the format of the Test Parameter Read command is incorrect, the VTU shall respond with the negative acknowledge (NACK). Any function of either the requesting or the responding VTU shall not be affected.

The Single Read command shall be used to retrieve all test parameters with ID values from 21_{16} to 26_{16} inclusive. In response to a Single Read command, the values for the test parameters (one value per parameter) shall be transferred in numerically increasing order of the parameter ID shown in Table 11-28. The format of the octets for each parameter shall be as specified in clause 11.4.1. Values formatted as multiple octets shall be mapped to the response in order of most significant to least significant octet. The LATN, SATN and SNRM format shall include five 2-octet values intended for 5 potentially available frequency bands for each transmission direction. The 2-octet values shall be sent in the order shown in Table 11-29. The value 00_{16} shall be used to indicate the disabled bands. Octets indicated as reserved shall be set to ZERO in the transmitter and ignored by the receiver. The SNRM test parameter shall, in addition to all SNRM-pb values (clause 11.4.1.1.6.3), include the overall SNRM value (clause 11.4.1.1.6.2). The first 2-octet value

is the overall SNRM, followed by the five 2-octet values of the SNRM-pb as specified in Table 11-29. For the ATTNDR, the use of either the basic or the improved method is configured during initialization (see clause 11.4.1.1.7). The ATTNDR test parameter is specified in Table 11-30.

If operating according to Annex A of [ITU-T G.993.5], the VTU-R response to a scalar read command for SATN and to a single read command shall have SATN values equal to the special value 1023. The VTU-O shall ignore this value (i.e., the VME shall not communicate this value to the EIA for storing in the CO-MIB SATNds object).

Table 11-29 – Order for sending LATN, SATN and SNRM-pb parameters

Octet number	Upstream direction	Downstream direction
1	US0	DS1
2		
3	US1	DS2
4		
5	US2	DS3
6		
7	US3	DS4
8		
9	US4	Reserved
10		

Table 11-30 – ATTNDR test parameter

Octet number	Basic method	Improved method
1-4	*ATTNDR*	*ATTNDR*
5	N/A	Reserved and set to 00_{16}
6	N/A	*ATTNDR_INP_act$_0$*
7	N/A	Reserved and set to 00_{16}
8	N/A	*ATTNDR_delay_act$_0$*
NOTE – The format of the fields is defined in clause 11.4.1.1.7.		

A Scalar Read command shall be used to retrieve a single test parameter. Support of this read command is optional. The ID of the test parameter to retrieve shall be indicated in the third octet of the read command as specified in Table 11-26. In response to a Scalar Read command, the VTU shall send the value of the test parameter if this command and the test parameter are supported by the VTU; otherwise the VTU shall send a NACK. The format of the octets for each parameter value shall be as described in clause 11.4.1. Values formatted as multiple octets shall be mapped to the response in order of most significant to least significant octet. The format of the LATN, SATN, SNRM and ATTNDR shall be identical to the format used in Single Read Command. The Far-end actual impulse noise protection (ID=27_{16}) shall include two 1-octet values and be sent in the order shown in Table 11-31. The value FF_{16} shall be used to indicate the disabled bearers.

Table 11-31 – Order for sending far-end actual impulse noise protection parameters

Octet number	Parameter
1	INP_act for bearer channel 0
2	INP_act for bearer channel 1

The "SATN for G.993.5 Annex A" command shall be used to retrieve SATN in case of operation according to Annex A of [ITU-T G.993.5]. It shall include five 2-octet values of TXpower_dBm_D(m) for 5 potentially available downstream bands. The format of the octets for each parameter shall be as specified for the actual aggregate transmit power (ACTATP) in clause 11.4.1.1.8. Values formatted as multiple octets shall be mapped to the response in order of most significant to least significant octet. The 2-octet values shall be sent in the order shown in Table 11-29. The value 00_{16} shall be used to indicate the disabled bands. Octets indicated as reserved shall be set to ZERO in the transmitter and ignored by the receiver.

In response to a "SATN for G.993.5 Annex A" command, the VTU shall send the value of SATN. The format of the octets for each parameter value shall be as described in clause 11.4.1. Values formatted as multiple octets shall be mapped to the response in order of most significant to least significant octet. The format of the SATN shall be identical to the format used in Scalar Read Command. The VTU-O shall convey this value for storing in the CO-MIB SATNds object.

In case the VTU-R detects a TIGAV or other OLR procedure after the SATN command and before the response, the VTU-R shall respond with SATN values equal to the special value 1023. The VTU-O shall convey this value for storing in the CO-MIB SATNds object and further reinitiate the SATN command. ~~The VME-O shall communicate this value to the EIA for storing in the CO-MIB SATNds object. The VME-O shall reinitiate the SATN command~~. Timing for this reinitiation is vendor discretionary.

Multiple Read and Next Multiple Read commands shall be used to retrieve test parameters of one subcarrier group. In response to a Multiple Read or Next Multiple Read command, the VTU shall send information for test parameters with ID 01_{16}, 03_{16}, and 04_{16} associated with the indicated subcarrier group. The Multiple Read command contains the index of the requested subcarrier group (see Table 11-26). If a Next Multiple Read command is to be sent, it shall only be sent after a Multiple Read command. In response to each subsequent Next Multiple Read command, the subcarrier group index shall be incremented by one. If the subcarrier group index exceeds 511 (see clause 11.4.1), the response shall be a NACK. The values of the PMD parameters per subcarrier group shall be inserted into the message in numerical order of the parameter ID shown in Table 11-28. The format of the octets for each parameter shall be as described in clause 11.4.1. Values that are formatted as multiple octets shall be mapped to the response in order of most significant to least significant octet.

A Block Read command shall be used to retrieve test parameters over a range of subcarrier groups. In response to a Block Read command, the VTU shall send information for test parameters with ID 01_{16}, 03_{16}, and 04_{16} associated with the specified block of subcarrier groups. For test parameters specified per subcarrier group, all values for subcarrier groups with indices from #start to #stop are transferred in a single response. If the subcarrier group index exceeds 511, the response shall be a NACK. The values of the PMD parameters per subcarrier group shall be inserted into the message in increasing order of the parameter ID shown in Table 11-28. The format of the octets for each parameter value shall be as described in clause 11.4.1. Values formatted as multiple octets shall be mapped to the response in order of most significant to least significant octet. The number of octets in a Block Read command shall not exceed the maximum length P of the eoc message specified in clause 11.2.3.1.

A Vector Block Read command shall be used to retrieve a single test parameter over a range of subcarrier groups. Support of this read command is optional. The ID of the test parameter to retrieve shall be indicated in the third octet of the read command as specified in Table 11-26. In response to a Vector Block Read command, the VTU shall send information for the test parameter associated with the specified block of subcarrier groups if this command is supported by the VTU; otherwise the VTU shall send a NACK. All values for subcarrier groups with indices from #start to #stop are transferred in a single response. If the subcarrier group index exceeds 511, the response shall be a NACK. The format of the octets for each parameter value shall be as described in clause 11.4.1. Values formatted as multiple octets shall be mapped to the response in order of most significant to least significant octet.

When transferring values of the channel transfer function Hlog(*f*), the quiet line noise QLN(*f*), and the signal-to-noise ratio SNR(*f*), the measurement time shall be included in the response for each test parameter. The ACK (see Table 11-27) is followed by the HLOG(*f*) measurement time and the value *m* (see clause 11.4.1.1.1), followed by the QLN(*f*) measurement time and value *n* (see clause 11.4.1.1.2), followed by the SNR(*f*) measurement time and value SNR (see clause 11.4.1.1.3), respectively. The measurement time shall be included only once in a response to a Block Read or Vector Block Read command, and shall be included for each test parameter in each response to a Multiple Read or Next Multiple Read command.

The values of some test parameters are represented using fewer bits than contained in the corresponding field defined for the response in Table 11-28. In the case that the field has more than one octet, the bits shall be mapped to the LSBs of the multi-octet field in the response. Unused MSBs in the multi-octet field shall be set to ZERO for unsigned quantities and to the value of the sign bit for signed quantities.

A.7.8   Signal attenuation per band (SATN-pb) (replaces clause 11.4.1.1.5 of [ITU-T G.993.2])

The signal attenuation in the mth downstream band is denoted as SATN_D(m), and the signal attenuation in the mth upstream band is denoted as SATN_U(m).

When operating in ITU-T G.993.5 Annex A, the signal attenuation of the mth upstream band, SATN_U(m) shall be calculated as specified in the main body of clause 11.4.1.1.5 of [ITU-T G.993.5].

When operating in accordance with Annex A of [ITU-T G.993.5], the signal attenuation of the mth downstream band, SATN_D(m), is defined as the difference in dB between the power received at the near end and that transmitted from the far end in the mth downstream band.

Mathematically, this corresponds to:

$$\text{SATN\_D}(m) = \text{TXpower\_dBm\_D}(m) - \text{RXpower\_dBm\_D}(m)$$

During initialization and loop diagnostic mode, the received signal power in dBm, RXpower_dBm_D(m), shall be computed as the received subcarrier power, summed over those subcarriers of this band that are in the MEDLEYds set. The VTU-R shall assume that during transmission of O-P-MEDLEY, the transmit PSD for subcarriers in the MEDLEYds set is at the MREFPSDds level. Therefore, the received signal power shall be fine-tuned with the g_i values for each subcarrier in the MEDLEYds set to estimate the signal power that will be received during showtime.

Mathematically, this corresponds to:

$$\text{RXpower\_dBm\_D}(m) = 10 \times \log_{10}\left(\sum_{i \in (MEDLEYds \cap DS(m))} \left(\text{Received\_subcarrier\_power\_mW}(i) \times g_i^2 \right) \right)$$

During showtime, the received signal power in dBm, Rxpower_dBm_D(m), shall be computed as the received subcarrier power in showtime, summed over those subcarriers of this band that are in the MEDLEYds set.

Mathematically, this corresponds to:

$$RXpower\_dBm\_D(m) = 10 \times \log_{10} \left(\sum_{i \in (MEDLEYds \cap DS(m))} \left(Received\_subcarrier\_power\_mW(i) \right) \right)$$

In both equations, MEDLEYds $\cap$ DS(m) denotes all subcarriers of the MEDLEYds set that fall into the mth downstream band, Received_subcarrier_power_mW is the received power on subcarrier i expressed in milli-Watts, and g_i is the gain (linear scale) for subcarrier i.

For the SATN value determined during initialization, the received signal power for each subcarrier i in the MEDLEYds set shall be fine-tuned with the g_i value conveyed in the O-PMD (for the upstream direction) and R-PMD (for the downstream direction) messages to estimate the signal power that will be received during showtime. During loop diagnostic mode, the fine tuning shall be restricted to using g_i values 0 (for subcarriers to which no bits can be allocated) and 1 (for subcarriers to which at least one bit can be allocated). For the SATN value determined during Showtime, the received signal subcarrier power shall be taken as measured.

For the SATN value determined during initialization and loop diagnostic mode, TXpower_dBm_D(m) shall be computed by the VTU-R as the aggregate transmit power, summed over the subcarriers of this band that are in the MEDLEYds set. The VTU-R shall assume that during transmission of O-P-MEDLEY, the transmit PSD for subcarriers in the MEDLEYds set is at the MREFPSDds level. Therefore, the transmitted signal power shall be fine-tuned with the g_i values for each subcarrier in the MEDLEYds set to estimate the signal power that will be transmitted during showtime.

Mathematically, this corresponds to:

$$TXpower\_dBm\_D(m) = 10 \times \log_{10} \Delta f + 10 \times \log_{10} \left(\sum_{i \in MEDLEYds \cap DS(m))} \left(10^{\frac{MREFPSD[i]}{10}} \times g_i^2 \right) \right)$$

where MEDLEYds $\cap$ DS(m) denotes all subcarriers of the MEDLEYds set that fall into the mth downstream band, *MREFPSD[i]* is the value of MREFPSDds for subcarrier i in dBm/Hz as conveyed by the O-PRM message, g_i is the gain (linear scale) for subcarrier i, and Δf is the subcarrier spacing in Hz.

The VTU-O, in cooperation with the VCE, shall update the downstream SATN value reported by the VTU-R during initialization using the correct TXpower_dBm_D(m) values. These shall be computed by the VTU-O, in cooperation with the VCE, as an estimate of the aggregate transmit power, summed over the subcarriers of this band that are in the MEDLEYds set, fine-tuned with the g_i values for each subcarrier in the MEDLEYds set to estimate the signal power that will be transmitted during showtime.

Mathematically, this corresponds to:

$$TXpower\_dBm\_D(m) = 10 log_{10} \left(\sum_{i \in (MEDLEYds \cap DS(m))} Pdirect\_Zi' \times g_i^2 \right)$$

where MEDLEYds $\cap$ DS(m) denotes all subcarriers of the MEDLEYds set that fall into the mth downstream band, and *Pdirect_Z$_i$'* is the power of the direct signal at the output of the precoder for subcarrier i, during O-P-MEDLEY, referred to the U-O interface, in milliWatts assuming the network input impedance is 100 Ohms resistive.

NOTE 1 – In actual deployments, the network/loop input impedance may deviate from 100 Ohms resistive.

NOTE 2 – In implementations using a precoder matrix P_i for subcarrier i, the *Pdirect_Zi′* may be computed using the diagonal coefficient of matrix P_i, "diag(P_i)", using the following equation:

$$Pdirect_{Zi}{}' = |diag(P_i)|^2 \times P_{Zi} = \Delta f \times 10^{\frac{MREFPSD(i)}{10}} \times (|diag(P_i)|)^2 \; .$$

For the downstream SATN value determined during initialization, the transmit signal power for each subcarrier i in the MEDLEYds set shall be fine-tuned with the g_i value conveyed in the R-PMD (for the downstream direction) messages to estimate the transmit signal power during showtime. During loop diagnostic mode, the fine tuning shall be restricted to using g_i values 0 (for subcarriers to which no bits can be allocated) and 1 (for subcarriers to which at least one bit can be allocated).

For the downstream SATN value determined during showtime, the VTU-R shall use the TXpower_dBm_D(m) values as communicated by the VTU-O in the SATN test parameter request command. These shall be computed by the VTU-O, in cooperation with the VCE, as an estimate of the aggregate transmit power, summed over the subcarriers of this band that are in the MEDLEYds set. In showtime this power already incorporates the effect of the g_i values.

Mathematically, this corresponds to:

$$TXpower\_dBm\_D(m) = 10log_{10}\left(\sum_{i\epsilon(MEDLEYds\cap DS(m))} Pdirect\_Zi'\right)$$

where MEDLEYds $\cap$ DS(m) denotes all subcarriers of the MEDLEYds set that fall into the mth downstream band, and *Pdirect_Zi′* is the power of the direct signal at the output of the precoder for subcarrier i, during showtime, referred to the U-O interface, in milliWatts assuming the network input impedance is 100 Ohms resistive.

NOTE 3 – In actual deployments, the network/loop input impedance may deviate from 100 Ohms resistive.

NOTE 4 – In implementations using a precoder matrix P_i for subcarrier i, the *Pdirect_Zi′* may be computed using the diagonal coefficient of matrix P_i, "diag(P_i)", using the following equation:

$$Pdirect_{Zi}{}' = |diag(P_i)|^2 \times P_{Zi} = \Delta f \times 10^{\frac{MREFPSD(i)}{10}} \times (|diag(P_i)| \times g_i)^2 \; .$$

The signal attenuation shall be measured by the receive PMD function during loop diagnostic mode and initialization (i.e., estimate the signal attenuation at the start of showtime). The measurement shall be updated on request from the far-end during showtime. The signal attenuation shall be sent to the far-end on request during showtime.

The signal attenuation per downstream band, SATN_D(m), shall be represented as a 10-bit unsigned integer *satn*, with the value of SATN_D(m) defined as SATN_D(m) = *satn*/10 dB. This data format supports an SATN_D(m) granularity of 0.1 dB and an SATN_D(m) dynamic range of 102.2 dB (0 to 102.2 dB).

An SATN_D(m) value indicated as *satn* = 1023 is a special value. It indicates that the signal attenuation is out of range to be represented or "undetermined".

A.7.9 Status parameter GAINSpsds

The status parameter *GAINSpsds* is defined as:

$$GAINSpsds_i = g_i \times 10^{\frac{\left(TXPSDdirect_{Zi}{}' - MREFPSDds(i)\right)}{20}}$$

where:

TXPSDdirect_Zi' is the PSD of the direct signal at the output of the precoder for subcarrier *i*, referred to the U-O interface, in dBm/Hz assuming the network input impedance is 100 Ohms resistive;

MREFPSDds is the *MREFPSDds* value as communicated in O-PRM in dBm/Hz.

The *GAINSpsds_i* shall be updated by the VTU-O, in cooperation with the VCE, upon OLR that change the g_i value, and upon TIGAV that change the *TXPSDdirectZi'* value.

NOTE 1 – The *GAINSpsds* is therefore only updated during the L0 link state.

The valid values for *GAINSpsds* are from 0 to approximately 1.33 (i.e., maximum valid value of g_i).

The *GAINSpsds* shall be represented as a 16-bit unsigned integer expressing the value of *GAINSpsds* in multiples of 1/512, with valid values from 0 to 682. All other values are reserved by ITU-T.

NOTE 2 – If the VTU-O does not operate according to this annex, the *GAINSpsds_i* are the actual g_i values.

NOTE 3 – In implementations using a precoder matrix P_i for subcarrier *i*, the *GAINSpsds* may be computed using the diagonal coefficient of matrix P_i, "diag(P_i)", using the following equation (see Figure 6-1):

$$GAINSpsds_i = g_i \times diag(P_i)$$

A.8 Management

This clause defines the CO-MIB configuration, status, and inventory parameters specific to Annex A operation. These parameters shall be supported if the VTU-O supports Annex A.

A.8.1 Configuration parameters

A.8.1.1 STRONGFEXT mode (STRONGFEXT_MODE)

The configuration parameter STRONGFEXT_MODE (see clause 7.3.1.17.1 of [ITU-T G.997.1]) is a configuration parameter used to control activation of G.993.5 Annex A during initialization.

This parameter has 4 valid values:

0: DISABLED: ITU-T G.993.5 Annex A not allowed. The "Support of strong FEXT mitigation" Npar(3) bit in the ITU-T G.994.1 CL message shall be set to ZERO.

1: PREFERRED: ITU-T G.993.5 Annex A is preferred by the operator. The "Support of strong FEXT mitigation" Npar(3) bit in the ITU-T G.994.1 CL message shall indicate whether the VTU-O supports this annex.

2: FORCED: Force the use of the ITU-T G.993.5 Annex A. The "Support of strong FEXT mitigation" Npar(3) bit in the ITU-T G.994.1 CL message shall indicate whether the VTU-O supports this annex. If the "Support of strong FEXT mitigation" Npar(3) bit is not set to ONE in the ITU-T G.994.1 MS message or the "ITU-T G.993.5" Spar(2) bit is not set to ONE in the ITU-T G.994.1 MS message, then the "ITU-T G.993.2" Spar(1) bit shall be set to ZERO in the MS.

3: FORCED_ABOVE_17MHZ:

- If the ITU-T G.994.1 MS message has the "ITU-T G.993.2" Spar(1) bit set to ONE and the "ITU-T G.993.5" Spar(2) bit set to ONE and the "Support of strong FEXT mitigation" Npar(3) bit set to ZERO, then the ITU-T G.994.1 MS message shall either

  – select operation according to a profile other than 30a and 35b, or,

  – select operation according to profile 35b, with a downstream and upstream SUPPORTEDCARRIERS set in O-SIGNATURE limited to subcarrier index 4095.

- If the ITU-T G.994.1 MS message has the "ITU-T G.993.2" Spar(1) bit is set to ONE and the "ITU-T G.993.5" Spar(2) bit set to ZERO, then the ITU-T G.994.1 MS message shall select operation according to any profile, with a downstream and upstream

SUPPORTEDCARRIERS set in O-SIGNATURE limited to a vendor discretionary subcarrier index smaller than or equal to 4095.

NOTE – The vendor discretionary highest subcarrier index should be chosen such that crosstalk generated to the other lines in the vectored group is sufficiently low, e.g. subcarrier 511 (which may correspond to ITU-T G.992.5 operation).

If the STRONGFEXT_MODE is set to PREFERRED, FORCED or FORCED_ABOVE_17MHz, then

• the RA-MODEds shall be set to Mode 3 (DYNAMIC) or 4 (DYNAMIC with SOS);

• the RTX_MODE_ds shall be set to RTX_FORCED, RTX_PREFERRED or RTX_TESTMODE.

NOTE – This annex is only applicable if the VTU is operating according to Annex Q of [ITU-T G.993.2], which requires mandatory support of SRA and downstream retransmission. This annex assumes that SRA and downstream retransmission are enabled in the CO-MIB.

If the STRONGFEXT_MODE is set to FORCED or to FORCED_ABOVE_17MHz for one line in vectored group, it shall be set to the same mode for all lines in the vectored group (i.e., all or none).

A.8.2   Status parameters

A.8.2.1   Actual STRONGFEXT mode (STRONGFEXT_MODE_ACTUAL)

The STRONGFEXT_MODE_ACTUAL (see clause 7.5.1.45.1 of ITU-T G.997.1) status parameter reports for the line whether or not operation in accordance with Annex A of [ITU-T G.993.5] is selected in the ITU-T G.994.1 MS message (regardless whether this selection is autonomous by the VTUs or forced through the CO-MIB).

The valid values are:

• NOT-SELECTED: ITU-T G.993.5 Annex A operation *is not* selected.

• SELECTED: ITU-T G.993.5 Annex A operation *is* selected.

A.8.3   Inventory parameters

A.8.3.1   STRONGFEXT mode support (STRONGFEXT_MODE_SUPPORT_O/R)

The STRONGFEXT_MODE_SUPPORT_O (see clause 7.4.15.1 of [ITU-T G.997.1]) and STRONGFEXT_MODE_SUPPORT_R (see clause 7.4.15.2 of [ITU-T G.997.1]) inventory parameters report, for the VTU-O and the VTU-R respectively, whether ITU-T G.993.5 Annex A operation is not supported (set to 0) or supported (set to 1).

Annex B

Vectored long reach VDSL2

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

B.1 Introduction

This annex defines the long reach mode for vectored VDSL2 (VDSL2-LR).

The VDSL2-LR mode is an optional functionality for both the VTU-O and VTU-R. This mode provides different behaviours for short loop, medium loop and long loop operation on different pairs in the same vectored group. The selection of short, medium, or long loop operation is autonomous, taking account of loop loss; unless the selection is overridden by network management.

The behaviours include that:

1) A deployment may host both VDSL2 and VDSL2-LR lines. The VDSL2-LR lines and the VDSL2 lines may be in the same vectored group.

2) If both VTU-O and VTU-R support VDSL2-LR mode, then operation according to this annex is selected during the ITU-T G.994.1 Handshake phase for both VTU-O and VTU-R.

3) Both VDSL2 lines and VDSL2-LR lines are configured to use a particular VDSL2 profile (e.g., 8a/b or 17a), depending on the desired service on VDSL2 lines. Both VDSL2 and VDSL2-LR lines start initialization according to the ITU-T G.993.5 procedure and the selected profile.

4) No overlapped spectrum is allowed in US0 – the frequency band from 25 to 138/276 kHz is used for US0 only and a regular VDSL2 bandplan is used above 138/276 kHz.

5) In VDSL2-LR mode, for the long loop operation, the spectrum is limited to US0 and DS1 up to subcarrier 511 (2.208 MHz).

6) Only the mandatory cyclic extension is supported in VDSL2-LR mode.

7) Unless explicitly stated otherwise in this annex, the VDSL2-LR mode supports all functionalities applicable to the main body of this Recommendation (e.g., DPBO).

8) Upstream crosstalk cancellation is not supported on lines where VDSL2-LR long loop operation is selected (since only the US0 band is used).

B.2 Overview of the initialization procedure

The VDSL2-LR initialization procedure includes two parts:

1) Regular ITU-T G.993.5 procedure (including ITU-T G.993.5 channel estimation) with minor modifications, and

2) Additional stages:

   • PROBING: During this stage, the VTU-R determines the length of the line and indicates to the VTU-O whether to continue the VDSL2-LR initialization in short-medium loop operation or in long loop operation. Following the indication from the VTU-R, both the VTU-O and the VTU-R continue the initialization of the line either in short-medium loop operation or in long loop operation;

   • TRAINING: This stage is present if the VTU-R selected to continue the initialization of the line in long loop operation. During this stage, the VTU-O and VTU-R train the line for long loop operation.

The framework of the initialization procedure is presented in Figure B.1. It illustrates VDSL2-LR initialization (compared to regular ITU-T G.993.5 initialization), using the following notations for the exchanged signals:

•	G.993.5 signals – used if the line is a regular ITU-T G.993.5 line, i.e., not operating according to this annex (a regular ITU-T G.993.5 line);

•	LR signals, short-medium – used if the line is selected during the PROBING stage to continue the VDSL2-LR initialization in short-medium loop operation (to become a short or medium VDSL2-LR line);

•	LR signals, long – used if the line is selected during the PROBING stage to continue the VDSL2-LR initialization in long loop operation (for a long VDSL2-LR line).

Messages	LR signals, long	LR signals, short-medium	ITU-T G.993.5 signals		ITU-T G.993.5 signals	LR signals, short-medium	LR signals, long	Messages
ITU-T G.994.1	ITU-T G.994.1 handshake				ITU-T G.994.1 handshake			ITU-T G.994.1
	O-P-QUIET 1				R-P-QUIET 1			
	O-P-VECTOR 0							
O-P-MSG-PCB-LR	O-P-PROBING-LR			VTU-R obtained loop timing		R-P-PROBING-LR		R-P-MSG-PCB-LR
				Decision short vs long				
	O-P-QUIET 1-LR					R-P-QUIET 1-LR		
	O-P-VECTOR 1-LR	O-P-VECTOR 1	O-P-VECTOR 1		R-P-QUIET 1	R-P-QUIET 1	R-P-QUIET 2-LR	
	O-P-TRAINING-LR						R-P-TRAINING-LR	
O-IDLE				O-SIGNATURE received			R-P-QUIET 1	
O-SIGNATURE	O-P-CHANNEL DISCOVERY V1				R-P-VECTOR 1		R-P-CHANNEL DISCOVERY 1 with SOC R-IDLE	
	O-P-SYNCHRO V1			Stard of bi-directional transmission				
O-IDLE	O-P-CHANNEL DISCOVERY 1			R-MSG 1 is received		R-P-CHANNEL DISCOVERY 1		R-IDLE
								R-MSG1
	O-P-SYNCHRO V1			End of CD early stages		R-P-SYNCHRO 1		
	O-P-PILOT 1	O-P-QUIET 2				R-P-LINEPROBE		
....	....					....		....

Left margin labels: Regular part of ITU-T G.993.5 initialization; Additional part performed in VDSL2-LR lines; Regular part of ITU-T G.993.5 initialization.

Center column label: Regular ITU-T G.993.5 CD phase.

G.993.5(15)-Amd.2(17)_FB.1

**Figure B.1 – Overview of the VDSL2-LR initialization
(compared to regular ITU-T G.993.5 initialization)**

B.3 ITU-T G.994.1 Handshake phase

During the ITU-T G.994.1 Handshake phase, it is determined whether the line is selected to be a VDSL2-LR line or selected to be a regular ITU-T G.993.5 line. The PROBING PSD (see clause B.6) in case the line is selected to be a VDSL2-LR line, is also indicated (via NOMPSD and *log_tssi* values). The defined Spar(2) codepoints belongs to the ITU-T G.993.2 code-tree and defined in Table 11.68.0.1/G.994.1 (Standard information field – ITU-T G.993.2 SPar(2) coding – Octet 2). The use of these codepoints in the ITU-T G.994.1 CL, CLR and MS messages is defined in Tables B.1 to B.8.

Table B.1 – VTU-O CL message SPar(2) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bit
Support of VDSL2-LR	Shall be set to ZERO if: • the VTU-O does not support VDSL2 Long Reach (VDSL2-LR) mode according to this annex, or, • none of short, medium or long loop operation type is allowed in the CO-MIB (see clause B.10.1.1), and may be set to ONE otherwise.
Spectrum bounds downstream	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE. If set to ONE, signifies that the VTU-O includes the spectrum bounds downstream defined in corresponding NPar(3).
Spectrum shaping downstream	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE. If set to ONE, signifies that the VTU-O includes the spectrum shaping downstream defined in corresponding NPar(3).
Spectrum bounds upstream	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE. If set to ONE, signifies that the VTU-O includes the spectrum bounds upstream defined in corresponding NPar(3).
Spectrum shaping upstream	Always set to ZERO.
Transmit signal images above the Nyquist frequency	Always set to ZERO.
Offset IDFT sample #0 downstream	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE.
Offset IDFT sample #0 upstream	Always set to ZERO.

Table B.2 – VTU-O CL message NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of NPar(3) bits
Support of VDSL2-LR	If the SPar(2) bit is set to ONE: Bit 1: Short loop operation type: Shall be set to ONE if and only if VDSL2-LR short loop operation is allowed in the CO-MIB (see clause B.10.1.1). Bit 2: Medium loop operation type: Shall be set to ONE if and only if VDSL2-LR medium loop operation is allowed in the CO-MIB (see clause B.10.1.1). Bit 3: Long loop operation type: Shall be set to ONE if and only if VDSL2-LR long loop operation is allowed in the CO-MIB (see clause B.10.1.1). Bit 4: Always set to ONE.
Spectrum bounds downstream	A parameter block indicating the nominal transmit PSD level. The parameter block length shall be 2 octets. The nominal transmit PSD level (*NOMPSDds*) shall be represented as a 9-bit 2's-complement signed value in 0.1 dB steps, –25.6 to +25.5 dB, relative to the value of –40 dBm/Hz, and shall be coded in bits 3 down to 1 in octet 1, bits 6 down to 1 in octet 2.

Table B.2 – VTU-O CL message NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of NPar(3) bits
Spectrum shaping downstream	A parameter block of pairs of a subcarrier index and the spectrum shaping *log_tssi* value at that subcarrier. Pairs shall be transmitted in ascending subcarrier index order. Each pair shall be represented as 4 octets. The parameter block length shall be a multiple of 4 octets. The maximum number of breakpoints equals 32.
	Codepoints shall be structured as:
	The subcarrier index shall be a 9-bit unsigned value, indicating subcarrier index 1 to $2 \times NSCds - 1$, coded in bits 3 down to 1 in octet 1, bits 6 down to 1 in octet 2;
	The indication whether the subcarrier is included in the SUPPORTEDCARRIERS set (indication set to 1) or not included in the SUPPORTEDCARRIERSset (indication set to 0). This indication is coded in bit 6 of octet 3;
	The spectrum shaping *log_tssi* values shall be represented in logarithmic scale as a 7-bit unsigned value in –0.5 dB steps, ranging from 0 dB (value 0) to –62.5 dB (value 125), coded in bit 1 of octet 3 and bits 6 down to 1 in octet 4. Value 127 is a special value, indicating the subcarrier is not transmitted (i.e., *tssi* = 0 in linear scale). Value 126 is a special value indicating that the *log_tssi* value on this subcarrier shall be interpolated according to clause 8.13.2.4 of G.992.3. At least one pair (of a subcarrier index and the spectrum shaping *log_tssi* value at that subcarrier) indicated as included in the SUPPORTEDCARRIERS set, shall have the *log_tssi* value set to 0 dB.
Spectrum bounds upstream	Parameter block with same definition and structure as spectrum bounds downstream, with *NOMPSD=NOMPSDus*.
Offset IDFT sample #0 downstream	Indicate the offset between the IDFT sample #0 of O-P-SEGUE 1-LR and O-P-CHANNEL DISCOVERY-V1 in samples at 4.416MHz. The value is coded as a 7-bits unsigned integer.

Table B.3 – VTU-R CLR message SPar(2) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bit
Support of VDSL2-LR	Shall be set to ONE if and only if the VTU-R supports VDSL2 Long Reach (VDSL2-LR) mode according to this annex.
Spectrum bounds downstream	Always set to ZERO.
Spectrum shaping downstream	Always set to ZERO.
Spectrum bounds upstream	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE. If set to ONE, signifies that the VTU-R includes the spectrum bounds upstream defined in corresponding NPar(3).
Spectrum shaping upstream	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE. If set to ONE, signifies that the VTU-R includes the spectrum shaping upstream defined in corresponding NPar(3).

Table B.3 – VTU-R CLR message SPar(2) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bit
Transmit signal images above the Nyquist frequency	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE. If set to ONE, signifies that the VTU-R includes the transmit signal images above the Nyquist frequency defined in corresponding NPar(3).
Offset IDFT sample #0 downstream	Always set to ZERO.
Offset IDFT sample #0 upstream	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE.

Table B.4 – VTU-R CLR message NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of NPar(3) bits
Support of VDSL2-LR	Bit 1: Always set to ONE. Bit 2: Always set to ONE. Bit 3: Always set to ONE. Bit 4: FMT-O-P-TREF2: If set to ONE, indicates that the VTU-R requests the VTU-O to transmit O-P-TREF symbols during O-P-ECT-LR. If set to ZERO, indicates that the VTU-R requests the VTU-O to transmit O-P-QUIET symbols during O-P-ECT-LR.
Spectrum bounds upstream	Parameter block with same definition and structure as spectrum bounds upstream parameter block in CL message.
Spectrum shaping upstream	Parameter block with same definition and structure as spectrum shaping downstream parameter block in CL message, with $NSC=NSCus$ and maximum number of breakpoints equals 16.
Transmit signal images above the Nyquist frequency	A parameter block indicating the type of the transmit signal images above the Nyquist frequency. The parameter block shall consist of a single octet. Codepoints shall be structured as bits 6 to 3 indicating the N value (for a $2N$ point IDFT, see clause 10.4.3 of [ITU-T G.993.2]) and bits 2 and 1 indicating the definition of the transmit signal images above the Nyquist frequency (see clause 10.4.3 of [ITU-T G.993.2]). The coding shall be as follows: • $(b_6b_5b_4b_3) = n$, with $1 \le n \le 15$ indicates that $N = 2^n$. • $(b_2b_1 = 01)$: Complex conjugate of the base-band signal. • $(b_2b_1 = 10)$: Zero filled. • $(b_2b_1 = 00)$: Other (none of the above). • $(b_2b_1 = 11)$: Reserved.
Offset IDFT sample #0 upstream	Indicate the offset between the IDFT sample #0 of R-P-SEGUE 1-LR and R-P-CHANNEL DISCOVERY 1 in samples at 276kHz. The value is coded as a 3-bits unsigned integer value.

Table B.5 – VTU-O MS message SPar(2) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bit
Support of VDSL2-LR	Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, indicates that both the VTU-O and the VTU-R shall continue initialization for VDSL2-LR mode as defined in this Annex. If set to ZERO, indicates that both the VTU-O and VTU-R shall continue initialization as defined in clause 10. If this bit is set to ONE, then the CE length SPar(2) bit shall be set to ZERO.
Spectrum bounds upstream	Always set to ZERO.
Spectrum shaping upstream	Always set to ZERO.
Spectrum bounds downstream	Always set to ZERO.
Spectrum shaping downstream	Always set to ZERO.
Transmit signal images above the Nyquist frequency	Always set to ZERO.
Offset IDFT sample #0 downstream	Always set to ZERO.
Offset IDFT sample #0 upstream	Always set to ZERO.

Table B.6 – VTU-O MS message NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of NPar(3) bits
Support of VDSL2-LR	Bit 1: Short loop: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, short loop operation shall be allowed. Bit 2: Medium loop: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, medium loop operation shall be allowed. Bit 3: Long loop: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, long loop operation shall be allowed. Bit 4: FMT-O-P-TREF2: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, the VTU-O shall transmit O-P-TREF symbols during O-P-ECT-LR. If set to ZERO, the VTU-O shall transmit O-P-QUIET symbols during O-P-ECT-LR.

Table B.7 – VTU-R MS message SPar(2) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bit
Support of VDSL2-LR	Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, indicates that both the VTU-O and the VTU-R shall continue initialization for VDSL2-LR mode as defined in this annex. If set to ZERO, indicates that both the VTU-O and VTU-R shall continue initialization as defined in clause 10. If this bit is set to ONE, then the CE length SPar(2) bit shall be set to ZERO.
Upstream spectrum bounds	Always set to ZERO.
Upstream spectrum shaping	Always set to ZERO.
Upstream spectrum bounds	Always set to ZERO.
Upstream spectrum shaping	Always set to ZERO.
Transmit signal images above the Nyquist frequency	Always set to ZERO.
Offset IDFT sample #0 downstream	Always set to ZERO.
Offset IDFT sample #0 upstream	Always set to ZERO.

Table B.8 – VTU-R MS message NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of NPar(3) bits
Support of VDSL2-LR	Bit 1: Short loop: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, short loop operation shall be allowed. Bit 2: Medium loop: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, medium loop operation shall be allowed. Bit 3: Long loop: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, long loop operation shall be allowed. Bit 4: FMT-O-P-TREF2: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, the VTU-O shall transmit O-P-TREF symbols during O-P-ECT-LR. If set to ZERO, the VTU-O shall transmit O-P-QUIET symbols during O-P-ECT-LR.

If the ITU-T G.994.1 MS message has the "Support of VDSL2-LR" Spar(2) bit set to ONE, then it shall:

• indicate use of the mandatory CE Length;

• indicate operation according to a profile other than profile 30a (see Tables 6-1 and Q.1 of [ITU-T G.993.2]);

• have the annex B US0 Spar(2) set to ONE and have one of the 25-138 kHz (A), 25-276 kHz (M) or 120-276 kHz (B) NPar(3) set to ONE.

Selection of the particular loop operation (short loop, medium loop, or long loop) occurs during the following stages of initialization, as described in clause B.2. The particular loop operation may be

selected only if allowed (i.e., if the corresponding ITU-T G.994.1 MS message "Short loop", "Medium loop" or "Long loop" Npar(3) bit is set to ONE)."

B.4   Signals sent by the VTU-O during the Channel Discovery and Training phase

The maximum duration of O-P-VECTOR 0, O-P-VECTOR 1-LR and O-P-VECTOR 1 is defined in clauses B.4.2, B.4.5 and B.4.7, respectively. In addition, if the bit "8192 superframes duration for O-P-VECTOR 1" is enabled in the ITU-T G.994.1 Handshake phase (see clause 10.2), then the sum of the durations of all stages starting from O-P-VECTOR 0 and up to but not including O-P-CHANNEL DISCOVERY V1 shall not exceed $8 \times 1024 \times 257$ symbols.

A VTU-R indicating "Support of VDSL2-LR mode" in the ITU-T G.994.1 CLR message, shall also indicate support of "8192 superframes duration for O-P-VECTOR 1".

NOTE – Regular ITU-T G.993.5 lines with the bit "8192 superframes duration for O-P-VECTOR 1" disabled in the ITU-T G.994.1 Handshake phase may initialize in a different joining group that does not include VDSL2-LR lines.

B.4.1   O-P-QUIET 1

After the ITU-T G.994.1 Handshake phase, the VTU-O shall start initialization with the O-P-QUIET 1 signal defined in clause 12.3.3.3.1.1 of [ITU-T G.993.2].
The duration of O-P-QUIET 1 signal shall be at least 512 but not longer than 1024 symbol periods.

The O-P-QUIET 1 signal shall be followed by the O-P-VECTOR 0 signal.

B.4.2   O-P-VECTOR 0

The O-P-VECTOR 0 signal shall be identical to the O-P-VECTOR 1 signal defined in clause 10.3.3.1. It includes all subcarriers from the downstream SUPPORTEDCARRIERS set. The PSD of the O-P-VECTOR 0 signal shall be derived using the same rules as for the PSD of the O-P-VECTOR 1 signal (see clause 10.3.3.1), except that the aggregate transmit power for the O-P-VECTOR 0 signal shall not exceed the minimum of the maximum aggregate downstream transmit power, as defined for the selected profile in Table 6-1 of [ITU-T G.993.2], and the MAXNOMATPds value configured in the CO-MIB.

During transmission of the O-P-VECTOR 0 signal, the VCE estimates the downstream FEXT channels from the initializing lines into the vectored lines based on the reported clipped error samples from the VTU-Rs of the vectored lines. From this point on, FEXT cancellation matrices are established in the VTU-Os for all vectored lines in the downstream direction and FEXT from the initializing line into vectored lines is cancelled.

The duration of O-P-VECTOR 0 is determined by the VTU-O, under VCE control. The VCE may select the duration of O-P-VECTOR 0 appropriately, with the aim to synchronize the start of O-P-PROBING-LR signals on all the VDSL2-LR lines of the vectored group.

The duration of O-P-VECTOR 0 shall not exceed $M \times 1024 \times 257$ symbols. If the bit "8192 superframes duration for O-P-VECTOR 1" is enabled in the ITU-T G.994.1 Handshake phase (see clause 10.2), then $M = 8$. Otherwise, $M = 1$.

NOTE – With $M = 8$, the maximum duration of O-P-VECTOR 0 will timeout the maximum duration over all stages starting from O-P-VECTOR 0 and up to but not including O-P-CHANNEL DISCOVERY V1 (see clause B.4).

The O-P-VECTOR 0 signal shall be followed by the O-P-PROBING-LR signals.

B.4.3   O-P-PROBING-LR

The O-P-PROBING-LR shall consist of a number of periodic signals, as defined in clause B.6. These signals are intended to synchronize the VTU-R, to allow it to estimate the length of the line so that it can indicate back to the VTU-O whether the initialization of the line shall continue either

in short-medium loop operation (to become a short or medium VDSL2-LR line), or in a long loop operation (for a long VDSL2-LR line).If long loop operation is selected, the VTU-O also receives an indication of the pilot tone assigned by the VTU-R and the required downstream power cut-back (PCB) determined by the VTU-R.

The O-P-PROBING-LR signals may be transmitted with an IDFT size that is different from the Initial IDFT size indicated in the ITU-T G.994.1 CL message. The IDFT size ($2N$) shall be at least 2048 (i.e., $n \geq 11$).

The PSD of the O-P-PROBING-LR signals shall be as defined in clause B.6.1.1.

The O-P-PROBING-LR signals shall be followed by the O-P-QUIET 1-LR signal.

NOTE – While the VTU-O transmits the O-P-PROBING-LR signals, it is recommended that the VCE freezes precoder updates for lines with the VTU-O in the O-SHOWTIME state.

B.4.4   O-P-QUIET 1-LR

The O-P-QUIET 1-LR signal shall be identical to the O-P-QUIET 1 signal.

While transmitting this signal, the VTU-O performs any reconfiguration necessary for the selected continuation of the initialization, either in short-medium loop operation (to become a short or medium VDSL2-LR line) or in long loop operation (for a long VDSL2-LR line).

The duration of the O-P-QUIET 1-LR signal shall be 64 symbols.

If the initialization of the line shall be continued in short-medium loop operation, then the O-P-QUIET 1-LR signal shall be followed by the O-P-VECTOR 1 signal defined in clause B.4.7.

If the initialization of the line shall be continued in long loop operation, then the O-P-QUIET 1-LR signal shall be followed by the O-P-VECTOR 1-LR signal.

NOTE – While the VTU-O transmits the O-P-QUIET 1-LR signal, it is recommended that the VCE freezes precoder updates for lines with the VTU-O in the O-SHOWTIME state.

B.4.5   O-P-VECTOR 1-LR

The O-P-VECTOR 1-LR signal shall be identical to the O-P-VECTOR 1 signal defined in clause 10.3.3.1, except that:

•   it shall include only all subcarriers from the downstream SUPPORTEDCARRIERS set up to subcarrier index 511 (up to about 2.2 MHz);

•   its PSD shall be the same as the PSD of the O-P-TRAINING-LR signals (see clause B.7.1.1);

•   it is transmitted with an IDFT size ($2N$) that may be different from the initial IDFT size indicated in the ITU-T G.994.1 CL message, but shall be at least 2048 (i.e., $n \geq 11$), so that there is no image above the subcarrier with index 511.

The duration of O-P-VECTOR 1-LR is determined by the VTU-O, under VCE control. The VCE may select the duration of O-P-VECTOR 1-LR appropriately, with the aim to synchronize the start of O-P-TRAINING-LR signals on all the VDSL2-LR lines in long loop operation of the vectored group.

The duration of O-P-VECTOR 1-LR shall not exceed $M \times 1024 \times 257$ symbols. If the bit "8192 superframes duration for O-P-VECTOR 1" is enabled in the ITU-T G.994.1 Handshake phase (see clause 10.2), then $M = 8$. Otherwise, $M = 1$.

NOTE – With $M = 8$, the maximum duration of O-P-VECTOR 1-LR will timeout the maximum duration over all stages starting from O-P-VECTOR 0 and up to but not including O-P-CHANNEL DISCOVERY V1 (see clause B.4).

The O-P-VECTOR 1-LR signal shall be followed by the O-P-TRAINING-LR signals.

The O-P-VECTOR 1-LR signal is necessary to adopt potential changes in impedance during reconfiguration of the VDSL2-LR line after it has been selected to be in long loop operation.

NOTE – The VTU-R uses spectrum up to 2.2 MHz during the PROBING stage, and may need to re-configure for short-medium loop operation, which may change its impedance and thus impact precoder settings for lines with the VTU-O in the O-SHOWTIME state. The impact of these changes will be accommodated during transmission of O-P-VECTOR 1.

B.4.6   O-P-TRAINING-LR

The O-P-TRAINING-LR signals are defined in clause B.7.

While the VTU-O transmits the O-P-TRAINING-LR signals, the VTU-R transmits the R-P-TRAINING-LR signals. The O/R-P-TRAINING-LR signals allow the VTU-O and VTU-R to train their echo cancellers (EC) and time domain equalizers (TEQ). The PSD of the O-P-TRAINING-LR signals shall be as defined in clause B.7.1.1.

After the EC and TEQ training, both VTUs are ready for SOC communications. Therefore, after O/R-P-TRAINING-LR signal exchange is complete, the line continues regular ITU-T G.993.5 initialization, exchanging corresponding messages over SOC.

The IDFT size during O-P-TRAINING-LR shall be the same as during O-P-VECTOR 1-LR.

NOTE – While the VTU-O transmits the O-P-TRAINING-LR signals, it is recommended that the VCE freezes precoder updates on subcarriers up to subcarrier index 511.

The duration of O-P-TRAINING-LR is variable. The maximum duration of O-P-TRAINING-LR shall respect the rule defined in clause B.4.

The O-P-TRAINING-LR signals shall be followed by the O-P-CHANNEL DISCOVERY V1 signal and the remainder of the channel discovery phase, as defined in clause B.4.8.

B.4.7   O-P-VECTOR 1

The O-P-VECTOR 1 signal shall be identical to the O-P-VECTOR 0 signal defined in clause B.4.2.

The duration of O-P-VECTOR 1 shall not exceed $M \times 1024 \times 257$ symbols. If the bit "8192 superframes duration for O-P-VECTOR 1" is enabled in the ITU-T G.994.1 Handshake phase (see clause 10.2), then $M = 8$. Otherwise, $M = 1$.

NOTE – With $M = 8$, the maximum duration of O-P-VECTOR 1 will timeout the maximum duration over all stages starting from O-P-VECTOR 0 and up to but not including O-P-CHANNEL DISCOVERY V1 (see clause B.4).

The O-P-VECTOR 1 signal shall be followed by the O-P-CHANNEL DISCOVERY V1 signal and the remainder of the channel discovery phase, as defined in clause B.4.8.

B.4.8   The G.993.5 Channel Discovery phase

If short-medium loop operation is selected in the PROBING stage, the ITU-T G.993.5 Channel Discovery phase shall be applied with the amendments defined in this clause. If long loop operation is selected in the PROBING stage, then the ITU-T G.993.5 Channel Discovery phase shall be applied with the amendments as specified in clause B.8.

B.4.8.1   O-SIGNATURE (amends clause 12.3.3.2.1.1 of [ITU-T G.993.2])

The value of the control parameter *MAXNOMATPds* indicated in Field #8 of O-SIGNATURE message shall be determined as the minimum of the maximum aggregate downstream transmit power as defined for the selected profile in Table 6-1 of [ITU-T G.993.2] and the MAXNOMATPds value configured in the CO-MIB.

B.4.8.2 O-UPDATE (amends clause 12.3.3.2.1.2 of [ITU-T G.993.2])

If the ITU-T G.994.1 MS message has the short loop bit set to ZERO, then the highest allowed upstream subcarrier indicated by the VTU-O in O-UPDATE (see Table 12-28 of [ITU-T G.993.2]) shall meet the condition for medium loop operation as defined in clause B.4.8.3 (i.e., forced medium loop operation).

B.4.8.3 O-PRM (amends clause 12.3.3.2.1.3 of [ITU-T G.993.2])

If the ITU-T G.994.1 MS message has the medium loop bit set to ONE and if the highest allowed upstream subcarrier indicated by the VTU-O in O-UPDATE (see Table 12-28 of [ITU-T G.993.2]) and the proposed highest downstream subcarrier indicated by the VTU-R in R-UPDATE (see Table 12-35 of [ITU-T G.993.2]) are both equal to or less than the highest subcarrier index defined for DS2 band in the applied bandplan and both do not exceed the value 1971 (8.5 MHz, see Table 6-1 of [ITU-T G.993.2]), then the VDSL2-LR line shall be in medium loop operation. Otherwise, the VDSL2-LR line shall be in short loop operation.

If the VDSL2-LR line is in medium loop operation, the value of the control parameter *MAXNOMATPds* shall be recalculated as the minimum of 20.5 dBm and the MAXNOMATPds value configured in the CO-MIB, regardless of the particular ITU-T G.993.2 profile selected during the ITU-T G.994.1 Handshake phase of initialization. If the VDSL2-LR line is in short loop operation, the value of the control parameter *MAXNOMATPds* shall remain equal to the value communicated in O-SIGNATURE.

The *MREFPSds* indicated in O-PRM (see Table 12-30 of [ITU-T G.993.2]) shall have an aggregate transmit power that shall not exceed this *MAXNOMATPds* value.

NOTE 1 – For medium loop operation, the *MREFPSDds* could have an aggregate transmit power that exceeds the maximum aggregate downstream transmit power (as defined in Tables 6-1 and Q.1 of [ITU-T G.993.2]) for the particular ITU-T G.993.2 profile selected during the ITU-T G.994.1 Handshake phase of initialization.

NOTE 2 – This *MAXNOMPSDds* value (as determined based on O/R-UPDATE) is known to both the VTU-O and VTU-R and does not need to be exchanged from VTU-O to VTU-R.

B.4.9 The ITU-T G.993.5 Training phase

If long loop operation is selected in the PROBING stage, then the ITU-T G.993.5 Training phase shall be applied with the amendments defined in clause B.8. If short-medium loop operation is selected in the PROBING stage, the original ITU-T G.993.5 training phase shall be used.

B.5 Signals sent by the VTU-R during the Channel Discovery and Training phase

B.5.1 R-P-QUIET 1

After the ITU-T G.994.1 Handshake phase, the VTU-R shall start initialization with the R-P-QUIET 1 signal defined in clause 12.3.3.3.2.1 of [ITU-T G.993.2].

The duration of R-P-QUIET 1 is determined by the VTU-O. Within 64 symbols after the VTU-O ending the first signal of O-P-PROBING-LR (O-P-COMB 2-LR, see clause B.6.1.3), the VTU-R shall end the R-P-QUIET 1 signal.

The R-P-QUIET 1 signal shall be followed by the R-P-PROBING-LR signals.

B.5.2 R-P-PROBING-LR

The R-P-PROBING-LR consists of a number of periodic signals, as defined in clause B.6.

While receiving the O-P-PROBING-LR signals, the VTU-R shall determine whether the initialization of the line shall continue either in short-medium loop operation (to become a short or medium VDSL2-LR line) or in long loop operation (for a long VDSL2-LR line). In the latter case,

the VTU-R shall also assign the pilot tone and determine the minimum downstream power cut-back (PCBds, see Table B.10), if needed.

The R-P-PROBING-LR signals shall be transmitted with the IDFT size and type of image as indicated by the VTU-R in the "Transmit signal images above the Nyquist frequency" block in the ITU-TG.994.1 CLR message. The IDFT size may be different from the Initial IDFT size indicated in the ITU-T G.994.1 CL message.

The PSD of the R-P-PROBING-LR signals shall be as defined in clause B.6.2.1.

The R-P-PROBING-LR signals shall be followed by the R-P-QUIET 1-LR signal.

B.5.3   R-P-QUIET 1-LR

The R-P-QUIET 1-LR signal shall be identical to the R-P-QUIET 1 signal.

While transmitting this signal, the VTU-R performs any reconfiguration necessary for the selected continuation of the initialization, either in short-medium loop operation (to become a short or medium VDSL2-LR line) or as a VDSL2-LR line (for a long VDSL2-LR line).

The duration of R-P-QUIET 1-LR signal shall be 64 symbol periods.

If the initialization shall be continued in short-medium loop operation, then the R-P-QUIET 1-LR signal shall be followed by the R-P-QUIET 1 signal defined in clause 10.3.4.1 and the remainder of the channel discovery phase shall be as defined in clause 10.3, except for the changes defined in clauses B.4.8 and B.10.4.1.

If the initialization shall be continued in long loop operation, then the R-P-QUIET 1-LR signal shall be followed by the R-P-QUIET 2-LR signal.

B.5.4   R-P-QUIET 2-LR

The R-P-QUIET 2-LR signal shall be identical to the R-P-QUIET 1 signal.

The duration of R-P-QUIET 2-LR is determined by the VTU-O. Within 64 symbols after the VTU-O ending the first signal of O-P-TRAINING-LR (O-P-REVERB 1-LR, see clause B.7.1.1), the VTU-R shall end the R-P-QUIET 2-LR signal.

The R-P-QUIET 2-LR signal shall be followed by the R-P-TRAINING-LR signals.

B.5.5   R-P-TRAINING-LR

The R-P-TRAINING-LR signals are defined in clause B.7.

While the VTU-R transmits the R-P-TRAINING-LR signals, the VTU-O transmits the O-P-TRAINING-LR signals. The O/R-P-TRAINING-LR signals allow the VTU-O and VTU-R to train their echo cancellers (EC) and time domain equalizers (TEQ). The PSD of the R-P-TRAINING-LR signals shall be the same as for the R-P-PROBING-LR signals (see clause B.6.1.1).

After EC and TEQ training, both VTUs are ready for SOC communications. After O/R-P-TRAINING-LR signal exchange is complete, the line continues regular ITU-T G.993.5 initialization, exchanging corresponding messages over SOC.

The IDFT size during R-P-TRAINING shall be as indicated by the VTU-R in the "Transmit signal images above the Nyquist frequency" block in the ITU-T G.994.1 CLR message.

The R-P-TRAINING-LR signals shall be followed by the R-P-QUIET 1 signal defined in clause 10.3.4.1 and the remainder of the channel discovery phase defined in clause 10.3.

B.5.6   The ITU-T G.993.5 Channel Discovery phase

If long loop operation is selected in the PROBING stage, then the ITU-T G.993.5 Channel Discovery phase shall be applied with the amendments defined in clause B.8. If short-medium loop

operation is selected in the PROBING stage, the ITU-T G.993.5 Channel Discovery phase shall be applied with the amendments defined in clause B.5.6.

In both cases, the value of the control parameter *MAXNOMATPus* shall be equal to the MAXNOMATPus value configured in the CO-MIB.

B.5.6.1 R-UPDATE (amends clause 12.3.3.2.2.2 of [ITU-T G.993.2])

If the ITU-T G.994.1 MS message has the short loop bit set to ZERO, then the proposed highest downstream subcarrier indicated by the VTU-R in R-UPDATE (see Table 12-35 of [ITU-T G.993.2]) shall meet the condition for medium loop operation as defined in clause B.4.8.3 (i.e., forced medium loop operation).

B.5.7 ITU-T G.993.5 Training phase

If long loop operation is selected in the PROBING stage, then the ITU-T G.993.5 Training phase shall be applied with amendments defined in the clause B.8. If short-medium loop operation is selected in the PROBING stage, the original ITU-T G.993.5 Training phase shall be applied.

B.6 O/R-P-PROBING-LR signal exchange

The O/R-P-PROBING-LR signal exchange uses signals defined in ITU-T G.992.5, with the constraint that the duration of signals and the transitions between different signals occurs on boundaries of DMT symbols with CE. This constraint is identical to the constraint defined in clause 12.3.6.1 of [ITU-T G.993.2] to send the O/R-P-PERIODIC signals. Because only the mandatory CE is supported in the VDSL2-LR mode, the duration of each signal is a multiple of 64 symbols with CE (or 69 symbols without CE).

The O/R-P-PROBING-LR signal exchange is depicted in Figure B.2.

NOTE – The duration of the O/R-P-PROBING-LR signal exchange is between 1.5s and 1.9s.

B.6.1 O-P-PROBING-LR signals

B.6.1.1 Transmit PSD of the O-P-PROBING-LR signals

The O-P-PROBING-LR transmit PSD (*PROBINGPSDds*) shall be derived from the *NOMPSD* and *log_tssi* values exchanged in the downstream spectrum bounds and downstream spectrum shaping parameter blocks of the ITU-T G.994.1 CL message during the ITU-T G.994.1 Handshake phase, as defined in clause 8.13.2.4 of [ITU-T G.992.3], and as:

$$PROBINGPSDds(f) = CL\_NOMPSDds + log\_tssi\_ds(f)$$

where *CL_NOMPSDds* is the *NOMPSDds* indicated by the VTU-O in the ITU-T G.994.1 CL message. The *CL_NOMPSDds* shall be less than or equal to the MAXNOMPSDds configured in the CO-MIB (see clause B.10.1.2).

The PSD limits for the O-P-PROBING-LR signals shall be the PSDMASKds. The *PROBINGPSDds(f)* shall not exceed PSDMASKds(*f*) minus 3.5dB, for all subcarriers in the SUPPORTEDCARRIERSds set with indices up to 511. The PSDMASKds(*f*) is defined in Table 7-4 of [ITU-T G.993.2] and shall be derived taking into account the LIMITMASKds as defined in clause B.9.

All subcarriers included in the O-P-PROBING-LR signals shall be transmitted at the *PROBINGPSDds*, with an accuracy of ±1dB at the U-O2 reference point.

The aggregate transmit power for the O-P-PROBING-LR signals shall not exceed the minimum of the maximum aggregate downstream transmit power as defined in clause B.9 for the corresponding annex of [ITU-T G.993.2] and the MAXNOMATPds value configured in the CO-MIB. The VTU-O shall determine the value of *CL_NOMPSDds* and *log_tssi_ds* such that the aggregate transmit power of the O-P-PROBING-LR signal shall not exceed the above value.

NOTE – For long loop operation, the O-P-PROBING-LR signals could have an aggregate transmit power that exceeds the maximum aggregate downstream transmit power (as defined in Tables 6-1 and Q.1 of [ITU-T G.993.2) for the particular ITU-T G.993.2 profile selected during the ITU-T G.994.1 Handshake phase of initialization. However, this is unlikely to happen since COMB symbols are used in the O-P-PROBING-LR signals.

B.6.1.2   Symbol definitions for the O-P-PROBING-LR signals

The O-P-QUIET symbol is defined as identical to the C-QUIET symbol defined in clause 8.13.3.1.1 of [ITU-T G.992.3].

The O-P-COMB symbol shall use the subcarrier set as defined in clause 8.13.3.1.2 of [ITU-T G.992.5]. For the purpose of defining the O-P-COMB subcarrier set, the value *NSCds* shall be set to 512. All O-P-COMB subcarriers with indices that are in the SUPPORTEDCARRIERSds set with indices up 511 shall be used. These subcarriers shall be modulated by 4-QAM. The value 11 shall be mapped to those subcarriers. The constellation points on those subcarriers shall be rotated based on the 2-bit number provided by the quadrant scrambler described in clause 12.3.6.2 of [ITU-T G.993.2]. The scrambler shall be used in reset mode (see clause 12.3.6.2.1 of [ITU-T G.993.2]).

The O-P-ICOMB symbol is defined as identical to the O-P-COMB symbol, except with the value 00 mapped on the same subcarriers.

All signals consisting of O-P-COMB or O-P-ICOMB symbols shall be implemented as periodic signals, such as O/R-P-PERIODIC 1 (see clause 12.3.6.1 of [ITU-T G.993.2]).

B.6.1.3   O-P-COMB 2-LR

The O-P-COMB 2-LR state is of fixed length. In the O-P-COMB 2-LR state, the VTU-O shall transmit 3648 O-P-COMB symbols.

The O-P-COMB 2-LR state shall be followed by the O-P-QUIET 3-LR state.

B.6.1.4   O-P-QUIET 3-LR

The O-P-QUIET 3-LR state is of variable length. In the O-P-QUIET 3-LR state, the VTU-O shall transmit a multiple of 64 O-P-QUIET symbols, with a minimum of 256 and a maximum of 960 O-P-QUIET symbols. The O-P-QUIET 3-LR state shall be followed by the O-P-COMB 3-LR state.

B.6.1.5   O-P-COMB 3-LR

The O-P-COMB 3-LR state is of fixed length. In the O-P-COMB 3-LR state, the VTU-O shall transmit 64 O-P-COMB symbols.

The O-P-COMB 3-LR state shall be followed by the O-P-ICOMB 2-LR state.

B.6.1.6   O-P-ICOMB 2-LR

The O-P-ICOMB 2-LR state is of fixed length. In the O-P-ICOMB 2-LR state, the VTU-O shall transmit 64 O-P-ICOMB symbols.

The O-P-ICOMB 2-LR state shall be followed by the O-P-QUIET 4-LR state.

B.6.1.7   O-P-QUIET 4-LR

The O-P-QUIET 4-LR state is of variable length. In the O-P-QUIET 4-LR state, the VTU-O shall transmit a multiple of 64 O-P-QUIET symbols, with a minimum of 1152 and a maximum of 1408 O-P-QUIET symbols.

The VTU-O shall receive and decode the content of the message R-MSG-PCB during this state.

The VTU-O shall continue to transmit O-P-QUIET symbols until after the VTU-R transitioning to the R-P-QUIET 4-LR state. Within 128 symbols after the VTU-R transitioning to the R-P-QUIET4-LR state, the VTU-O shall transition to the next state.

If the VTU-O has successfully received the R-P-MSG-PCB message, the O-P-QUIET 4-LR state shall be followed by the O-P-COMB 4-LR state. Otherwise, the VTU-O shall return to the O-SILENT state.

B.6.1.8   O-P-COMB 4-LR

The O-P-COMB 4-LR state is of fixed length. In the O-P-COMB 4-LR state, the VTU-O shall transmit 64 O-P-COMB symbols.

The O-P-COMB 4-LR signal serves as an acknowledgement of the successful reception of the R-P-MSG-PCB message.

The O-P-COMB 4-LR state shall be followed by the ICOMB 4-LR state.

B.6.1.9   O-P-ICOMB 4-LR

The O-P-ICOMB 4-LR state is of fixed length. In the O-P-ICOMB 4-LR state, the VTU-O shall transmit 64 O-P-ICOMB symbols.

The O-P-ICOMB 4-LR state shall be followed by the O-P-MSG-PCB-LR state.

B.6.1.10   O-P-MSG-PCB-LR

In downstream direction, the transmit power shall be further adjusted by a power cutback value determined by the VTU-O during the PROBING stage, based on the maximal used downstream subcarriers requested by the VTU-R in the R-P-MSG-PCB-LR message.

The O-P-MSG-PCB-LR state is of fixed length. In the O-P-MSG-PCB-LR state, the VTU-O shall transmit 512 symbols of O-P-COMB or O-P-ICOMB to modulate the O-P-MSG-PCB-LR message. The O-P-MSG-PCB-LR message conveys the VTU-O determined power cutback level for the downstream direction.

The O-P-MSG-PCB-LR message m is defined by:

$$m = \{ m_7, \ldots , m_0 \}$$

Bits shall be defined as shown in Table B.9.

Table B.9 – Bit definition for the O-P-MSG-PCB-LR message

Bit index	Parameter	Definition
3…0	O-PCB_DS	VTU-O final downstream power cutback in dB, represented as an unsigned integer in the 0 to 15 range (4-bit value with MSB in bit 3 and LSB in bit 0) (see Note).
7…4	Reserved by ITU-T	Shall be set to 0 and ignored by the receiver.
NOTE – This power cutback shall be further used instead of the minimum downstream power cutback indicated in R-MSG-PCB-LR message. The value shall be lower than or equal to the R-MIN_PCB_DS requested by the VTU-R. If the VTU-R indicated that the line shall continue the initialization in short-medium loop operation, this field shall be set to 0 and ignored by the VTU-R.		

The 8 bits m_0-m_7 shall be transmitted in 512 symbol periods (m_0 first and m_7 last). A ZERO bit shall be transmitted as 64 consecutive O-P-COMB symbols (1 bit per 69 symbols without CE). A ONE bit shall be transmitted as 64 consecutive O-P-ICOMB symbols.

The O-P-MSG-PCB-LR state also indicates to the VTU-R that the PROBING stage is complete.

The O-P-MSG-PCB-LR state shall be followed by the O-P-QUIET 1-LR state.

B.6.2   R-P-PROBING-LR signals

B.6.2.1   Transmit PSD of the R-P-PROBING-LR signals

The R-P-PROBING-LR transmit PSD (*PROBINGPSDus*) shall be derived from the *NOMPSD* and *log_tssi* values exchanged in the upstream spectrum bounds and upstream spectrum shaping parameter blocks of the ITU-T G.994.1 CLR message during the ITU-T G.994.1 Handshake phase, as defined in clause 8.13.2.4 of [ITU-T G.992.3], and as:

$$PROBINGPSDus(f) = MIN(CL\_NOMPSDus, CLR\_NOMPSDus) - PCBus + log\_tssi\_us(f),$$

where *CL_NOMPSDus* is the *NOMPSDus* indicated by the VTU-O in the CL message and *CLR_NOMPSDus* is the *NOMPSDus* indicated by the VTU-R in the ITU-T G.994.1 CLR message. The *CL_NOMPSDus* shall be less than or equal to the MAXNOMPSDus configured in the CO-MIB (see clause B.10.1.2).

The PSD limits for the R-P-PROBING-LR signals shall be the PSDMASKus. The *PROBINGPSDus(f)* shall not exceed PSDMASKus(*f*) minus 3.5 dB for all subcarriers in the SUPPORTEDCARRIERSus set in the US0 band [f_{0L}, f_{0H}]. The PSDMASKus(*f*) is defined in Table 7-4 of [ITU-T G.993.2] and shall be derived taking into account the LIMITMASKus as defined in clause B.9.

The VTU-R shall apply a *PCBus* = 10dB if the VTU-R determines that the line is short or medium, and shall apply a *PCBus* = 0dB if the VTU-R determines that the line is long. The VTU-R shall evaluate the length of the line before sending the first active symbol of R-P-PROBING-LR signal (see Figure B.2). The VTU-R shall use these rules of setting the *PCBus* regardless whether or not short, medium or long loop operation is allowed during the ITU-T G.994.1 Handshake phase (see clause B.3).

The transmit PSD of the R-P-LINEPROBE-LR signal shall not exceed the *PROBINGPSDus*.

All subcarriers included in the R-P-PROBING-LR signals shall be transmitted at the *PROBINGPSDus* lowered with *PCBus*, with an accuracy of ±1dB at the U-R2 reference point.

The aggregate transmit power for the R-P-PROBING-LR signals shall not exceed the minimum of the maximum aggregate upstream transmit power as defined for the selected profile in Table 6-1 of [ITU-T G.993.2] and the MAXNOMATPus value configured in the CO-MIB. The VTU-O shall determine the value of *CL_NOMPSDus* such that for any valid setting of *CLR_NOMPSDus*, *PCBus* and *log_tssi_us* chosen by the VTU-R, the aggregate transmit power of the R-P-PROBING-LR signal shall not exceed the above value.

B.6.2.2   Symbol definitions for the R-P-PROBING-LR signals

The R-P-QUIET symbol is defined as identical to the R-QUIET symbol defined in clause 8.13.3.2.1 of [ITU-T G.992.3].

The R-P-COMB symbol shall use the subcarrier set as defined in clause 8.13.3.2.2 of [ITU-T G.992.5]. For the purpose of defining the R-P-COMB subcarrier set, the value *NSCus* shall be set to 32 or 64, in accordance with the US0 PSD mask defined in clause B.9.2.2. All R-P-COMB subcarriers with indices in the passband of the US0 PSD mask shall be used. These subcarriers shall be modulated by 4-QAM. The value 11 shall be mapped to those subcarriers. The constellation points on these subcarriers shall be rotated based on the 2-bit number provided by the quadrant scrambler described in clause 12.3.6.2 of [ITU-T G.993.2]. The scrambler shall be used in reset mode (see clause 12.3.6.2.1 of [ITU-T G.993.2]).

The R-P-ICOMB symbol is defined as identical to the R-P-COMB symbol, except with the value 00 mapped on the same subcarriers.

All signals consisting of R-P-COMB or R-P-ICOMB symbols shall be implemented as periodic signals, such as O/R-P-PERIODIC 1 (see clause 12.3.6.1 of [ITU-T G.993.2]).

B.6.2.3   R-P-COMB 2-LR

The R-P-COMB 2-LR state is of fixed length. In the R-P-COMB 2-LR state, the VTU-R shall transmit 256 R-P-COMB symbols.

The R-P-COMB 2-LR state shall be followed by the R-P-ICOMB 1-LR state if the VTU-R desires to use the R-P-LINEPROBE-LR state. Otherwise the R-P-COMB 2-LR state shall be followed by the R-P-QUIET 3-LR state.

B.6.2.4   R-P-ICOMB 1-LR

The R-P-ICOMB 1-LR state is of fixed length. In the R-P-COMB 1-LR state, the VTU-R shall transmit 64 R-P-ICOMB symbols.

The R-P-ICOMB 1-LR state shall be followed by the R-P-LINEPROBE-LR state.

B.6.2.5   R-P-LINEPROBE-LR

The R-P-LINEPROBE-LR state is of fixed length. In the R-P-LINEPROBE-LR state, the VTU-R shall transmit a vendor-discretionary signal with a duration of 512 symbol periods.

The R-P-LINEPROBE-LR state shall be followed by the R-P-QUIET 3-LR state.

B.6.2.6   R-P-QUIET 3-LR

The R-P-QUIET 3-LR state is of variable length. In the R-P-QUIET 3-LR state, the VTU-R shall transmit a multiple of 64 R-P-QUIET symbols, with a minimum of 128 and a maximum of 320 R-P-QUIET symbols.

The VTU-R shall continue to transmit R-P-QUIET symbols until after the VTU-O transitioning to O-P-QUIET 4-LR. Within 128 symbols after the VTU-O transitioning to O-P-QUIET 4-LR, the VTU-R shall transition to the next state.

The R-P-QUIET 3-LR state shall be followed by the R-P-COMB 3-LR state.

B.6.2.7   R-P-COMB 3-LR

The R-P-COMB 3-LR state is of fixed length. In the R-P-COMB 3-LR state, the VTU-R shall transmit 64 R-P-COMB symbols.

The R-P-COMB 3-LR state shall be followed by the R-P-ICOMB 2-LR state.

B.6.2.8   R-P-ICOMB 2-LR

The R-P-ICOMB 2-LR state is of fixed length. In the R-P-ICOMB 2-LR state, the VTU-R shall transmit 64 R-P-ICOMB symbols.

The R-P-ICOMB 2-LR state shall be followed by the R-P-MSG-PCB-LR state.

B.6.2.9   R-P-MSG-PCB-LR

In downstream direction, the transmit power shall be reduced by a power cutback value. The minimum downstream power cutback value is determined by the VTU-R during the PROBING stage.

NOTE – The VTU-R can consider its receiver dynamic range as determined by observing O-P-COMB 2-LR, and the local line conditions determined by the optional R-P-LINEPROBE-LR when determining the minimum downstream power cutback value.

The R-P-MSG-PCB-LR state is of fixed length. In the R-P-MSG-PCB-LR state, the VTU-R shall transmit 1536 symbols of R-P-COMB or R-P-ICOMB to modulate the R-P-MSG-PCB message. The R-P-MSG-PCB message conveys the VTU-R determined minimum downstream power cutback for the downstream direction, and the downstream pilot tone used for timing recovery during different states.

The R-P-MSG-PCB message m is defined by:

$$m = \{ m_{23}, \dots , m_0 \},$$

where the bits shall be defined as shown in Table B.10.

Table B.10 – Bit definition for the R-P-MSG-PCB-LR message

Bit index	Parameter	Definition
[3:0]	*R-MIN_PCB_DS*	VTU-R minimum downstream power cutback in dB, represented as an unsigned integer in the 0 to 15 range (4-bit value with MSB in bit 3 and LSB in bit 0).
[12:4]	*O-P-PILOT*	Subcarrier index of downstream pilot tone, represented as an unsigned integer in the 32 to 511 range (9-bit value with MSB in bit 12 and LSB in bit 4) (see Notes 1 and 4).
13	*OPTYPE*	Shall be set to 0 if the initialization of the line shall continue in short-medium loop operation (to become a short or medium VDSL2-LR line). Shall be set to 1 if the initialization of the line shall continue in long loop operation (a long VDSL2-LR line). (see Notes 2 and 3)
[22:14]	*LAST_TONE_DS*	Subcarrier index of the highest transmitted downstream frequency in the TRAINING stage expressed as unsigned integer (9-bit value with MSB in bit 22 and LSB in bit 14) (Notes 4 and 5).
23	Reserved by ITU-T	Shall be set to 0 and ignored by the receiver.

NOTE 1 – The indicated *O-P-PILOT* value shall be used as the index of the O-P-TREF pilot subcarrier (see clause B.7.1.4) to support/recovery of the VTU-R timing during the O-P-TRAINING stage.

NOTE 2 – If *OPTYPE* bit is set to 0, the VTU-O shall ignore all other parameters of the message.

NOTE 3 – If the ITU-T G.994.1 MS message has the long loop bit set to ZERO, then the *OPTYPE* bit shall be set to ZERO. If the ITU-T G.994.1 MS message has both the short loop bit and medium loop bit set to ZERO, then the *OPTYPE* bit shall be set to ONE (i.e., forced long loop operation).

NOTE 4 – If the *OPTYPE* bit is set to 0 (the line shall continue the initialization in short-medium loop operation), this field shall be set to 491.

NOTE 5 – The valid values of *LAST_TONE_DS* are those associated with subcarriers from the *O-P-COMB* symbol set, as defined in clause B.6.1.2, and the additional valid value of 511.

The 24 bits m_0-m_{23} shall be transmitted in 1536 symbol periods (m_0 first and m_{23} last). A ZERO bit shall be transmitted as 64 consecutive R-P-COMB symbols (1 bit per 69 symbols without CE). A ONE bit shall be transmitted as 64 consecutive R-P-ICOMB symbols.

The R-P-MSG-PCB-LR state shall be followed by the R-P-QUIET 4-LR state.

B.6.2.10   R-P-QUIET 4-LR

The R-P-QUIET 4-LR state is of variable length. In the R-P-QUIET 4-LR state, the VTU-R shall transmit a multiple of 64 R-P-QUIET symbols, with a minimum of 64 and a maximum of 192 R-P-QUIET symbols.

If the VTU-R has successfully detected the O-P-COMB 4-LR signal, the R-P-QUIET 4-LR state shall be followed by the R-P-QUIET 1-LR state. Otherwise, the VTU-R shall return to the R-SILENT state.

B.6.3   Timeline of O/R-P-PROBING-LR signals
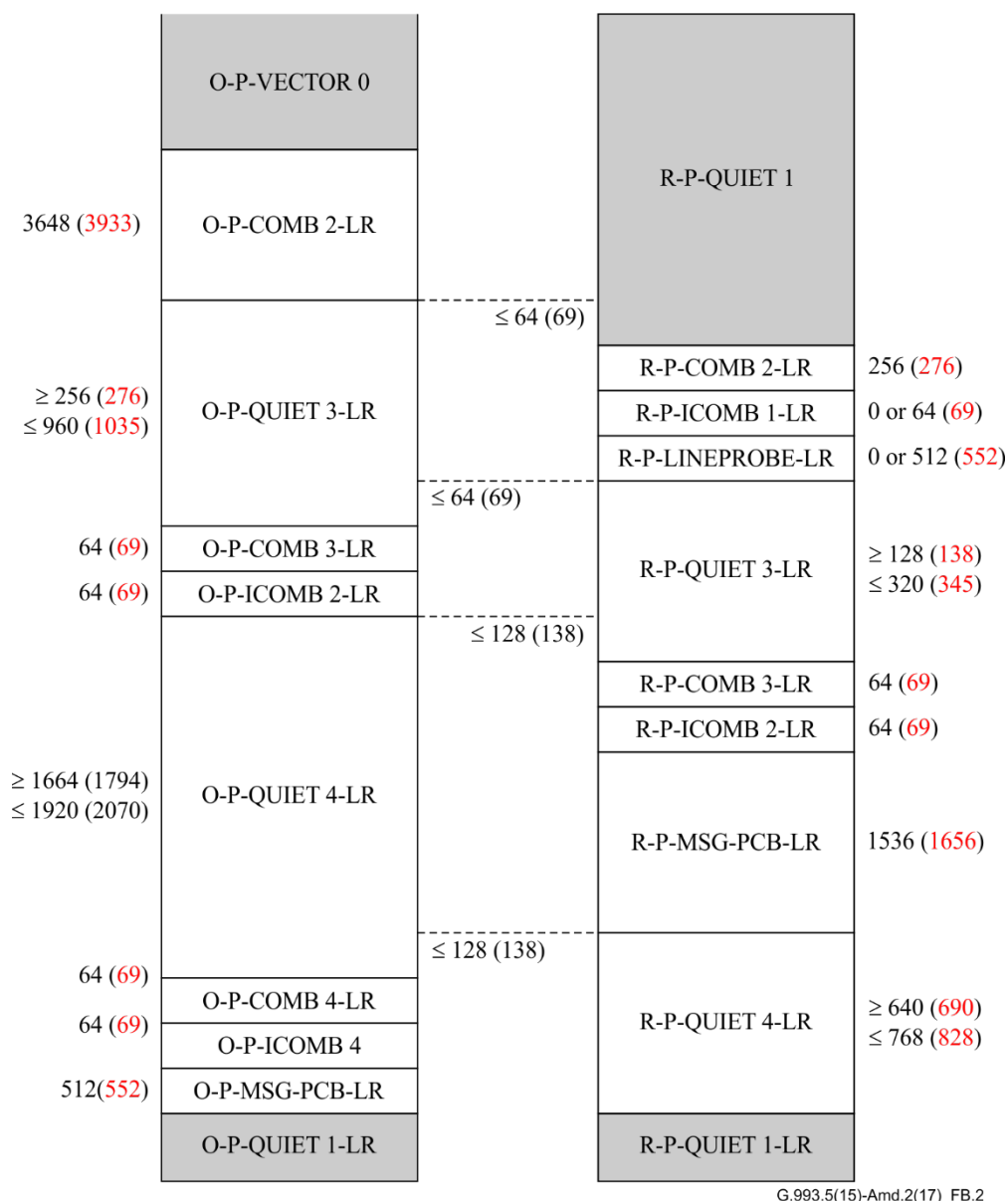
The signal exchange is depicted in Figure B.2.

Figure B.2 – Timeline of O/R-P-PROBING-LR signals

In Figure B.2, signal durations are expressed in symbols with CE (values in parenthesis are the signal durations expressed in symbols without CE). Signals shaded in grey are parts of the previous and the following stages of initialization (see Figure B.1).

B.7   O/R-P-TRAINING-LR signal exchange

The O/R-P-TRAINING-LR signal exchange is depicted in Figure B.4 and uses signals defined in [ITU-T G.992.5], with the constraint that the transitions between different signals occur on boundaries of DMT symbols with CE. The duration of each signal is a multiple of 64 symbols with CE (or 69 symbols without CE).

NOTE – The O/R-P-TRAINING-LR signal exchange allows training of the TEQ and EC before full duplex transmission. The duration of that exchange is between 1.9s and 9.7s.

B.7.1 O-P-TRAINING-LR signals

B.7.1.1 Transmit PSD of the O-P-TRAINING-LR signals

The O-P-TRAINING-LR transmit PSD (*TRAININGPSDds*) shall be derived from the *NOMPSD* and *log_tssi* values exchanged in the downstream spectrum bounds and downstream spectrum shaping parameter blocks of the ITU-T G.994.1 CL message during the ITU-T G.994.1 Handshake phase, as defined in clause 8.13.2.4 of [ITU-T G.992.3], and the *O-PCB_DS* value indicated by the VTU-O during the PROBING stage, as:

$$TRAININGPSDds(f) = NOMPSDds - PCBds + ceiled\_log\_tssi\_ds(f),$$

with

$$ceiled\_log\_tssi\_ds(f) = MIN(log\_tssi\_ds(f) + PCBds, 0 \text{ dB}),$$

and

$$PCBds = O\text{-}PCB\_DS.$$

All subcarriers included in the O-P-TRAINING-LR signals shall be transmitted at the *TRAININGPSDds*, with an accuracy of ±1dB at the U-O2 reference point.

The PSD limits for the O-P-TRAINING-LR signals shall be the PSDMASKds. The *TRAININGPSDds*(*f*) shall not exceed PSDMASKds(*f*) minus 3.5dB, for all subcarriers in the SUPPORTEDCARRIERSds set with indices up to 511. The PSDMASKds is defined in Table 7-4 of [ITU-T G.993.2] and shall be derived taking into account the LIMITMASKds as defined in clause B.9 using the highest sub-carrier with the index equal to *LAST_TONE_DS* value indicated by the VTU-R during the PROBING stage.

The aggregate transmit power for the O-P-TRAINING-LR signals shall not exceed the minimum of the maximum aggregate downstream transmit power as defined in clause B.9 for corresponding annex of [ITU-T G.993.2] and the MAXNOMATPds value configured in the CO-MIB.

The VTU-O shall determine the value of *CL_NOMPSDds, log_tssi_ds,* and *PCBds,* such that the aggregate transmit power of the O-P-TRAINING-LR signals shall not exceed the above value.

B.7.1.2 Symbol definitions for the O-P-TRAINING-LR signals

The O-P-REVERB symbol shall contain all subcarriers up to index 511. These subcarriers shall be modulated by 4-QAM. The value 11 shall be mapped to these subcarriers. The constellation points on these subcarriers shall be rotated based on the 2-bit number provided by the quadrant scrambler described in clause 12.3.6.2 of [ITU-T G.993.2]. The scrambler shall be used in reset mode (see clause 12.3.6.2.1 of [ITU-T G.993.2]).

The O-P-QUIET symbol is the same as defined for the O-P-PROBING-LR.

The O-P-TREF symbol shall be a single tone symbol. Only the *O-P-PILOT* subcarrier index specified by the VTU-R in the R-P-MSG-PCB message (i.e., the O-P-TREF pilot tone) shall be transmitted. The O-P-TREF pilot tone shall modulate the 4-QAM {0,0} constellation point. No power shall be transmitted on the other subcarriers (i.e., $X_i = Y_i = 0$).

The O-P-SEGUE symbol is defined as identical to the O-P-REVERB symbol, except with the value 00 mapped to the same subcarriers.

All signals consisting of O-P-REVERB, O-P-SEGUE or O-P-TREF symbols shall be implemented as periodic signals, such as O/R-P-PERIODIC 1 (see clause 12.3.6.1 of G.993.2).

The O-P-PILOT symbol is defined as identical to the symbols transmitted during the O-P-PILOT 1 of [ITU-T G.993.2] (see clause 12.3.3.3.1.4 of [ITU-T G.993.2]). Only the *O-P-PILOT* subcarrier index specified by the VTU-R in the R-P-MSG-PCB-LR message (i.e., the O-P-TREF pilot tone) shall be transmitted during the O-P-PILOT symbol.

B.7.1.3   O-P-REVERB 0-LR

The O-P-REVERB 0-LR state is of fixed length. In the O-P-REVERB 0-LR state, the VTU-O shall transmit 3648 O-P-REVERB symbols.

During the O-P-REVERB 0-LR state, the VTU-R restores loop timing, adjusts the AFE and acquires downstream symbol timing.

The O-P-REVERB 0-LR state shall be followed by the O-P-QUIET 5-LR state.

B.7.1.4   O-P-QUIET 5-LR

The O-P-QUIET 5-LR state is of fixed length. In the O-P-QUIET 5-LR state, the VTU-O shall transmit 128 O-P-QUIET symbols.

During the O-P-QUIET 5-LR state, the VTU-O detects R-P-REVERB 1-LR and then prepares for bidirectional transmission.

The O-P-QUIET 5-LR state shall be followed by the O-P-REVERB 1-LR state.

B.7.1.5   O-P-REVERB 1-LR

The O-P-REVERB 1-LR state is of fixed length. In the O-P-REVERB 1-LR state, the VTU-O shall transmit 512 O-P-REVERB symbols.

During the O-P-REVERB 1-LR state, the VTU-O may fine-tune its AGC (while the VTU-R is in the R-P-REVERB 1-LR state) and do adaptive AFE algorithms.

The O-P-REVERB 1-LR state shall be followed by the O-P-TREF 1-LR state.

B.7.1.6   O-P-TREF 1-LR

The O-P-TREF 1-LR state is of variable length. In the O-P-TREF 1-LR state, the VTU-O shall transmit a minimum of 512 and a maximum of 15872 O-P-TREF symbols.

During the O-P-TREF 1-LR state, VTU-O may train its TEQ.

The O-P-TREF 1-LR state shall be followed by the O-P-REVERB 2-LR state.

B.7.1.7   O-P-REVERB 2-LR

The O-P-REVERB 2-LR state is of fixed length. In the O-P-REVERB 2-LR state, the VTU-O shall transmit 64 O-P-REVERB symbols.

Transition to O-P-REVERB 2-LR state indicates to the VTU-R that VTU-O completed its TEQ training.

The O-P-REVERB 2-LR state shall be followed by the O-P-ECT-LR state.

B.7.1.8   O-P-ECT-LR

The O-P-ECT-LR state is of fixed length. In the O-P-ECT-LR state, the VTU-O shall transmit a vendor-discretionary signal with a duration of 512 symbol periods.

During this state, the VTU-O may train its echo canceller.

The O-P-ECT-LR state shall be followed by the O-P-REVERB 3-LR state.

B.7.1.9   O-P-REVERB 3-LR

The O-P-REVERB 3-LR state is of variable length. In the O-P-REVERB 3-LR state, the VTU-O shall transmit a minimum of 448 and a maximum of 15936 O-P-REVERB symbols.

The O-P-REVERB 3-LR state provides VTU-R with a training signal (presumable, for the TEQ).

The VTU-O shall continue to transmit O-P-REVERB symbols until after the VTU-R transitioning to the R-P-REVERB 3-LR state. Within 64 symbols after the VTU-R transitioning to the R-P-REVERB 3-LR state, the VTU-O shall transition to the next state.

In case the VTU-R has indicated in the ITU-T G.994.1 CLR message that it requires the VTU-O to transmit O-P-TREF symbols during the R-P-ECT-LR state (i.e., has set the "FMT-O-P-TREF2" bit to ONE), the O-P-REVERB 3-LR state shall be followed by the O-P-TREF 2-LR state. In case the VTU-R has indicated that it requires the VTU-O to transmit O-P-QUIET symbols during the R-P-ECT-LR state (i.e., has set the "FMT-O-P-TREF2" bit to ZERO), the O-P-REVERB 3-LR state shall be followed by the O-P-QUIET 6-LR state.

B.7.1.10   O-P-TREF 2-LR

The O-P-TREF 2-LR state is of fixed length. In the O-P-TREF 2-LR state, the VTU-O shall transmit 576 O-P-TREF symbols.

The O-P-TREF 2-LR state facilitates EC training at the VTU-R. The VTU-O shall ignore the signal transmitted by the VTU-R during this state.

The O-P-TREF 1-LR state shall be followed by the O-P-REVERB 4-LR state.

B.7.1.11   O-P-QUIET 6-LR

The O-P-QUIET 6-LR state is of fixed length. In the O-P-QUIET 6-LR state, the VTU-O shall transmit 576 O-P-QUIET symbols.

The VTU-O shall ignore the signal transmitted by the VTU-R during this state.

The O-P-QUIET 6-LR state shall be followed by the O-P-REVERB 4-LR state.

B.7.1.12   O-P-REVERB 4-LR

The O-P-REVERB 4-LR state is of fixed length. In the O-P-REVERB 4-LR state, the VTU-O shall transmit 1024 O-P-REVERB symbols.

During the O-P-REVERB 4-LR state, the VTU-O can adjust its parameters for bidirectional transmission.

The O-P-REVERB 4-LR state shall be followed by the O-P-SEGUE 1-LR state.
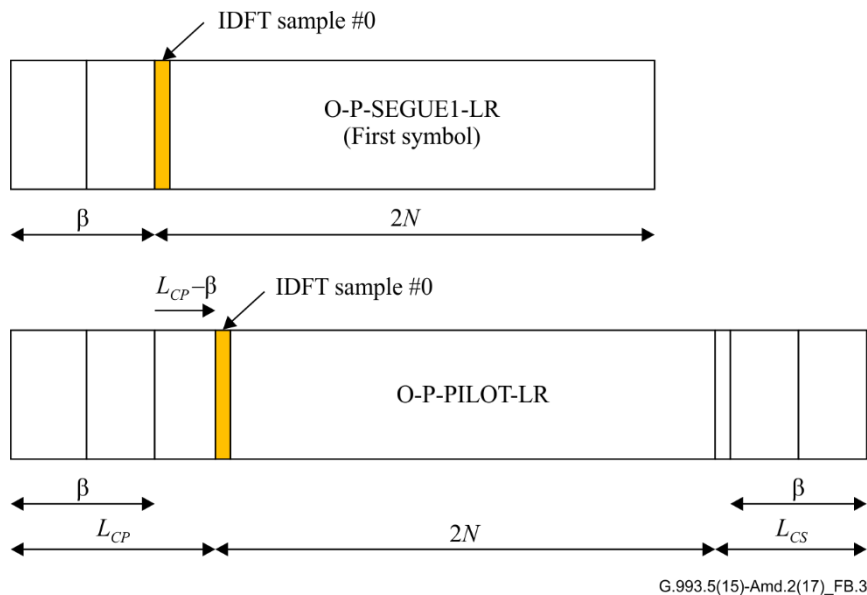
B.7.1.13   O-P-SEGUE 1-LR

The O-P-SEGUE 1-LR state is of fixed length. In the O-P-SEGUE1-LR state, the VTU-O shall transmit 64 O-P-SEGUE symbols. The first symbol of O-P-SEGUE 1-LR is used as reference time point to facilitate alignment between the timing of VDSL2-LR training and the G.993.5 Channel Discovery (see clause B.8.1). The O-P-SEGUE 1-LR state shall be followed by the the O-P-PILOT-LR state.

B.7.1.14   O-P-PILOT-LR

The O-P-PILOT-LR phase is intended to equalize the duration of the TRAINING phase between different lines of the vectored group. In the O-P-PILOT-LR state, the VTU-O shall transmit an integer number of O-P-PILOT symbols. The duration of the O-P-PILOT-LR state is variable, under the control of the VCE, and can be in the range from 128 to 31360 symbols.

The O-P-PILOT is a non-periodic signal. The alignment of the O-P-PILOT symbols and the O-P-SEGUE 1-LR state shall use two reference points associated with the IDFT sample #0 of specific symbols. The IDFT sample #0 is defined as the first sample of the block of $2N$ time samples generated by the IDFT.

The first reference point shall be the IDFT sample #0 of the first symbol of the O-P-SEGUE 1-LR state, and the second reference point is the IDFT sample #0 of the first symbol of the O-P-PILOT-LR state, as shown in the Figure B.3.

Figure B.3 – Reference samples for alignment of downstream symbols between the O-SEGUE 1-LR state and O-P-PILOT-LR state

The time offset expressed in samples between those reference points modulo the period of a DMT symbol with CE, i.e., $2N+L_{CE}$ samples, shall be as indicated by the VTU-O in the ITU-T G.994.1 Spar(2) codepoint "offset IDFT sample #0" indicated by the VTU-O. The parameter "offset IDFT sample #0" shall be an integer number of samples at the rate of 4.416 MHz.

NOTE – The value of this offset is equal to L_{CP}-β which is always less than or equal to L_{CE}, see Figure B.4. Knowledge of that offset by the receiver, allows VTU-R to derive the symbol timing during the O-P-PILOT-LR and transition into ITU-T G.993.5 Channel Discovery phase with timing acquired in the VDSL2-LR TRAINING stage. This, in turn, allows the re-use of TEQ settings and other transceiver settings obtained during the VDSL2-LR TRAINING stage.

The VCE uses O-P-PILOT-LR state to align the start of O-P-CHANNEL DISCOVERY V1 on all VDSL2-LR lines (regardless of short, medium or long loop operation type) and the regular ITU-T G.993.5 lines. The actual duration of the O-P-PILOT-LR state depends on the durations of the O-P-TREF 1-LR and O-P-REVERB 3-LR states: the sum of the durations of O-P-PILOT-LR, O-P-TREF 1-LR, and O-P-REVERB 3-LR states shall not exceed the sum of the maximum durations of O-P-TREF 1-LR and O-P-REVERB 3-LR and the minimum duration of O-P-PILOT-LR, i.e., 15872+15936+128 = 31936 symbols.

The O-P-PILOT-LR state shall be followed by the O-P-CHANNEL DISCOVERY V1 signal and the remainder of the ITU-T G.993.5 Channel Discovery phase with the amendments as specified in clause B.8.

B.7.2 R-P-TRAINING-LR signals

B.7.2.1 Transmit PSD of the R-P-TRAINING-LR signals

The R-P-TRAINING-LR transmit PSD (*TRAININGPSDus*) shall be identical to the *PROBINGPSDus*:

$$TRAININGPSDus(f) = PROBINGPSDus(f)$$

All subcarriers included in the R-P-TRAINING-LR signals shall be transmitted at the *TRAININGPSDus*, with an accuracy of ±1dB at the U-O2 reference point.

The PSD limits for the R-P-TRAINING-LR signals shall be the PSDMASKus. The PSDMASKus is defined in Table 7-4 of [ITU-T G.993.2] and shall be derived taking into account the LIMITMASKus as defined in clause B.9.

The maximum aggregate transmit power for the R-P-TRAINING-LR signals shall not exceed the minimum of the maximum aggregate upstream transmit power as defined for the selected profile in Table 6-1 of [ITU-T G.993.2] and the MAXNOMATPus value configured in the CO-MIB. The VTU-O shall determine the value of *CL_NOMPSDus* such that for any valid setting of *CLR_NOMPSDus*, *PCBus* and *log_tssi_us* chosen by the VTU-R, the aggregate transmit power of the R-P-TRAINING-LR signal shall not exceed the above value.

B.7.2.2   Symbol definitions for the R-P-TRAINING-LR signals

The R-P-QUIET symbol is the same as defined for the R-P-PROBING-LR.

The R-P-REVERB symbol shall contain all subcarriers up to index *NSCus-1*, with *NSCus* as defined in clause B.6.2.2. These subcarriers shall be modulated by 4-QAM. The value 11 shall be mapped to these subcarriers. The constellation points on these subcarriers shall be rotated based on the 2-bit number provided by the quadrant scrambler described in clause 12.3.6.2 of [ITU-T G.993.2]. The scrambler shall be used in reset mode (see clause 12.3.6.2.1 of [ITU-T G.993.2]).

The R-P-SEGUE symbol is defined as identical to the R-P-REVERB symbol, with the value 00 mapped to the same subcarriers.

All signals consisting of R-P-REVERB or R-P-SEGUE symbols shall be implemented as periodic signals, such as O/R-P-PERIODIC 1 (see clause 12.3.6.1 of [ITU-T G.993.2]).

B.7.2.3   R-P-REVERB 1-LR

The R-P-REVERB 1-LR state is of fixed length. In the R-P-REVERB 1-LR state, the VTU-O shall transmit 640 R-P-REVERB symbols.

During the R-P-REVERB 1-LR state, the VTU-R may fine-tune its AGC, does timing recovery and other adaptive AFE algorithms.

The R-P-REVERB 1-LR state shall be followed by the R-P-REVERB 2-LR state.

B.7.2.4   R-P-REVERB 2-LR

The R-P-REVERB 2-LR state is of variable length. In the R-P-REVERB 2-LR state, the VTU-R shall transmit a minimum of 384 and a maximum of 16000 R-P-REVERB symbols.

The R-P-REVERB 2-LR state provides VTU-O with a training signal (presumable, for the TEQ).

The VTU-R shall continue to transmit R-P-REVERB symbols until after the VTU-O transitioning to the O-P-REVERB 2-LR state. Within 64 symbols after the VTU-O transitioning to the O-P-REVERB 2-LR state, the VTU-R shall transition to the next state.

The R-P-REVERB 2-LR state shall be followed by the R-P-QUIET 5-LR state.

B.7.2.5   R-P-QUIET 5-LR

The R-P-QUIET 5-LR state is of variable length. In the R-P-QUIET 5-LR state, the VTU-R shall transmit a minimum of 1024 and a maximum of 16384 R-P-QUIET symbols. The number of symbols transmitted in the R-P-QUIET 5-LR state shall be a multiple of 512 symbols. However, the last R-P-QUIET symbol transmitted in the R-P-QUIET 5-LR state may be shortened by any integer number of samples (at the sample clock frequency $2N×\Delta f$, as defined in clause 10.4.4 of [ITU-T G.993.2]) to accommodate transmitter-to-receiver frame alignment.

During this state, the VTU-R shall ignore the signal transmitted by the VTU-O during the O-P-ECT-LR state. While the VTU-O is in the O-P-REVERB 3-LR state, the VTU-R may measure the downstream channel characteristics and train its TEQ. The VTU-R transitions to the next state when it has completed the necessary training.

The R-P-QUIET 5-LR state shall be followed by the R-P-REVERB 3-LR state.

B.7.2.6   R-P-REVERB 3-LR

The R-P-REVERB 3-LR state is of fixed length. In the R-P-REVERB 3-LR state, the VTU-R shall transmit 64 R-P-REVERB symbols.

Transition to R-P-REVERB 3-LR state indicates to the VTU-O that the VTU-R completed its TEQ training. It also provides a time marker for the R-P-ECT-LR state.

The R-P-REVERB 3-LR state shall be followed by the R-P-ECT-LR state.

B.7.2.7   R-P-ECT-LR

The R-P-ECT-LR state is of fixed length. In this state, the VTU-R shall transmit a vendor-discretionary signal with a duration of 512 symbol periods.

During this state, the VTU-R may train its echo canceller.

The R-P-ECT-LR state shall be followed by the R-P-REVERB 4-LR state.

B.7.2.8   R-P-REVERB 4-LR

The R-P-REVERB 4-LR state is of fixed length. In this state, the VTU-R shall transmit 1024 R-P-REVERB symbols.

During the R-P-REVERB 4-LR state, the VTU-R can adjust its parameters for bidirectional transmission.

The R-P-REVERB 4-LR state shall be followed by the R-P-SEGUE 1-LR state. The transition from the R-P-REVERB 4-LR state to the R-P-SEGUE 1-LR state is a time marker for the start time of R-P-QUIET 1 and for the VTU-R being ready to receive the O-SIGNATURE message.

B.7.2.9   R-P-SEGUE 1-LR

The R-P-SEGUE 1-LR state is of fixed length. In the R-P-SEGUE 1-LR state, the VTU-R shall transmit 64 R-P-SEGUE symbols. The first symbol of R-P-SEGUE 1-LR is used as reference point to keep the synchronization between VDSL-LR training and the G.993.5 Channel Discovery (see clause B.8.3).

The transition to the next state is a time marker for the end of the TRAINING stage and indicates that the VTU-R shall be ready to receive the O-SIGNATURE message.

The R-P-SEGUE 1-LR state shall be followed by the ITU-T G.993.5 R-P-QUIET1 state.

B.7.3   Timeline of O/R-P-TRAINING-LR signals
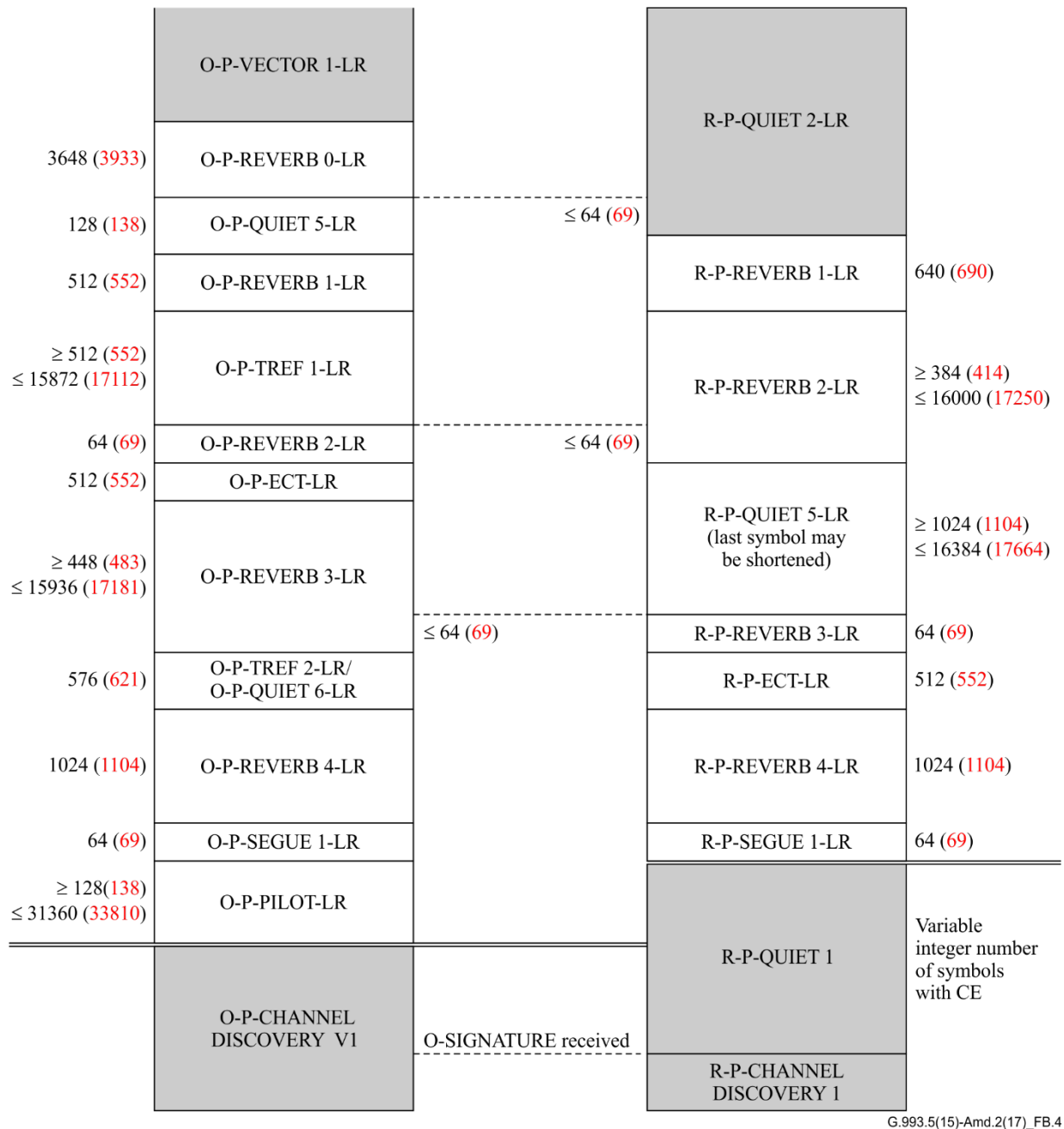
The signal exchange is depicted in Figure B.4.

Figure B.4 – Timeline of O/R-P-TRAINING-LR signals

In Figure B.4, signals durations are expressed in symbols with CE (values in parenthesis are signals durations expressed in symbols without CE). Signals shaded in grey are parts of the previous and the following stages of initialization (see Figure B.1).

NOTE – Training of TEQ can be shortened by the receiver in case TEQ is further trained during the VDSL2 initialization. With shortest TEQ training, the duration of this stage is about 1.9s.

B.8   ITU-T G.993.5 Channel Discovery phase and Training phase in long loop operation

This clause contains additional requirements on the ITU-T G.993.5 Channel Discovery phase and Training phase that apply if the long loop operation of VDSL2-LR is selected (see clauses B.4.8, B.4.9, B.5.6 and B.5.7).

The setting of the transmit path between the IDFT output and the corresponding U-interface of both the VTU-R and VTU-O that was established during the TRAINING stage shall be kept unchanged during the G.993.5 Channel Discovery phase and Training phase. The IDFT size and type of image used during the G.993.5 Channel Discovery and Training phases shall be the same as those used during the TRAINING stage.

B.8.1 ITU-T G.993.5 Channel Discovery phase in long loop operation

The SUPPORTEDCARRIERSds set shall be limited to subcarrier index 511.

The SUPPORTEDCARRIERSus set shall be limited to subcarrier index 31 for US0 type A, and to subcarrier index 63 for US0 types B and M.

B.8.1.1 Transition to ITU-T G.993.5 Channel Discovery phase

In the downstream direction, symbols in ITU-T G.993.5 Channel Discovery phase shall be aligned with symbols in O-P-PILOT-LR.

In the upstream, the transition from VDSL2-LR TRAINING stage to ITU-T G.993.5 Channel Discovery phase shall be aligned using two reference points associated with the IDFT sample #0 of specific symbols. The IDFT sample #0 is defined as the first sample of the block of $2N$ time samples generated by the IDFT.

The first reference point shall be the IDFT sample #0 of the first symbol of the R-P-SEGUE 1-LR state and the second reference point shall be the IDFT sample #0 of the first symbol of the R-P-CHANNEL DISCOVERY 1 signal, as shown in the Figure B.5.
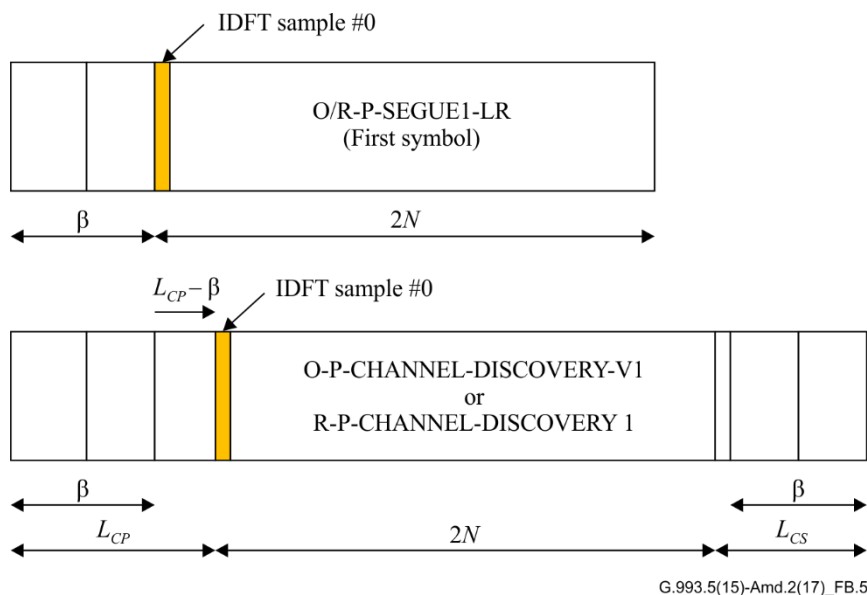

G.993.5(15)-Amd.2(17)_FB.5

Figure B.5 – Reference samples for alignment of upstream symbols between the VDSL2-LR TRAINING stage and ITU-T G.993.5 Channel Discovery phase

The time offset expressed in samples between those reference points modulo the period of a DMT symbol with CE, i.e., $2N+L_{CE}$ samples, shall be as indicated by the VTU-R in the ITU-T G.994.1 Spar(2) codepoint "offset IDFT sample #0". The parameter "offset IDFT sample #0" indicated by the VTU-R shall be an integer number of samples at the rate of 276 kHz.

NOTE – The value of this offset is equal to $L_{CP}-\beta$, which is always less than or equal to L_{CE}, see Figure B.5. Knowledge of that offset by the VTU-O, allows to derive the symbol timing during the ITU-T G.993.5 Channel Discovery phase from the one acquired in the VDSL2-LR TRAINING stage. This, in turn, allows the re-use TEQ settings and other transceiver settings obtained during the VDSL2-LR TRAINING stage.

B.8.1.2   Use of PILOT during R-P-LINEPROBE

If the ITU-T G.993.5 R-P-LINEPROBE signal is requested, the VTU-O shall transmit O-P-PILOT 1 and transition to O-P-PERIODIC 1 640 symbols after the end of transmission of O-P-SYNCHRO 1. The O-P-PILOT 1 shall use the tone index indicated during the PROBING stage.

B.8.1.3   Replacement of R-P-VECTOR signals

As upstream crosstalk cancelling is not active when the long loop operation of VDSL2-LR is selected, the R-P-VECTOR signals are removed or replaced by other signals.

The R-P-VECTOR 1 signal shall be replaced by R-P-CHANNEL DISCOVERY 1 with SOC sending R-IDLE until the O-P-SYNCHRO-V1 signal is received. After the O-P-SYNCHRO-V1 signal is received the VTU-R shall sent R-IDLE at least for the duration of 512 symbols before transmitting R-MSG 1.

B.8.1.4   O-SIGNATURE (amends clause 12.3.3.2.1.1 of [ITU-T G.993.2])

The value of the control parameter *MAXNOMATPds* indicated in the Field #8 of O-SIGNATURE message shall be determined as the minimum of the maximum aggregate downstream transmit power as defined in clause B.9 for the corresponding annex of ITU-T G.993.2 and the MAXNOMATPds value configured in the CO-MIB.

B.8.1.5   PSD adjustments during ITU-T G.993.5 Channel Discovery phase

The PSD adjustments defined in ITU-T G.993.5 Channel Discovery phase include potential changes of the downstream highest used subcarrier and the actual downstream transmit PSD, which may result in a different downstream transmit PSD than the one defined during the PROBING stage. To avoid changes in the transmission channel and corresponding degradations in the tuning of the TEQ, the mentioned adjustment of the PSD shall be done exclusively in frequency domain.

B.8.2   ITU-T G.993.5 Training phase in long loop operation

During the transition to the G.993.5 Training phase, the VTU-R shall keep symbol timing. To facilitate loop timing, the quiet symbols of O-P-VECTOR 1-1 shall be replaced by symbols containing a single subcarrier with the index of the downstream pilot tone indicated in the R-P-MSG-PCB message. The pilot tone shall be modulated with the constellation point (0,0).

To keep the position of the IDFT sample #0 between the Channel Discovery and the Training phases in upstream, the duration of R-P-QUIET V1 shall be an integer number of DMT symbols.

B.8.2.1   Replacement of R-P-VECTOR signals

The R-P-VECTOR 1-1 signal shall not be sent, i.e, the first signal of transceiver training phase is R-P-TRAINING 1.

The R-P-VECTOR 1-2 signal shall be replaced by R-P-TRAINING 1-2. The R-P-TRAINING 1-2 signal shall be identical to R-P-TRAINING 1.

B.9   Definition of limit PSD masks

This clause defines limit PSD masks and maximum aggregate transmit power (ATP) requirements applicable to VDSL2-LR mode in long loop operation. These requirements apply to the TRAINING-LR stage, the remainder of initialization and the SHOWTIME state.

B.9.1   Operation according to Annex A [ITU-T G.993.2]

VDSL2-LR mode according to Annex A of [ITU-T G.993.2] is not defined.

B.9.2 Operation according to Annex B of [ITU-T G.993.2]

B.9.2.1 Downstream Limit PSD mask and maximum aggregate transmit power

The US0 PSD type is selected in the ITU-T G.994.1 MS message. The corresponding LIMITMASKds for VDSL2-LR mode shall be as defined in Table B.7A of [ITU-T G.993.2] for PSD masks B8-11 (for US0 type A), B8-12 (for US0 type B) and B8-17 (for US0 type M), with flat extension at -100 dBm/Hz from 3.925 MHz to 30 MHz and flat extension at -110 dBm/Hz above 30 MHz, and with the modification defined in Table B.11.

The maximum aggregate downstream transmit power (as referred in clauses B.6.1.1 and B.8.1.4) shall be 20.5dBm, independent of the VDSL2 profile and US0 type selected in the ITU-T G.994.1 Handshake phase.

Table B.11 – Modification of the LIMITMASKds for VDSL2-LR mode

Frequency (kHz)	VDSL2-LR LIMITMASKds (dBm/Hz)
f_1	–36.50
$f_1 + 138$	–33.50
948.75	–33.50
1104	–36.50
NOTE – The value f_1 is 138 kHz for US0 type A and 276 kHz for US0 types B and M.	

B.9.2.2 Upstream limit PSD mask

The US0 PSD type is selected in the ITU-T G.994.1 MS message. The corresponding LIMITMASKus for VDSL2-LR mode shall be as defined in Table B.6A of [ITU-T G.993.2] for PSD masks B8-11 (for US0 type A), B8-12 (for US0 type B) and B8-17 (for US0 type M), with flat extension at –100 dBm/Hz from 686 kHz to 30 MHz and flat extension at -110 dBm/Hz above 30 MHz.

The *NSCus* shall be set to 32 for US0 type A and to 64 for US0 types B and M.

B.9.3 Operation according to Annex C of [ITU-T G.993.2]

VDSL2-LR mode according to Annex C of [ITU-T G.993.2] is not defined.

B.9.4 Operation according to Annex N of [ITU-T G.993.2]

VDSL2-LR mode according to Annex N of [ITU-T G.993.2] is not defined.

B.10 Management

This clause defines the CO-MIB configuration, status, and inventory parameters specific to the VDSL2-LR mode. These parameters shall be supported if the VTU-O supports VDSL2-LR mode.

B.10.1 Configuration parameters

B.10.1.1 VDSL2-LR enable (VDSL2-LR_ENABLE)

The configuration parameter VDSL2-LR_ENABLE (see clause 7.3.1.16.1 of [ITU-T G.997.1]) specifies for the line which VDSL2-LR operation types are allowed. It is defined as a bitmap, with following types:

• Short loop: Short loop operation according to this annex is allowed.

• Medium loop: Medium loop operation according to this annex is allowed.

• Long loop: Long loop operation according to this annex is allowed.

If none of the operation types are allowed, then the VDSL2-LR mode (i.e., operation according to this annex) is "disabled". If at least one of the operation types is allowed, then the VDSL2-LR mode (i.e., operation according to this annex) is "enabled" (see Table B.1).

B.10.1.2 Downstream maximum nominal power spectral density (MAXNOMPSDds)

The configuration parameter MAXNOMPSDds (see clause 7.3.1.2.1 of [ITU-T G.997.1]) specifies for the line the maximum value of the *NOMPSDds* (used to determine the *PROBINGPSDds*, see clause B.6.1.1) as indicated by the VTU-O in the downstream spectrum bounds in the ITU-T G.994.1 CL message.

B.10.1.3 Upstream maximum nominal power spectral density (MAXNOMPSDus)

The configuration parameter MAXNOMPSDus (see clause 7.3.1.2.2 of [ITU-T G.997.1]) specifies for the line the maximum value of the *NOMPSDus* (used to determine the *PROBINGPSDus*, see clause B.6.2.1) as indicated by the VTU-O in the upstream spectrum bounds in the ITU-T G.994.1 CL message.

B.10.1.4 Downstream PSD Mask (MIBMASKds) (amends clause 7.2.1.1 of [ITU-T G.993.2])

The configuration parameter MIBMASKds (see clause 7.3.1.2.9 of [ITU-T G.997.1]) represents the MIB PSD mask and shall lie at or below the maximum of the Limit PSD mask specified in the selected annex of [ITU-T G.993.2] and, if the VDSL2-LR mode is "enabled" (see clause B.10.1.1), the limit PSD mask defined in clause B.9. Its definition shall be under the network management control (a MIB-controlled mechanism), as defined in [ITU-T G.997.1].

The breakpoints used to construct the MIB PSD mask shall be specified so that the minimum of the limit PSD mask specified in the selected annex and the MIB PSD mask can be constructed using no more than 32 breakpoints in the frequency ranges in which the MIB PSD mask is specified.

B.10.1.5 VDSL2 PSD mask class selection (CLASSMASK)

If the VDSL2-LR mode is "enabled" (see clause B.10.1.1), then the configuration parameter CLASSMASK (see clause 7.3.1.2.15 of ITU-T G.997.1) shall be set to one of the Annex B classmasks 997-M2x, 998-M2x, 998ADE-M2x, 998E35-M2x or 998ADE35-M2x.

B.10.1.6 Downstream maximum nominal aggregate transmit power (MAXNOMATPds)

The configuration parameter MAXNOMATPds is defined in the CO-MIB (see clause 7.3.1.2.3 of [ITU-T G.997.1]) and specifies:

- an upperbound to the downstream aggregate transmit power during PROBING for all operation types (short loop, medium loop and long loop operation);

- an upperbound to the downstream aggregate transmit power during TRAINING for long loop operation;

- an upperbound to the downstream aggregate transmit power during O-P-VECTOR 1 for short-medium loop operation;

- an upperbound to the control parameter *MAXNOMATPds* in O-SIGNATURE for all operation types (short loop, medium loop and long loop operation); and

- an upperbound to the recalculated control parameter *MAXNOMATPds* for the determination of MREFPSDds in ITU-T G.993.5 Channel analysis and exchange phase for medium loop operation.

The MAXNOMATPds setting in the CO-MIB shall not exceed 20.5 dBm.

NOTE – In this annex, the MAXNOMATPds setting in the CO-MIB may exceed the maximum aggregate downstream transmit power specified in Table 6.1 of [ITU-T G.993.2].

B.10.1.7 Upstream maximum nominal aggregate transmit power (MAXNOMATPus)

The configuration parameter MAXNOMATPus is defined in the CO-MIB (see clause 7.3.1.2.4 of [ITU-T G.997.1]) and specifies:

•   an upperbound to the upstream aggregate transmit power during PROBING for all operation types (short loop, medium loop and long loop operation);

•   an upperbound to the upstream aggregate transmit power during TRAINING for long loop operation;

•   an upperbound to the control parameter *MAXNOMATPus*.

The MAXNOMATPus setting in the CO-MIB shall not exceed the maximum aggregate upstream transmit power specified in Table 6.1 of [ITU-T G.993.2].

B.10.2 Status parameters

B.10.2.1 VDSL2-LR actual operation type (VDSL2-LR_ACTOPTYPE)

The status parameter VDSL2-LR_ACTOPTYPE (see clause 7.5.1.44.1 of [ITU-T G.997.1]) reports the line's actual operation type (regardless whether this selection is autonomous by the VTU-R or forced through the CO-MIB).

The valid values are:

•   No operation type selected: Operation without this annex.

        ITU-T G.994.1 MS message has VDSL2-LR Spar(2) bit set to 0.

•   Short loop: Short loop operation according to this annex.

        ITU-T G.994.1 MS message has VDSL2-LR Spar(2) bit set to 1 and short-medium loop operation is selected in the PROBING stage and the condition for short loop operation (defined in clause B.4.8.3) is met.

•   Medium loop: Medium loop operation according to this annex.

        ITU-T G.994.1 MS message has VDSL2-LR Spar(2) bit set to 1 and short-medium loop operation is selected in the PROBING stage and the condition for medium loop operation (defined in clause B.4.8.3) is met.

•   Long loop: Long loop operation according to this annex.

        ITU-T G.994.1 MS message has VDSL2-LR Spar(2) bit set to 1 and long loop operation is selected in the PROBING stage.

B.10.3 Inventory parameters

B.10.3.1 VDSL2-LR support (VDSL2-LR_SUPPORT_O/R)

The VDSL2-LR_SUPPORT_O (see clause 7.4.14.1 of [ITU-T G.997.1]) and VDSL2-LR_SUPPORT_R (see clause 7.4.14.1 of [ITU-T G.997.1]) inventory parameters report, for the VTU-O and the VTU-R respectively, whether VDSL2-LR mode is not supported (set to 0) or supported (set to 1).

B.10.4 Test parameters

B.10.4.1 Test parameter group size

If the "Support of VDSL2-LR" bit was set to ONE in the last previous ITU-T G.994.1 MS message, the group size shall be determined according to the equation in clause 11.4.1 of [ITU-T G.993.2], with theta equal to the highest subcarrier index in the MEDLEY set for test parameters measured during the Channel Discovery phase and for test parameters measured during other phases.

NOTE – This clause applies to the VDSL2-LR mode, regardless whether short, medium or long loop operation is selected.

B.11 Nominal aggregate transmit power (NOMATP) (replaces clause 10.3.4.2.1 of [ITU-G.993.2])

NOTE – Unless otherwise specified, references in this clause refer to [ITU-T G.993.2].

The nominal aggregate transmit power (NOMATP) shall be computed by the following equation:

$$\text{NOMATP} = 10\log_{10}\Delta f + 10\log_{10}\left(\sum_{i \in \text{MEDLEY set}}\left(10^{\frac{\text{MREFPSD}[i]}{10}}\, g_i^2\right)\right),$$

where MREFPSD[i] and g_i are, respectively, the values of MREFPSD in dBm/Hz and gain (linear scale) for subcarrier i from the MEDLEY set (see clause 12.3.3.2.1.3), and Δf is the subcarrier spacing in Hz.

The downstream NOMATP (NOMATPds) shall be computed for subcarriers from the downstream MEDLEY set (MEDLEYds). The upstream NOMATP (NOMATPus) shall be computed for subcarriers from the upstream MEDLEY set (MEDLEYus).

The maximum NOMATP during ITU-T G.993.5 Channel analysis and exchange phase and during showtime is determined by the control parameter *MAXNOMATP*. The value of this control parameter is derived during initialization based on the CO-MIB configuration parameter MAXNOMATP as well as the operation type (short loop, medium loop, or long loop operation). The g_i settings at the VTU-O and VTU-R shall be such that the values of NOMATPds and NOMATPus do not exceed, respectively, the CO-MIB parameter MAXNOMATPds and MAXNOMATPus. To assist the proper gain setting at the VTU-O, the MAXNOMATPds is communicated from the VTU-O to the VTU-R during the Channel Discovery phase.

Appendix I

Crosstalk channel modelling

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

I.1   Scope

This appendix provides information on stochastic models for a MIMO FEXT coupling channel in digital subscriber line (DSL) transmission systems operating on twisted-pair cables. For a number of DSL systems, the FEXT coupling among them can be modelled as a MIMO system.

The models are derived using a statistical analysis of measurements of ingress energy into pairs of a cable from other pairs in the same cable. The data on which the models are based was gathered from measurements of actual loop plant deployed in various regions in the world.

I.2   Purpose

The purpose of this appendix is to provide the industry with a tool for simulating FEXT coupling among multiple DSL lines.

I.3   MIMO crosstalk channel model A

A model for the crosstalk channel for North America and Europe can be found in [b-ATIS-0600024]. This model is based on data gathered from measurements of actual loop plant deployed in North America and Europe. [b-ATIS-0600024] defines a MIMO crosstalk channel model based on these measurements and includes justification for the model.

I.4   MIMO crosstalk channel model C

The data on which this model is based was gathered from measurements of actual loop plant deployed in Japan.

I.4.1   Assumptions to crosstalk model

The crosstalk model is based upon a 0.4 mm (in diameter) polyethylene (PE) insulated cable called a colour coded polyethylene (CCP) cable. The pair binding structure applied to the PE insulated cable is given in Figure I.1, where pair numbers, #1-#10, are attached. In the figure, a quad is formed by twisting four insulated conductors (two pairs), and a binder group called a unit is formed by binding five quads (ten pairs). Although a PE insulated cable contains one to several units, we can ignore the effect of inter unit crosstalk for simplicity, as inter unit crosstalk is much smaller than intra unit crosstalk. Then, a single unit of ten pairs (five quads) of the PE insulated cable is applied to the crosstalk model.
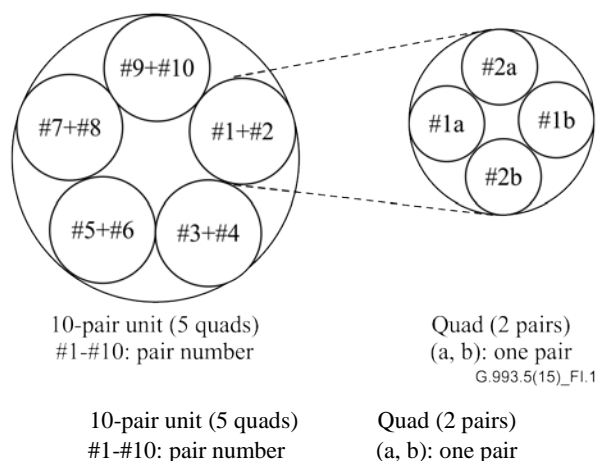
Figure I.1 – Cable model (0.4 mm PE insulated cable)

It is known that the probability density function (PDF) of crosstalk coupling (attenuation) losses in dB is a normal distribution with an average expressed by M (dB) and a standard deviation expressed by σ (dB). There are three inter pair location relationships in the unit of the PE insulated cable, which are intra quad, adjacent quad, and every second quad. So, there are three kinds of the population of the crosstalk coupling losses in the unit. The average M_k (dB) [k=1, 2, 3] and the standard deviation σ_k (dB) [k=1, 2, 3] of the FEXT coupling losses are given in Table I.1, where the indices, k=1, 2, 3, correspond to three inter pair location relationships in the unit that form each population.

Table I.1 – FEXT average and standard deviation

Item	k=1	k=2	k=3
	Intra quad	Adjacent quad	Every second quad
FEXT average M_k	69.2 (dB)	74.2 (dB)	75.7 (dB)
FEXT standard deviation σ_k	6.56 (dB)	8.15 (dB)	7.38 (dB)
NOTE – The value of M_k (dB) is given as the value of FEXT loss at $f=f_{FXT}=160*10^3$ (Hz) and $d=d_{FXT}=1*10^3$(m).			

I.4.2 Generation of a sample value for FEXT coupling loss

FEXT coupling loss random samples, $XT_k(i)$ (dB) [k=1, 2, 3], between any two pairs in the unit are given in Table I.2 in the form of the 10-by-10 matrix, where the index "k" shows the same as in Table I.1, and the index "i" shows that a different value can be given. It is assumed that the crosstalk from the interfering pair (#m) to the interfered pair (#n) is identical to the crosstalk from the interfering pair (#n) to the interfered pair (#m). Therefore, two sample group values are symmetric with respect to the diagonal line in Table I.2. Consequently, there can be a maximum of five different sample values for $XT_1(i)$ (k=1), a maximum of twenty different sample values for $XT_2(i)$ (k=2), and a maximum of twenty different sample values for $XT_3(i)$ (k=3).

Table I.2 – FEXT loss sample

I-ing \ I-ed	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
#1		$XT_1(1)$	$XT_2(1)$	$XT_2(2)$	$XT_3(1)$	$XT_3(2)$	$XT_3(3)$	$XT_3(4)$	$XT_2(3)$	$XT_2(4)$
#2	$XT_1(1)$		$XT_2(5)$	$XT_2(6)$	$XT_3(5)$	$XT_3(6)$	$XT_3(7)$	$XT_3(8)$	$XT_2(7)$	$XT_2(8)$
#3	$XT_2(1)$	$XT_2(5)$		$XT_1(2)$	$XT_2(9)$	$XT_2(10)$	$XT_3(9)$	$XT_3(10)$	$XT_3(11)$	$XT_3(12)$
#4	$XT_2(2)$	$XT_2(6)$	$XT_1(2)$		$XT_2(11)$	$XT_2(12)$	$XT_3(13)$	$XT_3(14)$	$XT_3(15)$	$XT_3(16)$
#5	$XT_3(1)$	$XT_3(5)$	$XT_2(9)$	$XT_2(11)$		$XT_1(3)$	$XT_2(13)$	$XT_2(14)$	$XT_3(17)$	$XT_3(18)$
#6	$XT_3(2)$	$XT_3(6)$	$XT_2(10)$	$XT_2(12)$	$XT_1(3)$		$XT_2(15)$	$XT_2(16)$	$XT_3(19)$	$XT_3(20)$
#7	$XT_3(3)$	$XT_3(7)$	$XT_3(9)$	$XT_3(13)$	$XT_2(13)$	$XT_2(15)$		$XT_1(4)$	$XT_2(17)$	$XT_2(18)$
#8	$XT_3(4)$	$XT_3(8)$	$XT_3(10)$	$XT_3(14)$	$XT_2(14)$	$XT_2(16)$	$XT_1(4)$		$XT_2(19)$	$XT_2(20)$
#9	$XT_2(3)$	$XT_2(7)$	$XT_3(11)$	$XT_3(15)$	$XT_3(17)$	$XT_3(19)$	$XT_2(17)$	$XT_2(19)$		$XT_1(5)$
#10	$XT_2(4)$	$XT_2(8)$	$XT_3(12)$	$XT_3(16)$	$XT_3(18)$	$XT_3(20)$	$XT_2(18)$	$XT_2(20)$	$XT_1(5)$	

I-ed: Interfered pair number

I-ing: Interfering pair number

When generating a random sample $XT_k(i)$ (dB), assuming the cumulative distribution point of Q (%) of the generated sample value is useful. The $XT_k(i)$ (dB) with the cumulative distribution point of Q (%) is given below, assuming a normal distribution with the average Mk (dB) and the standard deviation σ_k (dB) given in Table I.1. Table I.3 gives an example calculated by the equations below.

$$XT_k(i) = M_k + \Delta_k(i)$$

$$\Delta_k(i)\rho_i\sigma_k$$

$$pdf(u) = \frac{1}{\sqrt{2\pi}} e^{-\frac{u^2}{2}}$$

$$Q(\rho_i) = \int_{\rho_i}^{\infty} pdf(u)\,du$$

where k = 1, 2, 3,

when k = 1, i = 1, 2, 3,…, max(5),

when k = 2, i = 1, 2, 3,…, max(20),

when k = 3, i = 1, 2, 3,…, max(20),

M_k (dB): average of FEXT coupling losses at $f = f_{FXT}$ and $d = d_{FXT}$, see Table I.1

σ_k (dB): standard deviation of FEXT coupling losses, see Table I.3.

Table I.3 – Example of random sample $XT_k(i)$ with cumulative distribution point of Q (%)

Cumulative distribution point (%)	ρ_i	$XT_k(i)$ (dB)		
		k=1	*k=2*	*k=3*
		Intra quad	Adjacent quad	Every second quad
$Q(\rho_i)$=0.01(%)	3.72	93.6(dB)	104.5(dB)	103.2(dB)
$Q(\rho_i)$=0.1(%)	3.09	89.5(dB)	99.4(dB)	98.5(dB)
$Q(\rho_i)$=1(%)	2.33	84.5(dB)	93.2(dB)	92.9(dB)
$Q(\rho_i)$=5(%)	1.64	80.0(dB)	87.6(dB)	87.8(dB)
$Q(\rho_i)$=10(%)	1.28	77.6(dB)	84.6(dB)	85.1(dB)

Table I.3 – Example of random sample XT$_k$(i) with cumulative distribution point of Q (%)

Cumulative distribution point (%)	ρ_i	XT$_k$(i) (dB)		
		k=1	**k=2**	**k=3**
		Intra quad	**Adjacent quad**	**Every second quad**
Q(ρ_i)=20(%)	0.842	74.7(dB)	81.1(dB)	81.9(dB)
Q(ρ_i)=30(%)	0.524	72.6(dB)	78.5(dB)	79.6(dB)
Q(ρ_i)=40(%)	0.253	70.9(dB)	76.3(dB)	77.6(dB)
Q(ρ_i)=50(%)	0	69.2(dB)	74.2(dB)	75.7(dB)
Q(ρ_i)=60(%)	−0.253	67.5(dB)	72.1(dB)	73.8(dB)
Q(ρ_i)=70(%)	−0.524	65.8(dB)	69.9(dB)	71.8(dB)
Q(ρ_i)=80(%)	−0.842	63.7(dB)	67.3(dB)	69.5(dB)
Q(ρ_i)=90(%)	−1.28	60.8(dB)	63.8(dB)	66.3(dB)
Q(ρ_i)=95(%)	−1.64	58.4(dB)	60.8(dB)	63.6(dB)
Q(ρ_i)=99(%)	−2.33	53.9(dB)	55.2(dB)	58.5(dB)
Q(ρ_i)=99.9(%)	−3.09	48.9(dB)	49.0(dB)	52.9(dB)
Q(ρ_i)=99.99(%)	−3.72	44.8(dB)	43.9(dB)	48.2(dB)

I.4.3 FEXT coupling channel transfer function

The voltage transfer function of FEXT coupling channel is required for simulating the self-FEXT cancellation. It is given below as HFXT$_{ki}$(f, d), where the indices "k" and "i" show the same as XT$_k$(i). Φ_k(i) gives a FEXT coupling phase variation, and the value of Φ_k(i) (rad/m) is given as an arbitrary value within the range of 0-2π for each sample, which means that there can be a maximum of forty-five different values in Table I.2.

$$HFXT_{ki}(f,d) = e^{(-\gamma d - j\phi_k(i))} 10^{-XT_k(i)/20} \left(\frac{f}{f_{FXT}}\right) \left(\frac{d}{d_{FXT}}\right)^{1/2}$$

where

f (Hz),

d (m): FEXT coupling length (= line length)

y: line propagation constant (= α + jβ, see ITU-T G.993.1 Annex F.3)

XT$_k$(i) (dB): FEXT sample (at $f = f_{FXT}$ and at $d = d_{FXT}$)

ϕ_k (i)(rad/m): a uniformly distributed random variable over the range [0,2π].

A user of this model should populate the 10×10 coupling matrix described in Table I.2 using random draws from the tri-modal distributions for the geometric dependent couplings in Table I.1. These random draw values may be assessed to their relative likelihood by comparing them with the associated values provided in Table I.3.

Appendix II

Examples of VCE control of initialization process
in the activation of multiple lines in the vectored group

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

II.1   Introduction

Vectoring is designed for the FEXT cancellation across multiple VDSL2 lines. In clause 10, the initialization is described in detail mainly from the viewpoint of a single line. This appendix provides two examples of methods allowing the VCE to handle activation of multiple lines that attempt to join the vectored group in arbitrary order. If the bit "8192 superframes duration for O-P-VECTOR 1" is enabled in the ITU-T G.994.1 phase (see clause 10.2), the VCE may use the first method based on the handling lines that became late for the current initialization cycle in a waiting group. Alternatively, the VCE may use the second method based on ITU-T G.994.1 handshake capabilities to control the time when line is ready for joining.

II.2   VCE handling two groups of initializing lines

In this method, the VCE maintains initializing lines in two groups after the vectored group is started. One group is called "joining group" and the other is called "waiting group". Both of the groups have two states: the open state and the closed state. When a line enters the Channel Discovery phase of the initialization, it will be added to one of the groups. Table II.1 shows the decision to which group the line is added.

Table II.1 – VCE decision to which group the line is added

Joining group state	Open	Closed	Closed	Open
Waiting group state	Closed	Open	Closed	Open
Decision by the VCE for new lines	Added to the joining group	Added to the waiting group	Will be added to the waiting group when it opens	Not valid

Note that the joining group and the waiting group are never in the open state at the same time. The full mechanism is described as follows:

1.   The joining group is a group of lines which are controlled by the VCE for normal initialization. These lines are currently performing or about to perform a normal initialization process after the ITU-T G.994.1 phase. Initially, after the system power is on, the joining group is open and empty. Once the VCE starts FEXT channel coefficient estimation (VTU-O starts transmission O-P-VECTOR 1 signal), the joining group is closed. The joining group can be open again when the joining process is over (no lines remain in the joining group). When a line in the joining group drops during the initialization or reaches Showtime, it is removed from the joining group.

2.   The waiting group is a group of lines which are controlled by the VCE to wait prior to beginning their normal initialization after the ITU-T G.994.1 phase, until lines in the joining group complete their initialization. Initially, after the system power is on, the waiting group is closed and empty. The VCE can add new lines that have completed ITU-T G.994.1 handshake to the waiting group as follows:

–   if a line is ready to join the waiting group at an instant when the waiting group is open, it joins the waiting group and the VTU-O starts transmitting on the joining line the O-P-VECTOR 1 signal with all tones active until the lines in the joining group complete the initialization.

– if a line is ready to join the waiting group at an instant when the waiting group is closed, then the VTU-O proceeds as follows:

– if the bit "Use of O-P-VECTOR 1 flag tones only" is enabled in the ITU-T G.994.1 phase, the line joins the waiting group and the VTU-O starts transmitting on the joining line the O-P-VECTOR 1 signal with only flag tones active, while other tones are masked. When the waiting group opens, the VTU-O continues transmitting the O-P-VECTOR 1 signal now with all tones active until the lines in the joining group complete the initialization;

– if the bit "Use of O-P-VECTOR 1 flag tones only" is disabled in the ITU-T G.994.1 phase, the line waits up to 512 symbols for the waiting group to open. If the waiting group opens within 512 symbols, the VTU-O starts transmitting O-P-VECTOR 1 with all tones active until the lines in the joining group complete the initialization. Otherwise, the VTU-O returns to the state O-SILENT.

The waiting group can only be open when the joining group is closed. When the VCE estimates the FEXT channel coefficients, the waiting group is kept closed to avoid introducing non-orthogonal crosstalk from new lines. After the estimation of FEXT channel coefficients is finished, the waiting group can be open again. If a line in the waiting group drops during the initialization, it is removed from the waiting group.

3. When the joining lines transmit the O-P-VECTOR 1-1 and O-P-VECTOR 2-1 signals, the VCE estimates the downstream FEXT coupling coefficients from the lines of the waiting group into the lines that are in Showtime and into the lines of the joining group. Thus, the FEXT from the waiting group lines can be cancelled such that the SNR of the joining group lines can be measured with no impact of downstream FEXT from the waiting lines.

4. When the lines in the joining group are in the Channel Analysis and Exchange phase of initialization, the waiting group should be kept closed to avoid any new lines being added to the waiting group until all the joining lines have completed the SNR measurements. New lines cannot therefore disturb measuring SNR in the joining group in the Channel Analysis and Exchange phase.

5. Once there are no lines remaining in the joining group, all lines of the waiting group are moved into the joining group, and the waiting group is closed. After that, if the joining group is not empty, the VCE can start the Channel Discovery phase of the new initialization process. Otherwise, the joining group is kept open for the new activating lines thereafter.

The above procedure is illustrated in Figure II.1.

ITU-T G.993.5 Initialization phases	VCE	Joining group	Waiting group	New activating lines
Handshake	… …	Open	Closed	Be added to the joining group and initialize as normal
O-P-QUIET 1				
O-P-VECTOR 1	Receive error samples to estimate downstream coefficients from joining group lines to showtime lines	Closed	Closed	Be added to waiting group and transmits O-P-VECTOR 1 with only flag tones active
… …	… …		Open	Be added to the waiting group and transmits O-P-VECTOR 1 with all tones active
O-P-VECTOR 1-1	Receive error samples to update downstream coefficients from joining group lines to showtime lines		Closed	Be added to waiting group and transmits O-P-VECTOR 1 with only flag tones active
… …	… …		Open	Be added to the waiting group and transmit O-P-VECTOR 1 with all tones active
O-P-VECTOR 2-1	Receive error samples to estimate downstream coefficients from showtime and joining group lines **and waiting group lines** to joining group lines		Closed	Be added to waiting group and transmits O-P-VECTOR 1 with only flag tones active
O-P- SYNCHRO V4	… …			
Channel analysis and exchange	All line SNR estimation finished		Closed	Be blocked to add to waiting group until time out to drop
			Open	Be added to the waiting group and transmit O-P-VECTOR 1 with all tones active
Case 1: Showtime Case 2: O-P-VECTOR 1	Prepare for the next initialization procedure if there is no joining group lines or receive error samples to estimate the downstream coefficients from joining group lines to showtime lines	Case 1 : Open Case 2: Closed	Closed	Be added to the joining group and initialize as normal or be blocked to add to both groups until time out to drop

G.993.5(15) FII.1

Figure II.1 – Status of joining and waiting groups, and the new activating lines during initialization (in the case where the bit "Use of O-P-VECTOR 1 flag tones only" is enabled in the ITU-T G.994.1 phase)

With this controlling mechanism by the VCE, at least the following three benefits can be achieved:

1. For the waiting group lines, they can start transmission of the O-P-VECTOR 1 signal even if they complete the ITU-T G.994.1 phase after other joining lines entered the Channel Discovery phase. Thus, the time of the ITU-T G.994.1 phase is saved. The O-P-VECTOR 1 time may be significantly shortened because VCE already estimated crosstalk from the majority of lines in the waiting group into active lines.

2. In the multiple lines initialization scenarios, the majority of lines that enter the Channel Discovery phase after the VCE starts to estimate the FEXT coupling channel coefficients will be added to the waiting group. Hence, they can start their initialization process in a synchronized step after the current initialization process handled by the VCE is completed.

All lines can go to Showtime in not more than two cycles of the vectoring initialization process (from channel discovery to Channel Analysis and Exchange). Thus, initialization time is substantially reduced compared to the current initialization process, in which lines that arrive after the beginning of initialization are dropped back to handshake and their initialization could last for multiple cycles of the vectoring initialization process.

3.   If there are no new lines added to the waiting group after the SNR estimation during the Channel Analysis and Exchange phase, then the downstream FEXT channel coefficients from the lines of the waiting group into Showtime lines are already handled by the VCE, and the O-P-VECTOR 1 stage can be passed straight forwardly by applying the minimum O-P-VECTOR 1 duration of 4×257 symbols. This further saves initialization time.

II.3   VCE using handshake capabilities

The activation of multiple lines in the vectored group may be managed by the VCE through the use of ITU-T G.994.1 handshake capabilities as follows:

1.   When new lines in the vector group enter the ITU-T G.994.1 phase of initialization, the VTU-R may continually send R-TONES-REQ to initiate handshake as defined in [ITU-T G.994.1].

2.   The VCE knows the state of all of the transceivers undergoing ITU-T G.993.5 initialization. When the VCE detects completion or near-completion of the ITU-T G.993.5 initialization cycle for the current group of joining lines, the VCE enables the VTU-Os that are detecting R-TONES-REQ to respond with C-TONES to progress with handshake for constructing the next group of joining lines.

3.   The timeout of the VTU-Rs to the detection of O-SIGNATURE is vendor specific. It is observed that the duration of O-P-QUIET 1 is 1024 symbols maximum, that the duration of O-P-VECTOR 1 is 1024×257 symbols, and that the duration of O-IDLE is a maximum of 2000 symbols; this corresponds to a time period of approximately 66.5 seconds.

Appendix III

SNR-based FEXT channel estimation method

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

III.1 Tools

The SNR-based FEXT channel estimation method described in this appendix uses the reported SNR-ps (reported by the VTU-R to the VTU-O), as defined in clause 11.4.1 of [ITU T G.993.2].

III.2 Estimation of FEXT channels from a new line into existing lines

III.2.1 Introduction

Assuming K active lines (index i going from 0 to K–1) and one initializing line with number K, the downstream received signal at the CPE of victim line number i=0 can be written as:

$$y = Hx + n$$

$$y_0 = \underbrace{H_{0,0}x_0}_{\text{Useful signal}} + \underbrace{\sum_{i=1}^{K-1}H_{0,i}x_i}_{\text{FEXT from active lines}} + \underbrace{H_{0,K}x_K}_{\text{FEXT from new line}} + \underbrace{n_0}_{\text{External noise}} \qquad \text{(III-1)}$$

where:

$H_{0,0}$: The direct channel transfer function of the victim line.

$H_{0,i}$: For i=1 ... K–1 the FEXT crosstalk channel transfer function, from active line i to the victim line.

$H_{0,K}$: The FEXT crosstalk channel transfer function, from the new line K to the victim line.

x_0: The data symbols from the victim line, with variance σ_0^2.

x_i: For i=1 ... K, the data symbols from the active lines, with variance σ_i^2.

x_K: The data symbols from line K, with variance σ_K^2.

n_0: The external noise on the victim line, with variance σ_n^2.

NOTE – In equation III-1, it is assumed that the FEXT is not yet pre-compensated. The equations applicable in the presence of pre-compensation are presented in clause III.2.7.

The pre-coding matrix F is typically defined as $H^{-1}diag(H)$.

If $H = diag(H)(I + C)$ is defined, then F can be approximated (first order) by $F = I - \hat{C}$,

with $\hat{C}$ being an estimate of C.

Hence, the goal of channel estimation is to find the elements of C, with

$$C_{v,i} = \frac{H_{v,i}}{H_{v,v}}, \ v \neq i \ \text{ so in this case, with } v = 0, \text{ this becomes } C_{0,i} = \frac{H_{0,i}}{H_{0,0}}, \text{ for } i\text{=1 .. } K$$

III.2.2 Probing signal

Under normal conditions, the following model can be used as:
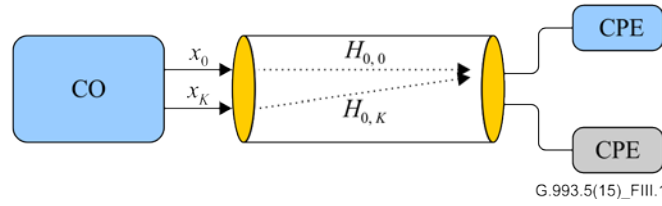

Figure III.1 – Crosstalk model – normal condition

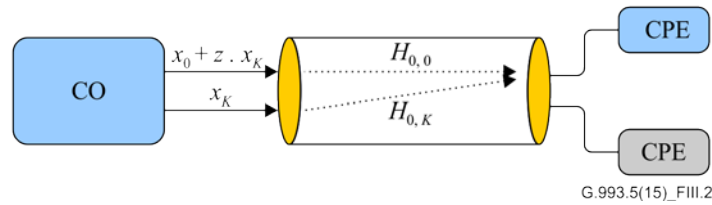Then, a special "probing" signal can be used to estimate the crosstalk channel.

Figure III.2 – Probing signal model – normal condition

The probing signal consists of a copy of the disturbing line, which is added to the victim. This leads to some interesting properties for the SNR.

Define SNR_b as the signal-to-noise ratio before the new line K is added:

$$SNR_b = \frac{\sigma_0^2 |H_{0,0}|^2}{\sum_{i=1}^{K-1} \sigma_i^2 |H_{0,i}|^2 + \sigma_{n_0}^2} \tag{III-2}$$

When the new line K is added, and depending on the probing factor z, we can define $SNR_a(z)$ as the signal-to-noise ratio after the new line K is added:

$$SNR_a(z) = \frac{\sigma_0^2 |H_{0,0}|^2}{\sum_{i=1}^{K-1} \sigma_i^2 |H_{0,i}|^2 + \sigma_K^2 |H_{0,K} + z \cdot H_{0,0}|^2 + \sigma_{n_0}^2} \tag{III-3}$$

Hence, these equations can be combined into the following equation:

$$\frac{1}{SNR_a(z)} = \frac{\sum_{i=1}^{K-1} \sigma_i^2 |H_{0,i}|^2 + \sigma_{n_0}^2 + \sigma_K^2 |H_{0,K} + z \cdot H_{0,0}|^2}{\sigma_0^2 |H_{0,0}|^2} = \frac{1}{SNR_b} + \frac{\sigma_K^2 |H_{0,K} + z \cdot H_{0,0}|^2}{\sigma_0^2 |H_{0,0}|^2} \tag{III-4}$$

The previous step assumes the background noise and the crosstalk from the other lines (1..K–1) to be constant during a single iteration.

$$\left| \frac{H_{0,K}}{H_{0,0}} + z \right|^2 = \frac{\sigma_0^2}{\sigma_K^2} \left(\frac{1}{SNR_a(z)} - \frac{1}{SNR_b} \right) \tag{III-5}$$

III.2.3 Graphical representation

Graphically, the effect of such probing signal on a QAM constellation point, can be represented as follows:
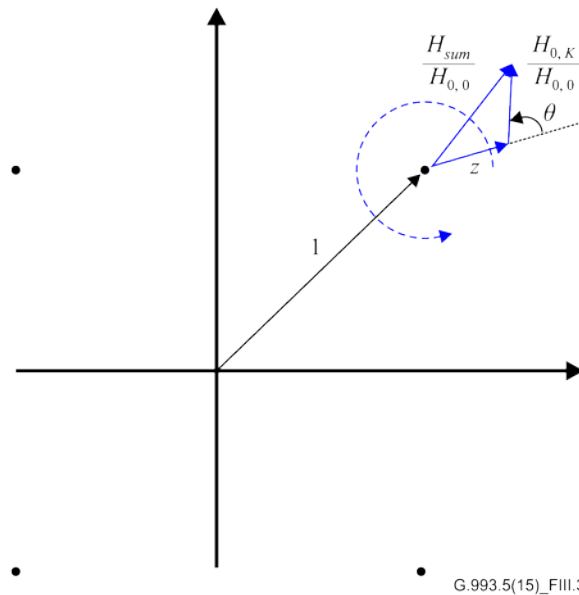

Figure III.3 – Effect of probing signal on constellation point

This figure assumes $\sigma_0^2 = \sigma_K^2$, in order not to be too complicated, but the result is easily generalized (in the equations) for the case where the signal variances on the victim and disturber lines are not identical.

Only the crosstalk of line K is shown. The crosstalk from lines $1..K–1$, is not shown, because they would make the figure too complex.

In the figure, we can identify the following elements:

–   the decoded constellation point (the FEQ scaled it back to a unity vector of size 1);

–   the probing vector z, which is added as noise on the direct channel of the victim line;

–   the crosstalk channel, normalized by the FEQ;

–   the angle θ between the probing vector z, and the normalized crosstalk channel (both are modulated with the same user data symbol x_k, therefore this angle remains constant);

–   the normalized total noise $\dfrac{H_{sum}}{H_{0,0}}$, which rotates around the constellation point.

III.2.4 Derivation of the equations for crosstalk channel estimation

In order to calculate the crosstalk channel $C_{0,K} = \dfrac{H_{0,K}}{H_{0,0}}$, we can derive the following equations.

Starting from equation III-5:

$$\left| \frac{H_{0,K}}{H_{0,0}} + z \right|^2 = \frac{\sigma_0^2}{\sigma_K^2} \left(\frac{1}{SNR_a(z)} - \frac{1}{SNR_b} \right) \tag{III-6}$$

when

         $z = 0$, this leads to:

$$\left|\frac{H_{0,K}}{H_{0,0}}\right|^2 = \frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(0)} - \frac{1}{SNR_b}\right)$$ (III-7)

when

$z = \varepsilon$, and applying trigonometry, we get:

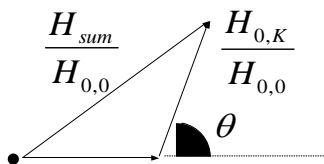**Figure III.4 – Detail of constellation point with $z = \varepsilon$**

$$\left|\frac{H_{0,K}}{H_{0,0}} + \varepsilon\right|^2 = \left|\frac{H_{0,K}}{H_{0,0}}\right|^2 + \varepsilon^2 - 2\cdot\varepsilon\cdot\left|\frac{H_{0,K}}{H_{0,0}}\right|\cos(\pi - \theta)$$

$$2\cdot\varepsilon\cdot\left|\frac{H_{0,K}}{H_{0,0}}\right|\cos(\theta) = \left|\frac{H_{0,K}}{H_{0,0}} + \varepsilon\right|^2 - \left|\frac{H_{0,K}}{H_{0,0}}\right|^2 - \varepsilon^2$$

$$2\cdot\varepsilon\cdot\left|\frac{H_{0,K}}{H_{0,0}}\right|\cos(\theta) = \frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(\varepsilon)} - \frac{1}{SNR_b}\right) - \frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(0)} - \frac{1}{SNR_b}\right) - \varepsilon^2$$

when

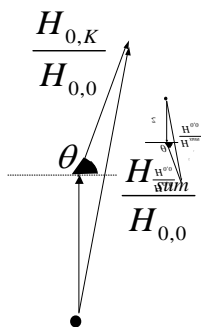$z = j\varepsilon$, we get:

Figure III.5 – Detail of constellation point with $z = j\varepsilon$

III.2.5 Equations for crosstalk channel estimation

Result, for $z = \varepsilon$

$$\left|\frac{H_{0,K}}{H_{0,0}}\right|\cos(\theta) = \frac{1}{2\varepsilon}\frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(\varepsilon)} - \frac{1}{SNR_a(0)}\right) - \frac{\varepsilon}{2}$$ (III-8)

Result, for $z = j\varepsilon$

$$\left|\frac{H_{0,K}}{H_{0,0}}\right|\sin(\theta) = \frac{1}{2\varepsilon}\frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(j\varepsilon)} - \frac{1}{SNR_a(0)}\right) - \frac{\varepsilon}{2}$$ (III-9)

Conclusion:

$$\frac{H_{0,K}}{H_{0,0}} = \left|\frac{H_{0,K}}{H_{0,0}}\right| \cos(\theta) + j \cdot \left|\frac{H_{0,K}}{H_{0,0}}\right| \sin(\theta) \tag{III-10}$$

III.2.6 Crosstalk channel estimation algorithm

Based on the previous equations, it can be seen that in order to calculate $C_{0,K} = \dfrac{H_{0,K}}{H_{0,0}}$, we need to calculate the amplitude and phase of this quantity, which are independent parameters.

By using equations III-8 and III-9, we have two independent equations, based on three SNR measurements, to calculate the real and imaginary parts of $C_{0,K}$ (two independent variables).

The following measurements are required:

– $SNR_a(0)$ the SNR after the new line K has initialized, without probing signal;

– $SNR_a(\varepsilon)$ the SNR after the new line K has initialized, with probing signal ε;

– $SNR_a(j\varepsilon)$ the SNR after the new line K has initialized, with probing signal $j\varepsilon$.

Hence, the algorithm consists of the following steps:

1)   start transmitting a MEDLEY-type signal on the new line K, with a reduced transmit PSD (No initialization);

2)   measure $SNR_a(0)$;

3)   from this value, a suitable value of ε can be chosen (such that the impact on the SNR is measurable, but not excessive), and a probing signal can be added (on every victim line simultaneously);

4)   measure $SNR_a(\varepsilon)$;

5)   change the probing signal to $j\varepsilon$;

6)   measure $SNR_a(j\varepsilon)$;

7)   calculate $\hat{C}_{0,K}$, for each victim line;

8)   start the pre-coding;

9)   increase the PSD of the MEDLEY-type signal on the new line;

10)   repeat from 2, until the MEDLEY-type signal PSD has reached the maximum allowed PSD of this line;

11)   the normal initialization sequence on this line can now start.

Typically, the algorithm converges in a few iterations.

III.2.7 Extended equations applicable while performing pre-compensation

In case pre-coding is active, there is no fundamental change to the equations.

The basic equation is equation III-1:

$$y = Hx + n$$

$$y_0 = \underbrace{H_{0,0}x_0}_{\text{Useful signal}} + \underbrace{\sum_{i=1}^{K-1}H_{0,i}x_i}_{\text{FEXT from active lines}} + \underbrace{H_{0,K}x_K}_{\text{FEXT from new line}} + \underbrace{n_0}_{\text{External noise}}$$

Knowing that $H = diag(H)(I+C)$, and when applying pre-coding, $w = Fx = (I - \hat{C})x$, this becomes:

$$\begin{aligned}
y &= H(I - \hat{C})x \\
&= Hx - H\hat{C}x \\
&= diag(H)(I+C)x - diag(H)(I+C)\hat{C}x \\
&\approx diag(H)x + diag(H)Cx - diag(H)\hat{C}x
\end{aligned}$$

$$y_0 = \underbrace{H_{0,0}x_0}_{\text{Useful signal}} + \underbrace{\sum_{i=1}^{K-1}H_{0,i}\left(C_{0,i} - \hat{C}_{0,i}\right)x_i}_{\text{Residual FEXT from active lines}} + \underbrace{H_{0,K}\left(C_{0,K} - \hat{C}_{0,K}\right)x_K}_{\text{Residual FEXT from line K}} + \underbrace{n_0}_{\text{External noise}}$$

$$= H_{0,0}x_0 + \sum_{i=1}^{K-1}H_{0,i}\Big|_{residual}x_i + H_{0,K}\Big|_{residual}x_K + n_0$$

Consequently, we can rewrite equations III-8 and III-9 as follows:

$$\left|\frac{H_{0,K}\big|_{residual}}{H_{0,0}}\right| \cos(\theta) = \frac{1}{2\varepsilon}\frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(\varepsilon)} - \frac{1}{SNR_a(0)}\right) - \frac{\varepsilon}{2} \qquad \text{(III-11)}$$

$$\left|\frac{H_{0,K}\big|_{residual}}{H_{0,0}}\right| \sin(\theta) = \frac{1}{2\varepsilon}\frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(j\varepsilon)} - \frac{1}{SNR_a(0)}\right) - \frac{\varepsilon}{2} \qquad \text{(III-12)}$$

Therefore, the main effect of pre-coding lies in the fact that a different value for ε needs to be chosen (see also step 4, in clause III.2.6) and that in fact for the residual crosstalk channel to be estimated:

_ ε needs to be such that the impact on SNR is measurable, but not excessive;

– when one knows that the residual crosstalk is estimated, the updating equation becomes trivial:

$$\hat{C}_{0,K}(t+1) = \hat{C}_{0,K}(t) + \frac{H_{0,K}\big|_{residual}}{H_{0,0}} \qquad \text{(III-13)}$$

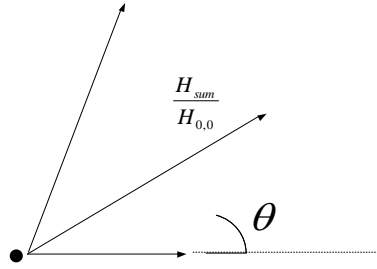This is also illustrated graphically, as in the previous figure:

Figure III.6 – Detail of constellation point with pre-coding

The red vector indicates the residual normalized crosstalk channel, for which a similar triangle can be constructed like before by applying a probing signal. Hence, all equations remain valid.

III.3 Estimation of FEXT channels from existing lines into a new line

III.3.1 Introduction

Denote the number of SNR measurements used for channel estimation as N. Each SNR measurement occurs over L DMT symbols and all lines are in Showtime when channel estimation takes place. Consider transmission on a single tone and denote the QAM data symbol intended for line i on DMT symbol l during SNR measurement n as $s_i^{(n)}(l)$. The actual signal transmitted by line i is denoted as $x_i^{(n)}(l)$.

III.3.2 Probing signal

When the new line K initializes, the existing lines continue to transmit their data as before

$$x_i^{(n)}(l) = s_i^{(n)}(l), \forall i < K$$

Channel identification is enabled by superimposing a probing signal onto the signal transmitted by the new VTU-O K

$$x_K^{(n)}(l) = s_K^{(n)}(l) + \varepsilon \sum_{i=1}^{K-1} z_i^{(n)} s_i^{(n)}(l) \tag{III-14}$$

Note that the probing signal consists of a linear combination of the signals transmitted on the existing lines 1 to $K-1$. A step size ε is chosen such that the impact of the probing signal on the SNR is less than 3.5 dB. This is done by first measuring the SNR of line K in the absence of any probing signal, which we denote $SNR_K^{(0)}$. The step size is then set as:

$$\varepsilon = \min_i \frac{1}{2} \frac{1}{\sqrt{SNR_K^{(0)}}} \frac{\sigma_K}{\sigma_i}$$

where σ_i^2 denotes the transmit power of line i. Note that $z_i^{(n)}$ is chosen such that

$$\sum_{i=1}^{K-1} \left| z_i^{(n)} \right|^2 = 1$$

III.3.3 Derivation of the equations for crosstalk channel estimation

Using equation III-14, the received signal on line K is:

$$y_K^{(n)}(l) = \sum_{i=1}^{K} h_{K,i} x_i^{(n)}(l) + w_K^{(n)}(l)$$

$$= h_{K,K} s_K^{(n)}(l) + \sum_{i=1}^{K-1} \left(h_{K,i} + \varepsilon z_i^{(n)} h_{K,K} \right) s_i^{(n)}(l) + w_K^{(n)}(l)$$

The signal power on line K will be measured by the VTU-R as:

$$\text{signal}_K = \frac{1}{L} \sum_{l=1}^{L} \left| h_{K,K} s_K^{(n)}(l) \right|^2 \tag{III-15}$$

$$\approx \left| h_{K,K} \right|^2 \sigma_K^2$$

The noise power on line K will be measured as:

$$\text{noise}_K = \frac{1}{L} \sum_{l=1}^{L} \left| y_K^{(n)}(l) - h_{K,K} s_K^{(n)}(l) \right|^2 \tag{III-16}$$

$$\approx \sum_{i=1}^{K-1} \left| h_{K,i} + \varepsilon z_i^{(n)} h_{K,K} \right|^2 \sigma_i^2 + \sigma_{W_K}^2$$

where $\sigma_{W_K}^2$ denotes the power of the background noise. The VTU-R will then report the measured SNR to the VTU-O as:

$$\text{SNR}_K^{(n)} = \text{signal}_K / \text{noise}_K$$

From equations III-15 and III-16:

$$\frac{1}{\text{SNR}_K^{(n)}} = \frac{\text{noise}_K}{\text{signal}_K}$$

$$\approx \frac{1}{\sigma_K^2} \left(\sum_{i=1}^{K-1} \left| \frac{h_{K,i}}{h_{K,K}} \sigma_i + \varepsilon z_i^{(n)} \sigma_i \right|^2 + \frac{\sigma_{W_K}^2}{\left| h_{K,K} \right|^2} \right) \tag{III-17}$$

$$= \frac{1}{\sigma_K^2} \left(\left\| \overline{\mathbf{a}} + \varepsilon \overline{\mathbf{b}}^{(n)} \right\|^2 + \frac{\sigma_{W_K}^2}{\left| h_{K,K} \right|^2} \right)$$

where we have defined $\overline{\mathbf{a}} = [\overline{a}_1 \dots \overline{a}_{K-1}]^T$, $\overline{\mathbf{b}}^{(n)} = [\overline{b}_1^{(n)} \dots \overline{b}_{K-1}^{(n)}]^T$ with

$$\overline{a}_i = \frac{h_{K,i}}{h_{K,K}} \sigma_i \tag{III-18}$$

and

$$\overline{b}_i^{(n)} = z_i^{(n)} \sigma_i \tag{III-19}$$

Applying the general form of Pythagoras' theorem:

$$\left\| \overline{\mathbf{a}} + \varepsilon \overline{\mathbf{b}}^{(n)} \right\|^2 = \left\| \overline{\mathbf{a}} \right\|^2 + \left\| \varepsilon \overline{\mathbf{b}}^{(n)} \right\|^2 + 2\varepsilon \operatorname{Re}\{ \overline{\mathbf{b}}^{(n)H} \overline{\mathbf{a}} \} \tag{III-20}$$

Decompose $\bar{\mathbf{a}}$ and $\bar{\mathbf{b}}^{(n)}$ into their real and imaginary components $a_{R,i} = \mathrm{Re}\{\bar{a}_i\}$, $a_{I,i} = \mathrm{Im}\{\bar{a}_i\}$, $b_{R,i}^{(n)} = \mathrm{Re}\{\bar{b}_i^{(n)}\}$, and $b_{I,i}^{(n)} = \mathrm{Im}\{\bar{b}_i^{(n)}\}$. Now:

$$\mathrm{Re}\{\bar{\mathbf{b}}^{(n)H}\bar{\mathbf{a}}\} = \sum_{i=1}^{K-1} a_{R,i} b_{R,i}^{(n)} + a_{I,i} b_{I,i}^{(n)}$$
$$= \mathbf{b}^{(n)H}\mathbf{a},$$

where we define

$$\mathbf{a} = [a_{R,1} \ldots a_{R,K-1} \; a_{I,1} \ldots a_{I,K-1}]^T, \tag{III-21}$$

and $\mathbf{b}^{(n)} = [b_{R,1}^{(n)} \ldots b_{R,K-1}^{(n)} \; b_{I,1}^{(n)} \ldots b_{I,K-1}^{(n)}]^T$. For convenience we also define $a_i = [\mathbf{a}]_i$ and $b_i^{(n)} = [\mathbf{b}^{(n)}]_i$. From equation III-20:

$$\left\|\bar{\mathbf{a}} + \varepsilon \bar{\mathbf{b}}^{(n)}\right\|^2 = \left\|\bar{\mathbf{a}}\right\|^2 + \left\|\varepsilon \bar{\mathbf{b}}^{(n)}\right\|^2 + 2\varepsilon \mathbf{b}^{(n)H}\mathbf{a}.$$

Now, from equation III-17:

$$\left\|\bar{\mathbf{a}}\right\|^2 + \left\|\varepsilon \bar{\mathbf{b}}^{(n)}\right\|^2 + 2\varepsilon \mathbf{b}^{(n)H}\mathbf{a} + \frac{\sigma_{W_K}^2}{\left|h_{K,K}\right|^2} = \frac{\sigma_K^2}{\mathrm{SNR}_K^{(n)}}.$$

Therefore

$$\varepsilon \mathbf{b}^{(n)H}\mathbf{a} + \frac{1}{2}\left\|\bar{\mathbf{a}}\right\|^2 + \frac{1}{2}\frac{\sigma_{W_K}^2}{\left|h_{K,K}\right|^2} = \frac{1}{2}\frac{\sigma_K^2}{\mathrm{SNR}_K^{(n)}} - \frac{1}{2}\left\|\varepsilon \bar{\mathbf{b}}^{(n)}\right\|^2.$$

Applying equation III-19 gives:

$$\varepsilon \mathbf{b}^{(n)H}\mathbf{a} + \frac{1}{2}\left\|\bar{\mathbf{a}}\right\|^2 + \frac{1}{2}\frac{\sigma_{W_K}^2}{\left|h_{K,K}\right|^2} = \frac{1}{2}\frac{\sigma_K^2}{\mathrm{SNR}_K^{(n)}} - \frac{1}{2}\varepsilon^2 \sum_{i=1}^{K-1}\left|z_i^{(n)}\right|^2 \sigma_i^2.$$

Define

$$c^{(n)} = \frac{1}{2}\frac{\sigma_K^2}{\mathrm{SNR}_K^{(n)}} - \frac{1}{2}\varepsilon^2 \sum_{i=1}^{K-1}\left|z_i^{(n)}\right|^2 \sigma_i^2. \tag{III-22}$$

Hence

$$\varepsilon \mathbf{b}^{(n)H}\mathbf{a} + \frac{1}{2}\left\|\bar{\mathbf{a}}\right\|^2 + \frac{1}{2}\frac{\sigma_{W_K}^2}{\left|h_{K,K}\right|^2} = c^{(n)}, \forall n. \tag{III-23}$$

Define an $M \times N$ matrix $\mathbf{P}$ with elements $p_{m,n} = [\mathbf{P}]_{m,n}$ that satisfies

$$\sum_{n=1}^{N} p_{m,n} = 0, \forall m \tag{III-24}$$

This will be referred to as the SNR combination matrix. Now, from equation III-23:

$$\sum_n p_{m,n} c^{(n)} = \varepsilon \sum_n p_{m,n} \mathbf{b}^{(n)^H} \mathbf{a} + \left(\frac{1}{2} \|\bar{\mathbf{a}}\|^2 + \frac{1}{2} \frac{\sigma_{W_K}^2}{|h_{K,K}|^2} \right) \sum_n p_{m,n}, \forall m.$$

Applying equation III-24, we have

$$\sum_n p_{m,n} c^{(n)} = \varepsilon \sum_n p_{m,n} \mathbf{b}^{(n)^H} \mathbf{a}, \forall m. \tag{III-25}$$

For each *n*, we will have one equation of the form of equation III-25. Collecting all of these equations into a matrix gives

$$\mathbf{P} \begin{bmatrix} c^{(1)} \\ \vdots \\ c^{(N)} \end{bmatrix} = \varepsilon \mathbf{P} \begin{bmatrix} \mathbf{b}^{(1)^H} \\ \vdots \\ \mathbf{b}^{(N)^H} \end{bmatrix} \mathbf{a}.$$

Define $\mathbf{c} = [c^{(1)} \dots c^{(N)}]^T$ and the probing matrix $\mathbf{B} = [\mathbf{b}^{(1)} \cdots \mathbf{b}^{(N)}]^H$. Hence

$$\varepsilon \mathbf{PBa} = \mathbf{Pc}$$

We can now find the least squares solution for **a** as

$$\mathbf{a} = \varepsilon^{-1} \mathrm{pinv}(\mathbf{PB})\mathbf{Pc}$$

where pinv(.) denotes the pseudo-inverse operation. Using equations III-18 and III-21, the normalized crosstalk coefficients can now be found as:

$$\frac{h_{K,i}}{h_{K,K}} = \frac{1}{\sigma_i}(a_i + j a_{K-1+i}) \tag{III-26}$$

which can be used to design the first order diagonalizing precompensator

$$\mathbf{F} = \mathbf{I}_K - \mathrm{offdiag}\left(\begin{bmatrix} \dfrac{h_{1,1}}{h_{1,1}} & \cdots & \dfrac{h_{1,K}}{h_{1,1}} \\ \vdots & \ddots & \vdots \\ \dfrac{h_{K,1}}{h_{K,K}} & \cdots & \dfrac{h_{K,K}}{h_{K,K}} \end{bmatrix} \right), \tag{III-27}$$

where we define the function $\mathrm{offdiag}(\mathbf{X}) = \mathbf{X} - \mathrm{diag}(\mathbf{X})$.

Note that in order for the set of equations to be sufficient to form an estimate of **a**, it is necessary that rank(**PB**) ≥ 2(*K*–1). There is an additional requirement that $\sum_n p_{m,n} = 0, \forall m,$ which effectively means that the size of **P** must be at least 2(*K*–1)×(2*K*–1). Hence using this algorithm, it is possible to form an estimate of the crosstalk channels after only 2*K*–1 SNR measurements.

III.3.4 Crosstalk channel estimation algorithm

The channel identification algorithm operates as follows:

–   precompute $\mathbf{G} = \text{pinv}(\mathbf{PB})\mathbf{P}$

–   precompute $d^{(n)} = \sum_{i=1}^{K-1} \left| z_i^{(n)} \right|^2 \sigma_i^2 / 2, \forall n$

–   for $i = 1...$number of iterations

–   transmit $x_K^{(0)}(l) = s_K^{(0)}(l)$ on line K

–   VTU-R reports $SNR_K^{(0)}$

–   Set step size $\varepsilon = \min_i \dfrac{1}{2} \dfrac{1}{\sqrt{\mathrm{SNR}_K^{(0)}}} \dfrac{\sigma_K}{\sigma_i}$

–   for $n = 1...N$

–   transmit $x_K^{(n)}(l) = s_K^{(n)}(l) + \sum_{i<K} z_i^{(n)} s_i^{(n)}(l)$ on line K

–   VTU-R reports $\mathrm{SNR}_K^{(n)}$

–   calculate $c^{(n)} = \dfrac{1}{2} \dfrac{\sigma_K^2}{\mathrm{SNR}_K^{(n)}} - \varepsilon^2 d^{(n)}$

–   end

– $\mathbf{a} = \varepsilon^{-1} \mathbf{Gc}$

– $\dfrac{h_{K,i}}{h_{K,K}} = \left(a_i + j a_{K-1+i}\right)/\sigma_i, \forall i$

–   update crosstalk precompensator using equation III-27

–   end

Note that in order to speed up computations, we have precomputed the pseudo-inverse $\mathbf{G}$ and the term $d^{(n)}$.

Bibliography

[b-ITU-T G.998.1]   Recommendation ITU-T G.998.1 (2005), *ATM-based multi-pair bonding*.

[b-ITU-T G.998.2]   Recommendation ITU-T G.998.2 (2005), *Ethernet-based multi-pair bonding*.

[b-ITU-T G.998.3]   Recommendation ITU-T G.998.3 (2005), *Multi-pair bonding using time-division inverse multiplexing*.

[b-ATIS-0600024]   ATIS Technical Report ATIS-0600024 (2009), *Multiple-Input Multiple-Output Crosstalk Channel Model*.

SERIES OF ITU-T RECOMMENDATIONS

Series A	Organization of the work of ITU-T
Series D	Tariff and accounting principles and international telecommunication/ICT economic and policy issues
Series E	Overall network operation, telephone service, service operation and human factors
Series F	Non-telephone telecommunication services
Series G	**Transmission systems and media, digital systems and networks**
Series H	Audiovisual and multimedia systems
Series I	Integrated services digital network
Series J	Cable networks and transmission of television, sound programme and other multimedia signals
Series K	Protection against interference
Series L	Environment and ICTs, climate change, e-waste, energy efficiency; construction, installation and protection of cables and other elements of outside plant
Series M	Telecommunication management, including TMN and network maintenance
Series N	Maintenance: international sound programme and television transmission circuits
Series O	Specifications of measuring equipment
Series P	Telephone transmission quality, telephone installations, local line networks
Series Q	Switching and signalling, and associated measurements and tests
Series R	Telegraph transmission
Series S	Telegraph services terminal equipment
Series T	Terminals for telematic services
Series U	Telegraph switching
Series V	Data communication over the telephone network
Series X	Data networks, open system communications and security
Series Y	Global information infrastructure, Internet protocol aspects, next-generation networks, Internet of Things and smart cities
Series Z	Languages and general software aspects for telecommunication systems