TECHNICAL REPORT

TR-273
Testing of Bonded, Multi-Pair xDSL Systems

Issue: 1
Issue Date: August 2012

Issue History

Issue Number	Approval Date	Publication Date	Issue Editor	Changes
1	21 August 2012	10 September 2012	Arlynn Wilson, ADTRAN	Original

Comments or questions about this Broadband Forum Technical Report should be directed to info@broadband-forum.org.

Editor	Arlynn Wilson	ADTRAN, Inc.
Metallic Transmission Working Group Chair	Les Brown	Lantiq
Vice Chairs	Massimo Sorbara Lincoln Lavoie	Ikanos UNH
Chief Editor	Michael Hanrahan	Huawei Technologies

TABLE OF CONTENTS

List of Figures

List of Tables

Executive Summary

This Broadband Forum Technical Report, TR-273, is part of the Broadband Suite. DSL bonding uses multiple DSL lines between two endpoints to convey an aggregate payload which is multiplexed across the multiple lines. Compared to single-line DSL, bonding N lines of similar rates enables the transport of approximately N times the data rate, or alternatively a longer line length for the same aggregate data rate. Typically, two to eight lines are bonded, but the number may be larger.

TR-273 provides testing methodology of multiport xDSL systems which use multi-pair bonding protocols, such as ITU-T G.998.1 (*ATM-based multi-pair bonding*), G.998.2 (*Ethernet- based multi-pair bonding*) and G.998.3 (*Multi-pair bonding using TDM*). The bonded lines may include DSLs specified by ITU-T Recommendations G.992.3 (ADSL2), G.992.5 (ADSL2plus), G.993.2 (VDSL2), and G.991.2 (SHDSL).

Appendix A/TR-273 provides advice for laboratory testing techniques for bonded DSL systems, including systems which include MIMO (multiple-input multiple-output) functionality. This includes laboratory techniques for simulating multiple lines and noise injected into the multiple lines.

1 Purpose and Scope

1.1 Purpose

TR-273 specifies a set of tests to be performed to assure the interoperability, functionality, and performance of the Layer 2 bonding functions. Included are tests for downstream and upstream throughput when the individual lines have equal and unequal bit-rates and cases where a bonded line is removed and restored.

1.2 Scope

TR-273 specifies the methods to test the interoperability, functionality, and performance of equipment performing DSL bonding. These tests address the Layer 2 bonding functions only, and it is assumed that the individual DSL transceivers also pass applicable DSL-specific testing requirements specified in TR-100/TR-105 (ADSL2/2plus) [2][3], TR-114/TR-115 (VDSL2) [4][5], and TR-60 Issue 2 (SHDSL) [1]. The equipment under test includes network-end equipment (such as a DSLAM) and remote-end equipment (such as a network termination device or CPE). Throughout this document the term CPE is used interchangeably to describe this remote equipment.

2 References and Terminology

2.1 Conventions

In this Technical Report, several words are used to signify the requirements of the specification. These words are always capitalized. More information can be found be in RFC 2119 [13].

SHALL	This word, or the term "REQUIRED", means that the definition is an absolute requirement of the specification.
SHALL NOT	This phrase means that the definition is an absolute prohibition of the specification.
SHOULD	This word, or the term "RECOMMENDED", means that there could exist valid reasons in particular circumstances to ignore this item, but the full implications need to be understood and carefully weighed before choosing a different course.
SHOULD NOT	This phrase, or the phrase "NOT RECOMMENDED" means that there could exist valid reasons in particular circumstances when the particular behavior is acceptable or even useful, but the full implications need to be understood and the case carefully weighed before implementing any behavior described with this label.
MAY	This word, or the term "OPTIONAL", means that this item is one of an allowed set of alternatives. An implementation that does not include this option SHALL be prepared to inter-operate with another implementation that does include the option.

2.2 References

The following references are of relevance to this Technical Report. At the time of publication, the editions indicated were valid. All references are subject to revision; users of this Technical Report are therefore encouraged to investigate the possibility of applying the most recent edition of the references listed below.
A list of currently valid Broadband Forum Technical Reports is published at www.broadband-forum.org.

Document	Title	Source	Year
[1] TR-60 Issue 2	*Interop Test Plan for SHDSL*	BBF	2005
[2] TR-100	*ADSL2/2plus Performance Test Plan*	BBF	2007
[3] TR-105	*ADSL2/2plus Functionality Test Plan*	BBF	2010
[4] TR-114	*VDSL2 Performance Test Plan*	BBF	2009

[5] TR-115	*VDSL2 Functionality Test Plan*	BBF	2009
[6] G.998.1	*ATM based multi-pair bonding.*	ITU-T	2005
[7] G.998.2	*Ethernet-based multi-pair bonding,* including all in force amendments.	ITU-T	2005
[8] G.998.3	*Multi-pair bonding using time-division inverse multiplexing,* including all in force errata.	ITU-T	2005
[9] G.992.3	*Asymmetric digital subscriber line transceivers 2 (ADSL2),* including all in force amendments and corrigenda.	ITU-T	2009
[10] G.992.5	*Asymmetric Digital Subscriber Line (ADSL) transceivers - Extended bandwidth ADSL2 (ADSL2plus),* including all in force corrigenda.	ITU-T	2009
[11] G.993.2	*Very high speed subscriber line transceivers 2 (VDSL2),* including all in force amendments.	ITU-T	2011
[12] G.991.2	*Single-pair high speed digital subscriber line (SHDSL) transceivers,* including all in force errata and amendments.	ITU-T	2003
[13] RFC 2119	*Key words for use in RFCs to Indicate Requirement Levels*	IETF	1997

2.3 Definitions

The following terminology is used throughout this Technical Report.

Binder management	The operational discipline used to segregate and assign specific cable pairs contained in a binder to specific ports of bonded equipment to improve the group performance.
Bonding group up	The bonding group is operationally up and is able to pass traffic.
Bookend multi-pair bonded system	A single box containing a small number of DSL ports is placed in the exchange or cabinet and another single box having equal number or fewer pairs is placed at the customer premises.
Bookend MIMO bonded system	A bookended multi-pair system which uses Multi-Input Multi-Output signal processing in an attempt to enhance performance.
Customer Premises Equipment	Remote-end equipment or network termination device
IMIX	Internet Mix is a set of Ethernet frame sizes and associated probability distributions intended to represent packet traffic typically seen on the Internet

2.4 Abbreviations

This Technical Report uses the following abbreviations:

AAL5	ATM Adaptation Layer 5
ADSL2	Asymmetric Digital Subscriber Line transceivers 2
ADSL2plus	Asymmetric Digital Subscriber Line (ADSL) transceivers – Extended bandwidth ADSL2
ATM	Asynchronous Transfer Mode
CPE	Customer Premises Equipment
CV	Code Violation
DSLAM	Digital Subscriber Line Access Multiplexer
FCS	Frame Check Sequence
FEXT	Far End Crosstalk
INP	Impulse Noise Protection
MAC	Media Access Control
MIMO	Multiple Input Multiple Output
MOP	Method of Procedure
MTU	Maximum Transmission Unit
NDR	Net Data Rate
NEXT	Near End Crosstalk
PTM	Packet Transfer Mode
SHDSL	Single pair High speed Digital Subscriber Line
TR	Technical Report
VDSL2	Very high speed Digital Subscriber Line transceivers 2
VLAN	Virtual Local Area Network

3 Technical Report Impact

3.1 Energy Efficiency

TR-273 has no impact on Energy Efficiency.

3.2 IPv6

TR-273 has no impact on IPv6.

3.3 Security

TR-273 has no impact on Security.

3.4 Privacy

TR-273 has no impact on Security.

4 Traffic Testing of Multi-Pair Bonding Systems

The bonded multi-pair DSL technology allows the creation of a larger data pipe. The equipment behavior should allow for minimal payload loss during events such as dropped links, impulse noise events and fluctuating noise.

4.1 Configuration

The configuration is as shown in Figure 1, with a bonding CPE connected to the DSLAM over N loops of very short lengths (back to back). A traffic generator/analyzer is connected to the DSLAM and the CPE. The DSLAM and CPE MUST support an MTU of at least 1500-bytes.

While the bonding layer tests may be performed using any DSL Physical Layer configuration, care must be given to ensure errors on the physical layer do not negatively impact the test results. For example, it may be necessary to ensure the Maximum Delay and Minimum INP configuration parameters are set to appropriate values.

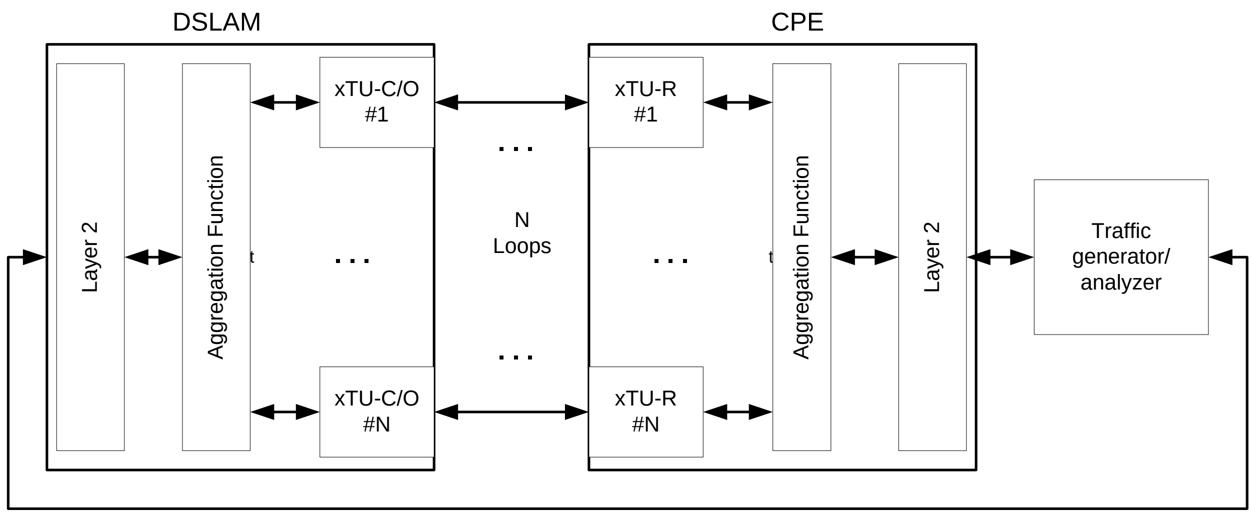

Figure 1. Test setup for traffic testing

4.2 Set up the Traffic Generator

The frame rate to be used for a given test is determined based on the required bonded net data rate (required_bonded_NDR) defined by Equation 1. The required_bonded_NDR SHALL be the minimum of:

- 95% of the achievable bonded net data rate (achievable_bonded_NDR), and
- the supported bonded net data rate (supported_bonded_NDR)

$$\text{required\_bonded\_NDR}\ (\text{bits/sec}) = MIN(0.95 \times \text{achievable\_bonded\_NDR},\ \text{supported\_bonded\_NDR})$$

Equation 1. Required bonded net data rate

The achievable_bonded_NDR (Equation 2) is calculated after training the multi-loops to their respective rates, by summing up all of their net data rates (NDR(i)), where N is the number of trained lines.

$$\text{achievable\_bonded\_NDR}\ (\text{bits/sec}) = \sum_{i=1}^{N} \text{NDR}(i)$$

Equation 2. Achievable bonded net data rate

The supported_bonded_NDR in a particular direction SHALL be the minimum of the DSLAM and CPE vendors' claimed maximum bonded net data rate. The vendor's claimed maximum bonded NDR may depend on the maximum user interface rate and/or may be frame size dependent.

The frame rate associated with the required_bonded_NDR depends on the frame size(s), the relative probability of the frame sizes in mixed frame testing, the protocol type (ATM, PTM) and the physical layer transmission type (G.991.2, G.992.3/5, G.993.2). These dependencies are accounted for in determining the average frame size for ATM using
Equation **3** or for PTM using Equation 4where M is the number of frame sizes used in mixed frame testing. The CRC_size for G.992.3/5 and G.993.2 is 2 bytes whereas G.991.2 has a CRC_size of 4 bytes.

$$\text{Average\_Frame\_Size\_of\_Mix}_{\text{ATM}}\left(\frac{\text{bytes}}{\text{frame}}\right) = \sum_{i=1}^{M} \text{frame\_probability}(i) \times \left(48 \times \left\lceil \frac{\text{frame\_size}(i) + 18}{48} \right\rceil\right)$$

Equation 3. Average frame size of mixed payload - ATM

$$\text{Average\_Frame\_Size\_of\_Mix}_{\text{PTM}}\left(\frac{\text{bytes}}{\text{frame}}\right) = \sum_{i=1}^{M} \text{frame\_probability}(i) \times \left[\text{frame\_size}(i) + (4 + \text{CRC\_size}) \times \left(\left\lceil \frac{\text{frame\_size}(i)}{\text{fragment\_size}} \right\rceil\right)\right]$$

Equation 4. Average frame size of mixed payload - PTM

where ⌈x⌉ denotes rounding to the higher integer, and, where fragment_size is implementation dependent and should be obtained from the equipment vendor(s) if it is not reported by the equipment, determined by the bonding segmentation function, and is a multiple of 4 between 64 and 512. The bonding segmentation function resides inside the Aggregation Function shown in Figure 1.

Finally, the required frame rate used for testing is determined for a given test using either Equation 5 (for ATM) or Equation 6 (for PTM).

$$\text{Required\_Frame\_Rate}_{\text{ATM}}\left(\frac{\text{frames}}{\text{sec}}\right)=\left\lfloor\frac{0.99\times\text{Required\_Bonded\_NDR}\times\frac{1}{8}\times\frac{48}{53}}{\text{Average\_Frame\_Size\_of\_Mix}_{\text{ATM}}}\right\rfloor$$

Equation 5. Required frame rate - ATM

$$\text{Required\_Frame\_Rate}_{\text{PTM}}\left(\frac{\text{frames}}{\text{sec}}\right)=\left\lfloor\frac{\text{Required\_Bonded\_NDR}\times\frac{1}{8}\times\frac{64}{65}}{\text{Average\_Frame\_Size\_of\_Mix}_{\text{PTM}}}\right\rfloor$$

Equation 6. Required frame rate - PTM

where: $\lfloor x\rfloor$ in the two equations above denotes the floor function.

The required frame rate to transmit the configured mix of frame lengths is defined so as to take into account the frame fragmentation and encapsulation overhead (see NOTE). The frame lengths defined in the tests are the frame lengths input to and output from the aggregation functions. DSLAM and/or CPE functionality that impacts frame length (e.g., VLAN tagging/removal) SHALL be disabled.

NOTE– The equation 3 for ATM bonding assumes that the overhead consists of AAL5 encapsulation with LLC SNAP and 1% ASM cells. Equation 4 for PTM bonding assumes that the overhead consists of the fragmentation overhead (2-octet header per fragment) and the 64/65 encapsulation overhead (2 or 4 -octets FCS and S and Ck demarcation octets per fragment and a sync octet every 65 octets). For different encapsulation methods the associated overhead must be taken into account.

The traffic configuration using mixed Ethernet frame lengths of [64, 598, 1500] bytes with a frame length probability distribution of [7/12, 4/12, 1/12] is called IMIX in the remainder of the document. The subsequent tests described in the document use either IMIX or fixed length frames. Fixed frame tests are performed using either 64, 256, 1024 and 1500 byte frame lengths. All frame sizes given are the frame size of the Ethernet frame, from its MAC destination address up to and including its 4-byte Ethernet FCS. In calculating the required frame rate using fixed lengths, the frame_probability is equal to 1.0. It may be needed to configure the traffic QoS class or queues in the DSLAM or to set up the traffic connection by sending some packets prior to starting the actual traffic tests.

4.3 Basic Bonding Functionality

The purpose of the test defined in Table 1 is to verify that the basic aggregation function (i.e., assembly and reassembly of cells/fragments) is performed successfully.
This test is executed for downstream and upstream simultaneously (i.e., with downstream and upstream traffic).

Table 1. Testing procedure for nominal bonding operation

Test Configuration	(1) The test setup SHALL be as shown in Figure 1. (2) Set up the loop simulators or real cable to a very short loop length (back to back). (3) Set up the traffic generator to send Ethernet frames in both directions.
Method of Procedure	(1) Configure the bonded group and place all N lines into the group. (2) Configure the DSLAM to the profile line configuration allowing maximum net data rates in both directions on all N loops. (3) Let the lines train and wait until the bonding group is up, then wait 60 seconds. (4) Set up the traffic generator to send IMIX in both directions at the required frame rate (using either Equation 5 or Equation 6). (5) Allow traffic to run for at least 10 seconds. (6) Run traffic test for at least 10 minutes. Record the upstream and downstream frame loss and throughput frame rate as frames per second. (7) Verify that no CVs occurred over the test period, if CVs occurred then repeat step 6 once.
Expected Result	The test is passed if no frame loss occurs over one test period, otherwise the test is declared failed..

4.4 Unidirectional Frame Rate Test

The purpose of the test defined in Table 2 is to verify the unidirectional error free frame rate for several frame length configurations.

This test is executed separately for downstream and upstream (i.e., with either downstream traffic or upstream traffic). The aggregation functions SHALL be enabled for both upstream and downstream, simultaneously. During unidirectional testing a low rate payload shall be generated in the opposite direction of arbitrary mix to ensure proper MAC learning behavior in the equipment.

Table 2. Unidirectional testing procedure of bonding operation

Test Configuration	(1) The test setup SHALL be as shown in Figure 1. (2) Set up the loop simulators or real cable to a very short loop length (back to back). (3) Set up the traffic generator/analyzer to send Ethernet frames in both directions.
Method of Procedure	(1) Configure the bonded group and place all N lines into the group. (2) Configure the DSLAM to the profile line configuration allowing maximum net data rates in both directions on all N loops. (3) Let the lines train and wait until the bonding group is up, then wait 60 seconds. (4) Set up the traffic generator to send IMIX in both directions at the required frame rate (using either Equation 5 or Equation 6). (5) Allow traffic to run for at least 10 seconds. (6) Run traffic test for at least 2 minutes. Record the appropriate upstream or downstream frame loss and throughput frame rate as frames per second. (7) Verify that no CVs occur over the test period, if CVs occurred then rerun the test which had CVs during the traffic test, once. (8) Repeat MOP(5) to MOP(7) 4 times using fixed length frames of [64, 256, 1024, 1500] using one frame size at a time (frame probability = 1). (9) Repeat MOP(4) to MOP(8) in the upstream direction
Expected Result	The test is passed if no frame loss occurs over any 2 minutes test period without CVs. Otherwise the test is declared as failed.

4.5 Bidirectional Frame Rate Test

The purpose of the test defined in Table 3 is to verify the bidirectional error free frame rate for several frame length configurations.

Table 3. Bidirectional testing procedure of bonding operation

Test Configuration	(1) The test setup SHALL be as shown in Figure 1. (2) Set up the loop simulators or real cable to a very short loop length (back to back). (3) Set up the traffic generator to send Ethernet frames in both directions.
Method of Procedure	(1) Configure the bonded group and place all N lines into the group. (2) Configure the DSLAM to the profile line configuration allowing maximum net data rates in both directions on all N loops. (3) Let the lines train and wait until the bonding group is up, then wait 60 seconds. (4) Set up the traffic generator to send IMIX in both directions at the required frame rate (using either Equation 5 or Equation 6) (5) Allow traffic to run for at least 10 seconds. (6) Run traffic test for at least 2 minutes. Record the appropriate upstream or downstream frame loss and throughput frame rate as frames per second. (7) Verify that no CVs occur over the test period, if CVs occurred then rerun the test which had CVs during the traffic test, once. (8) Repeat MOP(6) 4 times using fixed length frames of [64, 512, 1024, 1500] using one frame size at a time (frame probability = 1) at the required frame rate (using either Equation 5 or Equation 6) in the downstream direction while sending the IMIX traffic determined in MOP(4) in the upstream direction. (9) Repeat MOP(6) 4 times using fixed length frames of [64, 512, 1024, 1500] using one frame size at a time (frame probability = 1) at the required frame rate (using either Equation 5 or Equation 6) in the upstream direction while keeping the IMIX traffic determined in MOP(4) in the downstream direction.
Expected Result	The test is passed if for each of the 9 tests no frame loss occurs over any 2 minutes test period. Otherwise the test is declared as failed.

4.6 Frame Rate Test with Maximally Unequal Rates

The bonding standards provide the capability to bond together loops whose net rate differs by a factor of 4:1. The purpose of this test is to verify that the aggregation function can successfully bond multiple loops whose minimum versus maximum net data rates differ by a factor of 4. The testing configuration, method of procedure and expected results are outlined in Table 4.

Table 4. Test procedure for unequal net data rates

Test Configuration	(1) The test setup SHALL be as shown in Figure 1. (2) Set up the loop simulators or real cable to a very short loop length (back to back). (3) Set up the traffic generator to send Ethernet frames in both directions.
Method of Procedure	(1) Configure the bonded group and place all N lines into the group. (2) Configure the DSLAM to the profile line configuration allowing maximum net data rates in both directions on all N loops. (3) Let the lines train and wait until the bonding group is up, then wait 60 seconds.

	(4) Identify the line with the lowest actual net data rate, and record the rate as min_N. Reconfigure one line with a fixed net data rate equal to 25% of min_N, rounded up to the next 8kbit/s. Reconfigure the other N-1 lines with a fixed net data rate equal to min_N. Reinitalize the lines ensuring that the lowest actual net data rate of the lines is between 25% and 26% of the highest actual net data rate of the lines. (5) Let the lines retrain and wait until the bonding group is up, then wait 60 seconds. (6) Set up the traffic generator to send IMIX in the both directions at the required frame rate (using either Equation 5or Equation 6). (7) Record the upstream and downstream frame loss and frame rate as frames per second. The test SHALL be run for 2 minutes. Verify that no CVs occurred over the test period, if CVs occurred then rerun the test, once. (8) Repeat MOP(7) 4 times using fixed length frames of [64, 512, 1024, 1500] bytes using one frame size at a time (frame probability = 1) at the required frame rate (using either Equation 5 or Equation 6) in the downstream direction while sending the IMIX traffic determined in MOP(6) in the upstream direction. (9) Repeat MOP(2) to to MOP(8) in the other direction
Expected Result	The test is passed if (for each of the 5 downstream tests and for each of the 5 upstream tests) no frame loss occurs over the 2 minutes test period. Otherwise the test is declared as failed.

4.7 Bonding CPE Power Cycling Test

The purpose of the test defined in Table 5. Power cycle CPE test is to verify that a bonding group retrains and traffic is picked up again after a CPE powercycle.

Table 5. Power cycle CPE test

Test Configuration	(1) The test setup SHALL be as shown in Figure 1. (2) Set up the loop simulators or real cable to a very small loop length (back to back). (3) Set up the traffic generator to send Ethernet frames in both directions.
Method of Procedure	(1) Configure the bonded group and place all N lines into the group. (2) Configure the DSLAM to the profile line configuration allowing maximum net data rates in both directions on all N loops. (3) Let the lines train and wait until the bonding group is up, then wait 60 seconds. (4) Set up the traffic generator to send IMIX in the both directions at the required frame rate (using either Equation 5or Equation 6). (5) Record the upstream and downstream frame rate as frames per second. (6) Wait 2 minutes. (7) Switch off the CPE's power supply. The traffic generator continues to generate traffic. (8) Wait 20 seconds (9) Switch on the CPE's power supply (10) Let the lines retrain and wait until the bonding group is up, then wait 60 seconds. (11) The traffic measurement (frame loss/frame rate) SHALL be run for 2 minutes. (12) Verify that no CVs occurred over the 2 minutes test period, if CVs occurred then rerun the test, once.
Expected Result	The test is passed is no frame loss occurs over any 2 minutes test period. Otherwise the test is declared failed.

4.8 Test for Removal and Restoral of a Single Bonded Line to a Bonded Group

The test defined in Table 6 verifies a removal of a single bonded line out of a bonded group and a restoral to the bonded group without degradation of traffic, frame rate and minimal CVs.

Table 6: Test procedure for removal and restoral of a single bonded line to a bonded group

Test Configuration	(1) The test setup SHALL be as shown in Figure 1. (2) Set up the loop simulators or real cable to a very short loop length (back to back). (3) Set up the traffic generator to send Ethernet frames in both directions.
Method of Procedure	(1) Configure the bonded group and place all N lines into the group. (2) Configure the DSLAM to the profile line configuration allowing maximum net data rates in both directions on all N loops. (3) Let the lines train and wait until the bonding group is up, then wait 60 seconds. (4) Set up the traffic generator to send IMIX in the both directions at the required frame rate (using either Equation 5 or Equation 6). (5) Record the upstream and downstream frame rate as frames per second. The test SHALL be run for 2 minutes. (6) Verify that no CVs occurred over the 2 minutes test period. If CVs occurred then rerun the test, once. (7) Remove line #1 by physically disconnecting the wire pair at either end of the line. (8) Allow for 60 seconds to stabilize the loops and aggregation functions (9) Verify that the DSLAM reports that line #1 has left the bonded group. (10) Set the frame rate of both the upstream and downstream direction to the required frame rate (using either Equation 5 or Equation 6, with the actual net data rate of line #1 being zero). (11) Record the upstream and downstream frame rate as frames per second. The test SHALL be run for 2 minutes. (12) Verify that no CVs occurred over the 2 minutes test period. If CVs occurred then rerun the test, once. (13) Restore line#1. (14) Let the line train, then allow for 60 seconds to stabilize the loops and aggregation functions. (15) Verify that the DSLAM reports that line #1 has joined the bonded group. (16) Set the frame rate of both the upstream and downstream direction to the required frame rate (using either Equation 5 or Equation 6). (17) Record the upstream and downstream frame rate as frames per second. The test SHALL be run for 2 minutes. (18) Verify that no CVs occurred over the 2 minutes test period. If CVs occurred then rerun the test, once. (19) Repeat steps 7 to 18 (removal/restoral) for the remaining lines #2 to #N until all lines have been removed and restored to the bonding group.
Expected Result	The test is passed if for all lines no frame loss occurs over the 2 minutes test period before removal, over the 2 minutes test period during disconnect, and over the 2 minutes test period after restoral. Otherwise the test is declared failed.

Appendix I. Physical Layer Testing Recommendations

(Informative)

I.1 Rate versus Reach Testing of Multi-Pair DSL Systems

Multi-pair DSL systems provide a means of substantially improving the aggregate bandwidth available to a user by combining several DSL twisted pairs into a single information pipe. There are several standards available which facilitate flexible bonding of DSL as specified in ITU Recommendations G.998.1, .2 and .3 [6][7][8]. These pair bonding standards allow for DSL loops running at different rates to be combined into a single communication channel which is an improvement over Inverse Multiplexing over ATM (IMA). The underlying physical layer DSL may be standards based such as ADSL2/2plus [9][10], VDSL2 [11], enhanced SHDSL [12] or proprietary, non-standard transceivers.

Testing of multi-pair DSL systems can be partitioned into physical layer testing and higher layer testing. Real cable and/or line simulators are often used to evaluate the physical layer performance of the underlying xDSL technologies. The physical layer test setup and the details of the testing procedures should take into account the underlying transceiver and signal processing technologies being evaluated.

I.1.1 Testing Bookend Multi-Pair Bonded Systems

A bookend multi-pair solution is one in which a single box containing a small number of DSL ports is placed in the exchange or cabinet and another single box having equivalent or fewer pairs is placed at the customer premises. Typical port counts of the network side equipment are 8 or 16 while typical CPE equipment has 2, 4 or 8 ports. Figure 2 provides a representative example of a bookend circuit setup.

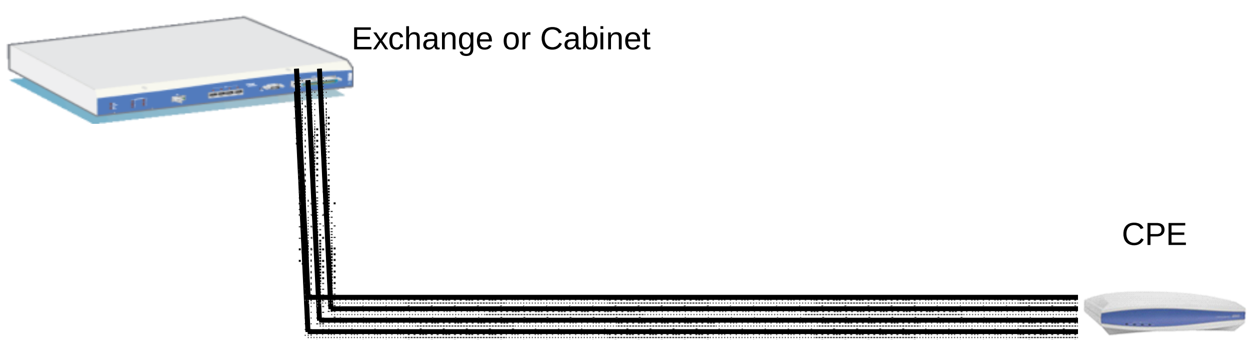

Figure 2. Bookend multi-pair xDSL

I.1.2 Rate versus Reach Testing of Standards Based DSL Bonded Systems

Multi-pair DSL bookend systems which utilize standards based DSL such as e.SHDSL[12], ADSL2/2plus [9][10] or VDSL2 [11] for their transceivers should be tested to the associated Broadband Forum physical layer performance testing document, i.e. TR-60 issue 2 [1], TR-100 [2] and TR-114 [4], respectively. Single port testing which subjects the bonded modems to very low white noise only, may not be applicable to bonded modems. During normal bonded operation there will be some crosstalk noise (typically higher than the white noise levels) present due to the operation of the other bonded DSL ports. Requiring ports of bonded DSL modems to individually satisfy white noise testing pass/fail criteria may result in overly constraining requirements and higher levels of complexity than is necessary.

Because each DSL single pair operates independently of every other pair in the group, doing the single pair physical layer tests on the bonded system along with the bonding layer tests defined in this working text is sufficient to characterize its performance. However, there is the potential for physical layer interactions via crosstalk between bonded pairs, particularly during multi-line startup of the bonded system, which may temporarily introduce dynamic DSL circuit joining and leaving within the bonded group. Real cable testing or line simulator testing that introduces this real world dynamic phenomenon should be considered. In the case of the standards based technology, real copper cable may be used for higher layer testing.

I.1.3 Testing Bookend MIMO or Crosstalk Cancelled Bonded Systems

Multi-pair DSL systems which claim to include advanced forms of signal processing or coordinated transmission such as MIMO, NEXT cancellation and FEXT cancellation, require much more care in performing physical layer performance testing. Caution to details in noise injection methodology, meaningful cable pair count and likely external noise sources should all be taken into account or unrealistically optimistic performance results may occur. MIMO systems are comprised of in-domain (MIMO group) DSL pairs. This on-board signal processing has access to all of these pairs and can use these pairs to remove noise correlation. In Figure 3, a typical deployment is shown where in-domain pairs are placed into a cable along with foreign DSL pairs along with two pair placement realizations viewed from a cross section of a typical cable. In the cross section cutaway diagram on the left, the MIMO group pairs (green circles) are shown purposefully placed into a common, single binder. This deployment strategy is referred to as binder management. When all of the MIMO pairs are in close physical proximity, then it would be expected that the noise measured by MIMO group pairs would have some correlation, but looking at the figure, the noise into pairs on the right side center binder would be substantially different (uncorrelated) to the noise seen by the pairs on the left side of the binder. Similarly, the noise on the pairs on the top of the binder would differ substantially from that seen by those MIMO pairs on the bottom of the binder. So the correlation of the noise (and the maximum MIMO processing gain) should be related to the expected position of the pairs in the cable and the number of foreign DSL disturbers expected to coexist in the cable.

In the right side of the cutaway diagram, the more typical case of random pair assignment is shown. Here the MIMO group's pairs are randomly placed in the cable and will likely show up scattered amongst several binder groups within the cable.

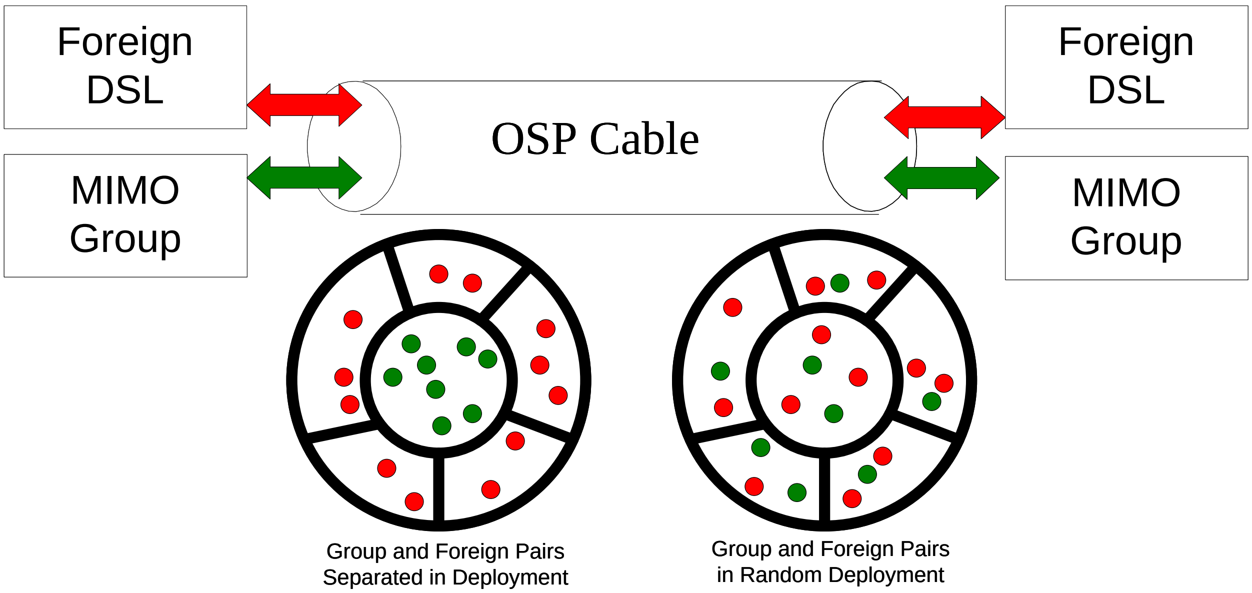

Figure 3. MIMO deployments into a cable with foreign DSL

In the random pair assignment case, it is apparent that the alien crosstalk noise resulting from the two foreign DSL pairs in the rightmost binder into the single MIMO pair in that same binder would have almost no correlation to the noise generated from the two foreign DSL pairs into the single MIMO group pair in the left most binder of the cable. The same commentary holds for the upper and lower binder groups.

The resulting mathematical representation from these real world pair assignments is provided in Equation 7. In the formula the MIMO transmitters are accounted for as $[Tx_i]_{MIMO}$, and foreign DSL crosstalk by $[Tx_i]_{NEXT}$ and $[Tx_i]_{FEXT}$ with additional additive white noise $[\nu_i]$. The channel matrix H is made up of direct, $(h_{i,i})$ and indirect paths $(h_{i,j})$, $i \neq j$, from the MIMO transmitters to the receivers. The foreign crosstalk is made up of the NEXT coupling matrix N, $(n_{i,j})$ and the FEXT coupling matrix F, $(f_{i,j})$ which couples the alien transmitters into the MIMO receivers.

$$\begin{bmatrix} y_1 \\ y_2 \\ \cdot \\ \cdot \\ \cdot \\ y_n \end{bmatrix} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,n} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,n} \\ \cdots \\ \cdots \\ \cdots \\ h_{n,1} & h_{n,2} & \cdots & h_{n,n} \end{bmatrix} \begin{bmatrix} Tx_1 \\ Tx_2 \\ \cdot \\ \cdot \\ \cdot \\ Tx_n \end{bmatrix}_{MIMO} + \begin{bmatrix} n_{1,1} & n_{1,2} & \cdots & n_{1,m} \\ n_{2,1} & n_{2,2} & \cdots & n_{2,m} \\ \cdots \\ \cdots \\ \cdots \\ n_{n,1} & n_{n,2} & \cdots & n_{n,m} \end{bmatrix} \begin{bmatrix} Tx_1 \\ Tx_2 \\ \cdot \\ \cdot \\ \cdot \\ Tx_m \end{bmatrix}_{NEXT} + \begin{bmatrix} f_{1,1} & f_{1,2} & \cdots & f_{1,m} \\ f_{2,1} & f_{2,2} & \cdots & f_{2,m} \\ \cdots \\ \cdots \\ \cdots \\ f_{n,1} & f_{n,2} & \cdots & f_{n,m} \end{bmatrix} \begin{bmatrix} Tx_1 \\ Tx_2 \\ \cdot \\ \cdot \\ \cdot \\ Tx_m \end{bmatrix}_{FEXT} + \begin{bmatrix} 1 0 \cdots 0 \\ 0 1 \cdots 0 \\ \cdots \\ \cdots \\ \cdots \\ 0 0 \cdots 1 \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \cdot \\ \cdot \\ \cdot \\ \nu_n \end{bmatrix}$$

Equation 7. **Received signal $[y_i]$ formula for MIMO deployments**

The reason MIMO technology performance is so sensitive to the testing methodology is because the signal processing characteristics yield extremely high rate versus reach performance in the event of an overly simplified test configuration. Consider the case of a testing which attempts to evaluate an 8 pair MIMO bookend solution with a single noise generator. The configuration may include real cable or a multi-pair line simulator. Figure 4 provides a diagram showing this overly simplified test setup. Typically, the noise power spectral density (PSD) is computed using NEXT and FEXT coupling functions and appropriately combined to represent dozens of disturbers.

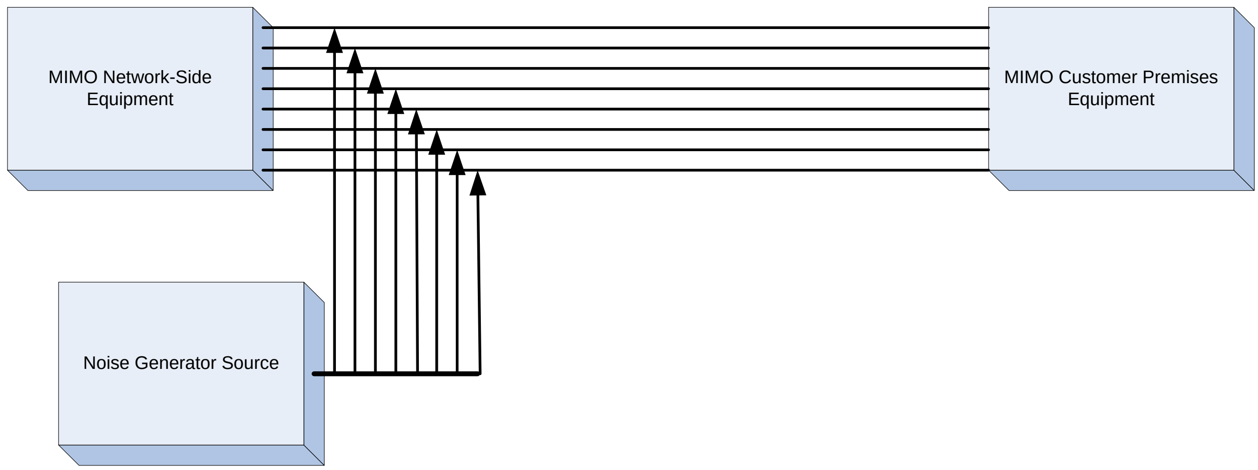

Figure 4. Single noise generator injecting "crosstalk" at CO side of a MIMO system

This simplified approach works for standards based bonded multi-pair DSL systems, but is NOT for MIMO based solutions. The reason is that the resulting formula for this testing configuration simplifies to Equation 8.

$$\begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ . \\ y_n \end{bmatrix} = \begin{bmatrix} h_{1,1}\ h_{1,2} \cdots h_{1,n} \\ h_{2,1}\ h_{2,2} \cdots h_{2,n} \\ \cdots \\ \cdots \\ \cdots \\ h_{n,1}\ h_{n,2} \cdots h_{n,n} \end{bmatrix} \begin{bmatrix} Tx_1 \\ Tx_2 \\ . \\ . \\ . \\ Tx_n \end{bmatrix}_{Group} + \begin{bmatrix} c_1 \\ c_2 \\ \cdots \\ \cdots \\ \cdots \\ c_n \end{bmatrix} v_{noise}$$

Equation 8. Received signal [y_i] formula of improper single noise source MIMO testing

Because all the foreign crosstalk signals are from the single noise generator source, they are 100% statistically correlated and the MIMO signal processing can easily remove the noise down to the residual white noise level.

To avoid this shortcoming, testing of multi-pair MIMO systems should use at least as many independent noise generating sources as there are in the MIMO group under test as in Figure 5. The correlation coupling box between the multiple noise generator sources and the MIMO pairs on the loops should be configured to be representative of the expected deployments in the network.

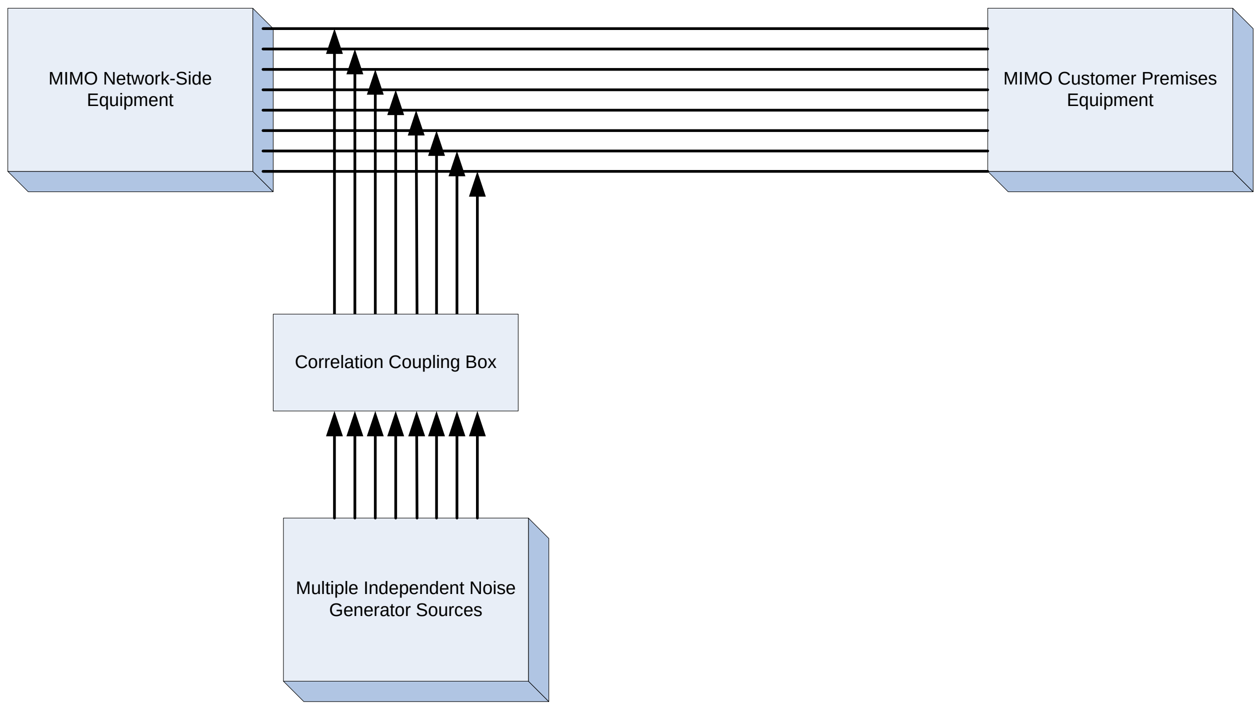

Figure 5. Proper MIMO performance testing configuration

In the bookend deployment of a MIMO system from a large central office, the feeder cable leaving the exchange is typically ≥ 1000 pairs, in fiber to the node applications typical pair counts are ≥ 300, fiber to the basement ≥ 100 and fiber to the curb between 4 and 24. Expected correlations for bookend 4, 8, 12 and 16 pair MIMO systems are for further study; and will be provided in Table 7.

Table 7. Foreign noise correlations for bookend MIMO multi-pair systems

	4 Pair		8 Pair		12 Pair		16 Pair	
Deployment	Net	CPE	Net	CPE	Net	CPE	Net	CPE
Exchange								
FTT-Cabinet/Node								
FTT-Building/Basement								
FTT-Distribution point/Curb/DP								

I.2 Testing Platform Based Multi-Pair Systems

Platform based deployment of multi-pair DSL systems come in many forms. The typical chassis type DSLAM/MSAP supports multiple cards and may be able to bond across the backplane to provide some redundancy in the event of a card failure. Stand alone platforms such as pizza boxes or outside plant hardened enclosures allow multiple multi-pair CPE to be connected to an RT or exchange via multiple twisted pairs.

I.2.1 Testing Platforms with Bonding CPE

When standards based DSL is used for the underlying physical layer of bonded DSL then the appropriate Broadband Forum performance test documents or the ITU Recommendation in the case of e.SHDSL[12] for that physical layer should be used for the physical layer testing. Typically, bonded ADSL2plus and VDSL2 based CPE are entering into the residential DSL market. In these two cases, the physical layer training rates on each individual loop should be tested according to TR-100 [2] or TR-114 [4], respectively. Single port testing which subjects the bonded modems to very low white noise only, may not be applicable to bonded modems. During normal bonded operation there will be some crosstalk noise (typically higher than the white noise levels) present due to the operation of the other bonded DSL ports. Requiring ports of bonded DSL modems to individually satisfy white noise testing pass/fail criteria may result in overly constraining requirements and higher levels of complexity than is necessary. Single loop packet testing specified in these BBF performance test for individual loops should be replaced with the multi-pair testing procedures specified in the layer II testing sections of this document. Because the standards based technology requires no special care in establishing noise injection on the loops may be tested on multi-line or single line simulators with simultaneous or serial noise injection. However, there is the potential for physical layer interactions via crosstalk between bonded pairs, particularly during multi-line startup of the bonded system, which may temporarily introduce dynamic DSL circuit joining and leaving within the bonded group. Real cable testing or line simulator testing that introduces this real world dynamic phenomenon should be considered.

In some chassis based platforms, multi-pair bonding functionality occurs across the chassis backplane with redundancy in bonding engines. This capability adds card level redundancy for higher service availability.

Appendix II. Example Vendor Supplied Supported Rate Table

(Informative)

The vendor should supply information relating to small frame size performance or maximum rate limitations which may be observed during testing as described in the description of supported bonded net data rates. Table 1 provides an example which describes the case when a single vendor supplies both CO and CPE equipment. When separate vendors are involved each vendor should supply their respective limitations.

Table 8. Vendor supplied supported bonded net data rates (example)

S frame size	US framesize	CO DS	CO US	CPE DS	CPE US
IMIX	IMIX				
64	IMIX				
256	IMIX				
1024	IMIX				
1500	IMIX				
IMIX	64				
IMIX	256				
IMIX	1024				
IMIX	1500				

End of Broadband Forum Technical Report TR-273

