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

Digital sections and digital line system – Access networks

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

Recommendation ITU-T G.993.5

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Recommendation ITU-T G.993.5

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

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.

The scope of Recommendation ITU-T G.993.5 is specifically limited to the self-FEXT (far-end crosstalk) cancellation in the downstream and upstream directions. This Recommendation 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 VDSL2 transceivers, not necessarily of the same profile. This Recommendation is intended to be implemented in conjunction with Recommendation ITU-T G.993.2.

History

Edition	Recommendation	Approval	Study Group
1.0	ITU-T G.993.5	2010-04-22	15

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.

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

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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.

The scope of this Recommendation is specifically limited to the self-FEXT (far-end crosstalk) cancellation in the downstream and upstream directions. This Recommendation 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 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+Amd.5]	Recommendation ITU-T G.994.1 (2007), *Handshake procedures for digital subscriber line (DSL) transceivers*, plus Amd.5 (2010).
[ITU-T G.997.1+Amd.1]	Recommendation ITU-T G.997.1 (2009), *Physical layer management for digital subscriber line (DSL) 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

This Recommendation adopts the definitions of [ITU-T G.993.2]. In addition, this Recommendation defines the following terms:

3.1 backchannel: The channel through which the VTU-R sends clipped error samples to the 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 ceiling: Rounding to the nearest higher integer, denoted as $\lceil x \rceil$.

3.3 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.

3.4 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).

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

3.6 flag tones: All sub-carriers with index equal to $10n+1$ or $10n+7$, with n an integer value. Flag tones are used to signal OLR transitions.

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

3.8 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.

3.9 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.

3.10 probe tones: All sub-carriers with index 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.

3.11 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.

3.12 vectored group: The set of lines over which transmission from the 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.

3.13 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

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

AFE	Analogue Front End
AN-MIB	Access Node Management Information Base
BDR	Backchannel Data Rate
CO	Central Office
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
ERB	Error Report Block
ETR	Expected Throughput
FEXT	Far-end crosstalk
L2+	Ethernet layer 2 and above
ME	Management Entity
NEXT	Near-end crosstalk
NDR	Net Data Rate
RT	Remote Terminal
SSC	Sync Symbol Counter
VBB	Vectored Band Block
VCE	Vectoring Control Entity

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 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 + Amd.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 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).

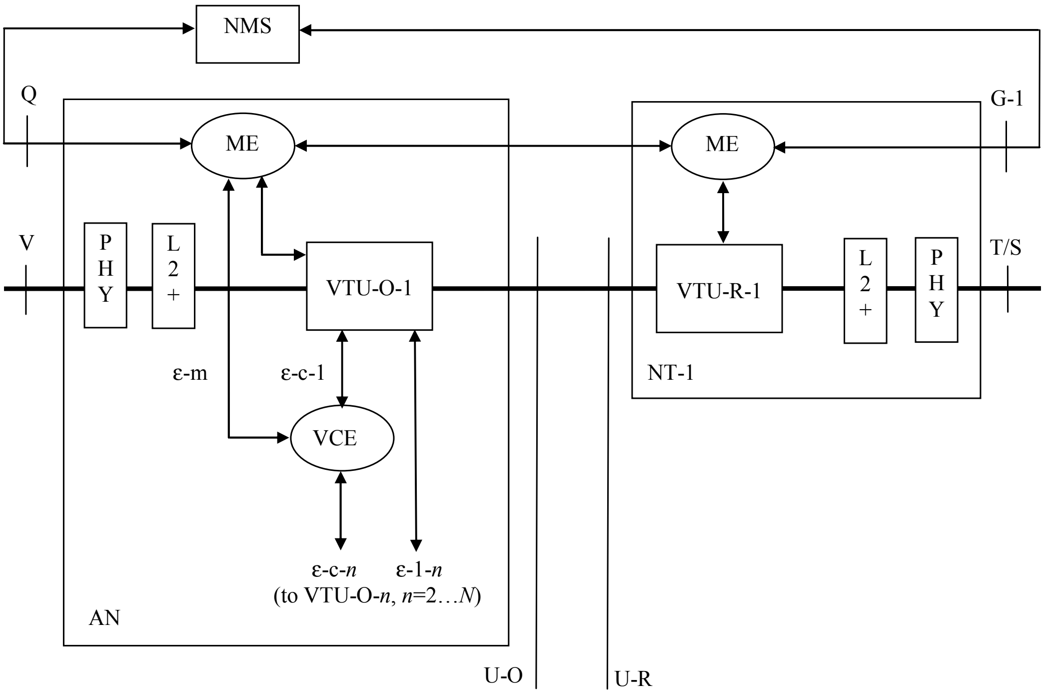


Figure 5-1 – Reference model for a vectored system (shown for line 1 in a vectored group of *N* lines)

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 transmitters (above the AM broadcast band) (HAM)) 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 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*×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 precoder may or may not be implemented in the same physical device as the other functional blocks shown in Figure 5-2.

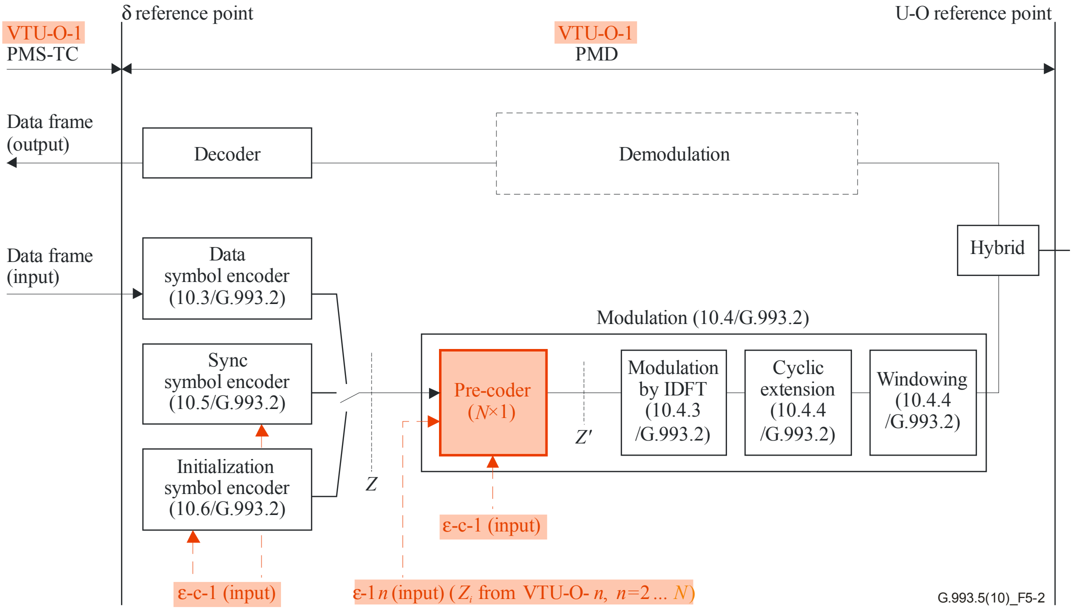


Figure 5-2 – VTU-O functional model of PMD sub-layer using *N*×1 pre-coder for downstream vectoring (shown for line 1 in vectored group of *N* lines)

The 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 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

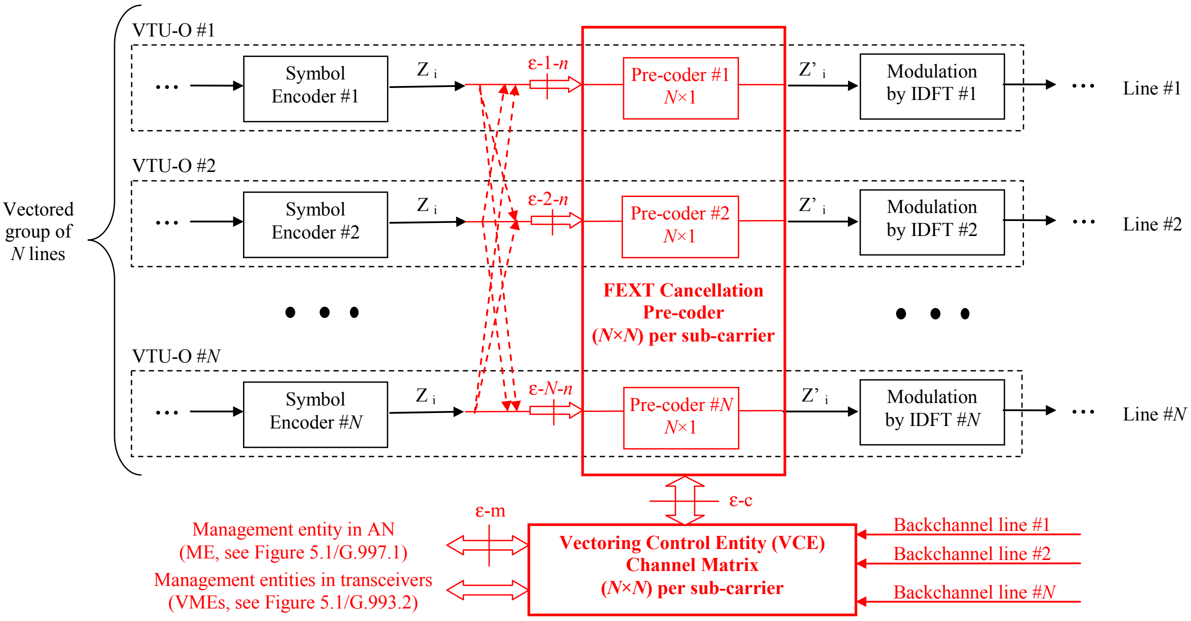
Figure 6-1 shows the functional model for the inclusion of downstream FEXT cancellation pre-coding at the AN for all lines in the vectored group, as a generalization of Figure 5-2 from a signal processing perspective. The model shows only the portion of an array of the downstream symbol encoders (which represent the data, sync or initialization symbol encoders shown in Figure 5-2) and the modulation by the 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 sub-carrier, 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 sub-carrier 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 sub-carrier 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.



Symbol Encoder represents the data, sync or initialization symbol encoder shown in Figure 5-2.

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, 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".

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 subclauses.

6.2.1 Synchronous mode

Under VCE control, all VTU-Os in the vectored group shall use the same sub-carrier spacing and symbol rate, and shall start transmission of 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 (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 8-6 and Table 8-7).

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 3.10) 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). 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.

The modulation of a 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 sync frame bits modulated on the flag tones (see clause 3.6) 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 sub-carriers, 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.

6.3 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 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.

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 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).

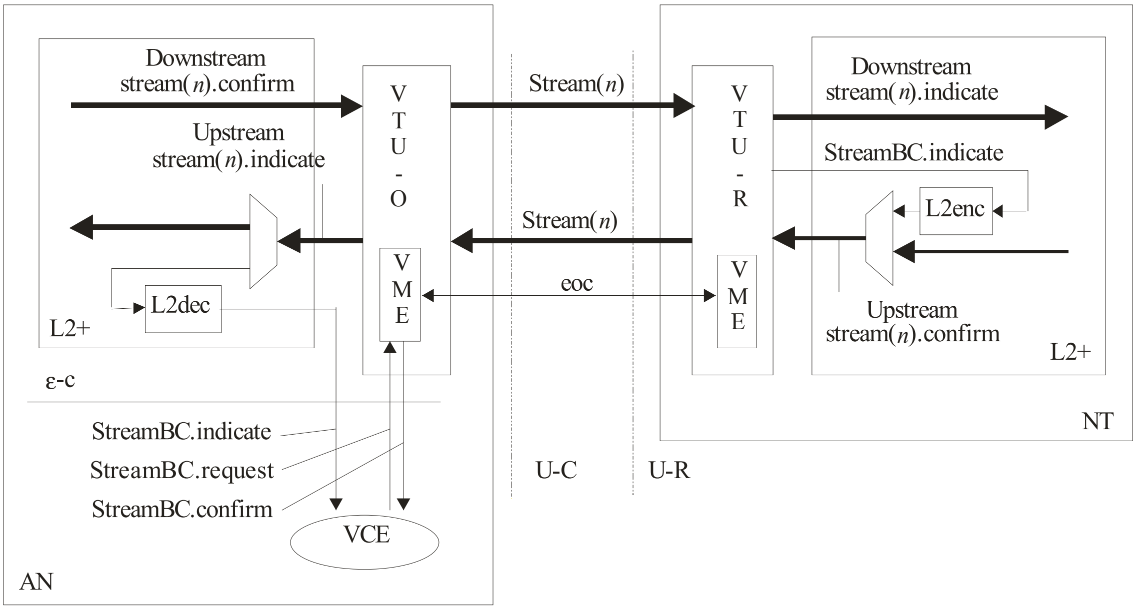


Figure 7-1 – Reference model for the Layer 2 encapsulated backchannel information flow

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 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).

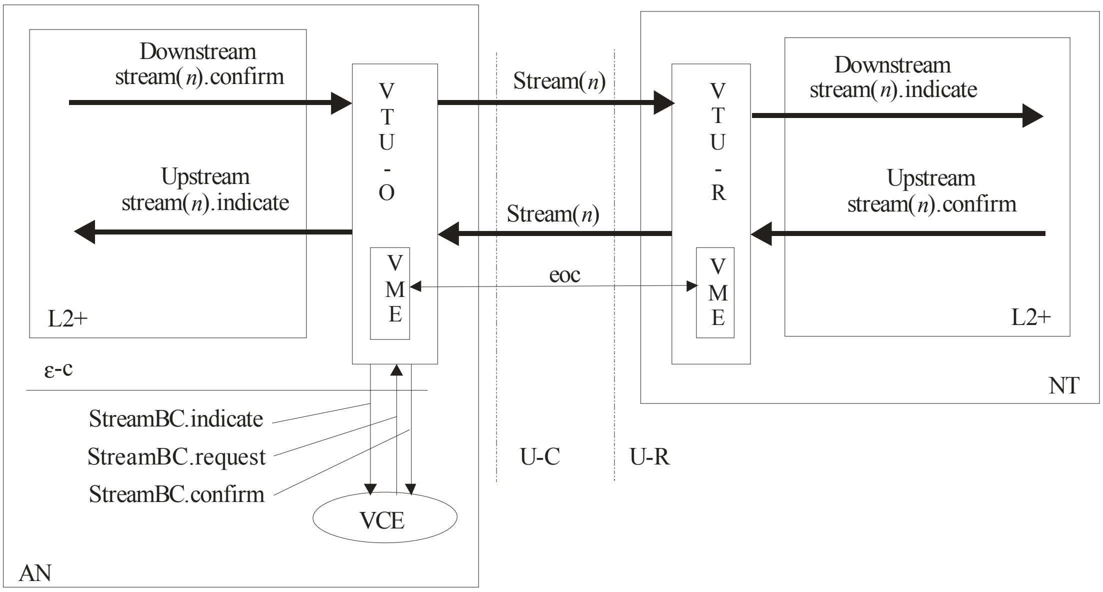


Figure 7-2 – Reference model for the eoc encapsulated backchannel information flow

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 sub-carriers 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".

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, have the same sign (i.e., all probe tones modulate the same 4-QAM constellation point, either 00 or 11, see clause 6.2.3). However, 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 sync symbol has a periodicity of 20 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 sub-carriers. 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 sub-carrier in a particular sync symbol. The normalized error sample represents the error between the received complex data sample Z normalized to the 4-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 sub-carriers, 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 $\hat{c}\_y = \pm 1$).

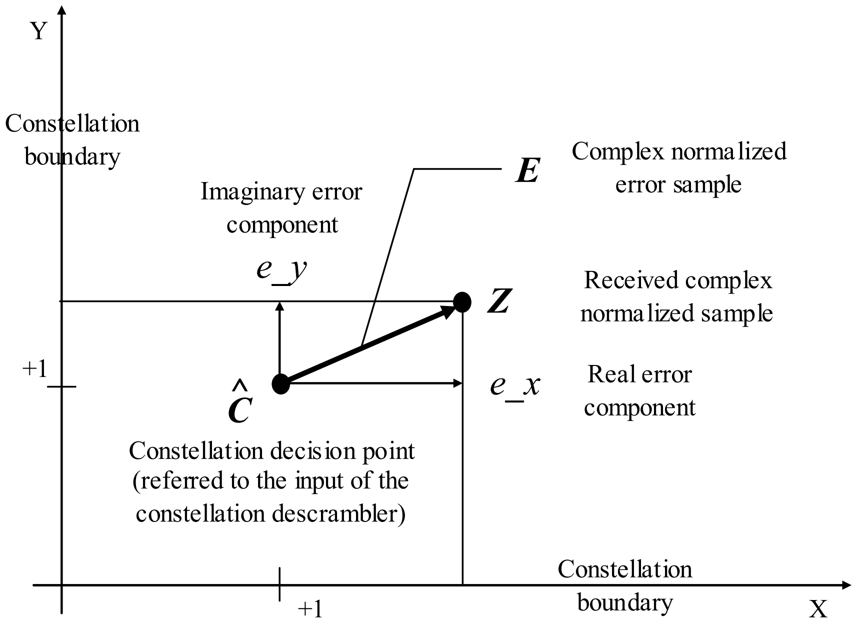


Figure 7-3 – Definition of the normalized error sample *E*

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 sub-carriers 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 (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 sub-carriers. *N_band* denotes the number of vectored bands configured. No more than 8 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 sub-carrier indices associated with the band. *N_carrier*(*vb*) denotes the number of sub-carriers in frequency band number *vb*, i.e., the index of the last sub-carrier minus the index of the first sub-carrier plus one. The index of the first (lowest frequency) sub-carrier 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 sub-carrier with the smallest index shall be transmitted first, followed by the clipped error sample of every F_subth sub-carrier within the vectored band. Configured by the VCE for each vectored downstream band separately.
F_block	The block size (number of sub-carriers) 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.
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 $\left\lceil \frac{N\_carrier}{F\_sub} \right\rceil$	1 and $\left\lceil \frac{N\_carrier}{F\_sub} \right\rceil$
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* = $\left\lceil \frac{N\_carrier}{F\_sub} \right\rceil$	1 (enable); 0 (disable) with *F_block* = $\left\lceil \frac{N\_carrier}{F\_sub} \right\rceil$

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 sub-carriers with indices $X = X\_L + n \times F\_sub$, where n gets all integer values 0, 1, 2, … for which $X\_L \le X \le X\_H$ and with X_L and X_H respectively, the indices of the lowest frequency and the highest frequency sub-carriers of the vectored downstream band. Clipped error samples of other sub-carriers shall not be reported.

On the sub-carriers 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 sub-carriers.

NOTE – It is the responsibility of the VTU-O and/or the VCE to identify and drop clipped error samples for sub-carriers 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, in 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 $2 \times F\_block$ 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 $B\_M = \max(S, L\_w - 1)$ (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 $0 \le B\_M \le B\_max$.

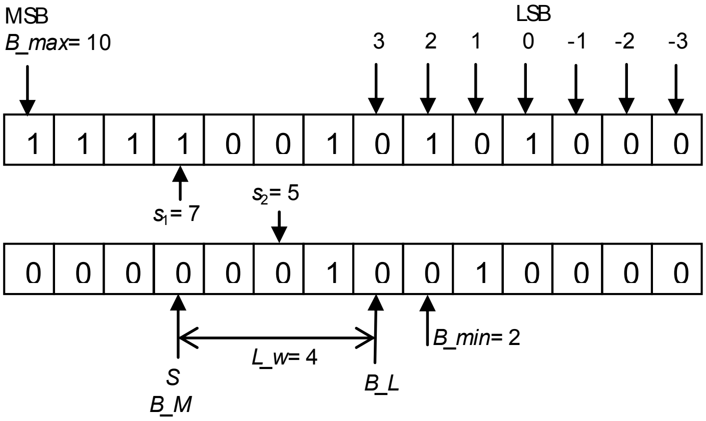


Figure 7-4 – Example of two registers, each representing a clipped error sample component

Figure 7-5 depicts an example of the reported bits (shown in 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.

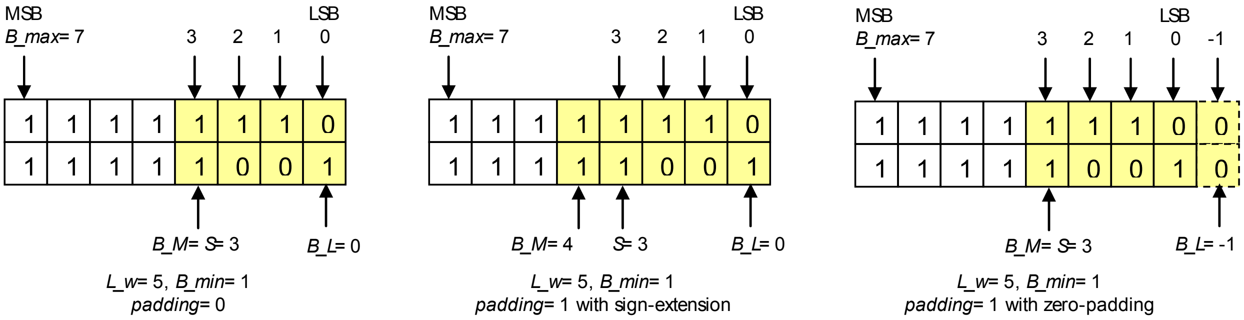


Figure 7-5 – Example of reported bits for a block of clipped error samples for different padding types

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

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

The blocks shall be identified by their numbers: $eb = 0$ to $N\_block(vb) - 1$, assigned in the ascending order of sub-carrier indices associated with the block. The last components of the last block that do not belong to the sub-carriers 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 8 vectored band blocks (VBB) 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 a ERB shall be in the ascending order of the vectored band numbers, i.e., starting from the vectored band associated with lowest sub-carrier 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).

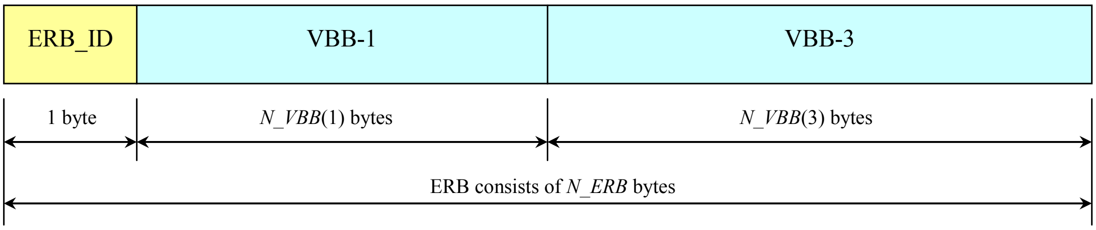


Figure 7-6 – ERB format (in case only vectored bands 1 and 3 are requested by the VCE)

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 MSB 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 nine LSB 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 sub-carriers with lowest indices and shall be transmitted first.

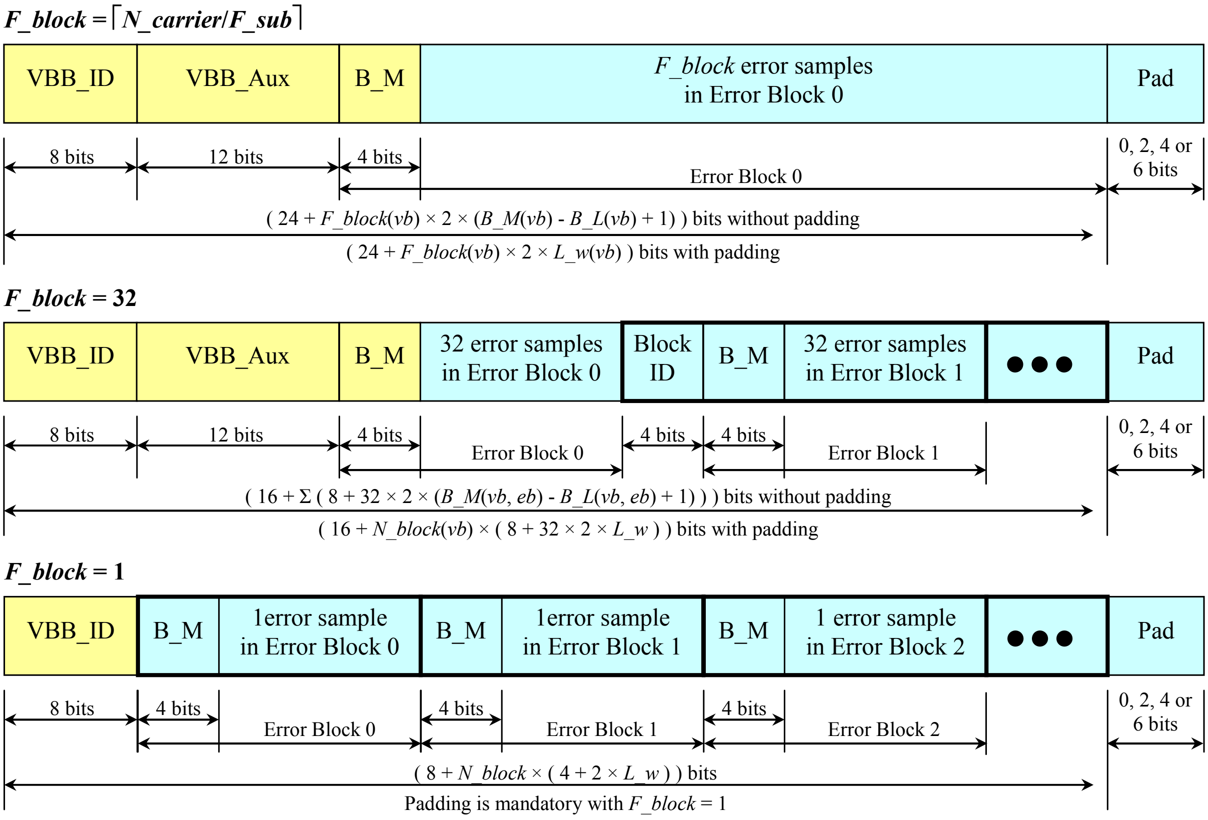


Figure 7-7 – VBB format depending on *F_block*

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, in assumption that the first block in the vectored band has the number 0.

In case *F_block* = 1 or $\left\lceil \frac{N\_carrier}{F\_sub} \right\rceil$, 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 sub-carrier 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:

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

where *e_x*(*sc*) and *e_y(sc*) are real and imaginary components of the normalized error estimated on sub-carrier *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 *ME*q 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×*F_block* clipped error sample components of *F_block* sub-carriers) 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 sub-carrier 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×*F_block*×(*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 sub-carrier 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.

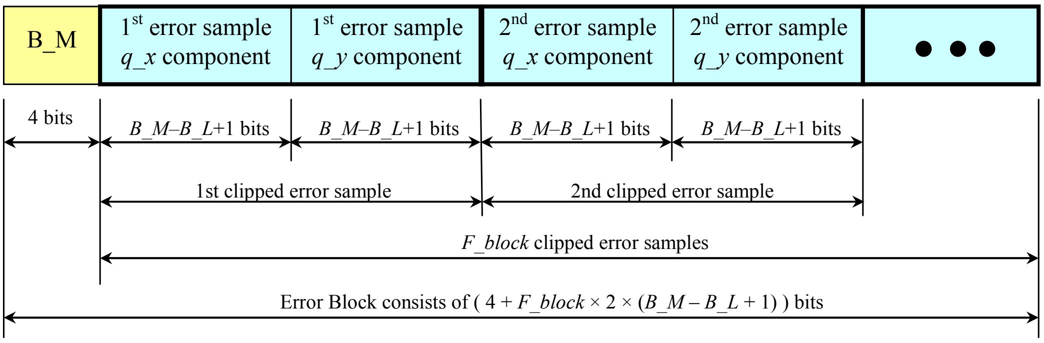


Figure 7-8 – Format of an error block

7.2.3.3 Backchannel data rate (informative)

In case $F\_block = \left\lceil \frac{N\_carrier}{F\_sub} \right\rceil$, 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:

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

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 backchannel data rate 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 count $SSC = m \times P + k$, where *P* is any integer in the range from 0 to $\lfloor (N\_SSC - 1 - k)/m \rfloor$, and *k* is the offset in the range from 0 to $m-1$. The VTU-R shall set k=0 for the first report after the VTU-O's error feedback request. If $z > 0$, the VTU-R shall increase *k* by 1 (MOD *m*) after each error sample shift period of *z* reports.

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 error sample shift period *z* is valid only for $m > 1$. The error sample shift period value of $z = 0$ is special and shall be used if no 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 – Denoting the *n*-th report is on sync symbol count SSC_n, the SSC_1 is a multiple of *m* and the SSC_n can be calculated for n>1 as follows:

If (z>0) and (n MOD z = 1) then $SSC_n = SSC_{n-1} + m + 1$; else $SSC_n = SSC_{n-1} + m$;

If ($SSC_n > N\_SSC - 1$) then $SSC_n = SSC_n$ MOD m.

For example, with *N_SSC*=1024, the reports are on the following sync symbol counts:

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

m=3 and *z*=128 then *SSC*=0, 3, …, 126*3, 127*3, 128*3+1, 129*3+1, …

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 subclauses.

7.3.1 Symbol alignment

Under VCE control, all VTU-Rs in the vectored group shall use the same sub-carrier 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 Tables 8-6 and 8-7). 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 sub-carriers of the upstream sync symbols during Initialization (see clause 10.3.4.1) and on the probe tones (see clause 3.10) 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. The pilot sequence shall be cyclically repeated after *Npilot_us* 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). Sub-carriers 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 3.10) 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 sync frame bits modulated on the flag tones (see clause 3.6) 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 sub-carriers, 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);
- 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.

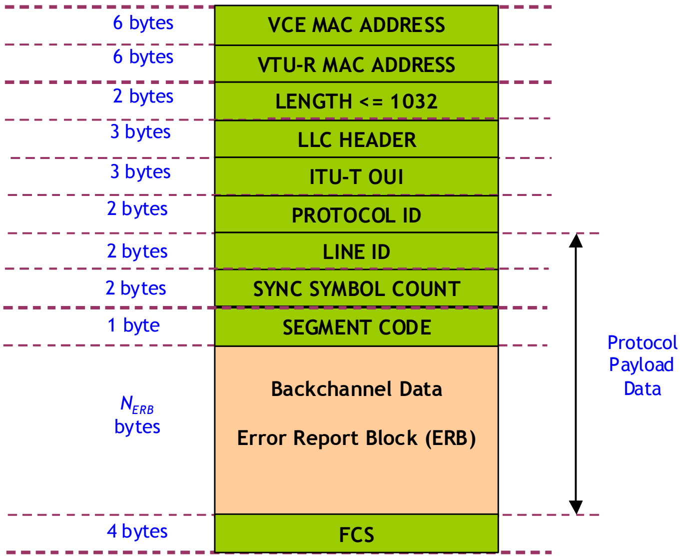


Figure 7-9 – Format of the Ethernet encapsulation of backchannel data message

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 sub-carriers 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 sub-carrier 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	$6 + 5 \times N\_band$ ($N\_band \leq 8$)	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): $00_2 - F\_block = \left\lceil \frac{N\_carrier}{F\_sub} \right\rceil$ $01_2 - F\_block = 1$ $10_2 - F\_block = 32$ 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 and communicate the updated pilot sequence for the vectored line (see clause 7.3.3) to the VTU-R VME. The command is 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.

The command message length depends on the length of the upstream pilot sequence (*Npilot_us* bits, with *Npilot_us* a power of 2 in the range from 8 to 512). 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 command transmitted by the VTU-O

Name	Length (Octets)	Octet number	Content
Pilot sequence configuration	3 + *Npilot_us*/8	2	01_{16} for change of upstream pilot sequence (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 + *Npilot_us*/8	Upstream pilot sequence bits, coded as defined for field #4 in Table 10-1.
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, the VTU-R shall apply the change only after sending the ACK message. If interruption of the current pilot sequence 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.

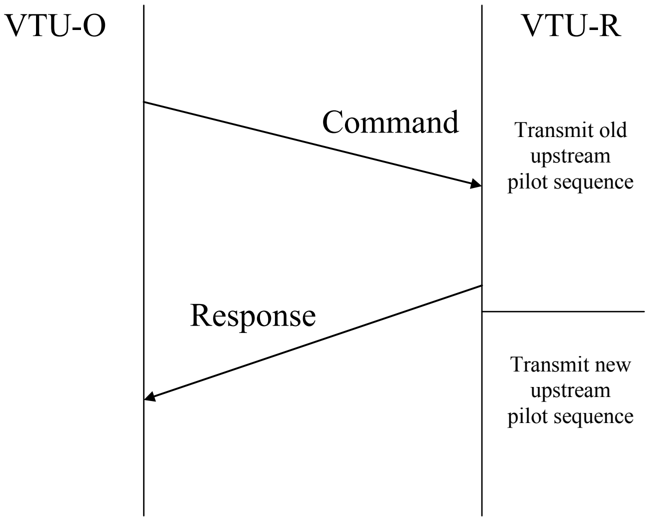


Figure 8-1 – Timing diagram of the pilot sequence update command and response

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.

If the VTU-R receives the Grant response, the VTU-R shall transmit zero power on all sub-carriers. The VTU-R shall make no changes to the characteristics of the transmission path. When the VTU-O observes the stopped transmission, it shall also stop transmitting. When the VTU-R observes the stopped transmission, it may change the characteristics of the transmission path at its own discretion.

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.

If the VTU-O receives the Grant response, the VTU-O shall transmit zero power on all sub-carriers. The VTU-O shall make no changes to the characteristics of the transmission path. When the VTU-R observes the stopped transmission, it shall also stop transmitting. When the VTU-O observes the stopped transmission, it may change the characteristics of the transmission path at its own discretion.

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

In the case of detection of far-end loss of power primitive *flpr* (see clause 11.3.3.2 of [ITU-T G.993.2]), it is recommended that the VTU-O switches off its transmit signal as soon as possible. Other mechanisms for mitigating the effect of a disorderly shutdown are for further study.

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).

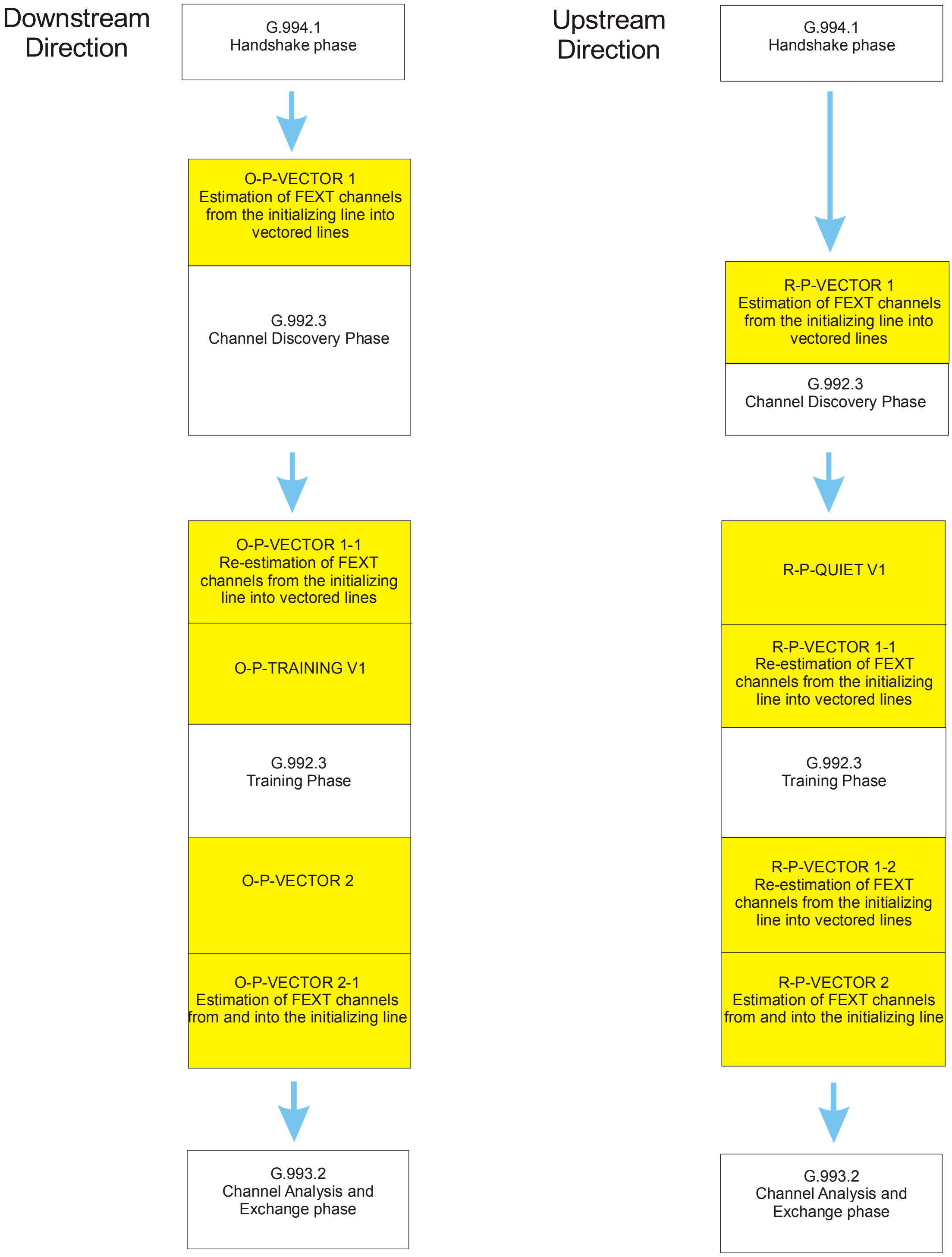


Figure 10-1 – ITU-T G.993.5 initialization overview

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 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].

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-VECTOR 1-1 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 – 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 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.

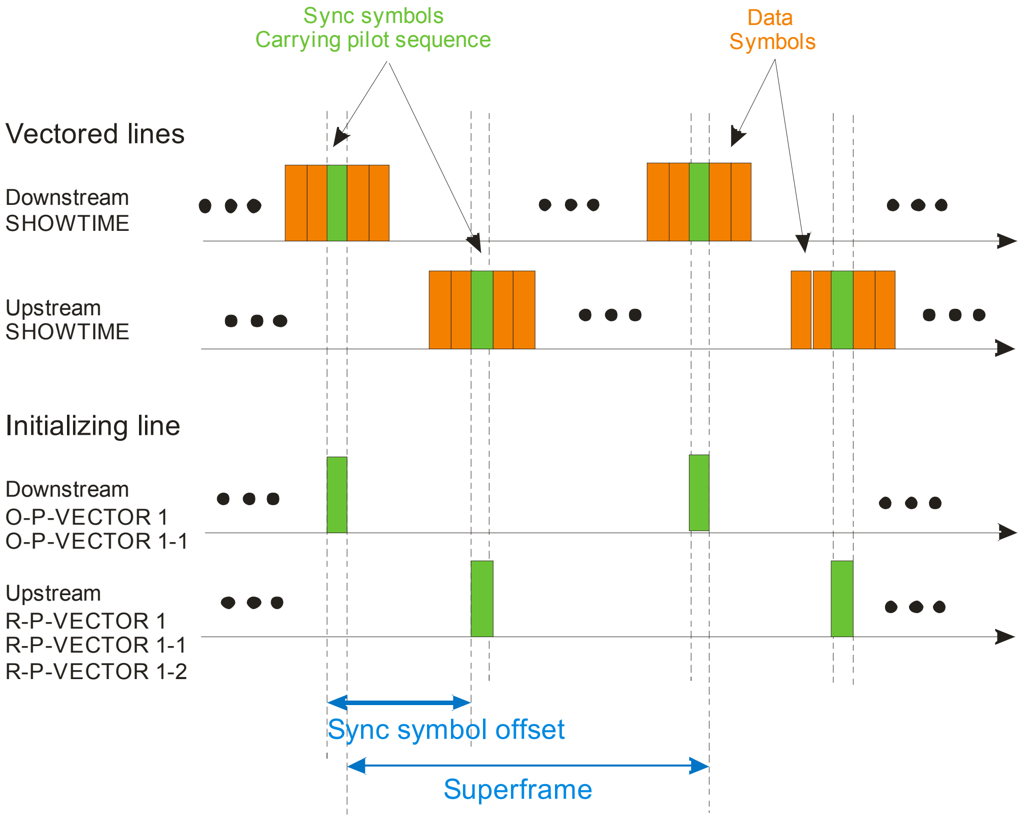


Figure 10-2 – Signal timing in the upstream and downstream directions (signals O-P-VECTOR 1 and R-P-VECTOR 1)

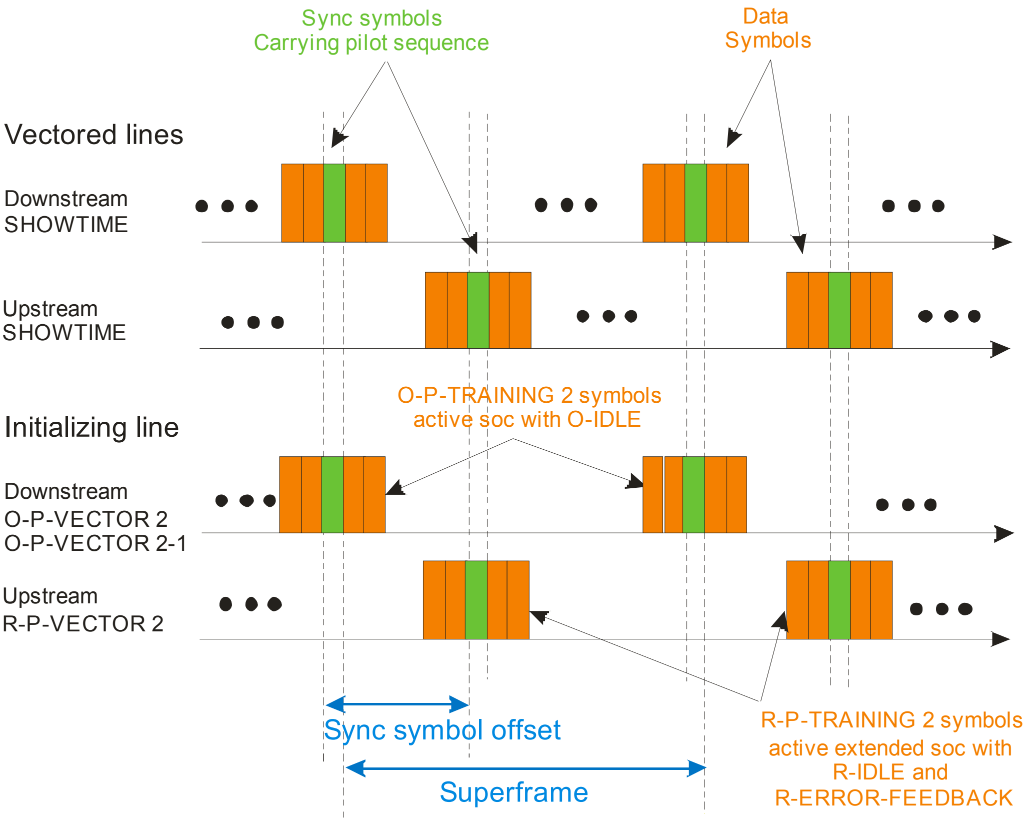


Figure 10-3 – Signal timing in the upstream and downstream directions (signals O-P-VECTOR 2 and R-P-VECTOR 2)

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 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 + Amd.5]).

The capabilities list (CL), capabilities list request (CLR) and mode select (MS) messages shall enable downstream vectoring.

The CLR message shall enable upstream vectoring. The CL message may enable upstream vectoring. The MS message shall enable upstream vectoring if and only if the last previous CL message indicated support by the VTU-O.

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

NOTE 1 – 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 2 – 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×N/32 (where 2×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.

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].

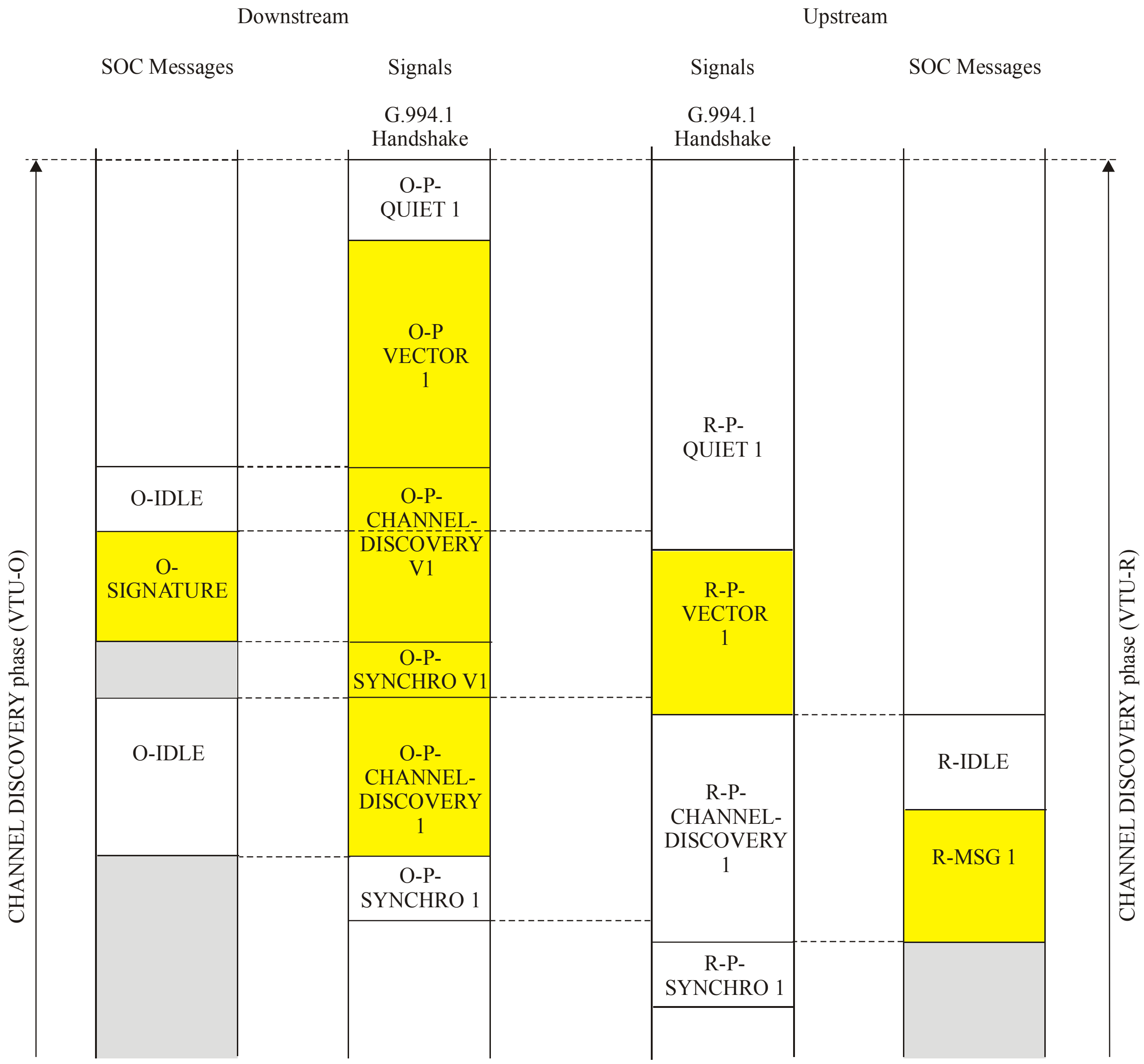


Figure 10-4 – Early stages of the Channel Discovery phase

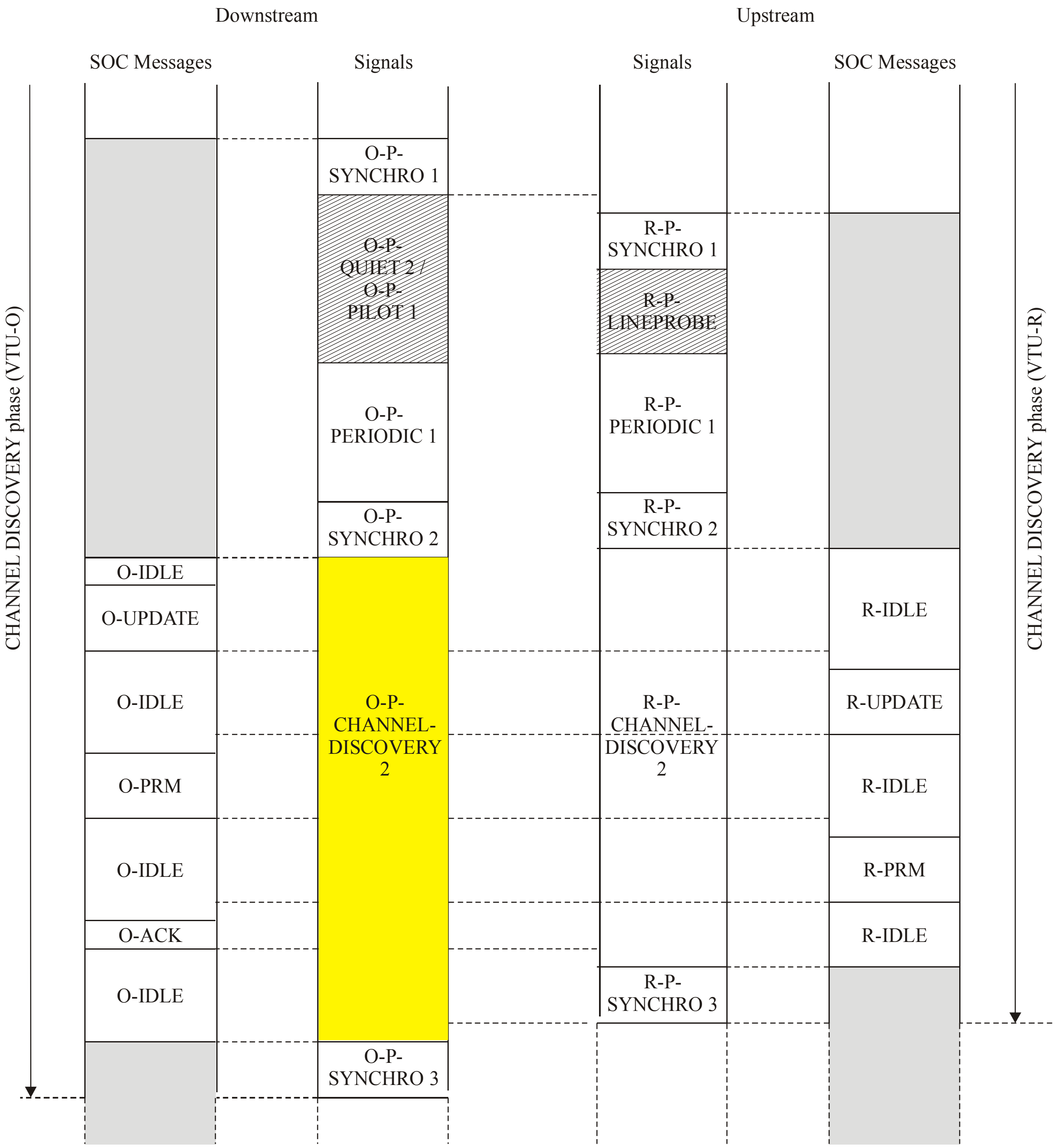


Figure 10-5 – Last stages of the Channel Discovery phase

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. The ITU-T G.993.5 parameter field contains several parameters needed for the FEXT cancellation operation, as shown in Table 10-1.

Table 10-1 – Parameter field in message O-SIGNATURE

Field	Content of field	Format
1	ITU-T G.993.5 parameter field length	1 byte
2	Vectored downstream bands	Bands descriptor
3	Upstream pilot sequence length	2 bytes
4	Upstream pilot sequence	(1-64) 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

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 10-1 shall be included in the ITU-T G.993.5 parameter field 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 8 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. 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.

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 used for maintaining the downstream sync counter. It is coded as an unsigned integer with a single valid value equal to 1024.

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 10-2.

Table 10-2 – 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 super-frame	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 10-2 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 super-frame", defines the maximum number (*Kmax)* of symbols in the super-frame 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 10-3.

Table 10-3 – 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 one bit per sync symbol repetitive sequence, assigned to the initializing line by the vectoring control entity (VCE). Each Sync symbol with a pilot sequence bit equal to ZERO shall modulate a 00 constellation point on all sub-carriers from the SUPPORTEDCARRIERSds set. Each Sync symbol with a pilot sequence bit equal to ONE shall modulate a 11 constellation point on all sub-carriers from the SUPPORTEDCARRIERSds set. 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 sub-carriers shall then be rotated by the quadrant scrambler defined in clause 12.3.6.2 of [ITU-T G.993.2].

For sync symbols, the transmit PSD of all sub-carriers shall be equal to CDPSDds.

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

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

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 sub-carriers 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 4x257 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 time position of the upstream pilot sequence, the VTU-O shall modulate the subset of sub-carriers 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 sub-carriers shall be modulated with the same information per symbol, i.e., either 00 or 11. Symbols whose sub-carriers 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 sub-carriers of the upstream sync symbol associated with this downstream sync symbol through the value of the offset.

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 8 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.

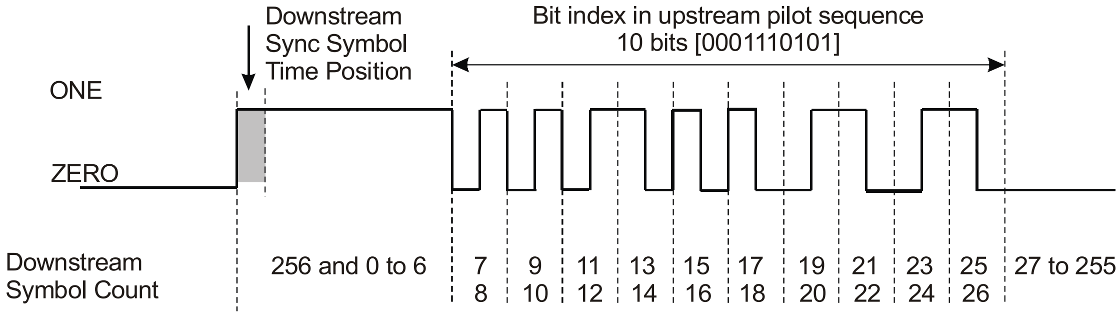


Figure 10-6 – Pattern modulated on subcarriers 10*n*+9 following the sync symbol position of the vectored lines.

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 one bit per sync symbol repetitive sequence, assigned to the initializing line by the VCE and communicated to the VTU-R in the O-SIGNATURE message. Each Sync symbol with a pilot sequence bit equal to ZERO shall modulate a 00 constellation point on all sub-carriers from the SUPPORTEDCARRIERSus set indicated in O-SIGNATURE. Each Sync symbol with a pilot sequence bit equal to ONE shall modulate a 11 constellation point on all sub-carriers of the

SUPPORTEDCARRIERSus. 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 sub-carriers 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 sub-carriers 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].

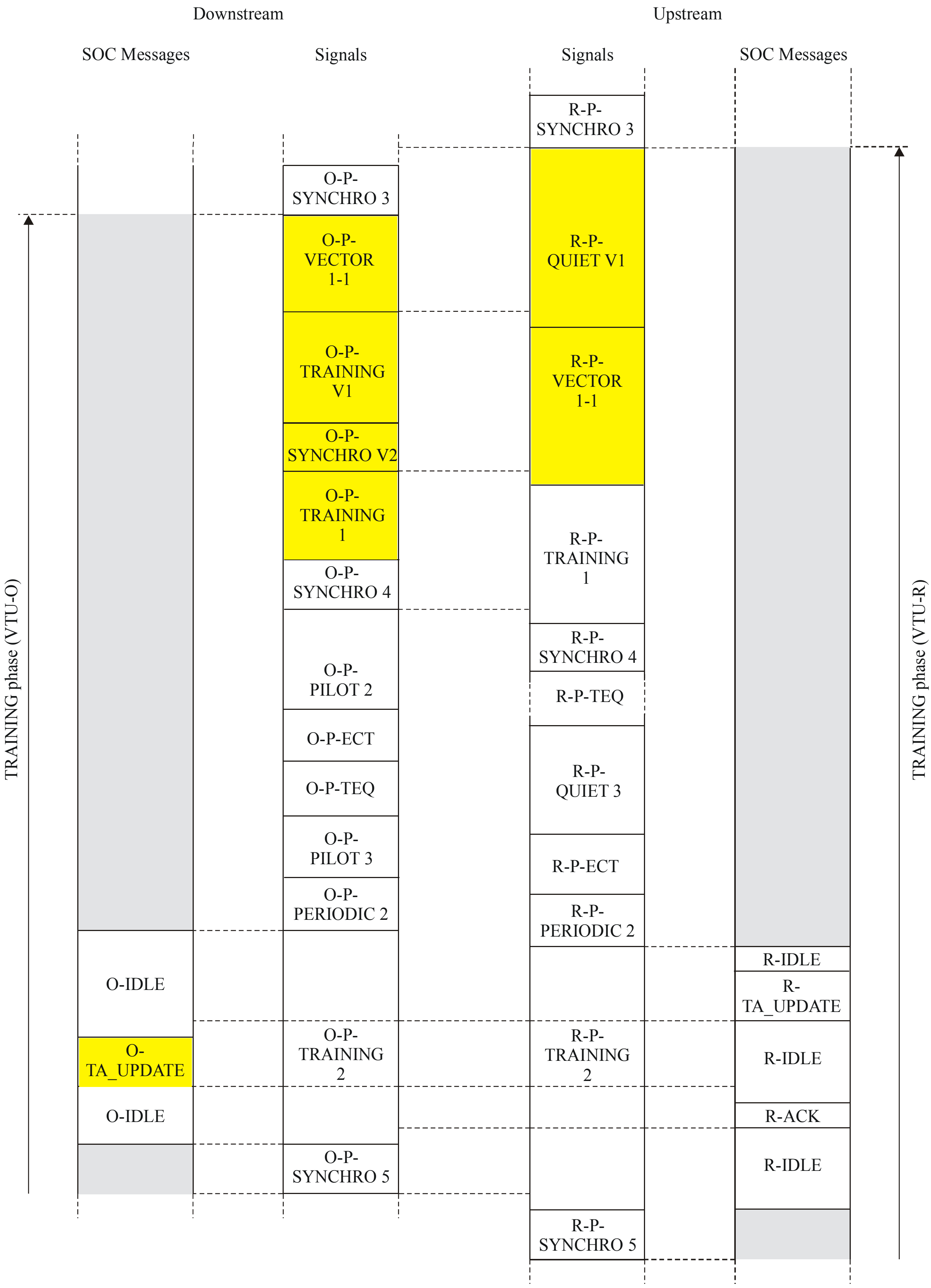


Figure 10-7 – Early stages of the Training phase

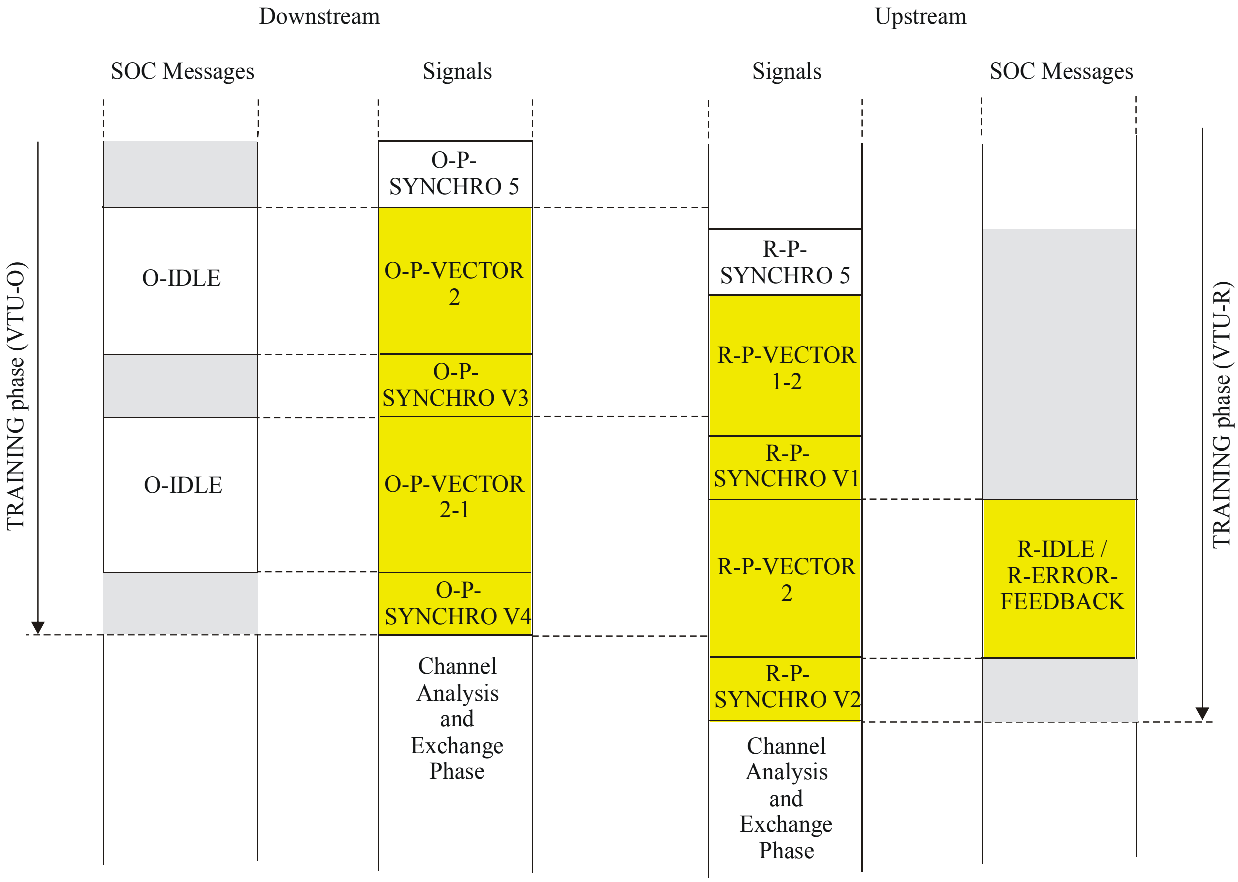


Figure 10-8 – Last stages of the Training phase

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 10-4.

Table 10-4 – 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 super-frame	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 10-4 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 super-frame", defines the number of symbols (K) in the super-frame 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 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 2 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 3 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.

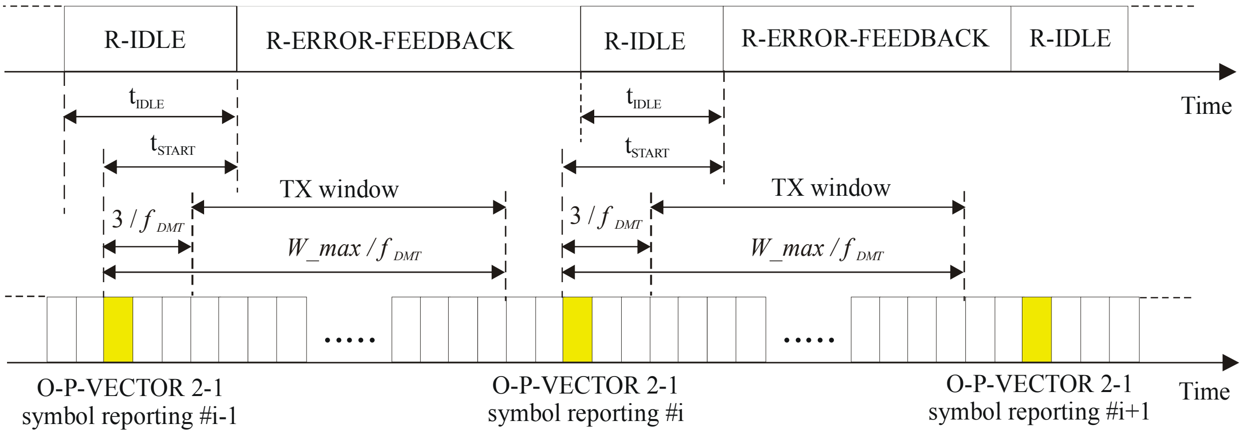


Figure 10-9 – Timeline of R-ERROR-FEEDBACK messages

Through the O-TA_UPDATE message, the VCE indicates how many FEXT estimation symbols per super-frame (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*, the VTU-R shall report clipped error samples for all the O-P-VECTOR 2-1 symbols of each downstream super-frame 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 10-5).

If the size of the R-ERROR_FEEDBACK message is larger than 1024 bytes, 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 16. All segments except the last one shall be set to be of the maximum allowed size of 1024 bytes.

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 + Amd.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 super-frame 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 10-5.

Table 10-5 – 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 $k = 0, \ldots, K - 1$ of the report in the super frame. 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 4 MSBs set to K–1 and the 10 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 sub-carriers 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 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 downstream pilot sequence (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 10-6, 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 10-6 – Bit mapping for R-P-VECTOR 2

Sub-carrier 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
$1/R$–1, $2/R$–1, $3/R$–1, ..., $n + 1/R$–1, ...	SOC message bits $\frac{16}{10 \cdot R} - 2$ and $\frac{16}{10 \cdot R} - 1$

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 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 10-7.

Table 10-7 – 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 10-7 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).

11 Configuration and test parameters

This Recommendation defines configuration parameters and test parameters that shall be accessible through the 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 + Amd.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 sub-carrier indices. Each pair represents the start and stop sub-carrier index of a frequency band in which FEXT cancellation is not required. Up to 8 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 + Amd.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 + Amd.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.

11.2 Test parameters

11.2.1 FEXT coupling coefficients (Xlogps)

11.2.1.1 Definition of FEXT coupling coefficients (Xlogps)

The FEXT insertion loss from line L_2 into line L_1 over frequency *f*, $FEXT\_IL_{L1,L2}(f)$, is defined as the ratio of the received FEXT PSD in a 100-ohm load on line L_1 to the transmit PSD (into a 100-ohm load) on line L_2. If the transmit PSD on line L_2 into a 100-ohm load is $REFERENCE\_PSD\_UO(f)$ and the received FEXT PSD on line L_1, while both ends are terminated with a 100-ohm load as shown in Figure 11-1, is $PSD\_UC\_FEXT(f)$, then the FEXT insertion loss from line L_2 into line L_1 in linear scale is given by the equation below:

$$FEXT\_IL_{L1,L2}(f) = \frac{PSD\_UC\_FEXT(f)}{REFERENCE\_PSD\_UO(f)}$$

The FEXT coupling coefficient from line L_2 into line L_1 over the frequency f is defined as the base-10 logarithm of the ratio of the FEXT insertion loss from line L_2 into line L_1 to the direct channel insertion loss of line L_1 (or the channel characteristic function, *H*, of line L_1) as follows:

$$X\log_{L1,L2}(f) = 10\log_{10}\left(\frac{FEXT\_IL_{L1,L2}(f)}{\left|H_{L1}(f)\right|^2}\right)$$

The FEXT coupling coefficient can also be represented in terms of the direct channel and the FEXT channel received PSDs on line L_1 as:

$$X\log_{L1,L2}(f) = 10\log_{10}\left(\frac{PSD\_UC\_FEXT(f)}{PSD\_UC\_DIRECT(f)}\right)$$

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

NOTE 1 – The definition is independent of the value of $REFERENCE\_PSD\_UO(f)$. However, it should be of the same order as typical transmitting PSD 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.

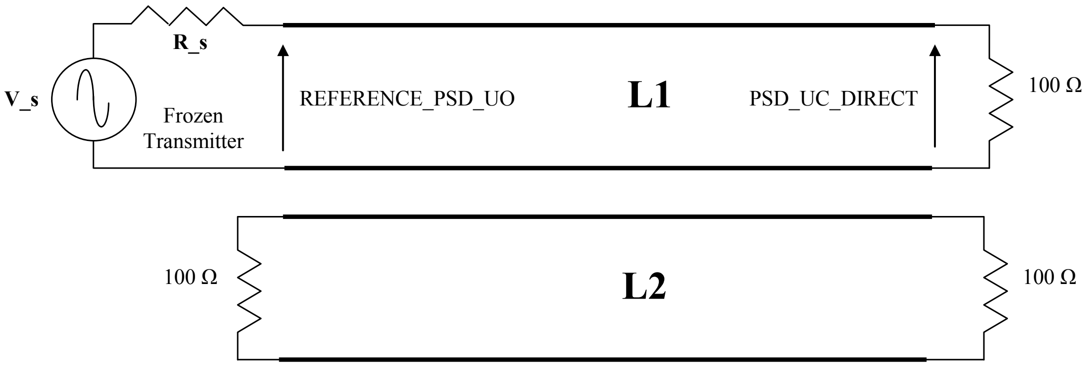


Figure 11-1 – Definition of Xlog (direct channel received PSD)

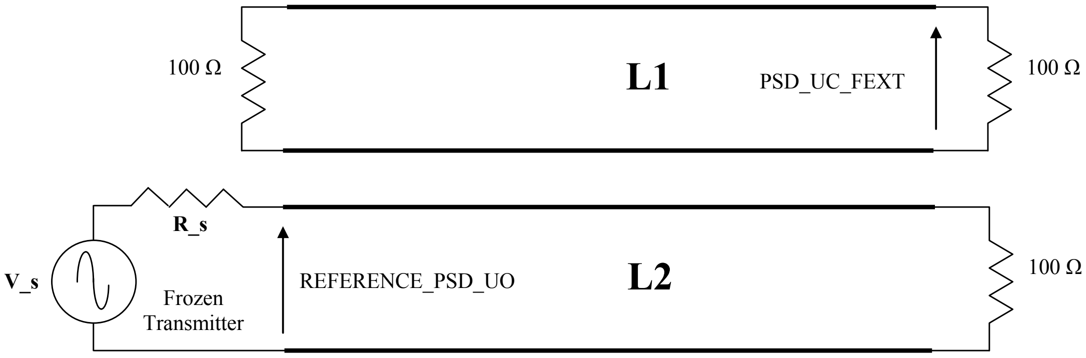


Figure 11-2 – Definition of Xlog (FEXT channel received PSD)

11.2.1.2 Reporting of downstream FEXT coupling coefficients (Xlogpsds)

The downstream FEXT coupling coefficient $Xlogpsds_{i,j}(n \times \Delta f)$ shall be stored and reported to the management entity upon request at least for all pairs of line indices (i, j) in the vectored group and sub-carrier indices $n = k \times G$ for which FEXT from line j into line i is estimated or cancelled over a frequency band containing the subcarrier index n. In this description, G is the sub-carrier group size for reporting the FEXT coupling and is restricted to powers of two less than or equal to 8 and $k = 0$ up to a maximum number of sub-carrier groups of 511.

The $Xlogpsds_{i,j}(k \times G \times \Delta f)$ shall be represented in a base-10 logarithmic format by an integer number $m(k)$, where $k = 0$ to 511. The $m(k)$ shall be coded as 10-bit unsigned integers. The value of $Xlogpsds_{i,j}(k \times G \times \Delta f)$ shall be defined as:

$$Xlogpsds_{i,j}(k \times G \times \Delta f) = 6 - (m(k)/10)$$

This data format supports an $Xlogpsds_{i,j}(f)$ granularity of 0.1 dB and an $Xlogpsds_{i,j}(f)$ dynamic range of approximately 102 dB (+6 dB to −96 dB).

An $Xlogpsds_{i,j}(k \times G \times \Delta f)$ value indicated as $m(k) = 2^{10} - 1$ is a special value. It indicates that no measurement could be done from line j into line i for subcarrier group k.

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

11.2.1.3 Reporting of upstream FEXT coupling coefficients (Xlogpsus)

For further study.

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 multiple-input multiple-output (MIMO) far-end crosstalk (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-pp-0600024]. This model is based on data gathered from measurements of actual loop plant deployed in North America and Europe and the Technical Report 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 4 insulated conductors (2 pairs), and a binder group called a unit is formed by binding 5 quads (10 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 10 pairs (5 quads) of the PE insulated cable is applied to the crosstalk model.

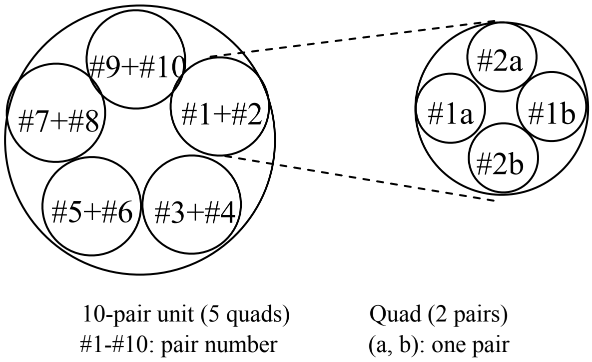


Figure I.1 – Cable model (0.4 mm PE insulated cable)

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 far-end crosstalk (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 $f=f_{FEXT}=160*10^3$ (Hz) and $d=d_{FEXT}=1*10^3$(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). So, 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-ed I-ing	#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 M_k (dB) and the standard deviation σ_k (dB) given in Table I.1. Table I.3 gives an example calculated by the equations below.

$$XT_k\ (i) = M_k + \Delta_k\ (i)$$

$$\Delta_k\ (i)\rho_i\sigma_k$$

$$pdf(u) = \frac{1}{\sqrt{2\pi}}e^{-}u^2/^2$$

$$Q(\rho_i) = \int_{\rho_i}^{\infty} pdf(u)du$$

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)
$Q(\rho_i)$=20(%)	0.842	74.7(dB)	81.1(dB)	81.9(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
$Q(\rho_i)$=30(%)	0.524	72.6(dB)	78.5(dB)	79.6(dB)
$Q(\rho_i)$=40(%)	0.253	70.9(dB)	76.3(dB)	77.6(dB)
$Q(\rho_i)$=50(%)	0	69.2(dB)	74.2(dB)	75.7(dB)
$Q(\rho_i)$=60(%)	–0.253	67.5(dB)	72.1(dB)	73.8(dB)
$Q(\rho_i)$=70(%)	–0.524	65.8(dB)	69.9(dB)	71.8(dB)
$Q(\rho_i)$=80(%)	–0.842	63.7(dB)	67.3(dB)	69.5(dB)
$Q(\rho_i)$=90(%)	–1.28	60.8(dB)	63.8(dB)	66.3(dB)
$Q(\rho_i)$=95(%)	–1.64	58.4(dB)	60.8(dB)	63.6(dB)
$Q(\rho_i)$=99(%)	–2.33	53.9(dB)	55.2(dB)	58.5(dB)
$Q(\rho_i)$=99.9(%)	–3.09	48.9(dB)	49.0(dB)	52.9(dB)
$Q(\rho_i)$=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 $XT_k(i)$. $\Phi_k(i)$ gives a FEXT coupling phase variation, and the value of $\Phi_k(i)$ (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 (= $\alpha + j\beta$, 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 $[0,2\pi]$

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

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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:

$$y = Hx + n$$

$$y_0 = \underbrace{H_{0,0}x_0}_{\text{Useful signal}} + \underbrace{\sum_{i=1}^{K-1} H_{0,i}x_i}_{\text{FEXT from active lines}} + \underbrace{H_{0,K}x_K}_{\text{FEXT from new line}} + \underbrace{n_0}_{\text{External noise}} \tag{III-1}$$

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 $H^{-1}diag(H)$.

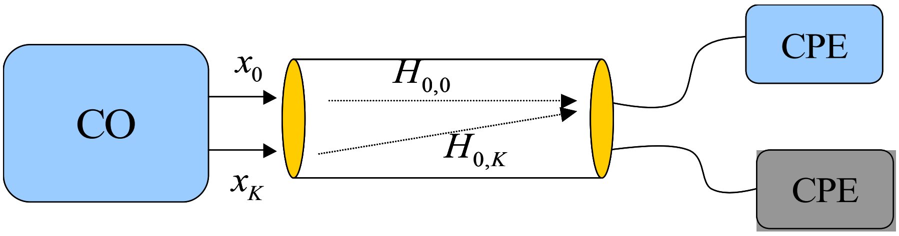
If $H = diag(H)(I + C)$ is defined, then F can be approximated (first order) by $F = I - \hat{C}$, with $\hat{C}$ being an estimate of C.

Hence, the goal of channel estimation is to find the elements of C, with

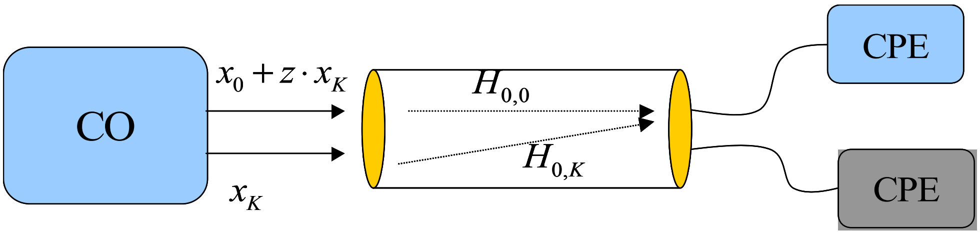
$C_{v,i} = \frac{H_{v,i}}{H_{v,v}}$, $v \neq i$ so in our case, with $v = 0$, this becomes $C_{0,i} = \frac{H_{0,i}}{H_{0,0}}$, for i=1 .. K

III.2.2 Probing signal

Under normal conditions, the following model can be used:



Then, a special "probing" signal can be used to estimate the crosstalk channel.



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:

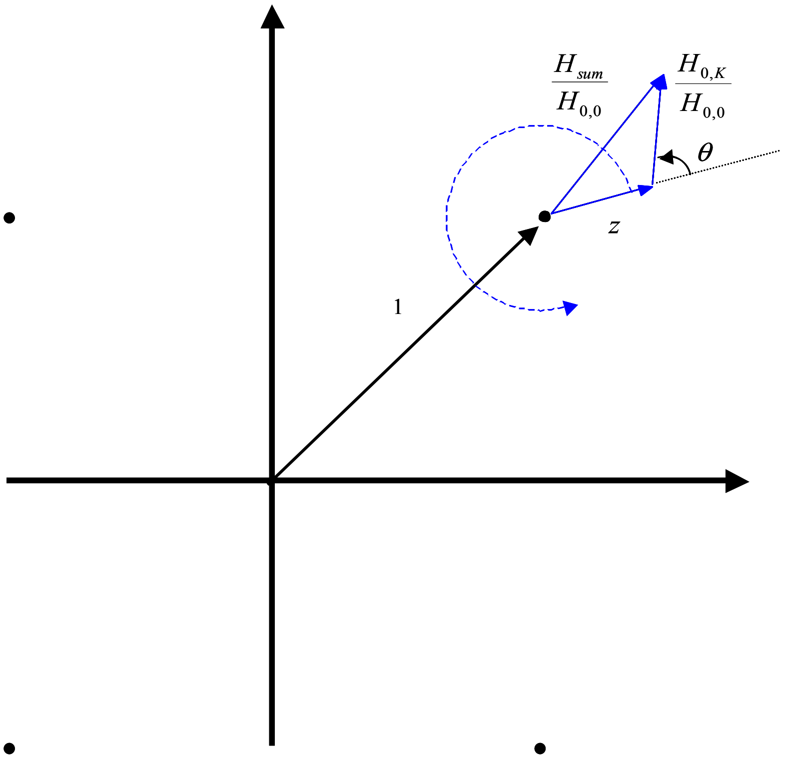
$$\frac{1}{SNR_a(z)} = \frac{\sum_{i=1}^{K-1} \sigma_i^2 |H_{0,i}|^2 + \sigma_{n_0}^2 + \sigma_K^2 |H_{0,K} + z \cdot H_{0,0}|^2}{\sigma_0^2 |H_{0,0}|^2} = \frac{1}{SNR_b} + \frac{\sigma_K^2 |H_{0,K} + z \cdot H_{0,0}|^2}{\sigma_0^2 |H_{0,0}|^2} \tag{III-4}$$

The previous step assumes the background noise and the crosstalk from the other lines (1..*K*–1) to be constant during a single iteration.

$$\left|\frac{H_{0,K}}{H_{0,0}}+z\right|^2=\frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(z)}-\frac{1}{SNR_b}\right) \qquad \text{(III-5)}$$

III.2.3 Graphical representation

Graphically, the effect of such probing signal on a QAM constellation point, can be represented as follows:



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 $\frac{H_{sum}}{H_{0,0}}$, which rotates around the constellation point.

III.2.4 Derivation of the equations for crosstalk channel estimation

In order to calculate the crosstalk channel $C_{0,K}=\frac{H_{0,K}}{H_{0,0}}$, we can derive the following equations.

Starting from equation III-5:

$$\left|\frac{H_{0,K}}{H_{0,0}}+z\right|^2=\frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(z)}-\frac{1}{SNR_b}\right) \qquad \text{(III-6)}$$

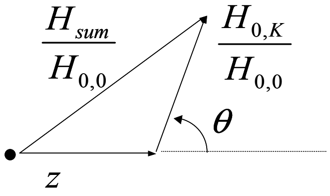
when

$z = 0$, this leads to:

$$\left|\frac{H_{0,K}}{H_{0,0}}\right|^2=\frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(0)}-\frac{1}{SNR_b}\right) \qquad \text{(III-7)}$$

when

$z = \varepsilon$, and applying trigonometry, we get:



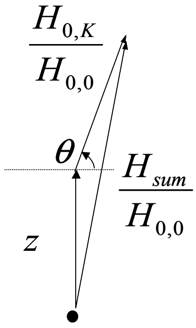
$$\left|\frac{H_{0,K}}{H_{0,0}}+\varepsilon\right|^2=\left|\frac{H_{0,K}}{H_{0,0}}\right|^2+\varepsilon^2-2\cdot\varepsilon\cdot\left|\frac{H_{0,K}}{H_{0,0}}\right|\cos(\pi-\theta)$$

$$2\cdot\varepsilon\cdot\left|\frac{H_{0,K}}{H_{0,0}}\right|\cos(\theta)=\left|\frac{H_{0,K}}{H_{0,0}}+\varepsilon\right|^2-\left|\frac{H_{0,K}}{H_{0,0}}\right|^2-\varepsilon^2$$

$$2\cdot\varepsilon\cdot\left|\frac{H_{0,K}}{H_{0,0}}\right|\cos(\theta)=\frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(\varepsilon)}-\frac{1}{SNR_b}\right)-\frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(0)}-\frac{1}{SNR_b}\right)-\varepsilon^2$$

when

$z = j\varepsilon$, we get:



III.2.5 Equations for crosstalk channel estimation

Result, for $z = \varepsilon$

$$\left|\frac{H_{0,K}}{H_{0,0}}\right| \cos(\theta) = \frac{1}{2\varepsilon}\frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(\varepsilon)} - \frac{1}{SNR_a(0)}\right) - \frac{\varepsilon}{2} \tag{III-8}$$

Result, for $z = j\varepsilon$

$$\left|\frac{H_{0,K}}{H_{0,0}}\right| \sin(\theta) = \frac{1}{2\varepsilon}\frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(j\varepsilon)} - \frac{1}{SNR_a(0)}\right) - \frac{\varepsilon}{2} \tag{III-9}$$

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 $C_{0,K} = \frac{H_{0,K}}{H_{0,0}}$, 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*ε

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_α (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:

$$\begin{aligned} y &= H\left(I - \hat{C}\right)x \\ &= Hx - H\hat{C}x \\ &= diag(H)(I + C)x - diag(H)(I + C)\hat{C}x \\ &\approx diag(H)x + diag(H)Cx - diag(H)\hat{C}x \end{aligned}$$

$$y_0 = \underbrace{H_{0,0}x_0}_{\text{Useful signal}} + \underbrace{\sum_{i=1}^{K-1} H_{0,i}\left(C_{0,i} - \hat{C}_{0,i}\right)x_i}_{\text{Residual FEXT from active lines}} + \underbrace{H_{0,K}\left(C_{0,K} - \hat{C}_{0,K}\right)x_K}_{\text{Residual FEXT from line K}} + \underbrace{n_0}_{\text{External noise}}$$

$$= H_{0,0}x_0 + \sum_{i=1}^{K-1} H_{0,i}\Big|_{residual} x_i + H_{0,K}\Big|_{residual} x_K + n_0$$

Consequently, we can rewrite equations III-8 and III-9 as follows:

$$\left|\frac{H_{0,K}\big|_{residual}}{H_{0,0}}\right| \cos(\theta) = \frac{1}{2\varepsilon}\frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(\varepsilon)} - \frac{1}{SNR_a(0)}\right) - \frac{\varepsilon}{2} \qquad \text{(III-11)}$$

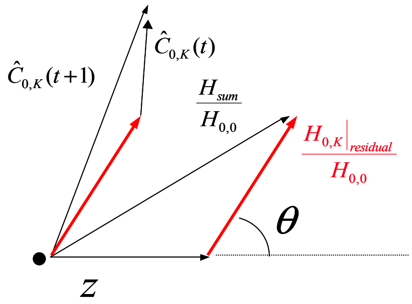
$$\left|\frac{H_{0,K}\big|_{residual}}{H_{0,0}}\right| \sin(\theta) = \frac{1}{2\varepsilon}\frac{\sigma_0^2}{\sigma_K^2}\left(\frac{1}{SNR_a(j\varepsilon)} - \frac{1}{SNR_a(0)}\right) - \frac{\varepsilon}{2} \qquad \text{(III-12)}$$

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:



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*

$$x_K^{(n)}(l) = s_K^{(n)}(l) + \varepsilon \sum_{i=1}^{K-1} z_i^{(n)} s_i^{(n)}(l) \qquad \text{(III-14)}$$

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:

$$\begin{aligned} y_K^{(n)}(l) &= \sum_{i=1}^{K} h_{K,i} x_i^{(n)}(l) + w_K^{(n)}(l) \\ &= h_{K,K} s_K^{(n)}(l) + \sum_{i=1}^{K-1} \left(h_{K,i} + \varepsilon z_i^{(n)} h_{K,K} \right) s_i^{(n)}(l) + w_K^{(n)}(l) \end{aligned}$$

The signal power on line *K* will be measured by the VTU-R as:

$$\begin{aligned} \mathrm{signal}_K &= \frac{1}{L} \sum_{l=1}^{L} \left| h_{K,K} s_K^{(n)}(l) \right|^2 \\ &\approx \left| h_{K,K} \right|^2 \sigma_K^2 \end{aligned} \qquad \text{(III-15)}$$

The noise power on line *K* will be measured as:

$$\begin{aligned} \mathrm{noise}_K &= \frac{1}{L} \sum_{l=1}^{L} \left| y_K^{(n)}(l) - h_{K,K} s_K^{(n)}(l) \right|^2 \\ &\approx \sum_{i=1}^{K-1} \left| h_{K,i} + \varepsilon z_i^{(n)} h_{K,K} \right|^2 \sigma_i^2 + \sigma_{W_K}^2 \end{aligned} \qquad \text{(III-16)}$$

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:

$$\mathrm{SNR}_K^{(n)} = \mathrm{signal}_K / \mathrm{noise}_K$$

From equations III-15 and III-16:

$$\begin{aligned} \frac{1}{\mathrm{SNR}_K^{(n)}} &= \frac{\mathrm{noise}_K}{\mathrm{signal}_K} \\ &\approx \frac{1}{\sigma_K^2} \left(\sum_{i=1}^{K-1} \left| \frac{h_{K,i}}{h_{K,K}} \sigma_i + \varepsilon z_i^{(n)} \sigma_i \right|^2 + \frac{\sigma_{W_K}^2}{\left| h_{K,K} \right|^2} \right) \\ &= \frac{1}{\sigma_K^2} \left(\left\| \overline{\mathbf{a}} + \varepsilon \overline{\mathbf{b}}^{(n)} \right\|^2 + \frac{\sigma_{W_K}^2}{\left| h_{K,K} \right|^2} \right) \end{aligned} \qquad \text{(III-17)}$$

where we have defined $\overline{\mathbf{a}} = [\overline{a}_1 \ldots \overline{a}_{K-1}]^T$, $\overline{\mathbf{b}}^{(n)} = [\overline{b}_1^{(n)} \ldots \overline{b}_{K-1}^{(n)}]^T$ with

$$\overline{a}_i = \frac{h_{K,i}}{h_{K,K}} \sigma_i \qquad \text{(III-18)}$$

and

$$\overline{b}_i^{(n)} = z_i^{(n)} \sigma_i \qquad \text{(III-19)}$$

Applying the general form of Pythagoras' theorem:

$$\left\| \overline{\mathbf{a}} + \varepsilon \overline{\mathbf{b}}^{(n)} \right\|^2 = \left\| \overline{\mathbf{a}} \right\|^2 + \left\| \varepsilon \overline{\mathbf{b}}^{(n)} \right\|^2 + 2\varepsilon \operatorname{Re}\{ \overline{\mathbf{b}}^{(n)^H} \overline{\mathbf{a}} \} \qquad \text{(III-20)}$$

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:

$$\begin{aligned}\mathrm{Re}\{\bar{\mathbf{b}}^{(n)H}\bar{\mathbf{a}}\} &= \sum_{i=1}^{K-1} a_{R,i}b_{R,i}^{(n)} + a_{I,i}b_{I,i}^{(n)} \\ &= \mathbf{b}^{(n)H}\mathbf{a},\end{aligned}$$

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:

$$\sum_n p_{m,n} c^{(n)} = \varepsilon \sum_n p_{m,n} \mathbf{b}^{(n)^H} \mathbf{a} + \left(\frac{1}{2} \|\bar{\mathbf{a}}\|^2 + \frac{1}{2} \frac{\sigma_{W_K}^2}{\left|h_{K,K}\right|^2} \right) \sum_n p_{m,n}, \forall m.$$

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 $\mathbf{c} = [c^{(1)} \ldots c^{(N)}]^T$ 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

$$\mathbf{a} = \varepsilon^{-1} \operatorname{pinv}(\mathbf{PB}) \mathbf{Pc}$$

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

$$\mathbf{F} = \mathbf{I}_K - \operatorname{offdiag}\left(\begin{bmatrix} \frac{h_{1,1}}{h_{1,1}} & \cdots & \frac{h_{1,K}}{h_{1,1}} \\ \vdots & \ddots & \vdots \\ \frac{h_{K,1}}{h_{K,K}} & \cdots & \frac{h_{K,K}}{h_{K,K}} \end{bmatrix} \right), \tag{III-27}$$

where we define the function $\operatorname{offdiag}(\mathbf{X}) = \mathbf{X} - \operatorname{diag}(\mathbf{X})$.

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)×(2K–1). Hence using this algorithm, it is possible to form an estimate of the crosstalk channels after only 2K–1 SNR measurements.

III.3.4 Crosstalk channel estimation algorithm

The channel identification algorithm operates as follows:

- precompute $\mathbf{G} = \operatorname{pinv}(\mathbf{PB})\mathbf{P}$
- 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 $\varepsilon = \min_i \frac{1}{2}\frac{1}{\sqrt{\mathrm{SNR}_K^{(0)}}}\frac{\sigma_K}{\sigma_i}$
–   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 $c^{(n)} = \frac{1}{2}\frac{\sigma_K^2}{\mathrm{SNR}_K^{(n)}} - \varepsilon^2 d^{(n)}$
–   end
–   $\mathbf{a} = \varepsilon^{-1}\mathbf{Gc}$
–   $\frac{h_{K,i}}{h_{K,K}} = (a_i + ja_{K-1+i})/\sigma_i, \forall i$
–   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 $d^{(n)}$.

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