

Advanced xDSL Line Testing and Fault Location for Service Providers

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1. Introduction

In an increasingly expanding online world, access service providers face many unique challenges. Subscribers are constantly demanding more bandwidth to support video, gaming, and other streaming content — simultaneously to multiple household members — and expect consistent performance from the access network. Furthermore, alternative carriers are constantly bombarding those subscribers with financially attractive deals to switch to their services. As a result of this ever-changing environment, operators must implement cost-effective strategies to anticipate problems and to address issues before the consumer is aware of them. All while providing rapid and effective service restoration when the consumer calls to complain.

Addressing these challenges is expensive, especially when the only answer seems to be more truck-rolls, so fault diagnosis, precise location, and full resolution must be accurate and timely, regardless of the underlying DSLAM and CPE vendors and types.

The access service providers' last (or first) mile is by the far the most geographically distributed and most expensive to maintain segment of the broadband network infrastructure. Operators rely on information about fault presence and location to answer the following kinds of questions:

- Is a line fault causing a degradation in service to the customer?
- What priority level should be assigned to a fault?
- Which team is best positioned to fix the fault? (For instance, an outside plant technician or a technician visit to the customer's premises.)
- What information does the technician need to first identify and locate the fault, and then to verify the fix?
- Who is responsible for fixing the fault? (For instance, in markets with access service unbundling it could be the infrastructure provider or the service provider.)

The correct answers to these questions have huge implications for operational efficiency and financial performance. Just one misguided decision to dispatch a field technician to the wrong location or a false diagnosis that results in multiple visits can cost the equivalent of 3 months to 9 months of revenue from the affected

customer. Additionally, the inability to accurately locate a fault may result in the service provider making excessive payments to the infrastructure provider for needless maintenance actions.

Given the importance of operational efficiency and cost control, service providers have long sought solutions that improve their ability to precisely detect and locate faults in the access segment through **line testing**. For POTS services and in the early days of xDSL, dedicated hardware solutions ("test-heads") were deployed at central office (CO) locations to perform narrowband tests on individual copper lines. These test-heads used a dedicated "test-bus" that ran through a POTS switch. Attempts to expand these solutions to further include wideband tests were thwarted, however, because some switches allow only low frequencies through the test-bus.

These hardware solutions are unattractive for broadband service deployments because it is prohibitively expensive to install and maintain a separate piece of hardware dedicated to line testing at low density nodes that serve a single, a few, or perhaps 100 customers:

- Hybrid broadband access models such as Fiber-to-the-Node (FTTN) and Fiber-to-the-Basement (FTTB);
- Higher-bandwidth xDSL technologies such as G.vector and G.fast require even shorter loop lengths which are served by deployment of even lower density DSLAMs such as Fiber-to-the-Distribution-Point (FTTdp).

This means that service providers have to install DSLAMs with integrated line testing capabilities for new deployments with smaller node sizes.

Thankfully, modern DSLAMs have added their own capabilities for line testing without requiring external hardware. Circuitry that previously required a separate test-head has been integrated with most vendors' DSLAMs. Line testing techniques enabled through DSLAM hardware include:

- **Double-Ended Line Testing (DELT)**, defined in the ITU-T Recommendations for ADSL2 [1], ADSL2+ [2], VDSL2 [3] and G.fast [4].
- **Single-Ended Line Testing (SELT)**, defined in ITU-T Recommendation G.996.2 [5].

- **Metallic Line Testing (MELT)**, defined in ITU-T Recommendation G.996.2 [5].

However, the results of DELT, SELT, and MELT testing and the useful interpretation of their results depend on a variety of factors, including CPE presence, loop length, and location and type of fault. Moreover, DSLAM vendors' implementation of DELT, SELT, and MELT circuitry and firmware in their systems is inconsistent and provides vendor-specific results that can undermine efforts to provide economical and efficient subscriber service. For these reasons, service providers prefer a solution with a unified software capability that **supports DSLAMs from multiple vendors, and which integrates inputs from multiple line testing techniques.**

The contents of this paper are organized as follows. Firstly, the DELT, SELT and MELT line testing techniques are described in Sections 2, 3 and 4 respectively. For each of the techniques, there is a description of the underlying principle, together with the outputs produced, and the related capabilities and limitations. Secondly, the concept of combining multiple line testing techniques is explained in Section 5, which also describes the benefits of this approach.

2. Double Ended Line Testing (DELT)

DELT is a wideband line testing technique used after a DSL modem has been installed on the subscriber premises. It relies on the equipment on both ends of the line to perform its testing, thus requiring a connected and available DELT-capable CPE.

2.1. Principle

DELT measures the characteristics of the line by transmitting special test signals from one end to the other,

and evaluating the signal received based on knowledge of the signal transmitted from the source. The CPE sends the measurements to the DSLAM via a management channel, and the DSLAM then makes available both the downstream and the upstream measurement data through the management interface. DELT measurements are performed during link initialization and during the link operation (“showtime”); they are non-disruptive to data transmission and to the operation of the equipment¹. Both the signals transmitted and the signals measured at the receiver are wideband in nature, and enable the characterization of the line's channel and noise over the entire spectrum used for xDSL transmission.

Figure 1 shows the principle of DELT testing.

2.2. Output Data

Key outputs produced by DELT include:

- **Channel Characteristics Function per subcarrier** (known as HLOG in logarithmic scale and as HLIN when represented as a complex number) estimates the attenuation of the transmission channel over frequency.
- **Quiet-Line-Noise per subcarrier (QLN)** estimates the received noise over frequency during a time of no signal transmission on the line.
- **Signal-to-Noise-Ratio per subcarrier (SNR)** estimates the signal to noise ratio over frequency.

DSLAMs additionally report during normal line operation on a range of **operational data**, including net data rate, SNR margin, line/signal attenuation, bits and gains allocations, transmitted PSD, and transmitted power. They also report various **performance data**

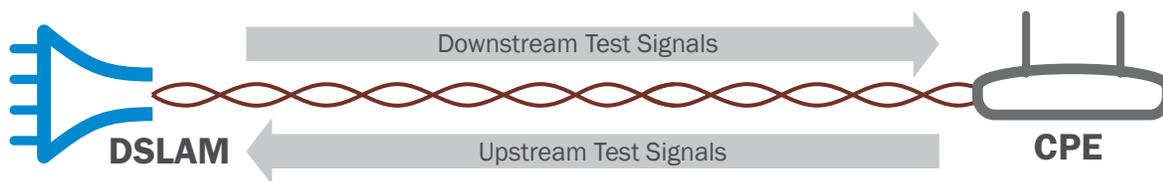


Figure 1: Illustration of DELT testing.

¹ ADSL2 and ADSL2+ standards also specify a disruptive DELT procedure which forces the link to reinitialize for DELT measurements to be performed. This procedure has become obsolete.

including code violations, forward error corrections, re-initializations, and retransmission counters. DELT data combined with operational and performance data provide a very clear picture of the link's status.

2.3. Capabilities and Limitations

The per-subcarrier quantities produced by DELT can accurately characterize both the channel and the noise environment. Inspection of these channel and noise characteristics can identify abnormal signatures that are then attributed to specific faults. Such faults include:

- Bad splice/connector
- Unbalanced wiring
- Bridged tap
- High-power noise
- AM/HAM RF noise
- Crosstalk noise

Additionally, the channel characteristics can help derive an estimate of the “electrical” loop length, which is an approximation of the physical loop length assuming that a certain type of cable is used. In summary, DELT results can be used very effectively by software to **detect one or multiple faults and to differentiate among them.**

However, collection of DELT data requires connecting operational equipment to both ends of the line. The line must be in good enough condition to support a connection and the transmission of data in both

directions. These conditions exclude DELT in some important scenarios when line testing is required:

- a. **Severe fault** is present on the line (e.g., a cut), which makes a connection impossible.
- b. **No CPE is installed, or a CPE is not operational** (e.g., not connected to the line or to power).

Another limitation of DELT is that the channel and noise characteristics are **insufficient on their own to provide information on the fault location.** Although DELT data are ideal for detecting multiple types of fault signatures, those signatures do not contain clues to the fault location. The fault location may be narrowed down by correlating fault detection results with “neighborhood” information about lines that are serving the same geographical area, or that are sharing the same sets of cables. As explained in the next sections, SELT and MELT data are very useful for fault location purposes.

3. Single Ended Line Testing (SELT)

SELT is a wideband line testing technique that is most often used for loop pre-qualification and may also be used for fault determination when the loop has been cut. Equipment must be connected to the line only on one of its ends (typically on the DSLAM side²).

3.1. Principle

The SELT system transmits wideband signals and then records the received signals that are reflected back from the line. The signal transmission and reception last for a brief period of time, typically on the order of tens of seconds. Figure 2 shows the principle of SELT testing.

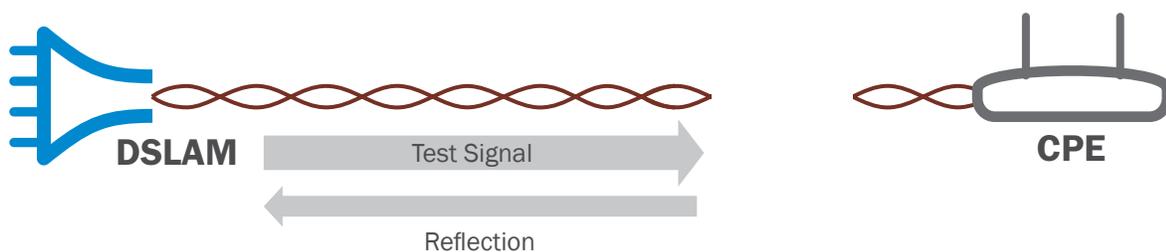


Figure 2: Illustration of SELT testing of a cut loop.

² A CPE-based SELT system has the advantage of being closer to most faults, which are typically located close to the customer premises. However, if the DSL link fails, there must be an alternate path for data transmission.

3.2. Output Data

The SELT system processes the received raw signals to produce the following outputs:

- **Uncalibrated Echo Response (UER)** represents the response of the reflection channel over frequency, without compensating for effects of the system's analog front end.
- **Variance of UER** captures the variation of the UER over frequency, which may occur because of noise during the measurement period.
- **Quiet-Line-Noise (QLN)** estimates the received noise over frequency during a time of no signal transmission on the line.

Among the above output data, the most useful is UER because it captures reflections that can be mapped to specific fault locations. Some DSLAMs may report additional derived parameters for the loop topology or for detected faults based on proprietary calculations.

3.3. Capabilities and Limitations

The great benefit of SELT data is that the UER captures information about reflections produced by faults. The UER response is reported in the frequency domain, but it can be analyzed either in the time domain reflectometry (TDR) or in the frequency domain reflectometry (FDR). TDR techniques map signal signatures occurring at different time instances to faults located at different distances from the SELT system. FDR techniques associate frequency-response signatures occurring at different frequencies with faults at different distances. The best practice is to use both TDR and FDR to derive from SELT data information such as:

- **Fault location**
- **Fault category** (e.g., series-fault, shunt-fault)
- **Fault severity**

The ability of SELT techniques to detect reflections is compromised when faults are located far from the SELT system. SELT measurements are typically **unable to capture reflections from faults located more than 3 km (10,000 feet) away from the DSLAM** because reflections produced by such faults are too weak, having to traverse the equivalent of a 6 km (20,000 feet) line.

Another limitation of SELT data is that they are **insufficient on their own to differentiate between the end of an unterminated line and a severe line fault**. It is thus impossible to rely only on SELT data to estimate loop length because it would be unclear whether a detected reflection comes from the end of the line or from a severe fault (e.g. corrosion or a break on one of the wires) in some other location. As explained in the later sections, this limitation may be obviated by using additional sources of line testing data.

4. Metallic Line Testing (MELT)

MELT is a DC/narrowband line testing technique that supports the measurements of the electrical line properties at DC, such as resistance, shorts, opens, and capacitance. These tests are not supported by DELT or SELT because DSL signals are coupled to the line inductively via transformers. Since MELT operates at DC and at frequencies below the xDSL spectrum, MELT testing can be performed without disrupting broadband services.

4.1. Principle

MELT injects signals on the line to measure resistance, capacitance, and complex admittance (conductance/susceptance). The voltage of the injected signals is controllable so that diodes in circuits connected to the loop can be selectively turned on or off. The AC frequency at which capacitance and admittance are measured is programmable between 10 and 1,000 Hz (typical value is 25 Hz). MELT also measures “foreign” voltage and currents (i.e., not injected by the equipment itself) at both DC and very low frequencies.

MELT results are reported with reference to three reference points:

- **tip wire**
- **ring wire**
- **ground.**

Since electrical properties are measured individually relative to these reference points, additional information becomes available for fault analysis. This is in contrast to techniques such as DELT and SELT that only capture information relative to signal transmission in differential mode (i.e., signal measured between tip and ring).

4.2. Output Data

MELT supports a wide variety of tests and results. The most common outputs of MELT systems are shown in Table 1 below.

Some DSLAMs may report additional derived parameters for wire faults and for detected foreign signals based on proprietary algorithms.

4.3. Capabilities and Limitations

MELT data are in many ways complementary to SELT data because there are several faults that can be detected by one technique, but not the other. MELT produces meaningful measurements even for very long loops because of the narrowband nature of its signals. In addition, MELT identifies issues such as foreign voltages

and insulation faults that can be impossible to accurately recognize using SELT. MELT also identifies issues such as bad splices or connectors, which are observable with SELT as well.

Wire-to-ground capacitance measurements obtained from MELT data can be used to estimate the loop-length. An accurate loop-length estimate is possible even with a break or cut, or severe corrosion on one of the wires because capacitance measurements are obtained individually for each wire.

An important MELT capability is the detection of a “signature” circuit placed at the interface between the outside plant and the customer premises. One type of such a signature circuit is a resistive-capacitive (RC) circuit that

Category	Quantity
Resistance	Resistance between tip and ring Resistance between ring and tip Resistance between tip and ground Resistance between ring and ground
Capacitance	Capacitance between tip and ring Capacitance between tip and ground Capacitance between ring and ground
Complex admittance	Conductance and susceptance between tip and ring Conductance and susceptance between tip and ground Conductance and susceptance between ring and ground
Foreign voltage	DC foreign voltage between tip and ring AC foreign voltage and frequency between tip and ring DC foreign voltage between tip and ground AC foreign voltage and frequency between tip and ground DC foreign voltage between ring and ground AC foreign voltage and frequency between ring and ground
Foreign current	DC foreign current on tip wire AC foreign current on tip wire DC foreign current on ring wire AC foreign current on ring wire (Not defined in [5] but reported by some DSLAMs)
Loop resistance with high metallic voltage	Resistance between tip and ring with high voltage applied Resistance between ring and tip with high voltage applied (Defined in [5] but not reported by all DSLAMs)
Loop capacitance with high metallic voltage	Resistance between tip and ring with high voltage applied (Defined in [5] but not reported by all DSLAMs)
Loop complex admittance with high metallic voltage	Conductance and susceptance between tip and ring with high voltage applied (Defined in [5] but not reported by all DSLAMs)

Table 1: Most common outputs of MELT systems.

does not affect the connection in normal operation but which can be detected by MELT measurements. A second type contains one or more diodes that remain turned off when typical xDSL signals are transmitted. MELT tests using high voltage turn on such diodes, and an analysis of the measured MELT quantities can point to the presence of this signature circuit. Detection of a signature circuit then clearly indicates that there is loop continuity at least up to the boundary between the outside plant and the customer premises.

MELT is known to have several limitations, including:

- Inability to detect a bad splice or connector that is located very close to the CPE.
- Ability to detect but not determine the location of a shunt resistive fault.
- Inability to detect a series resistive fault.
- Inability to detect noise in the higher frequencies.

These limitations can be overcome by using MELT in combination with SELT and DELT, as explained in the next section.

5. xELT-Expresse: Line Testing Best Practice

DELT, SELT and MELT testing, used individually, have important limitations that reduce their accuracy and their efficacy. Combining multiple techniques of line testing is the best practice for obtaining the most accurate, complete and revealing fault detection and

location results. ASSIA's **Expresse Line Testing (xELT-Expresse)** is uniquely designed to follow this practice, and is explained in detail in this section.

5.1. Principle

xELT-Expresse has two fundamental technical advantages compared to systems that rely only on one type of line testing: Firstly, **certain faults may be impossible to discover using one type of line testing data**, but may be detectable by using an alternative type of data. For example, SELT data may not reveal a fault that is located at a great distance from the DSLAM, which could be visible using MELT data. As a second example, MELT data may have difficulties seeing a fault that is very close to the CPE modem, although such a fault could be identified using SELT data. By combining multiple sources of line testing data, xELT-Expresse improves the ability to identify and locate a fault.

Secondly, xELT-Expresse obtains results **from multiple detection techniques and from multiple data sources** and combines these results based on the related confidence levels. For example, if method A detects a fault with low confidence and method B detects no fault with strong confidence, xELT-Expresse declares that there is no fault. This approach guarantees the highest level of accuracy given the available data.

As illustrated in Figure 3, xELT-Expresse algorithms take into account all available sources of data from the DSLAM and CPE including DELT, SELT, and MELT raw data. Importantly, xELT-Expresse also takes advantage of

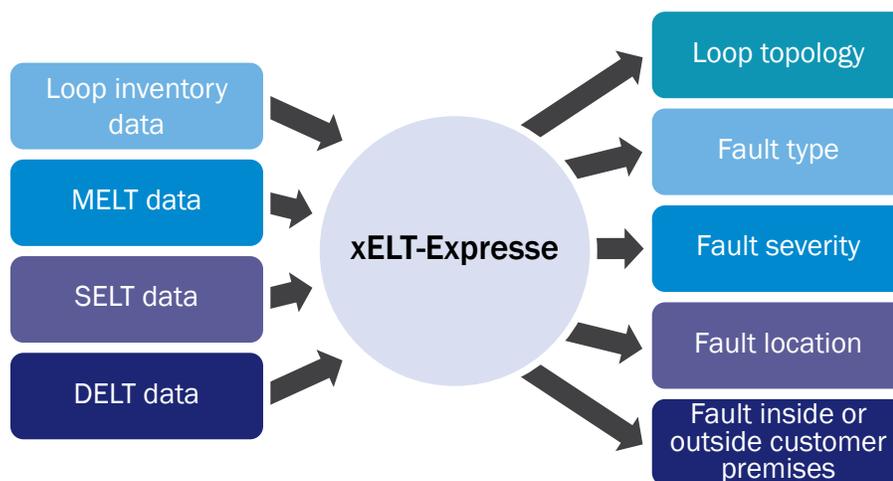


Figure 3: xELT-Expresse combines multiple sources of line testing data

the operator’s Loop Inventory Data, which are records of the loop plant that hold information about the type and the physical length of each cable segment serving a specified line.

xELT-Expresse does not require the availability of all data; it automatically determines what data is available and valid. If one or more of the sources of Figure 3 is not available, or if the produced data fail to pass certain consistency checks, then xELT-Expresse discards the data from those source(s) and continues with the remaining data. At a minimum, xELT-Expresse requires data from SELT or MELT.

Analysis results can be obtained either based on historical measurements or based on real-time testing. A system user requiring real-time results can control which sources of data to use for the analysis. For example, it is possible to restrict the testing to only include MELT and DELT data, so that the subscriber’s connection is not disrupted. Comparisons can be made between real-time and historical results to identify a developing degradation or to confirm a fix.

5.2. Output Data and Accuracy Benefits

xELT-Expresse produces the DELT, SELT and MELT output data explained in Sections 2.2, 3.2, and 4.2, and additionally produces the following analysis results:

- **Loop topology**, including total loop length.
- **Fault type**, including the type of the fault, and classifying the fault as either a bridged tap, a shunt-type fault (e.g. resistive short, water-in-the-cable), or as an open-type fault (e.g. bad splice, poor connector).
- **Fault severity**, which categorizes the fault as having a moderate, severe or critical impact on line performance.
- **Fault location**, which specifies the estimated fault location relative to the start and the end of the loop.
- **Fault inside or outside customer premises³**, which indicates whether the fault is before or after the network interface device marking the demarcation point between the outside plant and the home network.

Table 2 provides a summary of capabilities of each technique, and shows how xELT-Expresse delivers the combined set of capabilities of DELT, SELT and MELT.

Fault Analysis and Results Capability	DELT	SELT	MELT	xELT-Expresse
Operation with severe line fault	No	Yes	Yes	YES
Operation with no CPE installed and powered	No	Yes	Yes	YES
Fault detection (in general)	Yes	Yes	Yes	YES
Fault location (in general)	No	Yes	Yes	YES
Fault differentiation	Yes	Limited	Limited	YES
Fault location at distance over 3km	No	No	Yes	YES
Differentiation between unterminated line and severe line fault	No	No	Yes	YES
Loop length estimate with no faults	Yes	Yes	Yes	YES
Loop length estimate with single wire degradation or cut	No	No	Yes	YES
Detection of foreign voltage	No	No	Yes	YES
Detection of insulation fault	No	No	Yes	YES
Detection of “signature” circuit at interface between home network and outside plant	No	No	Yes	YES
Detection of bad splice very close to CPE	Yes	Yes	No	YES
Location of shunt resistive fault	No	Yes	No	YES
Detection of series resistive fault	No	Yes	No	YES

Table 2: Comparison of capabilities of DELT, SELT, MELT and xELT-Expresse techniques.

³ Additionally requires the presence of a signature circuit at the network interface device and the ClearView module of Expresse.

Table 3 shows two examples of loops with faults, and compares the analysis made possible by using only SELT and by using SELT plus DELT (or loop records).

Table 4 shows two examples of loops with faults, and compares the analysis made possible by using only MELT and by using MELT plus SELT plus DELT (or loop records).

Issue	Loop Configuration	SELT only	SELT plus DELT (or loop records)
Identify if fault is inside or outside the house	Loop length: 1000m Bad-splice located at: 500m	SELT data produce an echo response indicating a fault at 500m. The echo response does not show the end of the loop.	DELT or loop records provide a loop length estimate of about 1000m. The echo response from SELT indicates a fault at 500m. The combined analysis clearly shows that the fault must be outside the house.
Distinguish between shunt fault and bridged tap	Loop length: 1000m Bridged tap located at: 500m	SELT data produce an echo response indicating a fault at 500m. Echo response for shunt fault and bridged tap are similar, so no differentiation is possible.	DELT provides a clear indication for the presence of a bridged tap. Combined with the echo response, the analysis shows the presence of a bridged tap at a distance of 500m.

Table 3: Examples of fault detection and location with SELT, SELT plus DELT (or loop records).

Issue	Loop Configuration	MELT only	MELT plus DELT/SELT/loop records
Detect end-of-loop bad-splice	Loop length: 500m Bad-splice located at: 500m	No fault is detected.	SELT data clearly show the bad-splice at 500m. DELT (or loop records) further show that the loop length is about 500m, so the bad-splice is located at the end of the loop.
Locate shunt fault	Loop length: 1000m Shunt resistive fault located at: 500m	Fault is detected, but no location information can be provided.	SELT echo response shows a fault at 500m that can be either a bridged tap or a shunt fault. MELT data confirm the fault at 500m is a shunt fault and not a bridged tap. DELT (or loop records) show that the loop length is about 1000m, so the fault must be located outside the house.

Table 4: Examples of fault detection and location with MELT and with MELT plus SELT plus DELT (or loop records).

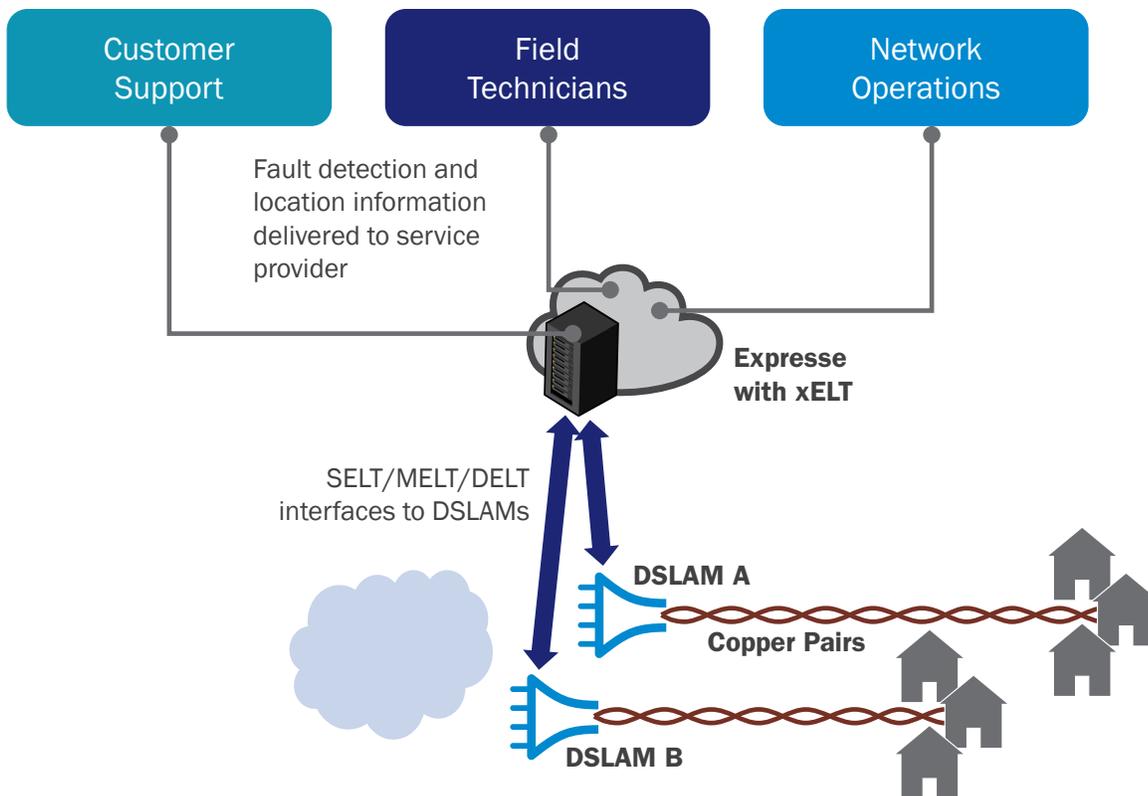


Figure 4: xELT-Expresse as a single system for fault detection and location.

5.3. Operational Benefits

xELT-Expresse is an equipment-vendor-independent software-based technique that uses standardized interfaces to communicate with modern DSLAMs that support DELT, SELT or MELT. It includes the following capabilities:

1. **Calibration** for discrepancies of measurement data that arise from circuit differences among vendors.
2. Automatic adjustment of the line testing options to those available with the corresponding DSLAM.
3. A fast, consistent, expert-system display of fault determination (type, location) for call center and field service personnel.

A service provider using xELT-Expresse enjoys the benefits of a single unified solution for all line testing. This is achieved because:

- A single system is used for analyzing multiple sources of data (which is preferred to deploying individual systems each catering to a specific type of data).
- A single system is used for performing fault detection and location across all DSLAM platforms in the network (which is preferred to deploying individual systems each catering to a specific DSLAM platform).

Figure 4 shows an example of deploying a xELT-Expresse system with multiple types of DSLAMs in a network. The figure also demonstrates how service provider operations teams can access the system and retrieve analysis results.

For more information on Express Line Testing (xELT-Expresse), please visit <http://www.assia-inc.com> or contact us.

References

- [1] ITU-T Recommendation G.992.3, Asymmetric Digital Subscriber Line transceivers 2 (ADSL2)
- [2] ITU-T Recommendation G.992.5, Asymmetric Digital Subscriber Line (ADSL) transceivers – Extended bandwidth ADSL2 (ADSL2plus)
- [3] ITU-T Recommendation G.993.2, Very high speed Digital Subscriber Line transceivers 2 (VDSL2)
- [4] ITU-T Recommendation G.9701, Fast Access to Subscriber Terminals (FAST)
- [5] ITU-T Recommendation G.996.2, Single-ended line testing for Digital Subscriber Lines (DSL)

Acronyms and Abbreviations

AC	Alternating Current
ADL	All Digital Loop (Line)
CO	Central Office
CPE	Customer Premises Equipment
DC	Direct Current
DELT	Double Ended Line Testing
FDR	Frequency Domain Reflectometry
FTTB	Fiber-To-The-Building or Fiber-To-The-Basement
FTTdp	Fiber-To-The-distribution-point
FTTEx	Fiber-To-The-Exchange
FTTN	Fiber-To-The-Node
HLIN	Channel Characteristics Function per subcarrier (using complex number representation)
HLOG	Channel Characteristics Function per subcarrier (in logarithmic scale)
MELT	Metallic Line Testing
OTT	Over The Top
POTS	Plain Old Telephone Service
PSD	Power Spectrum Density
QLN	Quiet Line Noise
SELT	Single Ended Line Testing
SNR	Signal to Noise Ratio
TDR	Time-Domain-Reflectometry
UER	Uncalibrated Echo Response
xELT	Pronounced “zelt” where x = any ELT test type



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