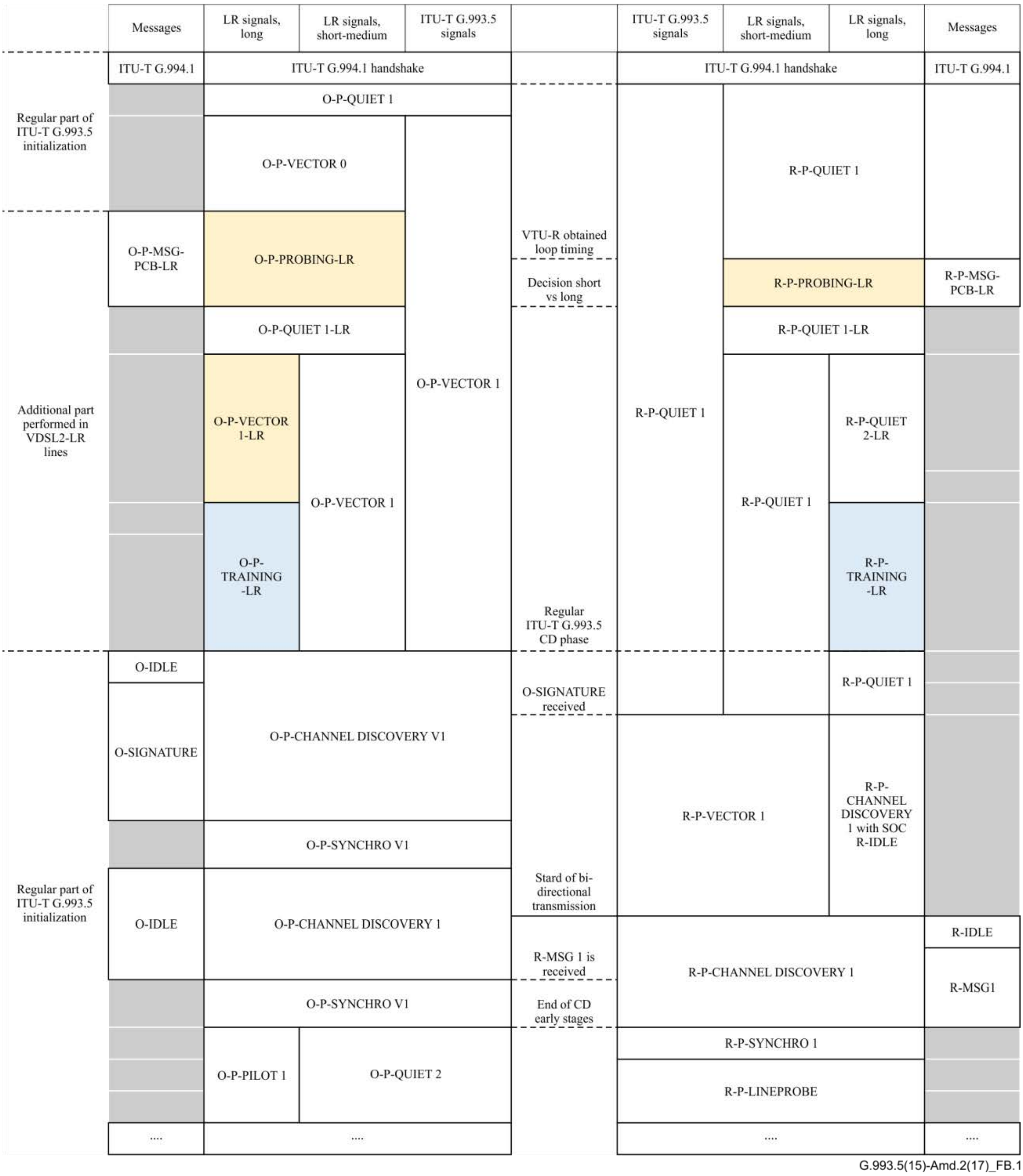


Figure B.1 – Overview of the VDSL2-LR initialization (compared to regular ITU-T G.993.5 initialization)

B.3 ITU-T G.994.1 Handshake phase

During the ITU-T G.994.1 Handshake phase, it is determined whether the line is selected to be a VDSL2-LR line or selected to be a regular ITU-T G.993.5 line. The PROBING PSD (see clause B.6) in case the line is selected to be a VDSL2-LR line, is also indicated (via NOMPSD and *log_tssi* values). The defined Spar(2) codepoints belongs to the ITU-T G.993.2 code-tree and defined in Table 11.68.0.1/G.994.1 (Standard information field – ITU-T G.993.2 SPar(2) coding – Octet 2). The use of these codepoints in the ITU-T G.994.1 CL, CLR and MS messages is defined in Tables B.1 to B.8.

Table B.1 – VTU-O CL message SPar(2) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bit
Support of VDSL2-LR	Shall be set to ZERO if: • the VTU-O does not support VDSL2 Long Reach (VDSL2-LR) mode according to this annex, or, • none of short, medium or long loop operation type is allowed in the CO-MIB (see clause B.10.1.1), and may be set to ONE otherwise.
Spectrum bounds downstream	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE. If set to ONE, signifies that the VTU-O includes the spectrum bounds downstream defined in corresponding NPar(3).
Spectrum shaping downstream	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE. If set to ONE, signifies that the VTU-O includes the spectrum shaping downstream defined in corresponding NPar(3).
Spectrum bounds upstream	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE. If set to ONE, signifies that the VTU-O includes the spectrum bounds upstream defined in corresponding NPar(3).
Spectrum shaping upstream	Always set to ZERO.
Transmit signal images above the Nyquist frequency	Always set to ZERO.
Offset IDFT sample #0 downstream	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE.
Offset IDFT sample #0 upstream	Always set to ZERO.

Table B.2 – VTU-O CL message NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of NPar(3) bits
Support of VDSL2-LR	If the SPar(2) bit is set to ONE: Bit 1: Short loop operation type: Shall be set to ONE if and only if VDSL2-LR short loop operation is allowed in the CO-MIB (see clause B.10.1.1). Bit 2: Medium loop operation type: Shall be set to ONE if and only if VDSL2-LR medium loop operation is allowed in the CO-MIB (see clause B.10.1.1). Bit 3: Long loop operation type: Shall be set to ONE if and only if VDSL2-LR long loop operation is allowed in the CO-MIB (see clause B.10.1.1). Bit 4: Always set to ONE.
Spectrum bounds downstream	A parameter block indicating the nominal transmit PSD level. The parameter block length shall be 2 octets. The nominal transmit PSD level (*NOMPSDds*) shall be represented as a 9-bit 2's-complement signed value in 0.1 dB steps, −25.6 to +25.5 dB, relative to the value of −40 dBm/Hz, and shall be coded in bits 3 down to 1 in octet 1, bits 6 down to 1 in octet 2.

Table B.2 – VTU-O CL message NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of NPar(3) bits
Spectrum shaping downstream	A parameter block of pairs of a subcarrier index and the spectrum shaping *log_tss*$_i$ value at that subcarrier. Pairs shall be transmitted in ascending subcarrier index order. Each pair shall be represented as 4 octets. The parameter block length shall be a multiple of 4 octets. The maximum number of breakpoints equals 32. Codepoints shall be structured as: The subcarrier index shall be a 9-bit unsigned value, indicating subcarrier index 1 to 2 × *NSCds* − 1, coded in bits 3 down to 1 in octet 1, bits 6 down to 1 in octet 2; The indication whether the subcarrier is included in the SUPPORTEDCARRIERS set (indication set to 1) or not included in the SUPPORTEDCARRIERSset (indication set to 0). This indication is coded in bit 6 of octet 3; The spectrum shaping *log_tss*$_i$ values shall be represented in logarithmic scale as a 7-bit unsigned value in –0.5 dB steps, ranging from 0 dB (value 0) to −62.5 dB (value 125), coded in bit 1 of octet 3 and bits 6 down to 1 in octet 4. Value 127 is a special value, indicating the subcarrier is not transmitted (i.e., *tss*$_i$ = 0 in linear scale). Value 126 is a special value indicating that the *log_tss*$_i$ value on this subcarrier shall be interpolated according to clause 8.13.2.4 of [ITU-T G.992.3]. At least one pair (of a subcarrier index and the spectrum shaping *log_tss*$_i$ value at that subcarrier) indicated as included in the SUPPORTEDCARRIERS set, shall have the *log_tss*$_i$ value set to 0 dB.
Spectrum bounds upstream	Parameter block with same definition and structure as spectrum bounds downstream, with *NOMPSD*=*NOMPSDus*.
Offset IDFT sample #0 downstream	Indicate the offset between the IDFT sample #0 of O-P-SEGUE 1-LR and O-P-CHANNEL DISCOVERY-V1 in samples at 4.416MHz. The value is coded as a 7-bits unsigned integer.

Table B.3 – VTU-R CLR message SPar(2) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bit
Support of VDSL2-LR	Shall be set to ONE if and only if the VTU-R supports VDSL2 Long Reach (VDSL2-LR) mode according to this annex.
Spectrum bounds downstream	Always set to ZERO.
Spectrum shaping downstream	Always set to ZERO.
Spectrum bounds upstream	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE. If set to ONE, signifies that the VTU-R includes the spectrum bounds upstream defined in corresponding NPar(3).
Spectrum shaping upstream	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE. If set to ONE, signifies that the VTU-R includes the spectrum shaping upstream defined in corresponding NPar(3).

Table B.3 – VTU-R CLR message SPar(2) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bit
Transmit signal images above the Nyquist frequency	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE. If set to ONE, signifies that the VTU-R includes the transmit signal images above the Nyquist frequency defined in corresponding NPar(3).
Offset IDFT sample #0 downstream	Always set to ZERO.
Offset IDFT sample #0 upstream	Shall be set to ONE if and only if the "Support of VDSL2-LR" bit is set to ONE.

Table B.4 – VTU-R CLR message NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of NPar(3) bits
Support of VDSL2-LR	Bit 1: Always set to ONE. Bit 2: Always set to ONE. Bit 3: Always set to ONE. Bit 4: FMT-O-P-TREF2: If set to ONE, indicates that the VTU-R requests the VTU-O to transmit O-P-TREF symbols during O-P-ECT-LR. If set to ZERO, indicates that the VTU-R requests the VTU-O to transmit O-P-QUIET symbols during O-P-ECT-LR.
Spectrum bounds upstream	Parameter block with same definition and structure as spectrum bounds upstream parameter block in CL message.
Spectrum shaping upstream	Parameter block with same definition and structure as spectrum shaping downstream parameter block in CL message, with *NSC=NSCus* and maximum number of breakpoints equals 16.
Transmit signal images above the Nyquist frequency	A parameter block indicating the type of the transmit signal images above the Nyquist frequency. The parameter block shall consist of a single octet. Codepoints shall be structured as bits 6 to 3 indicating the *N* value (for a *2N* point IDFT, see clause 10.4.3 of [ITU-T G.993.2]) and bits 2 and 1 indicating the definition of the transmit signal images above the Nyquist frequency (see clause 10.4.3 of [ITU-T G.993.2]). The coding shall be as follows: • ($b_6b_5b_4b_3$) = n, with $1 \le n \le 15$ indicates that $N = 2^n$. • (b_2b_1 = 01): Complex conjugate of the base-band signal. • (b_2b_1 = 10): Zero filled. • (b_2b_1 = 00): Other (none of the above). • (b_2b_1 = 11): Reserved.
Offset IDFT sample #0 upstream	Indicate the offset between the IDFT sample #0 of R-P-SEGUE 1-LR and R-P-CHANNEL DISCOVERY 1 in samples at 276kHz. The value is coded as a 3-bits unsigned integer value.

Table B.5 – VTU-O MS message SPar(2) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bit
Support of VDSL2-LR	Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, indicates that both the VTU-O and the VTU-R shall continue initialization for VDSL2-LR mode as defined in this Annex. If set to

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bit
	ZERO, indicates that both the VTU-O and VTU-R shall continue initialization as defined in clause 10. If this bit is set to ONE, then the CE length SPar(2) bit shall be set to ZERO.
Spectrum bounds upstream	Always set to ZERO.
Spectrum shaping upstream	Always set to ZERO.
Spectrum bounds downstream	Always set to ZERO.
Spectrum shaping downstream	Always set to ZERO.
Transmit signal images above the Nyquist frequency	Always set to ZERO.
Offset IDFT sample #0 downstream	Always set to ZERO.
Offset IDFT sample #0 upstream	Always set to ZERO.

Table B.6 – VTU-O MS message NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of NPar(3) bits
Support of VDSL2-LR	Bit 1: Short loop: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, short loop operation shall be allowed. Bit 2: Medium loop: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, medium loop operation shall be allowed. Bit 3: Long loop: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, long loop operation shall be allowed. Bit 4: FMT-O-P-TREF2: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, the VTU-O shall transmit O-P-TREF symbols during O-P-ECT-LR. If set to ZERO, the VTU-O shall transmit O-P-QUIET symbols during O-P-ECT-LR.

Table B.7 – VTU-R MS message SPar(2) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bit
Support of VDSL2-LR	Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, indicates that both the VTU-O and the VTU-R shall continue initialization for VDSL2-LR mode as defined in this annex. If set to ZERO, indicates that both the VTU-O and VTU-R shall continue initialization as defined in clause 10. If this bit is set to ONE, then the CE length SPar(2) bit shall be set to ZERO.
Upstream spectrum bounds	Always set to ZERO.
Upstream spectrum shaping	Always set to ZERO.
Upstream spectrum bounds	Always set to ZERO.
Upstream spectrum shaping	Always set to ZERO.
Transmit signal images above the	Always set to ZERO.

Table B.7 – VTU-R MS message SPar(2) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of SPar(2) bit
Nyquist frequency	
Offset IDFT sample #0 downstream	Always set to ZERO.
Offset IDFT sample #0 upstream	Always set to ZERO.

Table B.8 – VTU-R MS message NPar(3) bit definitions

ITU-T G.994.1 SPar(2) Bit	Definition of NPar(3) bits
Support of VDSL2-LR	Bit 1: Short loop: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, short loop operation shall be allowed. Bit 2: Medium loop: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, medium loop operation shall be allowed. Bit 3: Long loop: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, long loop operation shall be allowed. Bit 4: FMT-O-P-TREF2: Set to ONE if and only if both the last previous CLR and the last previous CL messages have set this bit to ONE. If set to ONE, the VTU-O shall transmit O-P-TREF symbols during O-P-ECT-LR. If set to ZERO, the VTU-O shall transmit O-P-QUIET symbols during O-P-ECT-LR.

If the ITU-T G.994.1 MS message has the "Support of VDSL2-LR" Spar(2) bit set to ONE, then it shall:

- indicate use of the mandatory CE Length;
- indicate operation according to a profile other than profile 30a (see Tables 6-1 and Q.1 of [ITU-T G.993.2]);
- have the annex B US0 Spar(2) set to ONE and have one of the 25-138 kHz (A), 25-276 kHz (M) or 120-276 kHz (B) NPar(3) set to ONE.

Selection of the particular loop operation (short loop, medium loop, or long loop) occurs during the following stages of initialization, as described in clause B.2. The particular loop operation may be selected only if allowed (i.e., if the corresponding ITU-T G.994.1 MS message "Short loop", "Medium loop" or "Long loop" Npar(3) bit is set to ONE)."

B.4 Signals sent by the VTU-O during the Channel Discovery and Training phase

The maximum duration of O-P-VECTOR 0, O-P-VECTOR 1-LR and O-P-VECTOR 1 is defined in clauses B.4.2, B.4.5 and B.4.7, respectively. In addition, if the bit "8192 superframes duration for O-P-VECTOR 1" is enabled in the ITU-T G.994.1 Handshake phase (see clause 10.2), then the sum of the durations of all stages starting from O-P-VECTOR 0 and up to but not including O-P-CHANNEL DISCOVERY V1 shall not exceed 8 ×1024 × 257 symbols.

A VTU-R indicating "Support of VDSL2-LR mode" in the ITU-T G.994.1 CLR message, shall also indicate support of "8192 superframes duration for O-P-VECTOR 1".

NOTE – Regular ITU-T G.993.5 lines with the bit "8192 superframes duration for O-P-VECTOR 1" disabled in the ITU-T G.994.1 Handshake phase may initialize in a different joining group that does not include VDSL2-LR lines.

B.4.1 O-P-QUIET 1

After the ITU-T G.994.1 Handshake phase, the VTU-O shall start initialization with the O-P-QUIET 1 signal defined in clause 12.3.3.3.1.1 of [ITU-T G.993.2].
The duration of O-P-QUIET 1 signal shall be at least 512 but not longer than 1024 symbol periods.

The O-P-QUIET 1 signal shall be followed by the O-P-VECTOR 0 signal.

B.4.2 O-P-VECTOR 0

The O-P-VECTOR 0 signal shall be identical to the O-P-VECTOR 1 signal defined in clause 10.3.3.1. It includes all subcarriers from the downstream SUPPORTEDCARRIERS set. The PSD of the O-P-VECTOR 0 signal shall be derived using the same rules as for the PSD of the O-P-VECTOR 1 signal (see clause 10.3.3.1), except that the aggregate transmit power for the O-P-VECTOR 0 signal shall not exceed the minimum of the maximum aggregate downstream transmit power, as defined for the selected profile in Table 6-1 of [ITU-T G.993.2], and the MAXNOMATPds value configured in the CO-MIB.

During transmission of the O-P-VECTOR 0 signal, the VCE estimates the downstream FEXT channels from the initializing lines into the vectored lines based on the reported clipped error samples from the VTU-Rs of the vectored lines. From this point on, FEXT cancellation matrices are established in the VTU-Os for all vectored lines in the downstream direction and FEXT from the initializing line into vectored lines is cancelled.

The duration of O-P-VECTOR 0 is determined by the VTU-O, under VCE control. The VCE may select the duration of O-P-VECTOR 0 appropriately, with the aim to synchronize the start of O-P-PROBING-LR signals on all the VDSL2-LR lines of the vectored group.

The duration of O-P-VECTOR 0 shall not exceed $M \times 1024 \times 257$ symbols. If the bit "8192 superframes duration for O-P-VECTOR 1" is enabled in the ITU-T G.994.1 Handshake phase (see clause 10.2), then $M = 8$. Otherwise, $M = 1$.

NOTE – With $M = 8$, the maximum duration of O-P-VECTOR 0 will timeout the maximum duration over all stages starting from O-P-VECTOR 0 and up to but not including O-P-CHANNEL DISCOVERY V1 (see clause B.4).

The O-P-VECTOR 0 signal shall be followed by the O-P-PROBING-LR signals.

B.4.3 O-P-PROBING-LR

The O-P-PROBING-LR shall consist of a number of periodic signals, as defined in clause B.6. These signals are intended to synchronize the VTU-R, to allow it to estimate the length of the line so that it can indicate back to the VTU-O whether the initialization of the line shall continue either in short-medium loop operation (to become a short or medium VDSL2-LR line), or in a long loop operation (for a long VDSL2-LR line).If long loop operation is selected, the VTU-O also receives an indication of the pilot tone assigned by the VTU-R and the required downstream power cut-back (PCB) determined by the VTU-R.

The O-P-PROBING-LR signals may be transmitted with an IDFT size that is different from the Initial IDFT size indicated in the ITU-T G.994.1 CL message. The IDFT size ($2N$) shall be at least 2048 (i.e., $n \geq 11$).

The PSD of the O-P-PROBING-LR signals shall be as defined in clause B.6.1.1.

The O-P-PROBING-LR signals shall be followed by the O-P-QUIET 1-LR signal.

NOTE – While the VTU-O transmits the O-P-PROBING-LR signals, it is recommended that the VCE freezes precoder updates for lines with the VTU-O in the O-SHOWTIME state.

B.4.4 O-P-QUIET 1-LR

The O-P-QUIET 1-LR signal shall be identical to the O-P-QUIET 1 signal.

While transmitting this signal, the VTU-O performs any reconfiguration necessary for the selected continuation of the initialization, either in short-medium loop operation (to become a short or medium VDSL2-LR line) or in long loop operation (for a long VDSL2-LR line).

The duration of the O-P-QUIET 1-LR signal shall be 64 symbols.

If the initialization of the line shall be continued in short-medium loop operation, then the O-P-QUIET 1-LR signal shall be followed by the O-P-VECTOR 1 signal defined in clause B.4.7.

If the initialization of the line shall be continued in long loop operation, then the O-P-QUIET 1-LR signal shall be followed by the O-P-VECTOR 1-LR signal.

NOTE – While the VTU-O transmits the O-P-QUIET 1-LR signal, it is recommended that the VCE freezes precoder updates for lines with the VTU-O in the O-SHOWTIME state.

B.4.5 O-P-VECTOR 1-LR

The O-P-VECTOR 1-LR signal shall be identical to the O-P-VECTOR 1 signal defined in clause 10.3.3.1, except that:

- it shall include only all subcarriers from the downstream SUPPORTEDCARRIERS set up to subcarrier index 511 (up to about 2.2 MHz);
- its PSD shall be the same as the PSD of the O-P-TRAINING-LR signals (see clause B.7.1.1);
- it is transmitted with an IDFT size (2*N*) that may be different from the initial IDFT size indicated in the ITU-T G.994.1 CL message, but shall be at least 2048 (i.e., $n \geq 11$), so that there is no image above the subcarrier with index 511.

The duration of O-P-VECTOR 1-LR is determined by the VTU-O, under VCE control. The VCE may select the duration of O-P-VECTOR 1-LR appropriately, with the aim to synchronize the start of O-P-TRAINING-LR signals on all the VDSL2-LR lines in long loop operation of the vectored group.

The duration of O-P-VECTOR 1-LR shall not exceed $M \times 1024 \times 257$ symbols. If the bit "8192 superframes duration for O-P-VECTOR 1" is enabled in the ITU-T G.994.1 Handshake phase (see clause 10.2), then $M = 8$. Otherwise, $M = 1$.

NOTE – With $M = 8$, the maximum duration of O-P-VECTOR 1-LR will timeout the maximum duration over all stages starting from O-P-VECTOR 0 and up to but not including O-P-CHANNEL DISCOVERY V1 (see clause B.4).

The O-P-VECTOR 1-LR signal shall be followed by the O-P-TRAINING-LR signals.

The O-P-VECTOR 1-LR signal is necessary to adopt potential changes in impedance during reconfiguration of the VDSL2-LR line after it has been selected to be in long loop operation.

NOTE – The VTU-R uses spectrum up to 2.2 MHz during the PROBING stage, and may need to re-configure for short-medium loop operation, which may change its impedance and thus impact precoder settings for lines with the VTU-O in the O-SHOWTIME state. The impact of these changes will be accommodated during transmission of O-P-VECTOR 1.

B.4.6 O-P-TRAINING-LR

The O-P-TRAINING-LR signals are defined in clause B.7.

While the VTU-O transmits the O-P-TRAINING-LR signals, the VTU-R transmits the R-P-TRAINING-LR signals. The O/R-P-TRAINING-LR signals allow the VTU-O and VTU-R to train their echo cancellers (EC) and time domain equalizers (TEQ). The PSD of the O-P-TRAINING-LR signals shall be as defined in clause B.7.1.1.

After the EC and TEQ training, both VTUs are ready for SOC communications. Therefore, after O/R-P-TRAINING-LR signal exchange is complete, the line continues regular ITU-T G.993.5 initialization, exchanging corresponding messages over SOC.

The IDFT size during O-P-TRAINING-LR shall be the same as during O-P-VECTOR 1-LR.

NOTE – While the VTU-O transmits the O-P-TRAINING-LR signals, it is recommended that the VCE freezes precoder updates on subcarriers up to subcarrier index 511.

The duration of O-P-TRAINING-LR is variable. The maximum duration of O-P-TRAINING-LR shall respect the rule defined in clause B.4.

The O-P-TRAINING-LR signals shall be followed by the O-P-CHANNEL DISCOVERY V1 signal and the remainder of the channel discovery phase, as defined in clause B.4.8.

B.4.7 O-P-VECTOR 1

The O-P-VECTOR 1 signal shall be identical to the O-P-VECTOR 0 signal defined in clause B.4.2.

The duration of O-P-VECTOR 1 shall not exceed $M \times 1024 \times 257$ symbols. If the bit "8192 superframes duration for O-P-VECTOR 1" is enabled in the ITU-T G.994.1 Handshake phase (see clause 10.2), then $M = 8$. Otherwise, $M = 1$.

NOTE – With $M = 8$, the maximum duration of O-P-VECTOR 1 will timeout the maximum duration over all stages starting from O-P-VECTOR 0 and up to but not including O-P-CHANNEL DISCOVERY V1 (see clause B.4).

The O-P-VECTOR 1 signal shall be followed by the O-P-CHANNEL DISCOVERY V1 signal and the remainder of the channel discovery phase, as defined in clause B.4.8.

B.4.8 The G.993.5 Channel Discovery phase

If short-medium loop operation is selected in the PROBING stage, the ITU-T G.993.5 Channel Discovery phase shall be applied with the amendments defined in this clause. If long loop operation is selected in the PROBING stage, then the ITU-T G.993.5 Channel Discovery phase shall be applied with the amendments as specified in clause B.8.

B.4.8.1 O-SIGNATURE (amends clause 12.3.3.2.1.1 of [ITU-T G.993.2])

Field #8 "Downstream nominal maximum aggregate transmit power (MAXNOMATPds)" is used to calculate the value of control parameter *MAXNOMATPds*, which determines the maximum wide-band power that the VTU-O is allowed to transmit. The value of the MAXNOMATPds communicated in field #28 shall not exceed the minimum of 20.5 dBm and the MAXNOMATPds value configured in the CO-MIB, regardless of the particular [ITU-T G.993.2] profile selected during the ITU-T G.994.1 Handshake phase of initialization.

The value of the control parameter *MAXNOMATPds* shall be calculated as the minimum of the maximum aggregate downstream transmit power as defined for the selected profile in Table 6-1 of [ITU-T G.993.2] and the MAXNOMATPds value indicated in the Field #8 of the O-SIGNATURE message.

NOTE 1 – The attention of the reader is drawn to the fact that the value of the control parameter *MAXNOMATPds* may be different from the value of MAXNOMATPds communicated in O-SIGNATURE, which is not the case for [ITU-T G.993.2].

NOTE 2 – The value of the control parameter *MAXNOMATPds* is known to both the VTU-O and VTU-R and does not need to be exchanged from VTU-O to VTU-R.

B.4.8.2 O-UPDATE (amends clause 12.3.3.2.1.2 of [ITU-T G.993.2])

If the ITU-T G.994.1 MS message has the short loop bit set to ZERO, then the highest allowed upstream subcarrier indicated by the VTU-O in O-UPDATE (see Table 12-28 of [ITU-T G.993.2]) shall meet the condition for medium loop operation as defined in clause B.4.8.3 (i.e., forced medium loop operation).

B.4.8.3 O-PRM (amends clause 12.3.3.2.1.3 of [ITU-T G.993.2])

If the ITU-T G.994.1 MS message has the medium loop bit set to ONE and if the highest allowed upstream subcarrier indicated by the VTU-O in O-UPDATE (see Table 12-28 of [ITU-T G.993.2]) and the proposed highest downstream subcarrier indicated by the VTU-R in R-UPDATE (see Table 12-35 of [ITU-T G.993.2]) are both equal to or less than the highest subcarrier index defined for DS2 band in the applied bandplan and both do not exceed the value 1971 (8.5 MHz, see Table 6-1 of [ITU-T G.993.2]), then the VDSL2-LR line shall be in medium loop operation. Otherwise, the VDSL2-LR line shall be in short loop operation.

If the VDSL2-LR line is in medium loop operation, the value of the control parameter *MAXNOMATPds* shall be changed to a value equal to the MAXNOMATPds value indicated in the Field #8 of O-SIGNATURE message. If the VDSL2-LR line is in short loop operation, the value of the control parameter *MAXNOMATPds* shall remain unchanged, as determined in clause B.4.8.1.

The *MREFPSds* indicated in O-PRM (see Table 12-30 of [ITU-T G.993.2]) shall have an aggregate transmit power that shall not exceed this *MAXNOMATPds* value.

NOTE – For medium loop operation, the *MREFPSDds* could have an aggregate transmit power that exceeds the maximum aggregate downstream transmit power (as defined in Tables 6-1 and Q.1 of [ITU-T G.993.2]) for the particular [ITU-T G.993.2] profile selected during the ITU-T G.994.1 Handshake phase of initialization.

B.4.9 The ITU-T G.993.5 Training phase

If long loop operation is selected in the PROBING stage, then the ITU-T G.993.5 Training phase shall be applied with the amendments defined in clause B.8. If short-medium loop operation is selected in the PROBING stage, the original ITU-T G.993.5 training phase shall be used.

B.5 Signals sent by the VTU-R during the Channel Discovery and Training phase

B.5.1 R-P-QUIET 1

After the ITU-T G.994.1 Handshake phase, the VTU-R shall start initialization with the R-P-QUIET 1 signal defined in clause 12.3.3.3.2.1 of [ITU-T G.993.2].

The duration of R-P-QUIET 1 is determined by the VTU-O. Within 64 symbols after the VTU-O ending the first signal of O-P-PROBING-LR (O-P-COMB 2-LR, see clause B.6.1.3), the VTU-R shall end the R-P-QUIET 1 signal.

The R-P-QUIET 1 signal shall be followed by the R-P-PROBING-LR signals.

B.5.2 R-P-PROBING-LR

The R-P-PROBING-LR consists of a number of periodic signals, as defined in clause B.6.

While receiving the O-P-PROBING-LR signals, the VTU-R shall determine whether the initialization of the line shall continue either in short-medium loop operation (to become a short or medium VDSL2-LR line) or in long loop operation (for a long VDSL2-LR line). In the latter case, the VTU-R shall also assign the pilot tone and determine the minimum downstream power cut-back (PCBds, see Table B.10), if needed.

The R-P-PROBING-LR signals shall be transmitted with the IDFT size and type of image as indicated by the VTU-R in the "Transmit signal images above the Nyquist frequency" block in the ITU-TG.994.1 CLR message. The IDFT size may be different from the Initial IDFT size indicated in the ITU-T G.994.1 CL message.

The PSD of the R-P-PROBING-LR signals shall be as defined in clause B.6.2.1.

The R-P-PROBING-LR signals shall be followed by the R-P-QUIET 1-LR signal.

B.5.3 R-P-QUIET 1-LR

The R-P-QUIET 1-LR signal shall be identical to the R-P-QUIET 1 signal.

While transmitting this signal, the VTU-R performs any reconfiguration necessary for the selected continuation of the initialization, either in short-medium loop operation (to become a short or medium VDSL2-LR line) or as a VDSL2-LR line (for a long VDSL2-LR line).

The duration of R-P-QUIET 1-LR signal shall be 64 symbol periods.

If the initialization shall be continued in short-medium loop operation, then the R-P-QUIET 1-LR signal shall be followed by the R-P-QUIET 1 signal defined in clause 10.3.4.1 and the remainder of the channel discovery phase shall be as defined in clause 10.3, except for the changes defined in clauses B.4.8 and B.10.4.1.

If the initialization shall be continued in long loop operation, then the R-P-QUIET 1-LR signal shall be followed by the R-P-QUIET 2-LR signal.

B.5.4 R-P-QUIET 2-LR

The R-P-QUIET 2-LR signal shall be identical to the R-P-QUIET 1 signal.

The duration of R-P-QUIET 2-LR is determined by the VTU-O. Within 64 symbols after the VTU-O ending the first signal of O-P-TRAINING-LR (O-P-REVERB 1-LR, see clause B.7.1.1), the VTU-R shall end the R-P-QUIET 2-LR signal.

The R-P-QUIET 2-LR signal shall be followed by the R-P-TRAINING-LR signals.

B.5.5 R-P-TRAINING-LR

The R-P-TRAINING-LR signals are defined in clause B.7.

While the VTU-R transmits the R-P-TRAINING-LR signals, the VTU-O transmits the O-P-TRAINING-LR signals. The O/R-P-TRAINING-LR signals allow the VTU-O and VTU-R to train their echo cancellers (EC) and time domain equalizers (TEQ). The PSD of the R-P-TRAINING-LR signals shall be the same as for the R-P-PROBING-LR signals (see clause B.6.1.1).

After EC and TEQ training, both VTUs are ready for SOC communications. After O/R-P-TRAINING-LR signal exchange is complete, the line continues regular ITU-T G.993.5 initialization, exchanging corresponding messages over SOC.

The IDFT size during R-P-TRAINING shall be as indicated by the VTU-R in the "Transmit signal images above the Nyquist frequency" block in the ITU-T G.994.1 CLR message.

The R-P-TRAINING-LR signals shall be followed by the R-P-QUIET 1 signal defined in clause 10.3.4.1 and the remainder of the channel discovery phase defined in clause 10.3.

B.5.6 The ITU-T G.993.5 Channel Discovery phase

If long loop operation is selected in the PROBING stage, then the ITU-T G.993.5 Channel Discovery phase shall be applied with the amendments defined in clause B.8. If short-medium loop operation is selected in the PROBING stage, the ITU-T G.993.5 Channel Discovery phase shall be applied with the amendments defined in clause B.5.6.

In both cases, the value of the control parameter *MAXNOMATPus* shall be as defined in clause B.10.1.7.

B.5.6.1 R-UPDATE (amends clause 12.3.3.2.2.2 of [ITU-T G.993.2])

If the ITU-T G.994.1 MS message has the short loop bit set to ZERO, then the proposed highest downstream subcarrier indicated by the VTU-R in R-UPDATE (see Table 12-35 of [ITU-T G.993.2]) shall meet the condition for medium loop operation as defined in clause B.4.8.3 (i.e., forced medium loop operation).

B.5.7 ITU-T G.993.5 Training phase

If long loop operation is selected in the PROBING stage, then the ITU-T G.993.5 Training phase shall be applied with amendments defined in the clause B.8. If short-medium loop operation is selected in the PROBING stage, the original ITU-T G.993.5 Training phase shall be applied.

B.6 O/R-P-PROBING-LR signal exchange

The O/R-P-PROBING-LR signal exchange uses signals defined in ITU-T G.992.5, with the constraint that the duration of signals and the transitions between different signals occurs on boundaries of DMT symbols with CE. This constraint is identical to the constraint defined in clause 12.3.6.1 of [ITU-T G.993.2] to send the O/R-P-PERIODIC signals. Because only the mandatory CE is supported in the VDSL2-LR mode, the duration of each signal is a multiple of 64 symbols with CE (or 69 symbols without CE).

The O/R-P-PROBING-LR signal exchange is depicted in Figure B.2.

NOTE – The duration of the O/R-P-PROBING-LR signal exchange is between 1.5 s and 1.9 s.

B.6.1 O-P-PROBING-LR signals

B.6.1.1 Transmit PSD of the O-P-PROBING-LR signals

The O-P-PROBING-LR transmit PSD (*PROBINGPSDds*) shall be derived from the *NOMPSD* and *log_tssi* values exchanged in the downstream spectrum bounds and downstream spectrum shaping parameter blocks of the ITU-T G.994.1 CL message during the ITU-T G.994.1 Handshake phase, as defined in clause 8.13.2.4 of [ITU-T G.992.3], and as:

$$PROBINGPSDds(f) = CL\_NOMPSDds + log\_tssi\_ds(f)$$

where *CL_NOMPSDds* is the *NOMPSDds* indicated by the VTU-O in the ITU-T G.994.1 CL message. The *CL_NOMPSDds* shall be less than or equal to the MAXNOMPSDds configured in the CO-MIB (see clause B.10.1.2).

The PSD limits for the O-P-PROBING-LR signals shall be the PSDMASKds. The *PROBINGPSDds*(*f*) shall not exceed PSDMASKds(*f*) minus 3.5dB, for all subcarriers in the SUPPORTEDCARRIERSds set with indices up to 511. The PSDMASKds(*f*) is defined in Table 7-4 of [ITU-T G.993.2] and shall be derived taking into account the LIMITMASKds as defined in clause B.9.

All subcarriers included in the O-P-PROBING-LR signals shall be transmitted at the *PROBINGPSDds*, with an accuracy of ±1dB at the U-O2 reference point.

The aggregate transmit power for the O-P-PROBING-LR signals shall not exceed the minimum of the maximum aggregate downstream transmit power as defined in clause B.9 for the corresponding annex of [ITU-T G.993.2] and the MAXNOMATPds value configured in the CO-MIB. The VTU-O shall determine the value of *CL_NOMPSDds* and *log_tssi_ds* such that the aggregate transmit power of the O-P-PROBING-LR signal shall not exceed the above value.

NOTE – For long loop operation, the O-P-PROBING-LR signals could have an aggregate transmit power that exceeds the maximum aggregate downstream transmit power (as defined in Tables 6-1 and Q.1 of [ITU-T G.993.2) for the particular ITU-T G.993.2 profile selected during the ITU-T G.994.1 Handshake phase of initialization. However, this is unlikely to happen since COMB symbols are used in the O-P-PROBING-LR signals.

B.6.1.2 Symbol definitions for the O-P-PROBING-LR signals

The O-P-QUIET symbol is defined as identical to the C-QUIET symbol defined in clause 8.13.3.1.1 of [ITU-T G.992.3].

The O-P-COMB symbol shall use the subcarrier set as defined in clause 8.13.3.1.2 of [ITU-T G.992.5]. For the purpose of defining the O-P-COMB subcarrier set, the value *NSCds* shall be set to 512. All O-P-COMB subcarriers with indices that are in the SUPPORTEDCARRIERSds set with indices up 511 shall be used. These subcarriers shall be modulated by 4-QAM. The value 11 shall be mapped to those subcarriers. The constellation points on those subcarriers shall be rotated based on the 2-bit number provided by the quadrant scrambler described in clause 12.3.6.2 of [ITU-T G.993.2]. The scrambler shall be used in reset mode (see clause 12.3.6.2.1 of [ITU-T G.993.2]).

The O-P-ICOMB symbol is defined as identical to the O-P-COMB symbol, except with the value 00 mapped on the same subcarriers.

All signals consisting of O-P-COMB or O-P-ICOMB symbols shall be implemented as periodic signals, such as O/R-P-PERIODIC 1 (see clause 12.3.6.1 of [ITU-T G.993.2]).

B.6.1.3 O-P-COMB 2-LR

The O-P-COMB 2-LR state is of fixed length. In the O-P-COMB 2-LR state, the VTU-O shall transmit 3648 O-P-COMB symbols.

The O-P-COMB 2-LR state shall be followed by the O-P-QUIET 3-LR state.

B.6.1.4 O-P-QUIET 3-LR

The O-P-QUIET 3-LR state is of variable length. In the O-P-QUIET 3-LR state, the VTU-O shall transmit a multiple of 64 O-P-QUIET symbols, with a minimum of 256 and a maximum of 960 O-P-QUIET symbols. The O-P-QUIET 3-LR state shall be followed by the O-P-COMB 3-LR state.

B.6.1.5 O-P-COMB 3-LR

The O-P-COMB 3-LR state is of fixed length. In the O-P-COMB 3-LR state, the VTU-O shall transmit 64 O-P-COMB symbols.

The O-P-COMB 3-LR state shall be followed by the O-P-ICOMB 2-LR state.

B.6.1.6 O-P-ICOMB 2-LR

The O-P-ICOMB 2-LR state is of fixed length. In the O-P-ICOMB 2-LR state, the VTU-O shall transmit 64 O-P-ICOMB symbols.

The O-P-ICOMB 2-LR state shall be followed by the O-P-QUIET 4-LR state.

B.6.1.7 O-P-QUIET 4-LR

The O-P-QUIET 4-LR state is of variable length. In the O-P-QUIET 4-LR state, the VTU-O shall transmit a multiple of 64 O-P-QUIET symbols, with a minimum of 1152 and a maximum of 1408 O-P-QUIET symbols.

The VTU-O shall receive and decode the content of the message R-MSG-PCB during this state.

The VTU-O shall continue to transmit O-P-QUIET symbols until after the VTU-R transitioning to the R-P-QUIET 4-LR state. Within 128 symbols after the VTU-R transitioning to the R-P-QUIET4-LR state, the VTU-O shall transition to the next state.

If the VTU-O has successfully received the R-P-MSG-PCB message, the O-P-QUIET 4-LR state shall be followed by the O-P-COMB 4-LR state. Otherwise, the VTU-O shall return to the O-SILENT state.

B.6.1.8 O-P-COMB 4-LR

The O-P-COMB 4-LR state is of fixed length. In the O-P-COMB 4-LR state, the VTU-O shall transmit 64 O-P-COMB symbols.

The O-P-COMB 4-LR signal serves as an acknowledgement of the successful reception of the R-P-MSG-PCB message.

The O-P-COMB 4-LR state shall be followed by the ICOMB 4-LR state.

B.6.1.9 O-P-ICOMB 4-LR

The O-P-ICOMB 4-LR state is of fixed length. In the O-P-ICOMB 4-LR state, the VTU-O shall transmit 64 O-P-ICOMB symbols.

The O-P-ICOMB 4-LR state shall be followed by the O-P-MSG-PCB-LR state.

B.6.1.10 O-P-MSG-PCB-LR

In downstream direction, the transmit power shall be further adjusted by a power cutback value determined by the VTU-O during the PROBING stage, based on the maximal used downstream subcarriers requested by the VTU-R in the R-P-MSG-PCB-LR message.

The O-P-MSG-PCB-LR state is of fixed length. In the O-P-MSG-PCB-LR state, the VTU-O shall transmit 512 symbols of O-P-COMB or O-P-ICOMB to modulate the O-P-MSG-PCB-LR message. The O-P-MSG-PCB-LR message conveys the VTU-O determined power cutback level for the downstream direction.

The O-P-MSG-PCB-LR message m is defined by:

$$m = \{ m_7, \ldots , m_0 \}$$

Bits shall be defined as shown in Table B.9.

Table B.9 – Bit definition for the O-P-MSG-PCB-LR message

Bit index	Parameter	Definition
3…0	*O-PCB_DS*	VTU-O final downstream power cutback in dB, represented as an unsigned integer in the 0 to 15 range (4-bit value with MSB in bit 3 and LSB in bit 0) (see Note).
7…4	Reserved by ITU-T	Shall be set to 0 and ignored by the receiver.
NOTE – This power cutback shall be further used instead of the minimum downstream power cutback indicated in R-MSG-PCB-LR message. The value shall be lower than or equal to the R-MIN_PCB_DS requested by the VTU-R. If the VTU-R indicated that the line shall continue the initialization in short-medium loop operation, this field shall be set to 0 and ignored by the VTU-R.		

The 8 bits m_0-m_7 shall be transmitted in 512 symbol periods (m_0 first and m_7 last). A ZERO bit shall be transmitted as 64 consecutive O-P-COMB symbols (1 bit per 69 symbols without CE). A ONE bit shall be transmitted as 64 consecutive O-P-ICOMB symbols.

The O-P-MSG-PCB-LR state also indicates to the VTU-R that the PROBING stage is complete.

The O-P-MSG-PCB-LR state shall be followed by the O-P-QUIET 1-LR state.

B.6.2 R-P-PROBING-LR signals

B.6.2.1 Transmit PSD of the R-P-PROBING-LR signals

The R-P-PROBING-LR transmit PSD (*PROBINGPSDus*) shall be derived from the *NOMPSD* and *log_tssi* values exchanged in the upstream spectrum bounds and upstream spectrum shaping parameter blocks of the ITU-T G.994.1 CLR message during the ITU-T G.994.1 Handshake phase, as defined in clause 8.13.2.4 of [ITU-T G.992.3], and as:

$$PROBINGPSDus(f) = MIN(CL\_NOMPSDus, CLR\_NOMPSDus) – PCBus + log\_tssi\_us(f),$$

where *CL_NOMPSDus* is the *NOMPSDus* indicated by the VTU-O in the CL message and *CLR_NOMPSDus* is the *NOMPSDus* indicated by the VTU-R in the ITU-T G.994.1 CLR message. The *CL_NOMPSDus* shall be less than or equal to the MAXNOMPSDus configured in the CO-MIB (see clause B.10.1.2).

The PSD limits for the R-P-PROBING-LR signals shall be the PSDMASKus. The *PROBINGPSDus*(*f*) shall not exceed PSDMASKus(*f*) minus 3.5 dB for all subcarriers in the SUPPORTEDCARRIERSus set in the US0 band [f_{0L}, f_{0H}]. The PSDMASKus(*f*) is defined in Table 7-4 of [ITU-T G.993.2] and shall be derived taking into account the LIMITMASKus as defined in clause B.9.

The VTU-R shall apply a *PCBus* = 10dB if the VTU-R determines that the line is short or medium, and shall apply a *PCBus* = 0dB if the VTU-R determines that the line is long. The VTU-R shall evaluate the length of the line before sending the first active symbol of R-P-PROBING-LR signal (see Figure B.2). The VTU-R shall use these rules of setting the *PCBus* regardless whether or not short, medium or long loop operation is allowed during the ITU-T G.994.1 Handshake phase (see clause B.3).

The transmit PSD of the R-P-LINEPROBE-LR signal shall not exceed the *PROBINGPSDus*.

All subcarriers included in the R-P-PROBING-LR signals shall be transmitted at the *PROBINGPSDus* lowered with *PCBus*, with an accuracy of ±1dB at the U-R2 reference point.

The aggregate transmit power for the R-P-PROBING-LR signals shall not exceed the value of the control parameter *MAXNOMATPus* as defined in clause B.10.1.7. The VTU-O shall determine the value of *CL_NOMPSDus* such that for any valid setting of *CLR_NOMPSDus*, *PCBus* and *log_tssi_us* chosen by the VTU-R, the aggregate transmit power of the R-P-PROBING-LR signal shall not exceed the above value.

B.6.2.2 Symbol definitions for the R-P-PROBING-LR signals

The R-P-QUIET symbol is defined as identical to the R-QUIET symbol defined in clause 8.13.3.2.1 of [ITU-T G.992.3].

The R-P-COMB symbol shall use the subcarrier set as defined in clause 8.13.3.2.2 of [ITU-T G.992.5]. For the purpose of defining the R-P-COMB subcarrier set, the value *NSCus* shall be set to 32 or 64, in accordance with the US0 PSD mask defined in clause B.9.2.2. All R-P-COMB subcarriers with indices in the passband of the US0 PSD mask shall be used. These subcarriers shall be modulated by 4-QAM. The value 11 shall be mapped to those subcarriers. The constellation points on these subcarriers shall be rotated based on the 2-bit number provided by the quadrant scrambler described in clause 12.3.6.2 of [ITU-T G.993.2]. The scrambler shall be used in reset mode (see clause 12.3.6.2.1 of [ITU-T G.993.2]).

The R-P-ICOMB symbol is defined as identical to the R-P-COMB symbol, except with the value 00 mapped on the same subcarriers.

All signals consisting of R-P-COMB or R-P-ICOMB symbols shall be implemented as periodic signals, such as O/R-P-PERIODIC 1 (see clause 12.3.6.1 of [ITU-T G.993.2]).

B.6.2.3 R-P-COMB 2-LR

The R-P-COMB 2-LR state is of fixed length. In the R-P-COMB 2-LR state, the VTU-R shall transmit 256 R-P-COMB symbols.

The R-P-COMB 2-LR state shall be followed by the R-P-ICOMB 1-LR state if the VTU-R desires to use the R-P-LINEPROBE-LR state. Otherwise the R-P-COMB 2-LR state shall be followed by the R-P-QUIET 3-LR state.

B.6.2.4 R-P-ICOMB 1-LR

The R-P-ICOMB 1-LR state is of fixed length. In the R-P-COMB 1-LR state, the VTU-R shall transmit 64 R-P-ICOMB symbols.

The R-P-ICOMB 1-LR state shall be followed by the R-P-LINEPROBE-LR state.

B.6.2.5 R-P-LINEPROBE-LR

The R-P-LINEPROBE-LR state is of fixed length. In the R-P-LINEPROBE-LR state, the VTU-R shall transmit a vendor-discretionary signal with a duration of 512 symbol periods.

The R-P-LINEPROBE-LR state shall be followed by the R-P-QUIET 3-LR state.

B.6.2.6 R-P-QUIET 3-LR

The R-P-QUIET 3-LR state is of variable length. In the R-P-QUIET 3-LR state, the VTU-R shall transmit a multiple of 64 R-P-QUIET symbols, with a minimum of 128 and a maximum of 320 R-P-QUIET symbols.

The VTU-R shall continue to transmit R-P-QUIET symbols until after the VTU-O transitioning to O-P-QUIET 4-LR. Within 128 symbols after the VTU-O transitioning to O-P-QUIET 4-LR, the VTU-R shall transition to the next state.

The R-P-QUIET 3-LR state shall be followed by the R-P-COMB 3-LR state.

B.6.2.7 R-P-COMB 3-LR

The R-P-COMB 3-LR state is of fixed length. In the R-P-COMB 3-LR state, the VTU-R shall transmit 64 R-P-COMB symbols.

The R-P-COMB 3-LR state shall be followed by the R-P-ICOMB 2-LR state.

B.6.2.8 R-P-ICOMB 2-LR

The R-P-ICOMB 2-LR state is of fixed length. In the R-P-ICOMB 2-LR state, the VTU-R shall transmit 64 R-P-ICOMB symbols.

The R-P-ICOMB 2-LR state shall be followed by the R-P-MSG-PCB-LR state.

B.6.2.9 R-P-MSG-PCB-LR

In downstream direction, the transmit power shall be reduced by a power cutback value. The minimum downstream power cutback value is determined by the VTU-R during the PROBING stage.

NOTE – The VTU-R can consider its receiver dynamic range as determined by observing O-P-COMB 2-LR, and the local line conditions determined by the optional R-P-LINEPROBE-LR when determining the minimum downstream power cutback value.

The R-P-MSG-PCB-LR state is of fixed length. In the R-P-MSG-PCB-LR state, the VTU-R shall transmit 1536 symbols of R-P-COMB or R-P-ICOMB to modulate the R-P-MSG-PCB message. The R-P-MSG-PCB message conveys the VTU-R determined minimum downstream power cutback for the downstream direction, and the downstream pilot tone used for timing recovery during different states.

The R-P-MSG-PCB message m is defined by:

$$m = \{ m_{23}, \ldots , m_0 \},$$

where the bits shall be defined as shown in Table B.10.

Table B.10 – Bit definition for the R-P-MSG-PCB-LR message

Bit index	Parameter	Definition
[3:0]	*R-MIN_PCB_DS*	VTU-R minimum downstream power cutback in dB, represented as an unsigned integer in the 0 to 15 range (4-bit value with MSB in bit 3 and LSB in bit 0).
[12:4]	*O-P-PILOT*	Subcarrier index of downstream pilot tone, represented as an unsigned integer in the 32 to 511 range (9-bit value with MSB in bit 12 and LSB in bit 4) (see Notes 1 and 4).
13	*OPTYPE*	Shall be set to 0 if the initialization of the line shall continue in short-medium loop operation (to become a short or medium VDSL2-LR line). Shall be set to 1 if the initialization of the line shall continue in long loop operation (a long VDSL2-LR line). (see Notes 2 and 3)
[22:14]	*LAST_TONE_DS*	Subcarrier index of the highest transmitted downstream frequency in the TRAINING stage expressed as unsigned integer (9-bit value with MSB in bit 22 and LSB in bit 14) (Notes 4 and 5).
23	Reserved by ITU-T	Shall be set to 0 and ignored by the receiver.
NOTE 1 – The indicated *O-P-PILOT* value shall be used as the index of the O-P-TREF pilot subcarrier (see clause B.7.1.4) to support/recovery of the VTU-R timing during the O-P-TRAINING stage. NOTE 2 – If *OPTYPE* bit is set to 0, the VTU-O shall ignore all other parameters of the message. NOTE 3 – If the ITU-T G.994.1 MS message has the long loop bit set to ZERO, then the *OPTYPE* bit shall be set to ZERO. If the ITU-T G.994.1 MS message has both the short loop bit and medium loop bit set to ZERO, then the *OPTYPE* bit shall be set to ONE (i.e., forced long loop operation). NOTE 4 – If the *OPTYPE* bit is set to 0 (the line shall continue the initialization in short-medium loop operation), this field shall be set to 491. NOTE 5 – The valid values of *LAST_TONE_DS* are those associated with subcarriers from the *O-P-COMB* symbol set, as defined in clause B.6.1.2, and the additional valid value of 511.		

The 24 bits m_0-m_{23} shall be transmitted in 1536 symbol periods (m_0 first and m_{23} last). A ZERO bit shall be transmitted as 64 consecutive R-P-COMB symbols (1 bit per 69 symbols without CE). A ONE bit shall be transmitted as 64 consecutive R-P-ICOMB symbols.

The R-P-MSG-PCB-LR state shall be followed by the R-P-QUIET 4-LR state.

B.6.2.10 R-P-QUIET 4-LR

The R-P-QUIET 4-LR state is of variable length. In the R-P-QUIET 4-LR state, the VTU-R shall transmit a multiple of 64 R-P-QUIET symbols, with a minimum of 64 and a maximum of 192 R-P-QUIET symbols.

If the VTU-R has successfully detected the O-P-COMB 4-LR signal, the R-P-QUIET 4-LR state shall be followed by the R-P-QUIET 1-LR state. Otherwise, the VTU-R shall return to the R-SILENT state.

B.6.3 Timeline of O/R-P-PROBING-LR signals

The signal exchange is depicted in Figure B.2.

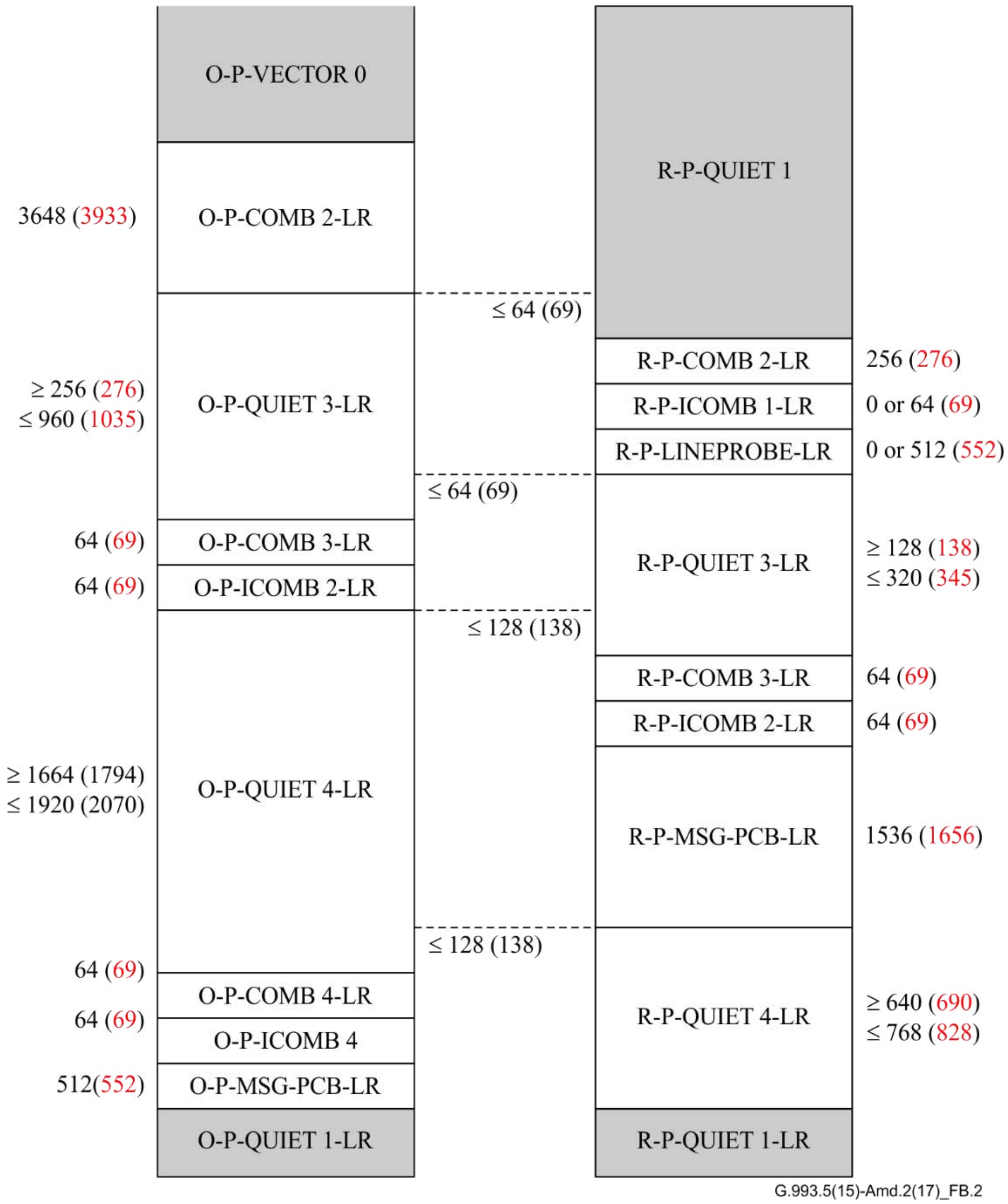


Figure B.2 – Timeline of O/R-P-PROBING-LR signals

In Figure B.2, signal durations are expressed in symbols with CE (values in parenthesis are the signal durations expressed in symbols without CE). Signals shaded in grey are parts of the previous and the following stages of initialization (see Figure B.1).

B.7 O/R-P-TRAINING-LR signal exchange

The O/R-P-TRAINING-LR signal exchange is depicted in Figure B.4 and uses signals defined in [ITU-T G.992.5], with the constraint that the transitions between different signals occur on boundaries of DMT symbols with CE. The duration of each signal is a multiple of 64 symbols with CE (or 69 symbols without CE).

NOTE – The O/R-P-TRAINING-LR signal exchange allows training of the TEQ and EC before full duplex transmission. The duration of that exchange is between 1.9s and 9.7s.

B.7.1 O-P-TRAINING-LR signals

B.7.1.1 Transmit PSD of the O-P-TRAINING-LR signals

The O-P-TRAINING-LR transmit PSD (*TRAININGPSDds*) shall be derived from the *NOMPSD* and *log_tssi* values exchanged in the downstream spectrum bounds and downstream spectrum shaping parameter blocks of the ITU-T G.994.1 CL message during the ITU-T G.994.1 Handshake phase, as defined in clause 8.13.2.4 of [ITU-T G.992.3], and the *O-PCB_DS* value indicated by the VTU-O during the PROBING stage, as:

$$TRAININGPSDds(f) = NOMPSDds - PCBds + ceiled\_log\_tssi\_ds(f),$$

with

$$ceiled\_log\_tssi\_ds(f) = MIN(log\_tssi\_ds(f) + PCBds, 0\ dB),$$

and

$$PCBds = O\text{-}PCB\_DS.$$

All subcarriers included in the O-P-TRAINING-LR signals shall be transmitted at the *TRAININGPSDds*, with an accuracy of ±1dB at the U-O2 reference point.

The PSD limits for the O-P-TRAINING-LR signals shall be the PSDMASKds. The *TRAININGPSDds*(*f*) shall not exceed PSDMASKds(*f*) minus 3.5dB, for all subcarriers in the SUPPORTEDCARRIERSds set with indices up to 511. The PSDMASKds is defined in Table 7-4 of [ITU-T G.993.2] and shall be derived taking into account the LIMITMASKds as defined in clause B.9 using the highest sub-carrier with the index equal to *LAST_TONE_DS* value indicated by the VTU-R during the PROBING stage.

The aggregate transmit power for the O-P-TRAINING-LR signals shall not exceed the minimum of the maximum aggregate downstream transmit power as defined in clause B.9 for corresponding annex of [ITU-T G.993.2] and the MAXNOMATPds value configured in the CO-MIB.

The VTU-O shall determine the value of *CL_NOMPSDds*, *log_tssi_ds*, and *PCBds*, such that the aggregate transmit power of the O-P-TRAINING-LR signals shall not exceed the above value.

B.7.1.2 Symbol definitions for the O-P-TRAINING-LR signals

The O-P-REVERB symbol shall contain all subcarriers up to index 511. These subcarriers shall be modulated by 4-QAM. The value 11 shall be mapped to these subcarriers. The constellation points on these subcarriers shall be rotated based on the 2-bit number provided by the quadrant scrambler described in clause 12.3.6.2 of [ITU-T G.993.2]. The scrambler shall be used in reset mode (see clause 12.3.6.2.1 of [ITU-T G.993.2]).

The O-P-QUIET symbol is the same as defined for the O-P-PROBING-LR.

The O-P-TREF symbol shall be a single tone symbol. Only the *O-P-PILOT* subcarrier index specified by the VTU-R in the R-P-MSG-PCB message (i.e., the O-P-TREF pilot tone) shall be transmitted. The O-P-TREF pilot tone shall modulate the 4-QAM {0,0} constellation point. No power shall be transmitted on the other subcarriers (i.e., $X_i = Y_i = 0$).

The O-P-SEGUE symbol is defined as identical to the O-P-REVERB symbol, except with the value 00 mapped to the same subcarriers.

All signals consisting of O-P-REVERB, O-P-SEGUE or O-P-TREF symbols shall be implemented as periodic signals, such as O/R-P-PERIODIC 1 (see clause 12.3.6.1 of G.993.2).

The O-P-PILOT symbol is defined as identical to the symbols transmitted during the O-P-PILOT 1 of [ITU-T G.993.2] (see clause 12.3.3.3.1.4 of [ITU-T G.993.2]). Only the *O-P-PILOT* subcarrier index specified by the VTU-R in the R-P-MSG-PCB-LR message (i.e., the O-P-TREF pilot tone) shall be transmitted during the O-P-PILOT symbol.

B.7.1.3 O-P-REVERB 0-LR

The O-P-REVERB 0-LR state is of fixed length. In the O-P-REVERB 0-LR state, the VTU-O shall transmit 3648 O-P-REVERB symbols.

During the O-P-REVERB 0-LR state, the VTU-R restores loop timing, adjusts the AFE and acquires downstream symbol timing.

The O-P-REVERB 0-LR state shall be followed by the O-P-QUIET 5-LR state.

B.7.1.4 O-P-QUIET 5-LR

The O-P-QUIET 5-LR state is of fixed length. In the O-P-QUIET 5-LR state, the VTU-O shall transmit 128 O-P-QUIET symbols.

During the O-P-QUIET 5-LR state, the VTU-O detects R-P-REVERB 1-LR and then prepares for bidirectional transmission.

The O-P-QUIET 5-LR state shall be followed by the O-P-REVERB 1-LR state.

B.7.1.5 O-P-REVERB 1-LR

The O-P-REVERB 1-LR state is of fixed length. In the O-P-REVERB 1-LR state, the VTU-O shall transmit 512 O-P-REVERB symbols.

During the O-P-REVERB 1-LR state, the VTU-O may fine-tune its AGC (while the VTU-R is in the R-P-REVERB 1-LR state) and do adaptive AFE algorithms.

The O-P-REVERB 1-LR state shall be followed by the O-P-TREF 1-LR state.

B.7.1.6 O-P-TREF 1-LR

The O-P-TREF 1-LR state is of variable length. In the O-P-TREF 1-LR state, the VTU-O shall transmit a minimum of 512 and a maximum of 15872 O-P-TREF symbols.

During the O-P-TREF 1-LR state, VTU-O may train its TEQ.

The O-P-TREF 1-LR state shall be followed by the O-P-REVERB 2-LR state.

B.7.1.7 O-P-REVERB 2-LR

The O-P-REVERB 2-LR state is of fixed length. In the O-P-REVERB 2-LR state, the VTU-O shall transmit 64 O-P-REVERB symbols.

Transition to O-P-REVERB 2-LR state indicates to the VTU-R that VTU-O completed its TEQ training.

The O-P-REVERB 2-LR state shall be followed by the O-P-ECT-LR state.

B.7.1.8 O-P-ECT-LR

The O-P-ECT-LR state is of fixed length. In the O-P-ECT-LR state, the VTU-O shall transmit a vendor-discretionary signal with a duration of 512 symbol periods.

During this state, the VTU-O may train its echo canceller.

The O-P-ECT-LR state shall be followed by the O-P-REVERB 3-LR state.

B.7.1.9 O-P-REVERB 3-LR

The O-P-REVERB 3-LR state is of variable length. In the O-P-REVERB 3-LR state, the VTU-O shall transmit a minimum of 448 and a maximum of 15936 O-P-REVERB symbols.

The O-P-REVERB 3-LR state provides VTU-R with a training signal (presumable, for the TEQ).

The VTU-O shall continue to transmit O-P-REVERB symbols until after the VTU-R transitioning to the R-P-REVERB 3-LR state. Within 64 symbols after the VTU-R transitioning to the R-P-REVERB 3-LR state, the VTU-O shall transition to the next state.

In case the VTU-R has indicated in the ITU-T G.994.1 CLR message that it requires the VTU-O to transmit O-P-TREF symbols during the R-P-ECT-LR state (i.e., has set the "FMT-O-P-TREF2" bit to ONE), the O-P-REVERB 3-LR state shall be followed by the O-P-TREF 2-LR state. In case the VTU-R has indicated that it requires the VTU-O to transmit O-P-QUIET symbols during the R-P-ECT-LR state (i.e., has set the "FMT-O-P-TREF2" bit to ZERO), the O-P-REVERB 3-LR state shall be followed by the O-P-QUIET 6-LR state.

B.7.1.10 O-P-TREF 2-LR

The O-P-TREF 2-LR state is of fixed length. In the O-P-TREF 2-LR state, the VTU-O shall transmit 576 O-P-TREF symbols.

The O-P-TREF 2-LR state facilitates EC training at the VTU-R. The VTU-O shall ignore the signal transmitted by the VTU-R during this state.

The O-P-TREF 1-LR state shall be followed by the O-P-REVERB 4-LR state.

B.7.1.11 O-P-QUIET 6-LR

The O-P-QUIET 6-LR state is of fixed length. In the O-P-QUIET 6-LR state, the VTU-O shall transmit 576 O-P-QUIET symbols.

The VTU-O shall ignore the signal transmitted by the VTU-R during this state.

The O-P-QUIET 6-LR state shall be followed by the O-P-REVERB 4-LR state.

B.7.1.12 O-P-REVERB 4-LR

The O-P-REVERB 4-LR state is of fixed length. In the O-P-REVERB 4-LR state, the VTU-O shall transmit 1024 O-P-REVERB symbols.

During the O-P-REVERB 4-LR state, the VTU-O can adjust its parameters for bidirectional transmission.

The O-P-REVERB 4-LR state shall be followed by the O-P-SEGUE 1-LR state.

B.7.1.13 O-P-SEGUE 1-LR

The O-P-SEGUE 1-LR state is of fixed length. In the O-P-SEGUE1-LR state, the VTU-O shall transmit 64 O-P-SEGUE symbols. The first symbol of O-P-SEGUE 1-LR is used as reference time point to facilitate alignment between the timing of VDSL2-LR training and the G.993.5 Channel Discovery (see clause B.8.1). The O-P-SEGUE 1-LR state shall be followed by the O-P-PILOT-LR state.

B.7.1.14 O-P-PILOT-LR

The O-P-PILOT-LR phase is intended to equalize the duration of the TRAINING phase between different lines of the vectored group. In the O-P-PILOT-LR state, the VTU-O shall transmit an integer number of O-P-PILOT symbols. The duration of the O-P-PILOT-LR state is variable, under the control of the VCE, and can be in the range from 128 to 31360 symbols.

The O-P-PILOT is a non-periodic signal. The alignment of the O-P-PILOT symbols and the O-P-SEGUE 1-LR state shall use two reference points associated with the IDFT sample #0 of specific symbols. The IDFT sample #0 is defined as the first sample of the block of 2N time samples generated by the IDFT.

The first reference point shall be the IDFT sample #0 of the first symbol of the O-P-SEGUE 1-LR state, and the second reference point is the IDFT sample #0 of the first symbol of the O-P-PILOT-LR state, as shown in the Figure B.3.

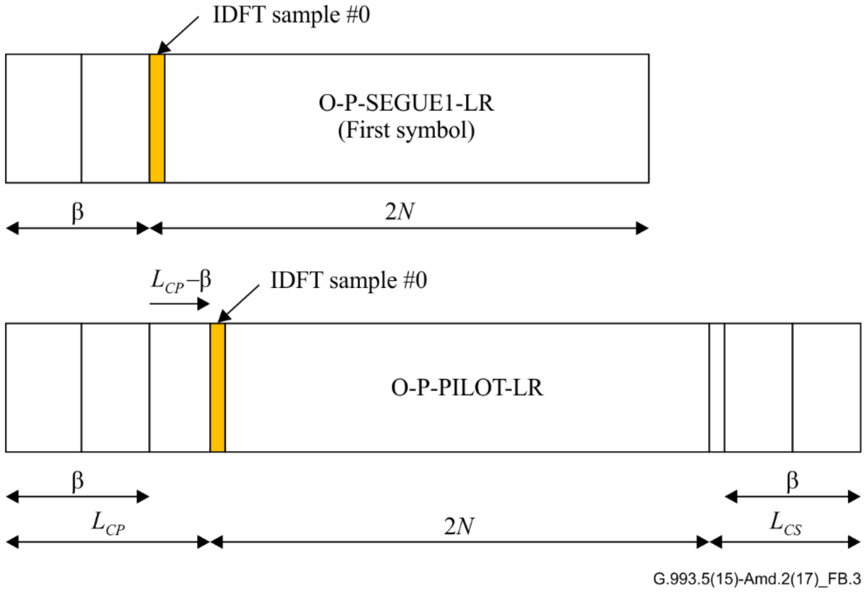


Figure B.3 – Reference samples for alignment of downstream symbols between the O-SEGUE 1-LR state and O-P-PILOT-LR state

The time offset expressed in samples between those reference points modulo the period of a DMT symbol with CE, i.e., $2N+L_{CE}$ samples, shall be as indicated by the VTU-O in the ITU-T G.994.1 Spar(2) codepoint "offset IDFT sample #0" indicated by the VTU-O. The parameter "offset IDFT sample #0" shall be an integer number of samples at the rate of 4.416 MHz.

NOTE – The value of this offset is equal to L_{CP}-β which is always less than or equal to L_{CE}, see Figure B.4. Knowledge of that offset by the receiver, allows VTU-R to derive the symbol timing during the O-P-PILOT-LR and transition into ITU-T G.993.5 Channel Discovery phase with timing acquired in the VDSL2-LR TRAINING stage. This, in turn, allows the re-use of TEQ settings and other transceiver settings obtained during the VDSL2-LR TRAINING stage.

The VCE uses O-P-PILOT-LR state to align the start of O-P-CHANNEL DISCOVERY V1 on all VDSL2-LR lines (regardless of short, medium or long loop operation type) and the regular ITU-T G.993.5 lines. The actual duration of the O-P-PILOT-LR state depends on the durations of the O-P-TREF 1-LR and O-P-REVERB 3-LR states: the sum of the durations of O-P-PILOT-LR, O-P-TREF 1-LR, and O-P-REVERB 3-LR states shall not exceed the sum of the maximum durations of O-P-TREF 1-LR and O-P-REVERB 3-LR and the minimum duration of O-P-PILOT-LR, i.e., 15872+15936+128 = 31936 symbols.

The O-P-PILOT-LR state shall be followed by the O-P-CHANNEL DISCOVERY V1 signal and the remainder of the ITU-T G.993.5 Channel Discovery phase with the amendments as specified in clause B.8.

B.7.2 R-P-TRAINING-LR signals

B.7.2.1 Transmit PSD of the R-P-TRAINING-LR signals

The R-P-TRAINING-LR transmit PSD (*TRAININGPSDus*) shall be identical to the *PROBINGPSDus*:

$$TRAININGPSDus(f) = PROBINGPSDus(f)$$

All subcarriers included in the R-P-TRAINING-LR signals shall be transmitted at the *TRAININGPSDus*, with an accuracy of ±1dB at the U-O2 reference point.

The PSD limits for the R-P-TRAINING-LR signals shall be the PSDMASKus. The PSDMASKus is defined in Table 7-4 of [ITU-T G.993.2] and shall be derived taking into account the LIMITMASKus as defined in clause B.9.

The maximum aggregate transmit power for the R-P-TRAINING-LR signals shall not exceed the value of the control parameter *MAXNOMATPus* as defined in clause B.10.1.7. The VTU-O shall determine the value of *CL_NOMPSDus* such that for any valid setting of *CLR_NOMPSDus*, *PCBus* and *log_tssi_us* chosen by the VTU-R, the aggregate transmit power of the R-P-TRAINING-LR signal shall not exceed the above value.

B.7.2.2 Symbol definitions for the R-P-TRAINING-LR signals

The R-P-QUIET symbol is the same as defined for the R-P-PROBING-LR.

The R-P-REVERB symbol shall contain all subcarriers up to index *NSCus-1*, with *NSCus* as defined in clause B.6.2.2. These subcarriers shall be modulated by 4-QAM. The value 11 shall be mapped to these subcarriers. The constellation points on these subcarriers shall be rotated based on the 2-bit number provided by the quadrant scrambler described in clause 12.3.6.2 of [ITU-T G.993.2]. The scrambler shall be used in reset mode (see clause 12.3.6.2.1 of [ITU-T G.993.2]).

The R-P-SEGUE symbol is defined as identical to the R-P-REVERB symbol, with the value 00 mapped to the same subcarriers.

All signals consisting of R-P-REVERB or R-P-SEGUE symbols shall be implemented as periodic signals, such as O/R-P-PERIODIC 1 (see clause 12.3.6.1 of [ITU-T G.993.2]).

B.7.2.3 R-P-REVERB 1-LR

The R-P-REVERB 1-LR state is of fixed length. In the R-P-REVERB 1-LR state, the VTU-O shall transmit 640 R-P-REVERB symbols.

During the R-P-REVERB 1-LR state, the VTU-R may fine-tune its AGC, does timing recovery and other adaptive AFE algorithms.

The R-P-REVERB 1-LR state shall be followed by the R-P-REVERB 2-LR state.

B.7.2.4 R-P-REVERB 2-LR

The R-P-REVERB 2-LR state is of variable length. In the R-P-REVERB 2-LR state, the VTU-R shall transmit a minimum of 384 and a maximum of 16000 R-P-REVERB symbols.

The R-P-REVERB 2-LR state provides VTU-O with a training signal (presumable, for the TEQ).

The VTU-R shall continue to transmit R-P-REVERB symbols until after the VTU-O transitioning to the O-P-REVERB 2-LR state. Within 64 symbols after the VTU-O transitioning to the O-P-REVERB 2-LR state, the VTU-R shall transition to the next state.

The R-P-REVERB 2-LR state shall be followed by the R-P-QUIET 5-LR state.

B.7.2.5 R-P-QUIET 5-LR

The R-P-QUIET 5-LR state is of variable length. In the R-P-QUIET 5-LR state, the VTU-R shall transmit a minimum of 1024 and a maximum of 16384 R-P-QUIET symbols. The number of symbols transmitted in the R-P-QUIET 5-LR state shall be a multiple of 512 symbols. However, the last R-P-QUIET symbol transmitted in the R-P-QUIET 5-LR state may be shortened by any integer number of samples (at the sample clock frequency $2N\times\Delta f$, as defined in clause 10.4.4 of [ITU-T G.993.2]) to accommodate transmitter-to-receiver frame alignment.

During this state, the VTU-R shall ignore the signal transmitted by the VTU-O during the O-P-ECT-LR state. While the VTU-O is in the O-P-REVERB 3-LR state, the VTU-R may measure the downstream channel characteristics and train its TEQ. The VTU-R transitions to the next state when it has completed the necessary training.

The R-P-QUIET 5-LR state shall be followed by the R-P-REVERB 3-LR state.

B.7.2.6 R-P-REVERB 3-LR

The R-P-REVERB 3-LR state is of fixed length. In the R-P-REVERB 3-LR state, the VTU-R shall transmit 64 R-P-REVERB symbols.

Transition to R-P-REVERB 3-LR state indicates to the VTU-O that the VTU-R completed its TEQ training. It also provides a time marker for the R-P-ECT-LR state.

The R-P-REVERB 3-LR state shall be followed by the R-P-ECT-LR state.

B.7.2.7 R-P-ECT-LR

The R-P-ECT-LR state is of fixed length. In this state, the VTU-R shall transmit a vendor-discretionary signal with a duration of 512 symbol periods.

During this state, the VTU-R may train its echo canceller.

The R-P-ECT-LR state shall be followed by the R-P-REVERB 4-LR state.

B.7.2.8 R-P-REVERB 4-LR

The R-P-REVERB 4-LR state is of fixed length. In this state, the VTU-R shall transmit 1024 R-P-REVERB symbols.

During the R-P-REVERB 4-LR state, the VTU-R can adjust its parameters for bidirectional transmission.

The R-P-REVERB 4-LR state shall be followed by the R-P-SEGUE 1-LR state. The transition from the R-P-REVERB 4-LR state to the R-P-SEGUE 1-LR state is a time marker for the start time of R-P-QUIET 1 and for the VTU-R being ready to receive the O-SIGNATURE message.

B.7.2.9 R-P-SEGUE 1-LR

The R-P-SEGUE 1-LR state is of fixed length. In the R-P-SEGUE 1-LR state, the VTU-R shall transmit 64 R-P-SEGUE symbols. The first symbol of R-P-SEGUE 1-LR is used as reference point to keep the synchronization between VDSL-LR training and the ITU-T G.993.5 Channel Discovery (see clause B.8.3).

The transition to the next state is a time marker for the end of the TRAINING stage and indicates that the VTU-R shall be ready to receive the O-SIGNATURE message.

The R-P-SEGUE 1-LR state shall be followed by the ITU-T G.993.5 R-P-QUIET1 state.

B.7.3 Timeline of O/R-P-TRAINING-LR signals

The signal exchange is depicted in Figure B.4.

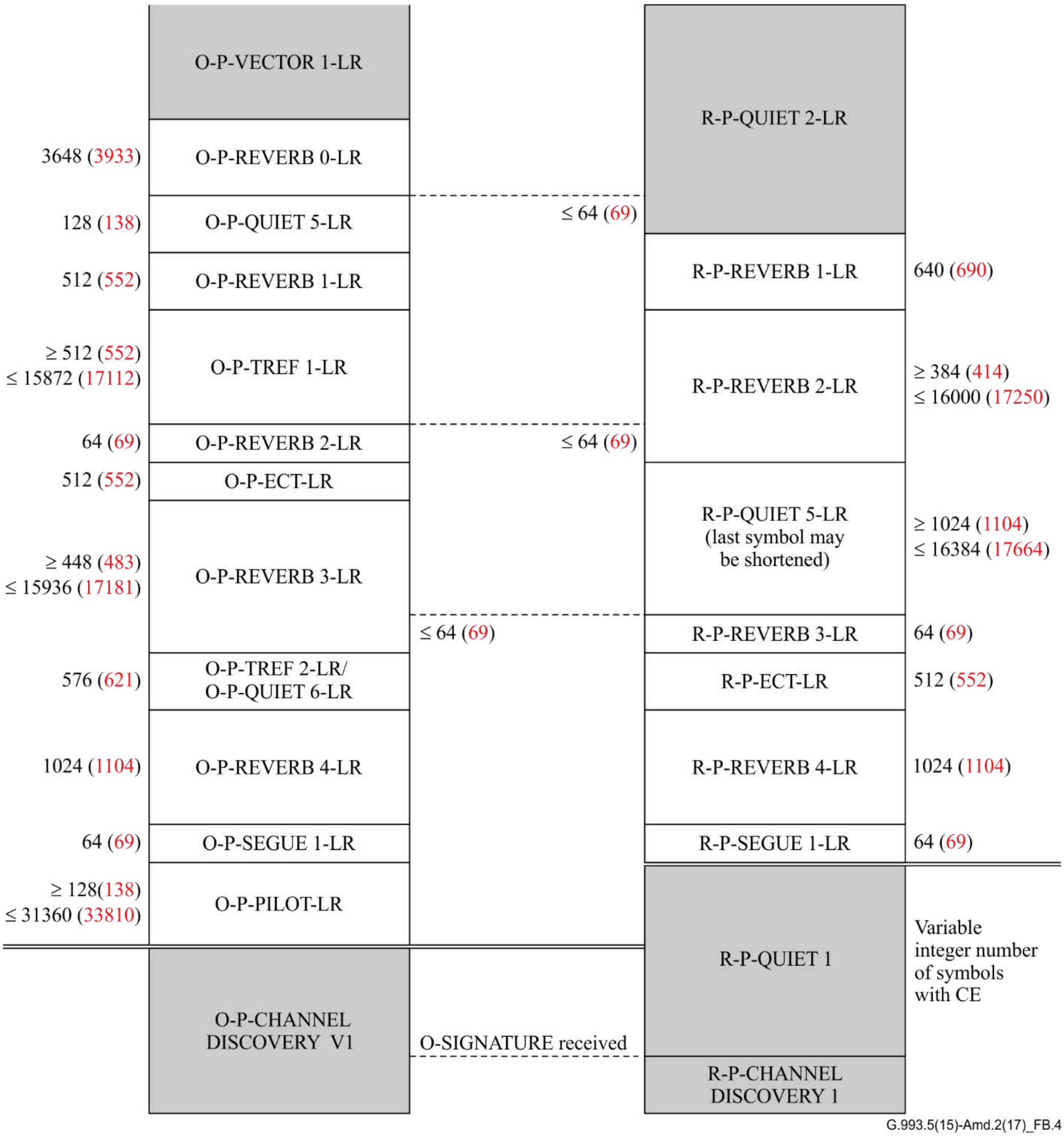


Figure B.4 – Timeline of O/R-P-TRAINING-LR signals

In Figure B.4, signals durations are expressed in symbols with CE (values in parenthesis are signals durations expressed in symbols without CE). Signals shaded in grey are parts of the previous and the following stages of initialization (see Figure B.1).

NOTE – Training of TEQ can be shortened by the receiver in case TEQ is further trained during the VDSL2 initialization. With shortest TEQ training, the duration of this stage is about 1.9s.

B.8 ITU-T G.993.5 Channel Discovery phase and Training phase in long loop operation

This clause contains additional requirements on the ITU-T G.993.5 Channel Discovery phase and Training phase that apply if the long loop operation of VDSL2-LR is selected (see clauses B.4.8, B.4.9, B.5.6 and B.5.7).

The setting of the transmit path between the IDFT output and the corresponding U-interface of both the VTU-R and VTU-O that was established during the TRAINING stage shall be kept unchanged during the ITU-T G.993.5 Channel Discovery phase and Training phase. The IDFT size and type of image used during the ITU-T G.993.5 Channel Discovery and Training phases shall be the same as those used during the TRAINING stage.

B.8.1 ITU-T G.993.5 Channel Discovery phase in long loop operation

The SUPPORTEDCARRIERSds set shall be limited to subcarrier index 511.

The SUPPORTEDCARRIERSus set shall be limited to subcarrier index 31 for US0 type A, and to subcarrier index 63 for US0 types B and M.

B.8.1.1 Transition to ITU-T G.993.5 Channel Discovery phase

In the downstream direction, symbols in ITU-T G.993.5 Channel Discovery phase shall be aligned with symbols in O-P-PILOT-LR.

In the upstream, the transition from VDSL2-LR TRAINING stage to ITU-T G.993.5 Channel Discovery phase shall be aligned using two reference points associated with the IDFT sample #0 of specific symbols. The IDFT sample #0 is defined as the first sample of the block of *2N* time samples generated by the IDFT.

The first reference point shall be the IDFT sample #0 of the first symbol of the R-P-SEGUE 1-LR state and the second reference point shall be the IDFT sample #0 of the first symbol of the R-P-CHANNEL DISCOVERY 1 signal, as shown in the Figure B.5.

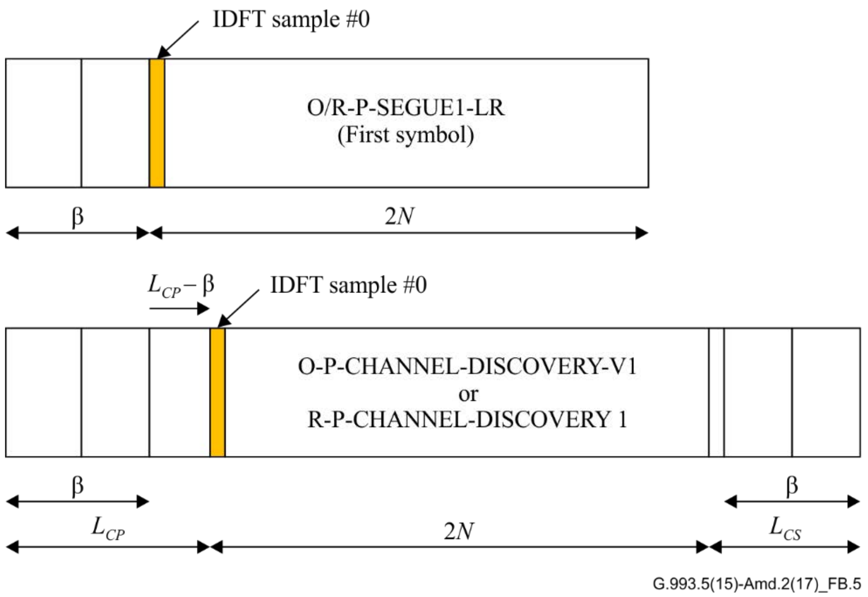


Figure B.5 – Reference samples for alignment of upstream symbols between the VDSL2-LR TRAINING stage and ITU-T G.993.5 Channel Discovery phase

The time offset expressed in samples between those reference points modulo the period of a DMT symbol with CE, i.e., $2N+L_{CE}$ samples, shall be as indicated by the VTU-R in the ITU-T G.994.1 Spar(2) codepoint "offset IDFT sample #0". The parameter "offset IDFT sample #0" indicated by the VTU-R shall be an integer number of samples at the rate of 276 kHz.

NOTE – The value of this offset is equal to L_{CP}-β, which is always less than or equal to L_{CE}, see Figure B.5. Knowledge of that offset by the VTU-O, allows to derive the symbol timing during the ITU-T G.993.5 Channel Discovery phase from the one acquired in the VDSL2-LR TRAINING stage. This, in turn, allows the re-use TEQ settings and other transceiver settings obtained during the VDSL2-LR TRAINING stage.

B.8.1.2 Use of PILOT during R-P-LINEPROBE

If the ITU-T G.993.5 R-P-LINEPROBE signal is requested, the VTU-O shall transmit O-P-PILOT 1 and transition to O-P-PERIODIC 1 640 symbols after the end of transmission of O-P-SYNCHRO 1. The O-P-PILOT 1 shall use the tone index indicated during the PROBING stage.

B.8.1.3 Replacement of R-P-VECTOR signals

As upstream crosstalk cancelling is not active when the long loop operation of VDSL2-LR is selected, the R-P-VECTOR signals are removed or replaced by other signals.

The R-P-VECTOR 1 signal shall be replaced by R-P-CHANNEL DISCOVERY 1 with SOC sending R-IDLE until the O-P-SYNCHRO-V1 signal is received. After the O-P-SYNCHRO-V1 signal is received the VTU-R shall sent R-IDLE at least for the duration of 512 symbols before transmitting R-MSG 1.

B.8.1.4 O-SIGNATURE (amends clause 12.3.3.2.1.1 of [ITU-T G.993.2])

Field #8 "Downstream nominal maximum aggregate transmit power (MAXNOMATPds)" indicates the value of the control parameter *MAXNOMATPds*, which determines the maximum wide-band power that the VTU-O is allowed to transmit. The value of the *MAXNOMATPds* shall not exceed the minimum of the maximum aggregate downstream transmit power as defined in clause B.9 for the corresponding annex of [ITU-T G.993.2] and the MAXNOMATPds value configured in the CO-MIB, regardless of the particular [ITU-T G.993.2] profile selected during the ITU-T G.994.1 Handshake phase of initialization.

B.8.1.5 PSD adjustments during ITU-T G.993.5 Channel Discovery phase

The PSD adjustments defined in ITU-T G.993.5 Channel Discovery phase include potential changes of the downstream highest used subcarrier and the actual downstream transmit PSD, which may result in a different downstream transmit PSD than the one defined during the PROBING stage. To avoid changes in the transmission channel and corresponding degradations in the tuning of the TEQ, the mentioned adjustment of the PSD shall be done exclusively in frequency domain.

B.8.2 ITU-T G.993.5 Training phase in long loop operation

During the transition to the ITU-T G.993.5 Training phase, the VTU-R shall keep symbol timing. To facilitate loop timing, the quiet symbols of O-P-VECTOR 1-1 shall be replaced by symbols containing a single subcarrier with the index of the downstream pilot tone indicated in the R-P-MSG-PCB message. The pilot tone shall be modulated with the constellation point (0,0).

To keep the position of the IDFT sample #0 between the Channel Discovery and the Training phases in upstream, the duration of R-P-QUIET V1 shall be an integer number of DMT symbols.

B.8.2.1 Replacement of R-P-VECTOR signals

The R-P-VECTOR 1-1 signal shall not be sent, i.e, the first signal of transceiver training phase is R-P-TRAINING 1.

The R-P-VECTOR 1-2 signal shall be replaced by R-P-TRAINING 1-2. The R-P-TRAINING 1-2 signal shall be identical to R-P-TRAINING 1.

The sync symbols in the R-P-VECTOR 2 shall be replaced by R-P-TRAINING 2 symbols with the extended SOC channel activated.

B.9 Definition of limit PSD masks

This clause defines limit PSD masks and maximum aggregate transmit power (ATP) requirements applicable to VDSL2-LR mode in long loop operation. These requirements apply to the TRAINING-LR stage, the remainder of initialization and the SHOWTIME state.

B.9.1 Operation according to Annex A [ITU-T G.993.2]

VDSL2-LR mode according to Annex A of [ITU-T G.993.2] is not defined.

B.9.2 Operation according to Annex B of [ITU-T G.993.2]

B.9.2.1 Downstream Limit PSD mask and maximum aggregate transmit power

The US0 PSD type is selected in the ITU-T G.994.1 MS message. The corresponding LIMITMASKds for VDSL2-LR mode shall be as defined in Table B.7A of [ITU-T G.993.2] for PSD masks B8-11 (for US0 type A), B8-12 (for US0 type B) and B8-17 (for US0 type M), with flat extension at −100 dBm/Hz from 3.925 MHz to 30 MHz and flat extension at −110 dBm/Hz above 30 MHz, and with the modification defined in Table B.11.

The maximum aggregate downstream transmit power (as referred in clauses B.6.1.1 and B.8.1.4) shall be 20.5 dBm, independent of the VDSL2 profile and US0 type selected in the ITU-T G.994.1 Handshake phase.

Table B.11 – Modification of the LIMITMASKds for VDSL2-LR mode

Frequency (kHz)	**VDSL2-LR LIMITMASKds (dBm/Hz)**
f_1	−36.50
$f_1 + 138$	−33.50
948.75	−33.50
1104	−36.50
NOTE – The value f_1 is 138 kHz for US0 type A and 276 kHz for US0 types B and M.	

B.9.2.2 Upstream limit PSD mask

The US0 PSD type is selected in the ITU-T G.994.1 MS message. The corresponding LIMITMASKus for VDSL2-LR mode shall be as defined in Table B.6A of [ITU-T G.993.2] for PSD masks B8-11 (for US0 type A), B8-12 (for US0 type B) and B8-17 (for US0 type M), with flat extension at −100 dBm/Hz from 686 kHz to 30 MHz and flat extension at −110 dBm/Hz above 30 MHz.

The *NSCus* shall be set to 32 for US0 type A and to 64 for US0 types B and M.

B.9.3 Operation according to Annex C of [ITU-T G.993.2]

VDSL2-LR mode according to Annex C of [ITU-T G.993.2] is not defined.

B.9.4 Operation according to Annex N of [ITU-T G.993.2]

VDSL2-LR mode according to Annex N of [ITU-T G.993.2] is not defined.

B.10 Management

This clause defines the CO-MIB configuration, status, and inventory parameters specific to the VDSL2-LR mode. These parameters shall be supported if the VTU-O supports VDSL2-LR mode.

B.10.1 Configuration parameters

B.10.1.1 VDSL2-LR enable (VDSL2-LR_ENABLE)

The configuration parameter VDSL2-LR_ENABLE (see clause 7.3.1.16.1 of [ITU-T G.997.1]) specifies for the line which VDSL2-LR operation types are allowed. It is defined as a bitmap, with following types:

- Short loop: Short loop operation according to this annex is allowed.
- Medium loop: Medium loop operation according to this annex is allowed.
- Long loop: Long loop operation according to this annex is allowed.

If none of the operation types are allowed, then the VDSL2-LR mode (i.e., operation according to this annex) is "disabled". If at least one of the operation types is allowed, then the VDSL2-LR mode (i.e., operation according to this annex) is "enabled" (see Table B.1).

B.10.1.2 Downstream maximum nominal power spectral density (MAXNOMPSDds)

The configuration parameter MAXNOMPSDds (see clause 7.3.1.2.1 of [ITU-T G.997.1]) specifies for the line the maximum value of the *NOMPSDds* (used to determine the *PROBINGPSDds*, see clause B.6.1.1) as indicated by the VTU-O in the downstream spectrum bounds in the ITU-T G.994.1 CL message.

B.10.1.3 Upstream maximum nominal power spectral density (MAXNOMPSDus)

The configuration parameter MAXNOMPSDus (see clause 7.3.1.2.2 of [ITU-T G.997.1]) specifies for the line the maximum value of the *NOMPSDus* (used to determine the *PROBINGPSDus*, see clause B.6.2.1) as indicated by the VTU-O in the upstream spectrum bounds in the ITU-T G.994.1 CL message.

B.10.1.4 Downstream PSD Mask (MIBMASKds) (amends clause 7.2.1.1 of [ITU-T G.993.2])

The configuration parameter MIBMASKds (see clause 7.3.1.2.9 of [ITU-T G.997.1]) represents the MIB PSD mask and shall lie at or below the maximum of the Limit PSD mask specified in the selected annex of [ITU-T G.993.2] and, if the VDSL2-LR mode is "enabled" (see clause B.10.1.1), the limit PSD mask defined in clause B.9. Its definition shall be under the network management control (a MIB-controlled mechanism), as defined in [ITU-T G.997.1].

The breakpoints used to construct the MIB PSD mask shall be specified so that the minimum of the limit PSD mask specified in the selected annex and the MIB PSD mask can be constructed using no more than 32 breakpoints in the frequency ranges in which the MIB PSD mask is specified.

B.10.1.5 VDSL2 PSD mask class selection (CLASSMASK)

If the VDSL2-LR mode is "enabled" (see clause B.10.1.1), then the configuration parameter CLASSMASK (see clause 7.3.1.2.15 of [ITU-T G.997.1]) shall be set to one of the Annex B classmasks 997-M2x, 998-M2x, 998ADE-M2x, 998E35-M2x or 998ADE35-M2x.

B.10.1.6 Downstream maximum nominal aggregate transmit power (MAXNOMATPds)

The configuration parameter MAXNOMATPds is defined in the CO-MIB (see clause 7.3.1.2.3 of [ITU-T G.997.1]) and specifies:

- an upperbound to the downstream aggregate transmit power during PROBING for all operation types (short loop, medium loop and long loop operation);
- an upperbound to the downstream aggregate transmit power during TRAINING for long loop operation;
- an upperbound to the downstream aggregate transmit power during O-P-VECTOR 1 for short-medium loop operation;

- an upperbound to the control parameter *MAXNOMATPds* in O-SIGNATURE for all operation types (short loop, medium loop and long loop operation); and
- an upperbound to the recalculated control parameter *MAXNOMATPds* for the determination of MREFPSDds in ITU-T G.993.5 Channel analysis and exchange phase for medium loop operation.

The MAXNOMATPds setting in the CO-MIB shall not exceed 20.5 dBm.

NOTE – In this annex, the MAXNOMATPds setting in the CO-MIB may exceed the maximum aggregate downstream transmit power specified in Table 6.1 of [ITU-T G.993.2].

B.10.1.7 Upstream maximum nominal aggregate transmit power (*MAXNOMATPus*)

The control parameter *MAXNOMATPus* is determined by the maximum aggregate upstream transmit power specified in Table 6-1 of [ITU-T G.993.2].

NOTE – There is no configuration parameter MAXNOMATPus defined in the CO-MIB (see Table 7.15 of [ITU-T G.997.1]).

B.10.2 Status parameters

B.10.2.1 VDSL2-LR actual operation type (VDSL2-LR_ACTOPTYPE)

The status parameter VDSL2-LR_ACTOPTYPE (see clause 7.5.1.44.1 of [ITU-T G.997.1]) reports the line's actual operation type (regardless whether this selection is autonomous by the VTU-R or forced through the CO-MIB).

The valid values are:

- No operation type selected: Operation without this annex.

  ITU-T G.994.1 MS message has VDSL2-LR Spar(2) bit set to 0.
- Short loop: Short loop operation according to this annex.

  ITU-T G.994.1 MS message has VDSL2-LR Spar(2) bit set to 1 and short-medium loop operation is selected in the PROBING stage and the condition for short loop operation (defined in clause B.4.8.3) is met.
- Medium loop: Medium loop operation according to this annex.

  ITU-T G.994.1 MS message has VDSL2-LR Spar(2) bit set to 1 and short-medium loop operation is selected in the PROBING stage and the condition for medium loop operation (defined in clause B.4.8.3) is met.
- Long loop: Long loop operation according to this annex.

  ITU-T G.994.1 MS message has VDSL2-LR Spar(2) bit set to 1 and long loop operation is selected in the PROBING stage.

B.10.3 Inventory parameters

B.10.3.1 VDSL2-LR support (VDSL2-LR_SUPPORT_O/R)

The VDSL2-LR_SUPPORT_O (see clause 7.4.14.1 of [ITU-T G.997.1]) and VDSL2-LR_SUPPORT_R (see clause 7.4.14.1 of [ITU-T G.997.1]) inventory parameters report, for the VTU-O and the VTU-R respectively, whether VDSL2-LR mode is not supported (set to 0) or supported (set to 1).

B.10.4 Test parameters

B.10.4.1 Test parameter group size

If the "Support of VDSL2-LR" bit was set to ONE in the last previous ITU-T G.994.1 MS message, the group size shall be determined according to the equation in clause 11.4.1 of [ITU-T G.993.2], with theta equal to the highest subcarrier index in the MEDLEY set for test parameters measured during the Channel Discovery phase and for test parameters measured during other phases.

NOTE – This clause applies to the VDSL2-LR mode, regardless whether short, medium or long loop operation is selected.

B.11 Nominal aggregate transmit power (NOMATP) (replaces clause 10.3.4.2.1 of [ITU-G.993.2])

NOTE – Unless otherwise specified, references in this clause refer to [ITU-T G.993.2].

The nominal aggregate transmit power (NOMATP) shall be computed by the following equation:

$$\text{NOMATP} = 10\log_{10}\Delta f + 10\log_{10}\left(\sum_{i\in\text{MEDLEY set}}\left(10^{\frac{\text{MREFPSD}[i]}{10}} g_i^2\right)\right),$$

where MREFPSD[i] and g_i are, respectively, the values of MREFPSD in dBm/Hz and gain (linear scale) for subcarrier i from the MEDLEY set (see clause 12.3.3.2.1.3), and Δf is the subcarrier spacing in Hz.

The downstream NOMATP (NOMATPds) shall be computed for subcarriers from the downstream MEDLEY set (MEDLEYds). The upstream NOMATP (NOMATPus) shall be computed for subcarriers from the upstream MEDLEY set (MEDLEYus).

The maximum NOMATPds during ITU-T G.993.5 Channel analysis and exchange phase and during showtime is determined by the control parameter *MAXNOMATPds*. The value of this control parameter is derived during initialization based on the CO-MIB configuration parameter MAXNOMATPds, the value of the MAXNOMATPds indicated in the Field #8 of O-SIGNATURE message, as well as the operation type (short loop, medium loop, or long loop operation).

The g_i settings at the VTU-O and VTU-R shall be such that the values of NOMATPds and NOMATPus do not exceed, respectively, the control parameter *MAXNOMATPds* and *MAXNOMATPus*.

Appendix I

Crosstalk channel modelling

(This appendix does not form an integral part of this Recommendation.)

I.1 Scope

This appendix provides information on stochastic models for a MIMO FEXT coupling channel in digital subscriber line (DSL) transmission systems operating on twisted-pair cables. For a number of DSL systems, the FEXT coupling among them can be modelled as a MIMO system.

The models are derived using a statistical analysis of measurements of ingress energy into pairs of a cable from other pairs in the same cable. The data on which the models are based was gathered from measurements of actual loop plant deployed in various regions in the world.

I.2 Purpose

The purpose of this appendix is to provide the industry with a tool for simulating FEXT coupling among multiple DSL lines.

I.3 MIMO crosstalk channel model A

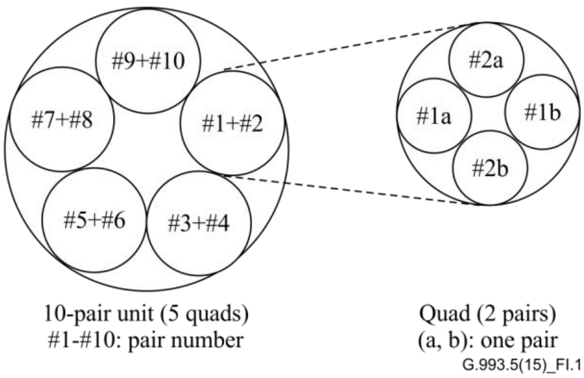
A model for the crosstalk channel for North America and Europe can be found in [b-ATIS-0600024]. This model is based on data gathered from measurements of actual loop plant deployed in North America and Europe. [b-ATIS-0600024] defines a MIMO crosstalk channel model based on these measurements and includes justification for the model.

I.4 MIMO crosstalk channel model C

The data on which this model is based was gathered from measurements of actual loop plant deployed in Japan.

I.4.1 Assumptions to crosstalk model

The crosstalk model is based upon a 0.4 mm (in diameter) polyethylene (PE) insulated cable called a colour coded polyethylene (CCP) cable. The pair binding structure applied to the PE insulated cable is given in Figure I.1, where pair numbers, #1-#10, are attached. In the Figure, a quad is formed by twisting four insulated conductors (two pairs), and a binder group called a unit is formed by binding five quads (ten pairs). Although a PE insulated cable contains one to several units, we can ignore the effect of inter unit crosstalk for simplicity, as inter unit crosstalk is much smaller than intra unit crosstalk. Then, a single unit of ten pairs (five quads) of the PE insulated cable is applied to the crosstalk model.



10-pair unit (5 quads) Quad (2 pairs)
#1-#10: pair number (a, b): one pair

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

It is known that the probability density function (PDF) of crosstalk coupling (attenuation) losses in dB is a normal distribution with an average expressed by *M* (dB) and a standard deviation expressed by σ (dB). There are three inter pair location relationships in the unit of the PE insulated cable, which are intra quad, adjacent quad, and every second quad. So, there are three kinds of the population of the crosstalk coupling losses in the unit. The average M_k (dB) [k=1, 2, 3] and the standard deviation σ_k (dB) [k=1, 2, 3] of the FEXT coupling losses are given in Table I.1, where the indices, k=1, 2, 3, correspond to three inter pair location relationships in the unit that form each population.

Table I.1 – FEXT average and standard deviation

Item	*k*=1	*k*=2	*k*=3
	Intra quad	**Adjacent quad**	**Every second quad**
FEXT average M_k	69.2 (dB)	74.2 (dB)	75.7 (dB)
FEXT standard deviation σ_k	6.56 (dB)	8.15 (dB)	7.38 (dB)
NOTE – The value of M_k (dB) is given as the value of FEXT loss at $f=f_{FXT}=160*10^3$ (Hz) and $d=d_{FXT}=1*10^3$(m).			

I.4.2 Generation of a sample value for FEXT coupling loss

FEXT coupling loss random samples, $XT_k(i)$ (dB) [k=1, 2, 3], between any two pairs in the unit are given in Table I.2 in the form of the 10-by-10 matrix, where the index "*k*" shows the same as in Table I.1, and the index "*i*" shows that a different value can be given. It is assumed that the crosstalk from the interfering pair (#*m*) to the interfered pair (#*n*) is identical to the crosstalk from the interfering pair (#*n*) to the interfered pair (#*m*). Therefore, two sample group values are symmetric with respect to the diagonal line in Table I.2. Consequently, there can be a maximum of five different sample values for $XT_1(i)$ (k=1), a maximum of twenty different sample values for $XT_2(i)$ (k=2), and a maximum of twenty different sample values for $XT_3(i)$ (k=3).

Table I.2 – FEXT loss sample

I-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.

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

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

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

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

where k = 1, 2, 3,

when k = 1, i = 1, 2, 3,…, max(5)

when k = 2, i = 1, 2, 3,…, max(20)

when k = 3, i = 1, 2, 3,…, max(20)

M_k (dB): average of FEXT coupling losses at $f = f_{FXT}$ and $d = d_{FXT}$, see Table I.1

σ_k (dB): standard deviation of FEXT coupling losses, see Table I.3.

Table I.3 – Example of random sample $XT_k(i)$ with cumulative distribution point of Q (%)

Cumulative distribution point (%)	ρ_i	$XT_k(i)$ (dB)		
		k=1	k=2	k=3
		Intra quad	Adjacent quad	Every second quad
$Q(\rho_i)$=0.01(%)	3.72	93.6(dB)	104.5(dB)	103.2(dB)
$Q(\rho_i)$=0.1(%)	3.09	89.5(dB)	99.4(dB)	98.5(dB)
$Q(\rho_i)$=1(%)	2.33	84.5(dB)	93.2(dB)	92.9(dB)
$Q(\rho_i)$=5(%)	1.64	80.0(dB)	87.6(dB)	87.8(dB)
$Q(\rho_i)$=10(%)	1.28	77.6(dB)	84.6(dB)	85.1(dB)

Table I.3 – Example of random sample $XT_k(i)$ with cumulative distribution point of Q (%)

Cumulative distribution point (%)	ρ_i	$XT_k(i)$ (dB)		
		k=1	k=2	k=3
		Intra quad	Adjacent quad	Every second quad
$Q(\rho_i)$=20(%)	0.842	74.7(dB)	81.1(dB)	81.9(dB)
$Q(\rho_i)$=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 (= α + jβ, see ITU-T G.993.1 Annex F.3)

$XT_k(i)$ (dB): FEXT sample (at $f = f_{FXT}$ and at $d = d_{FXT}$)

ϕ_k (i)(rad/m): a uniformly distributed random variable over the range [0,2π].

A user of this model should populate the 10×10 coupling matrix described in Table I.2 using random draws from the tri-modal distributions for the geometric dependent couplings in Table I.1. These random draw values may be assessed to their relative likelihood by comparing them with the associated values provided in Table I.3.

Appendix II

Examples of VCE control of initialization process in the activation of multiple lines in the vectored group

(This appendix does not form an integral part of this Recommendation.)

II.1 Introduction

Vectoring is designed for the FEXT cancellation across multiple VDSL2 lines. In clause 10, the initialization is described in detail mainly from the viewpoint of a single line. This appendix provides two examples of methods allowing the VCE to handle activation of multiple lines that attempt to join the vectored group in arbitrary order. If the bit "8192 superframes duration for O-P-VECTOR 1" is enabled in the ITU-T G.994.1 phase (see clause 10.2), the VCE may use the first method based on the handling lines that became late for the current initialization cycle in a waiting group. Alternatively, the VCE may use the second method based on ITU-T G.994.1 handshake capabilities to control the time when line is ready for joining.

II.2 VCE handling two groups of initializing lines

In this method, the VCE maintains initializing lines in two groups after the vectored group is started. One group is called "joining group" and the other is called "waiting group". Both of the groups have two states: the open state and the closed state. When a line enters the Channel Discovery phase of the initialization, it will be added to one of the groups. Table II.1 shows the decision to which group the line is added.

Table II.1 – VCE decision to which group the line is added

Joining group state	Open	Closed	Closed	Open
Waiting group state	Closed	Open	Closed	Open
Decision by the VCE for new lines	Added to the joining group	Added to the waiting group	Will be added to the waiting group when it opens	Not valid

Note that the joining group and the waiting group are never in the open state at the same time. The full mechanism is described as follows:

1. The joining group is a group of lines which are controlled by the VCE for normal initialization. These lines are currently performing or about to perform a normal initialization process after the ITU-T G.994.1 phase. Initially, after the system power is on, the joining group is open and empty. Once the VCE starts FEXT channel coefficient estimation (VTU-O starts transmission O-P-VECTOR 1 signal), the joining group is closed. The joining group can be open again when the joining process is over (no lines remain in the joining group). When a line in the joining group drops during the initialization or reaches Showtime, it is removed from the joining group.
2. The waiting group is a group of lines which are controlled by the VCE to wait prior to beginning their normal initialization after the ITU-T G.994.1 phase, until lines in the joining group complete their initialization. Initially, after the system power is on, the waiting group is closed and empty. The VCE can add new lines that have completed ITU-T G.994.1 handshake to the waiting group as follows:
   - if a line is ready to join the waiting group at an instant when the waiting group is open, it joins the waiting group and the VTU-O starts transmitting on the joining line the O-P-VECTOR 1 signal with all tones active until the lines in the joining group complete the initialization.

– if a line is ready to join the waiting group at an instant when the waiting group is closed, then the VTU-O proceeds as follows:
  - if the bit "Use of O-P-VECTOR 1 flag tones only" is enabled in the ITU-T G.994.1 phase, the line joins the waiting group and the VTU-O starts transmitting on the joining line the O-P-VECTOR 1 signal with only flag tones active, while other tones are masked. When the waiting group opens, the VTU-O continues transmitting the O-P-VECTOR 1 signal now with all tones active until the lines in the joining group complete the initialization;
  - if the bit "Use of O-P-VECTOR 1 flag tones only" is disabled in the ITU-T G.994.1 phase, the line waits up to 512 symbols for the waiting group to open. If the waiting group opens within 512 symbols, the VTU-O starts transmitting O-P-VECTOR 1 with all tones active until the lines in the joining group complete the initialization. Otherwise, the VTU-O returns to the state O-SILENT.

  The waiting group can only be open when the joining group is closed. When the VCE estimates the FEXT channel coefficients, the waiting group is kept closed to avoid introducing non-orthogonal crosstalk from new lines. After the estimation of FEXT channel coefficients is finished, the waiting group can be open again. If a line in the waiting group drops during the initialization, it is removed from the waiting group.

3. When the joining lines transmit the O-P-VECTOR 1-1 and O-P-VECTOR 2-1 signals, the VCE estimates the downstream FEXT coupling coefficients from the lines of the waiting group into the lines that are in Showtime and into the lines of the joining group. Thus, the FEXT from the waiting group lines can be cancelled such that the SNR of the joining group lines can be measured with no impact of downstream FEXT from the waiting lines.
4. When the lines in the joining group are in the Channel Analysis and Exchange phase of initialization, the waiting group should be kept closed to avoid any new lines being added to the waiting group until all the joining lines have completed the SNR measurements. New lines cannot therefore disturb measuring SNR in the joining group in the Channel Analysis and Exchange phase.
5. Once there are no lines remaining in the joining group, all lines of the waiting group are moved into the joining group, and the waiting group is closed. After that, if the joining group is not empty, the VCE can start the Channel Discovery phase of the new initialization process. Otherwise, the joining group is kept open for the new activating lines thereafter.

The above procedure is illustrated in Figure II.1.

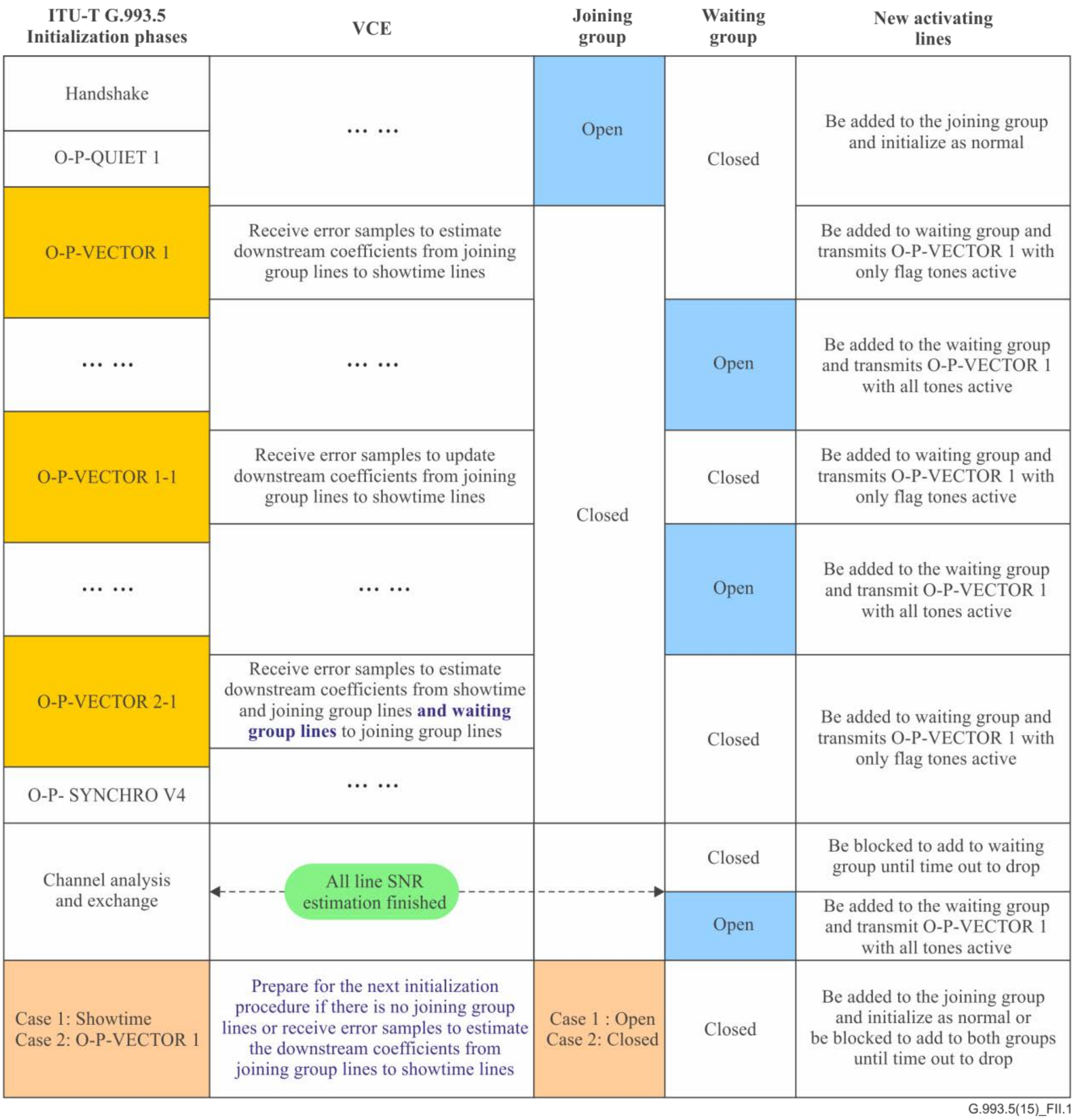


Figure II.1 – Status of joining and waiting groups, and the new activating lines during initialization (in the case where the bit "Use of O-P-VECTOR 1 flag tones only" is enabled in the ITU-T G.994.1 phase)

With this controlling mechanism by the VCE, at least the following three benefits can be achieved:

1. For the waiting group lines, they can start transmission of the O-P-VECTOR 1 signal even if they complete the ITU-T G.994.1 phase after other joining lines entered the Channel Discovery phase. Thus, the time of the ITU-T G.994.1 phase is saved. The O-P-VECTOR 1 time may be significantly shortened because VCE already estimated crosstalk from the majority of lines in the waiting group into active lines.

2. In the multiple lines initialization scenarios, the majority of lines that enter the Channel Discovery phase after the VCE starts to estimate the FEXT coupling channel coefficients will be added to the waiting group. Hence, they can start their initialization process in a synchronized step after the current initialization process handled by the VCE is completed. All lines can go to Showtime in not more than two cycles of the vectoring initialization process (from channel discovery to Channel Analysis and Exchange). Thus, initialization

time is substantially reduced compared to the current initialization process, in which lines that arrive after the beginning of initialization are dropped back to handshake and their initialization could last for multiple cycles of the vectoring initialization process.

3. If there are no new lines added to the waiting group after the SNR estimation during the Channel Analysis and Exchange phase, then the downstream FEXT channel coefficients from the lines of the waiting group into Showtime lines are already handled by the VCE, and the O-P-VECTOR 1 stage can be passed straight forwardly by applying the minimum O-P-VECTOR 1 duration of 4 × 257 symbols. This further saves initialization time.

II.3 VCE using handshake capabilities

The activation of multiple lines in the vectored group may be managed by the VCE through the use of ITU-T G.994.1 handshake capabilities as follows:

1. When new lines in the vector group enter the ITU-T G.994.1 phase of initialization, the VTU-R may continually send R-TONES-REQ to initiate handshake as defined in [ITU-T G.994.1].
2. The VCE knows the state of all of the transceivers undergoing ITU-T G.993.5 initialization. When the VCE detects completion or near-completion of the ITU-T G.993.5 initialization cycle for the current group of joining lines, the VCE enables the VTU-Os that are detecting R-TONES-REQ to respond with C-TONES to progress with handshake for constructing the next group of joining lines.
3. The timeout of the VTU-Rs to the detection of O-SIGNATURE is vendor specific. It is observed that the duration of O-P-QUIET 1 is 1024 symbols maximum, that the duration of O-P-VECTOR 1 is 1024 × 257 symbols, and that the duration of O-IDLE is a maximum of 2000 symbols; this corresponds to a time period of approximately 66.5 seconds.

Appendix III

SNR-based FEXT channel estimation method

(This appendix does not form an integral part of this Recommendation.)

III.1 Tools

The SNR-based FEXT channel estimation method described in this appendix uses the reported SNR-ps (reported by the VTU-R to the VTU-O), as defined in clause 11.4.1 of [ITU T G.993.2].

III.2 Estimation of FEXT channels from a new line into existing lines

III.2.1 Introduction

Assuming *K* active lines (index *i* going from 0 to *K*–1) and one initializing line with number *K*, the downstream received signal at the CPE of victim line number *i*=0 can be written as:

$$y = Hx + n$$

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

where:

$H_{0,0}$: The direct channel transfer function of the victim line.

$H_{0,i}$: For i=1 ... *K*–1 the FEXT crosstalk channel transfer function, from active line *i* to the victim line.

$H_{0,K}$: The FEXT crosstalk channel transfer function, from the new line *K* to the victim line.

x_0: The data symbols from the victim line, with variance σ_0^2.

x_i: For *i*=1 ... *K*, the data symbols from the active lines, with variance σ_i^2.

x_K: The data symbols from line *K*, with variance σ_K^2.

n_0: The external noise on the victim line, with variance σ_n^2.

NOTE – In equation III-1, it is assumed that the FEXT is not yet pre-compensated. The equations applicable in the presence of pre-compensation are presented in clause III.2.7.

The pre-coding matrix F is typically defined as $H^{-1}diag(H)$.

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

with $\hat{C}$ being an estimate of C.

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

$C_{v,i} = \frac{H_{v,i}}{H_{v,v}}$, $v \neq i$ so in this 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 as:

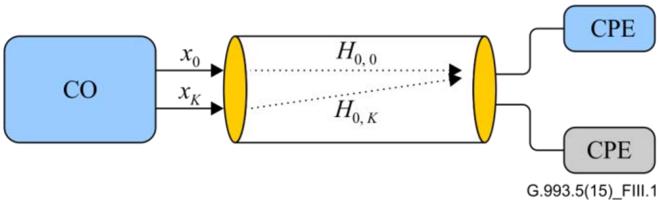


Figure III.1 – Crosstalk model – normal condition

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

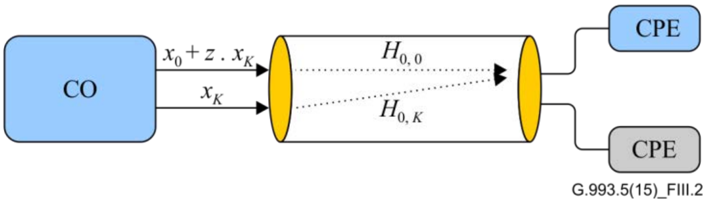


Figure III.2 – Probing signal model – normal condition

The probing signal consists of a copy of the disturbing line, which is added to the victim. This leads to some interesting properties for the SNR.

Define SNR_b as the signal-to-noise ratio before the new line *K* is added:

$$SNR_b = \frac{\sigma_0^2 |H_{0,0}|^2}{\sum_{i=1}^{K-1} \sigma_i^2 |H_{0,i}|^2 + \sigma_{n_0}^2} \qquad \text{(III-2)}$$

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:

$$SNR_a(z) = \frac{\sigma_0^2 |H_{0,0}|^2}{\sum_{i=1}^{K-1} \sigma_i^2 |H_{0,i}|^2 + \sigma_K^2 |H_{0,K} + z \cdot H_{0,0}|^2 + \sigma_{n_0}^2} \qquad \text{(III-3)}$$

Hence, these equations can be combined into the following equation:

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

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:

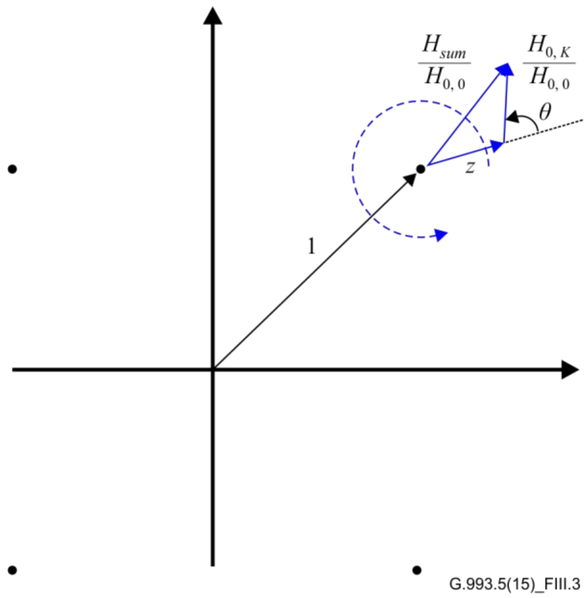


Figure III.3 – Effect of probing signal on constellation point

This figure assumes $\sigma_0^2 = \sigma_K^2$, in order not to be too complicated, but the result is easily generalized (in the equations) for the case where the signal variances on the victim and disturber lines are not identical.

Only the crosstalk of line *K* is shown. The crosstalk from lines 1..*K*–1, is not shown, because they would make the figure too complex.

In the figure, we can identify the following elements:

– the decoded constellation point (the FEQ scaled it back to a unity vector of size 1);

– the probing vector z, which is added as noise on the direct channel of the victim line;

– the crosstalk channel, normalized by the FEQ;

– the angle θ between the probing vector z, and the normalized crosstalk channel (both are modulated with the same user data symbol x_k, therefore this angle remains constant);

– the normalized total noise $\frac{H_{sum}}{H_{0,0}}$, 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 = ε, and applying trigonometry, we get:

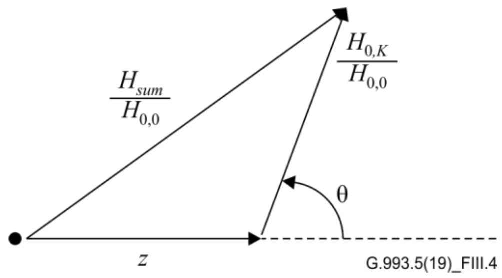


Figure III.4 – Detail of constellation point with z = ε

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

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

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

when

z = $j\varepsilon$, we get:

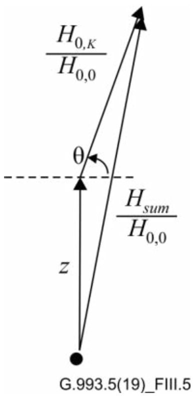


Figure III.5 – Detail of constellation point with z = jε

III.2.5 Equations for crosstalk channel estimation

Result, for $z = \varepsilon$

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

Result, for $z = j\varepsilon$

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

Conclusion:

$$\frac{H_{0,K}}{H_{0,0}} = \left|\frac{H_{0,K}}{H_{0,0}}\right| \cos(\theta) + j \cdot \left|\frac{H_{0,K}}{H_{0,0}}\right| \sin(\theta) \qquad \text{(III-10)}$$

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_a (0);

3) from this value, a suitable value of ε can be chosen (such that the impact on the SNR is measurable, but not excessive), and a probing signal can be added (on every victim line simultaneously);

4) measure $SNR_a(\varepsilon)$;

5) change the probing signal to $j\varepsilon$;

6) measure $SNR_a(j\varepsilon)$;

7) calculate $\hat{C}_{0,K}$, for each victim line;

8) start the pre-coding;

9) increase the PSD of the MEDLEY-type signal on the new line;

10) repeat from 2, until the MEDLEY-type signal PSD has reached the maximum allowed PSD of this line;

11) the normal initialization sequence on this line can now start.

Typically, the algorithm converges in a few iterations.

III.2.7 Extended equations applicable while performing pre-compensation

In case pre-coding is active, there is no fundamental change to the equations.

The basic equation is equation III-1:

$$y = Hx + n$$

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

Knowing that $H = diag(H)(I + C)$, and when applying pre-coding, $w = Fx = (I - \hat{C})x$, this becomes:

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

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

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

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:

$$\hat{C}_{0,K}(t+1) = \hat{C}_{0,K}(t) + \frac{H_{0,K}|_{residual}}{H_{0,0}} \qquad \text{(III-13)}$$

This is also illustrated graphically, as in the previous figure:

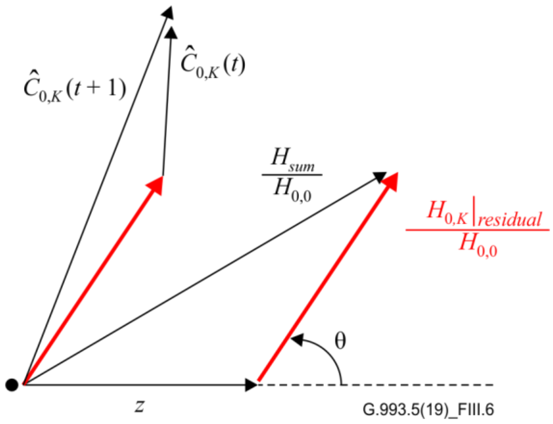


Figure III.6 – Detail of constellation point with pre-coding

The red vector indicates the residual normalized crosstalk channel, for which a similar triangle can be constructed like before by applying a probing signal. Hence, all equations remain valid.

III.3 Estimation of FEXT channels from existing lines into a new line

III.3.1 Introduction

Denote the number of SNR measurements used for channel estimation as *N*. Each SNR measurement occurs over *L* DMT symbols and all lines are in Showtime when channel estimation takes place. Consider transmission on a single tone and denote the QAM data symbol intended for line *i* on DMT symbol *l* during SNR measurement *n* as $s_i^{(n)}(l)$. The actual signal transmitted by line *i* is denoted as $x_i^{(n)}(l)$.

III.3.2 Probing signal

When the new line *K* initializes, the existing lines continue to transmit their data as before

$$x_i^{(n)}(l) = s_i^{(n)}(l), \forall i < K$$

Channel identification is enabled by superimposing a probing signal onto the signal transmitted by the new VTU-O *K*

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

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:

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

The noise power on line K will be measured as:

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

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:

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

From equations III-15 and III-16:

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

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

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

and

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

Applying the general form of Pythagoras' theorem:

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

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

$$\mathbf{a} = [a_{R,1}\ldots a_{R,K-1}\ a_{I,1}\ldots a_{I,K-1}]^T, \qquad \text{(III-21)}$$

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:

$$\left\|\bar{\mathbf{a}} + \varepsilon\bar{\mathbf{b}}^{(n)}\right\|^2 = \|\bar{\mathbf{a}}\|^2 + \left\|\varepsilon\bar{\mathbf{b}}^{(n)}\right\|^2 + 2\varepsilon\mathbf{b}^{(n)H}\mathbf{a}.$$

Now, from equation III-17:

$$\|\bar{\mathbf{a}}\|^2 + \left\|\varepsilon\bar{\mathbf{b}}^{(n)}\right\|^2 + 2\varepsilon\mathbf{b}^{(n)H}\mathbf{a} + \frac{\sigma_{W_K}^2}{|h_{K,K}|^2} = \frac{\sigma_K^2}{\mathrm{SNR}_K^{(n)}}.$$

Therefore

$$\varepsilon\mathbf{b}^{(n)H}\mathbf{a} + \frac{1}{2}\|\bar{\mathbf{a}}\|^2 + \frac{1}{2}\frac{\sigma_{W_K}^2}{|h_{K,K}|^2} = \frac{1}{2}\frac{\sigma_K^2}{\mathrm{SNR}_K^{(n)}} - \frac{1}{2}\left\|\varepsilon\bar{\mathbf{b}}^{(n)}\right\|^2.$$

Applying equation III-19 gives:

$$\varepsilon\mathbf{b}^{(n)H}\mathbf{a} + \frac{1}{2}\|\bar{\mathbf{a}}\|^2 + \frac{1}{2}\frac{\sigma_{W_K}^2}{|h_{K,K}|^2} = \frac{1}{2}\frac{\sigma_K^2}{\mathrm{SNR}_K^{(n)}} - \frac{1}{2}\varepsilon^2\sum_{i=1}^{K-1}\left|z_i^{(n)}\right|^2\sigma_i^2.$$

Define

$$c^{(n)} = \frac{1}{2}\frac{\sigma_K^2}{\mathrm{SNR}_K^{(n)}} - \frac{1}{2}\varepsilon^2\sum_{i=1}^{K-1}\left|z_i^{(n)}\right|^2\sigma_i^2. \qquad \text{(III-22)}$$

Hence

$$\varepsilon\mathbf{b}^{(n)H}\mathbf{a} + \frac{1}{2}\|\bar{\mathbf{a}}\|^2 + \frac{1}{2}\frac{\sigma_{W_K}^2}{|h_{K,K}|^2} = c^{(n)}, \forall n. \qquad \text{(III-23)}$$

Define an $M \times N$ matrix $\mathbf{P}$ with elements $p_{m,n} = [\mathbf{P}]_{m,n}$ that satisfies

$$\sum_{n=1}^{N} p_{m,n} = 0, \forall m \qquad \text{(III-24)}$$

This will be referred to as the SNR combination matrix. Now, from equation III-23:

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

Applying equation III-24, we have

$$\sum_{n} p_{m,n} c^{(n)} = \varepsilon \sum_{n} p_{m,n} \mathbf{b}^{(n)H} \mathbf{a}, \forall m. \qquad \text{(III-25)}$$

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 $\operatorname{pinv}(.)$ denotes the pseudo-inverse operation. Using equations III-18 and III-21, the normalized crosstalk coefficients can now be found as:

$$\frac{h_{K,i}}{h_{K,K}} = \frac{1}{\sigma_i} (a_i + j a_{K-1+i}) \qquad \text{(III-26)}$$

which can be used to design the first order diagonalizing precompensator

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

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 $\mathbf{G} = \text{pinv}(\mathbf{PB})\mathbf{P}$

– precompute $d^{(n)} = \sum_{i=1}^{K-1} \left| z_i^{(n)} \right|^2 \sigma_i^2 / 2, \forall n$

– for i = 1...number of iterations

– transmit $x_K^{(0)}(l) = s_K^{(0)}(l)$ on line K

– VTU-R reports $SNR_K^{(0)}$

– Set step size $\varepsilon = \min_i \frac{1}{2} \frac{1}{\sqrt{\text{SNR}_K^{(0)}}} \frac{\sigma_K}{\sigma_i}$

– 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 $\text{SNR}_K^{(n)}$

– calculate $c^{(n)} = \frac{1}{2} \frac{\sigma_K^2}{\text{SNR}_K^{(n)}} - \varepsilon^2 d^{(n)}$

– end

– $\mathbf{a} = \varepsilon^{-1} \mathbf{Gc}$

– $\frac{h_{K,i}}{h_{K,K}} = \left(a_i + j a_{K-1+i} \right) / \sigma_i, \forall i$

– update crosstalk precompensator using equation III-27

– end

Note that in order to speed up computations, we have precomputed the pseudo-inverse $\mathbf{G}$ and the term $d^{(n)}$.

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