Single-Ended Loop Testing (SELT)
Expectations and Realities

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1. Introduction

Deployment of DSL modems is increasing throughout the world as subscribers flock to high-speed broadband access. However, operators worldwide are struggling to meet this surging demand, especially when faced with the prospect of how to cost-effectively provision and troubleshoot DSL service.

Too often, the "holy grail" of DSL self-install is the exception rather than the rule. Expensive truck rolls are an all-too-frequent occurrence when it comes to DSL provisioning, yet without a truck roll, few operators can assert with any degree of certainty the highest data rate a new DSL subscriber could achieve. If market growth is to continue, and possibly accelerate, and if operators are to maximize profit potential, the issue of cost-efficient DSL provisioning and troubleshooting must be addressed.

Single-ended loop testing (SELT), like metallic testing from the POTS world, is an automated way of testing a DSL loop from one end of the line, either from the central office (CO) or, less likely, from the subscriber's end. Unlike dual-ended loop testing (DELT), where someone, usually the operator's technician, must install a DSL modem or some sort of test device at the consumer's end of the line, SELT does not require a technician or any equipment at the subscriber site.

"What operators need today is a method for efficiently making thorough loop qualification a part of their daily operational practices," said Dr. Rob F.M. van den Brink, Senior Scientist of Fixed Access Networks at KPN Research. "Loop qualification through direct connection of dedicated hardware is expensive and, therefore, unattractive. But if DSL chips were to provide performance parameters to the management system, in a uniform manner with sufficient accuracy, then the performance data could be read periodically (perhaps once a month) for all deployed lines, and a database of real measurements could be constructed. Then when a potential new customer requested DSL service, the operator could more easily decide whether that request could be granted."

This vision and desire to incorporate SELT into the DSL chipset is driven by the sophistication of analog circuitry and signal processing available in modern DSL modems. Many believe SELT can be incorporated into the DSL chipset for negligible additional cost/complexity and with sufficient range and accuracy to meet operator requirements.

This white paper addresses the expectations and realities of incorporating SELT in DSL chipsets. It discusses the value and requirements of SELT within the context of DSL deployment and compares SELT to other line testing technologies. It describes the current effort to standardize SELT, including the agreed reference model, and discusses the value of such standardization to the DSL industry. Using a functional model, the various blocks required to realize SELT are described. Using a simplistic performance model, it is demonstrated that common analog component variations may in fact limit SELT performance. A method to improve performance is then presented, and simulation results illustrate its potential benefits.

1.1 Motivations

Operators today are striving to improve the way they interface with customers throughout the DSL subscription and provisioning process. The goal is to create a favorable first impression and then follow through by delivering what was promised. As with any customer service relationship, the key to improving the DSL start-up process is to give the customer good, solid information and then stand behind it. Unfortunately, some DSL operators and carriers don't always have adequate information about their physical networks to make promises with a high enough level of confidence. Consequently, data rates provisioned to customers are typically quite conservative, i.e., low relative to what many loops could support.

Much of the loop plant was installed decades ago, and over the years the loops have undergone changes that may or may not have been documented. Whatever the state of the operator's records, prudent operators will want to empirically qualify the characteristics of a loop before a specific level of DSL service is incorporated into a subscriber contract.

For example, many operators base their DSL price structures on the data transfer rates they promise subscribers. But before new subscribers can be assured they will receive the service level (i.e., data rate) they requested, the operator needs to know more about the customer's local loop because the characteristics of the loop will have a decided effect on the quality and performance level of the DSL service. The operator will want to know how long the loop is, whether it is made up of mixed-gauge wiring, whether bridge taps are present and where they are located, whether loading coils are present on the loop, and several other pertinent parameters that influence the achievable data rate.

Without SELT, the operator's only alternatives are (a) to offer a very low, high-confidence data rate, or (b) to dispatch a technician to the subscriber's site to take a series of measurements to determine the maximum data rate the loop can support. With SELT, however, operators can find out much of what they need to know without dispatching a technician.

Ultimately, SELT reduces an operator's DSL provisioning and maintenance expenses while simultaneously providing a more positive experience for customers.

1.2 Operational Scenarios

There are three major operational scenarios where SELT can be of assistance to the operator:

- **Post-DSLAM installation:** In this scenario, no customer premise equipment (CPE) has been installed, but the physical loop has been pre-wired to the digital subscriber line access multiplexer (DSLAM). SELT can, with low complexity measurements and analysis, provide simple verification that the DSLAM port is physically connected to a physical loop and provide loading coil detection. This measurement would confirm that the craftsperson has properly wired the DSLAM and could alert the operator to the need for a truck roll to remove loading coils.

- **Pre-DSL Service Activation:** Again, no CPE has been installed, but the physical loop has been pre-wired to the DSLAM and verified through post-DSLAM installation tests. Now the objective is loop pre-qualification (line characterization, noise measurement, etc.) for the purpose of estimating what data rate the loop is capable of supporting. Accuracy of the pre-qualification estimates is important. If the loop is capable of supporting 1.5 Mbps but only 768 kbps is offered, then the operator misses out on potential revenue. If the loop is only

truly capable of 768 kbps but the pre-qualification somehow suggests it can support 1.5 Mbps, then the operator risks an unnecessary truck roll to resolve an unsatisfactory connection rate and an unhappy and frustrated customer. Because both types of inaccuracy result in increased operator costs, this scenario requires the highest accuracy of SELT measurements and analysis. To achieve high accuracy, it should be fairly intuitive that as the loop topology grows longer and more complicated that SELT complexity increases. Section 3 will address the impact of the requirement for very accurate SELT measurements on implementation complexity.

- **Post-DSL Service Activation:** In this scenario, a CPE is installed and satisfactory performance was previously achieved, but now a problem has arisen. Possible reasons for service disruption include disconnection of the loop, a physical break in the loop, changes in loop noise, equipment failures, etc. The ADSL2 standard has provisions for dual-ended loop testing (DELT) using coordinated transmission and measurement between the CPE and CO modems. DELT does not require that the modems be capable of achieving data transmission, is a fairly robust tool, and could certainly be used for post-service activation problem solving. However, it cannot be used to identify loop cut versus equipment failure and other problems where cooperation from the CPE is absent. In these cases, SELT can be used to compare the current loop topology estimate against previous saved estimates. If all that is necessary is a coarse loop topology estimate (i.e., a determination that the loop length is now much shorter than previously recorded), SELT complexity can be low-to-medium. If the full accuracy and range similar loop pre-qualification is required, then SELT complexity is correspondingly high.

It is worth noting that a common initial assumption of all three scenarios is that the loop is wired to the DSLAM. Depending upon the operator and where the DSLAM is installed, this may not be a reasonable assumption. In a standard CO, a great deal of work is required to rewire the main distribution frame (MDF) and connect a subscriber's loop to a DSLAM. As such, it is unlikely that an operator will build out a CO with DSLAMs and pre-wire all subscribers in advance. It is more likely that the operator will connect individual subscribers after they request service. In this case, loop pre-qualification via the DSL chipset on the DSLAM may be too late to be truly useful. In this case, operators may prefer (or be forced) to rely on existing (possibly upgraded) metallic test access unit (MTAU) equipment to obtain a first estimate of data rate capability to a customer.

In remote cabinet DSLAM deployments, on the other hand, it is more likely that customers would be pre-wired to a DSLAM. Furthermore, it is very unlikely that MTAU equipment would be deployed in a remote cabinet. For both of these reasons, SELT has great value in a remote cabinet deployment. Additionally, as the DSLAM is located fairly close to customers, loop pre-qualification range and accuracy requirements are reduced, in turn decreasing the complexity of SELT measurement and analysis.

Table 1 summarizes a variety of deployment scenarios for DSL and describes their potentially different SELT requirements as well as the value of SELT for each scenario.

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Table 1: SELT Requirements by DSL Deployment Scenario

Deployment Model	Assumptions	SELT range/accuracy requirement	How can SELT help?
Multi-Tenant Unit	• Less than 7 kft (2.1 km) • No broadband test head present in basement or cabinet	Low	• Enables in-building line testing without requiring a test head at the site • Helps with identification of new noise sources impacting service in the building
Public Network Cabinet	• Less than 7 kft (2.1 km) • Area- and power-limited	Low	• Enables testing capability from the cabinet without requiring a test head • May provide enough information for a call center technician in conjunction with the user to correct the problem over the phone without requiring a truck roll • If line is cut, SELT could help identify which ports were impacted
Long Loop	• No constraints on loop length • Narrowband MTAU present; no broadband test head present	High Calibration required (see Note 1)	• Enables broadband testing capability without requiring a test head purchase/upgrade • Enables accurate line testing under all loop lengths
All Digital Loop	• No constraints on loop length • No underlying POTS service = no access to MTAU	High Calibration required (see Note 1)	• Enables broadband testing from a loop that doesn't have MTAU

Note 1: A case for the need for calibration to achieve high SELT accuracy/range will be made in Section 3.

1.3   Comparison to other line testing technologies (MTAU, DELT)

Table 2 compares the capabilities of various line testing technologies that could be used by operators for one or more of the operational and deployment scenarios discussed in Section 1.2.

Table 2: Comparison of Line Testing Technologies

(√ = measured, E = estimated, ? = TBD)

Line Parameter	Metallic Test Access Unit (MTAU) Existing Technology	Broadband MTAU Future Technology	SELT	DELT
Pre-Qualification	?	√	√	
Requires DSLAM Pre-wiring			√	
Maintenance	?	√	√	√
Requires CPE Installed				√
Access to DC/POTS Frequencies	√	√		
Line Capacitance @ DC	√	√		
Line Resistance @ DC	√	√		
Foreign Voltages	√ (narrow BW)	√	√	
Loop Topology				
Length(s)	√	√	√	
Gauge(s)	√	√	√	
Bridgetap Detection				
Location		√	√	
Length		√	√	
Gauge		√	√	
Loading Coil				
Detection	√	√	√	
Location	√	√	√	
Wide Band Noise Measurement		√	√	
Near End		√	√	
Far End		?	√	
DSL Parameters				
SNR/Carrier		E	E	√
Loop Attenuation		E	E	√
Line Noise		E	E	√
Data Rate		E	E	√

1.4   Standardization Efforts

Standards are very important to industry for a variety of reasons. First, standards seed development of technology by cooperatively bringing together "expert" participants in the industry and providing a peer review forum that enables rapid development of new ideas and solutions. Second, standards support and encourage interoperability amongst multiple vendors by defining an agreed upon minimum base feature sets and a set of common test points at interfaces. Finally, standards speed market acceptance by enabling multiple vendors to participate and compete, and by providing equipment vendors with a common set of product specifications.

As a new technology, realization and widespread deployment of SELT would benefit greatly by the development of standards. The development of a SELT standard would certainly benefit operators because the loop testing environment would remain constant across different vendors' DSLAMs and DSL modems, simplifying the task of integrating DSL equipment from various vendors into a heterogeneous environment. Furthermore, a layered approach to any standard gives equipment manufacturers the flexibility they need to: develop only those layers they wish to provide, use external equipment to realize a layer, or even combine or collapse layers. By specifying the interfaces between the layers, developers are free to innovate differentiated products. In addition, a SELT standard would promulgate consistent testing techniques in the industry and simplify an operator's migration from one vendor's DSLAM or DSL modem to another vendor's platforms.

As Tom Starr, Senior Member of Technical Staff of SBC TRI, noted, "SELT would be most useful if it were standardized to assure the same measured results regardless of equipment vendor."

Dr. van den Brink agrees: "The interface between the chip and the management system needs to be standardized so external software systems can read the data and construct a database. Furthermore, standardization allows the approach to be technology-independent – information acquired by the ADSL chip on one loop can be used to decide whether SDSL service can be supported on another loop."

Standardization and adoption of SELT will contribute to the continued growth of the DSL market and in the long-run help operators more cost-effectively provision service by meeting the demands of an ever-increasing subscriber base.

Even with the benefits inherent in SELT, the standards development process will probably be long. Work on G.selt is ongoing in the ITU in Study Group 15, Question 4 under the project G.selt. Figure 1 shows the G.selt functional model agreed to at the October 2002 ITU meeting. The functional model consists of three layers[1].

The SELT-PMD (single-ended loop test – physical-medium dependent) function performs observations on the physical medium to which the G.selt device is connected. (The term "observations" is used as synonymous with "measurements.") Two types of measurements can be distinguished: measurements that are associated with an excitation of the physical medium by the functional block and measurements that do not require excitation. A sequence of measurements of the first measurement type is defined as the measurements associated with a

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[1] The following description of the three layers was taken from ITU contribution OJ-114.

sequence of corresponding excitations. The result of a measurement is a quantity represented as a parameter (one- or more dimensional, discrete or continuous). From these parameters, "secondary" parameters are derived, usually through multiple measurements. An example of such "secondary" parameters may be the echo impulse response[2].

The fact that the functional block is connected to the physical medium motivates calling it "PMD." The prefix SELT indicates that this functional block is specific to single-ended loop testing. However, in some instantiations, this may be the same as, or nearly the same as, instantiations of the xTU-PMD functional block.

The middle functional block is called the **SELT-P** (single-ended loop test – processing). The definition of SELT-P is as follows:

The SELT-P function transforms the secondary parameters into parameters defined in the MIB. These MIB elements, so-called "primary parameters," directly reflect the characteristics of the loop under test. Examples include: topology of the loop, loop make-up, noise on the loop[3].

The third functional block is denoted **SELT-ME** (single-ended loop test - management entity). It is defined as follows:

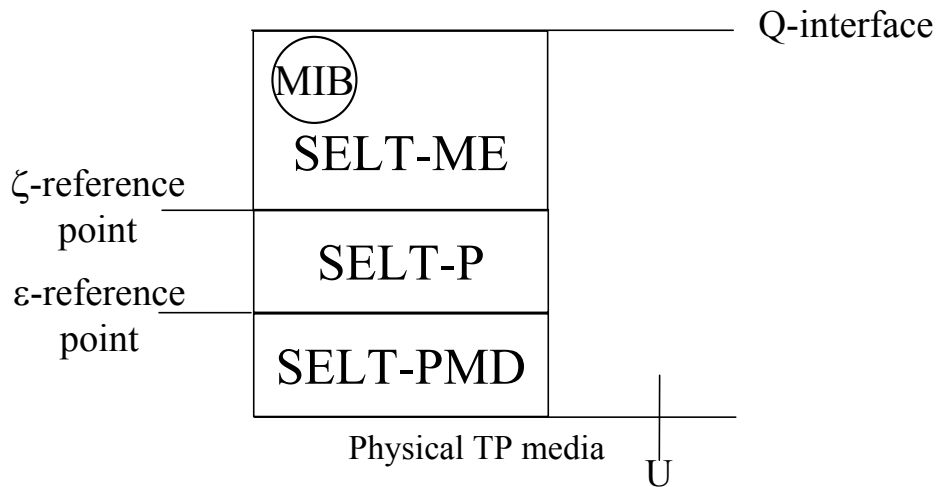*The SELT-ME manages the Management Information Block and communicates with the OSS over the Q-interface.*

Figure 1: G.selt Functional Model[4]

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[2] Other secondary parameters could be thought of, but the purpose here is to indicate that some first transformation of the measured parameters is done.

[3] An explicit and exclusive definition of the list of primary parameters and the format in which they are to be represented is part of the G.selt standardization effort.

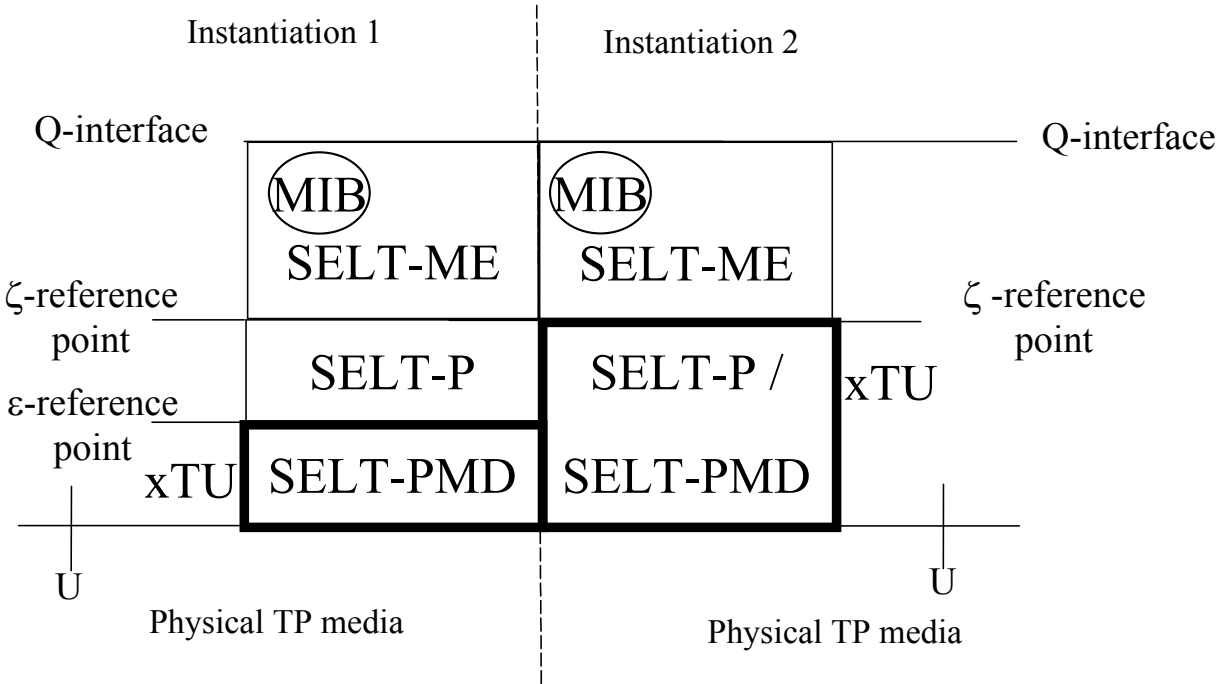[4] Figure taken from ITU contribution OJ-114.

Figure 2: Two Implementation Examples Where G.selt Functions Are Supported Within an xTU-C or an xTU-R[5]

Depending upon the required performance of SELT, the implementation complexity may vary. As will be discussed below, the majority of SELT complexity resides in the SELT-P layer. Given this fact, the expectation that SELT is an infrequent operation and that it will likely be unacceptable to increase chipset cost/complexity to incorporate SELT, it is anticipated by the authors that Instantiation 1 will be the prevalent deployment model for SELT.

Given the likelihood that the various layers of SELT will be realized in different entities within the DSLAM, the importance of G.selt becomes readily apparent. G.selt will ensure the consistency of reported parameters desired by operators and interoperability between vendors of SELT-PMD, SELT-P and SELT-ME technology. Without G.selt, the industry risks propagation of non-interoperable proprietary solutions, and operators cannot expect consistency between DSLAM vendors and between different DSL modem technologies. G.selt is truly required to meet the goals of operators to reduce costs and ensure customer satisfaction.

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[5] Figure taken from ITU contribution OJ-114.

2. Architectural Breakdown of SELT

It is expected that most architectures to realize SELT will follow the functional reference model discussed above for G.selt. As such, there will be some entity with access to the physical loop taking various measurements. A second entity then processes those measurements to obtain a variety of estimated loop and DSL parameters. Finally, a third entity makes those estimated parameters available to the operator via a MIB. This section describes the three entities in more detail.

2.1 Data Gathering (Measurement)

Some of the standard measurement techniques that can be used for SELT include:

- Time-domain reflectometry (TDR): An impulse is transmitted into the loop. The shape and delay of the reflection(s) contain information about where various impedance mismatches occur. For example, if the loop is a single un-terminated piece of cable, the reflection will be inverted (due to open termination), and the shape will represent that due to passing through the cable twice. The reflection can thus be used to determine the length and gauge of the wire. To assist with weak reflections and mitigating the effects of loop noise, typically a train of impulses is used and the reflections averaged. If the transmitted impulse also passes through the analog front end (AFE) of the modem, then any reflections due to any local impedance mismatches must be compensated.

- Frequency-domain reflectometry (FDR): The loop is sounded with a swept sinusoid to identify frequencies that either resonate or are "dead." For example, peaks in the measured receive signal correspond to frequencies that create standing waves. Standing wave frequencies provide information about the length of the cable.

- One-Port Scattering Parameter, i.e., S11 or echo response: This method is similar to FDR, but instead of looking for individual frequencies, a complete echo response measurement is utilized. From the echo response, the input impedance of the loop can be determined, from which the loop topology can be determined.

- Power spectral density (PSD) of noise on the line: In this measurement the transmitter is quiet, and the modem measures the loop noise present.

While it may not be immediately apparent, with the exception of the PSD measurement, all the other measurement techniques contain identical information about the loop. For example, transmitting a "pure" impulse into the loop is equivalent to transmitting a spectrally flat signal as is typically done for S11 measurements. The two are related by the Fourier transform. Similarly, the measurement results are related by the Fourier transform. If a shaped impulse is used for TDR, the echo response can still be derived from the TDR measurement, except now the transmit impulse shape must be deconvolved from the received signal. Thus, all the measurement techniques can provide identical information about the loop. In practice, there may be differences, but they are due to implementation details and limitations rather than theoretical differences. For example, in most ADSL modems the transmit signal is generated via an inverse fast Fourier transform (IFFT). As such, only discrete frequencies can be transmitted and measured. This limitation might make it difficult for an ADSL modem to produce the very fine frequency spacing used in common FDR techniques. However, an ADSL modem can still obtain the same SELT accuracy via an echo response measurement. Additionally, if a long TDR trace is captured, it could be Fourier transformed to obtain finer frequency spacing than that normally associated with the echo response measured in the ADSL modem.

While the measurement techniques all contain identical information about the loop, there may be advantages to one technique over another during the analysis phase. The advantages

depend upon the preferred algorithm(s) in use in the analysis engine and the parameters associated with the various measurements (e.g., sampling rate, start and stop frequencies, etc.). It is certainly possible that a given analysis engine may request more than one type of measurement be taken to improve the overall accuracy of the resulting estimate(s).

Ultimately, the measurement used will need to be negotiated between the analysis engine and the measurement unit. G.selt will specify the interface for such a negotiation and the actual return of measurement results. Clearly associated with any measurement must be the associated parameters (e.g., sampling rate, start and stop frequencies, etc.). Finally, to ensure interoperability, G.selt will need to specify some minimum set of measurements and parameters that must be supported. Because different DSL modems have different typical transmit and receive signal processing, the minimum SELT feature set may change with DSL technology. The ultimate goal of specifying minimum feature sets is to ensure that the SELT estimates reported for a given loop would not vary appreciably from vendor to vendor or from modem standard to modem standard. Any modem that is compliant to G.selt would provide consistent results to the operator.

It is the authors' opinion that incorporating the capability for SELT measurements with sufficient accuracy and flexibility adds insignificantly to DSL chip cost and complexity. For this reason, it is expected that all future chipsets could be capable of supporting a future G.selt standard. Further, most current modems could also support G.selt, albeit with a lower set of capabilities.

2.2   Data Analysis

The data analysis engine is responsible for using the SELT measurements to estimate a variety of parameters and DSL capabilities associated with the loop, including:

- Loop Topology - loop length, bridge taps length/number. Also important is the potentially unknown remote termination impedance. Figure 3 shows a generic loop topology model consisting of five segments, each with its own length and gauge. The objective of SELT is to provide the operator with an estimate of the loop topology that mimics the actual topology as closely as possible. As Figure 3 indicates, estimating the loop topology is a multi-variate optimization problem whose complexity will depend upon the accuracy and range requirements as well as the number of unknowns. Because different operators build their networks using different design rules (i.e., maximum number of segments per loop, gauges allowed for each segment, etc.), it is advantageous to have some means to provide these rules to the analysis engine. Such input either eliminates or at least places bounds on the unknowns, which can significantly increase both range and accuracy of the SELT estimates while potentially lowering complexity.

- Loading Coils - detection and location(s). Not all regions worldwide use loading coils. Where they are used, they are typically deployed with fairly strict design rules. Again, if the analysis engine knows if loading coils are allowed, and, if so, how they may be present, algorithm complexity can be eased.

- Loop Attenuation/Insertion Loss – having estimated the loop topology parameters, the attenuation/insertion loss of the loop can be computed. This calculation is fairly straightforward and simple.

- Crosstalk profile – using the measured near-end loop noise PSD, an estimate can be made of the type and number of crosstalkers present. Again, this is a multi-variate optimization problem.

- Far-end loop noise – using the estimated crosstalker profile, an estimate of the loop noise present at the far end can be made. However, many assumptions are required to perform such an estimate. It is unclear at present how accurately far-end loop noise estimates can be made. Clearly, the accuracy will depend upon the bandwidth over which near-end PSD measurements are taken. Many existing CO DSL modems may only support a relatively narrow receive frequency range, which will increase the difficulty of estimating the much wider bandwidth far-end loop noise.

- Achievable downstream and upstream data rates – with an estimate of the loop attenuation and near- and far-end noise, an estimate of the achievable downstream and upstream data rates can be made. However, even if all previous SELT estimates are perfect, an estimate of the achievable data rates can only be approximate, as it depends heavily on chipset vendor, chipset version, modem model, software version, etc.

It should be clear to the reader that the data analysis processes required to compute an accurate estimate of achievable data rates is involved, lengthy and complex. While the digital signal processors (DSPs) in modern DSL modems typically have the horsepower to perform these computations, the program memory requirements for these functions are large. Adding extra memory to a chipset to support SELT would have a significant negative impact on cost. Given the expectation that SELT will be an infrequent operation, it makes sense to amortize the memory requirement for SELT across as many ports as possible. For these reasons it makes more sense for the analysis portion of SELT to reside outside the DSL chipset – either in an existing linecard processor or in an existing/new processor elsewhere in the DSLAM.
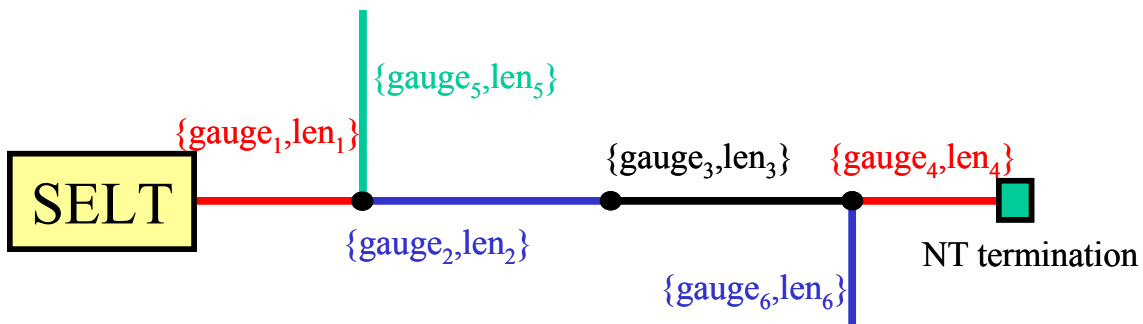

Figure 3: Generic Loop Topology Model

2.3 Data Distribution

The final step for SELT is the distribution of the estimated parameters via a MIB into the Operations Support System (OSS). It is necessary to integrate the control of and the results from SELT into a form that can be used either by customer sales representatives, support representatives or craftspeople. Today, this level of integration does not exist for DSL. However, it does exist for existing MTAU equipment, and it is expected that that technology could be reused. However, a porting of OSS support into the DSLAM is required.

3. Performance and Implementation Issues

Section 1.2 described the various scenarios in which SELT might be used and the associated requirements on accuracy. This section considers the impact of accuracy on implementation and the trade-off between performance and SELT complexity.

SELT performance – meaning accuracy – is dependent on the quality of measurements taken during the data gathering phase. More accurate measurements translate to more reliable SELT results. Accuracy of measurements is dependent on several factors.

Component variations will cause SELT measurements to be inaccurate or misleading. To limit the impact of component variations and allow access to the largest measurement bandwidth possible, it is desirable to provide a means to bypass or disable various transmit and receive filters. However, with such flexibility comes the ability to take SELT measurements in a non-spectrally friendly manner. For example, typically an ADSL modem only transmits in the downstream direction above tone 32 (i.e., above 138 kHz). This constraint prohibits the modem from taking SELT measurements on lower frequencies – frequencies that can be crucial for loop parameter estimation on long loops. Clearly, allowing an ADSL modem taking SELT measurements to transmit at frequencies well below tone 32 is advantageous. It seems logical that if the modem does not transmit at levels above those of other services transmitting at those frequencies, it should not cause problems to other services, and spectral friendliness during SELT should be assured. The ADSL modem would then be able to access lower frequencies without disrupting existing services. To ensure spectral compatibility with ongoing services, in G.selt the ITU will need to set spectral bounds for SELT measurements.

Although some components such as filters can be bypassed for SELT measurements, others cannot because they are integral to the DSL modem's operation. Thus, some other way of removing their effects on SELT measurements must be used if accurate SELT measurements are to be achieved. One candidate method is calibration, which is the process of establishing a known baseline prior to taking SELT measurements.

While it is believed that calibration can easily be accomplished for on-chip components and filter responses, it is more difficult to calibrate the transformer and line coupling components. Unfortunately, lack of calibration of these components can effectively limit the working range of SELT. It is expected that these limitations apply equally to all chipset and line card vendors: transformers are universally used for the environmental isolation they provide, and line coupling is simply necessary. Thus, the expectations of SELT in the marketplace may be misleading and based upon simplistic simulations that don't factor in component variations in blocks common to all modern DSL designs.

It is possible to calibrate the non-bypassable components by adding relays or analog switches to the line card; however, doing so would increase board area and cost, could negatively impact the mean time between failure (MTBF), and may cause performance degradations when the DSL modem operates normally, i.e., not in SELT mode. Clearly, the viability of calibration is a topic for further study.

3.1 Performance Examples

This section presents two examples that illustrate the impact of component tolerance on SELT accuracy and the improvements possible via calibration.

In the first example, the impact of component tolerances is evaluated when calibration is not utilized. By design, an overly simplistic and optimistic simulation setup is used. The objective is to illustrate the best performance that can be achieved under idealized circumstances and with a minimum of parameter tolerances. The results indicate that there will definitely be practical limitations on the performance of SELT under even more realistic expected circumstances. Figure 4 shows the AFE model used for the simulations. This model represents a "classic" topology without any modern sophistication present in most commercial DSL modems. In some sense, assuming that the transformer and line coupling must remain, this topology represents an ideal implementation for SELT. Simple differential amplifiers drive directly into the transformer, and the receive signal is measured across a single 100 ohm resistor ("balance"). The components with tolerances are those related to the transformer and line coupling (see Figure 4).

Assuming the loop is known to be only a single straight segment of 26AWG cable, there is no additive loop or AFE noise, and the remote-end is terminated by a high-impedance load for all frequencies, Figure 5 shows the resulting SELT performance. The lines represent the mean achieved across 200 monte-carlo runs, and the error bars show the corresponding standard deviation when the inductances and capacitors have tolerances of 5%, 2% and 1%. As shown, for 5% results are acceptable to 7 kft, for 2% to 8 kft, and for 1% to 9 kft. Beyond these limits, either the estimated mean is incorrect, or the standard deviation of the results becomes unacceptably large. It should be noted that if the transformer and line coupling components are known precisely, the identification algorithms are accurate beyond 18 kft for noiseless conditions. Algorithms for TDR, FDR, and S11 based schemes all performed essentially the same under these simulation conditions.

The results indicate that without calibration and with expected component tolerances, SELT accuracy is limited to around 7 kft of 26AWG (or 2.1 km of 0.4 mm). To provide more accurate results for longer loops, some sort of calibration on the external components is required. It should be remembered that the above simulations are definitely idealized. As such, they are probably optimistic in the performance that can be achieved with SELT, which further illustrates the need for calibration for loops longer than 7 kft or so.

One way to understand the behavior illustrated in Figure 5 is to realize that as loop length increases, the input impedance of the loop approaches the characteristic impedance of 26AWG cable. As such, the difference in input impedance of the loop from one length to the next becomes extremely small for medium-to-long cables. As this occurs, variations in the transformer and line coupling (and loop and AFE noise) may overwhelm the difference in measurement from one loop length to the next. Viewed alternatively, for a TDR algorithm the magnitude of the reflection becomes quite small and can be easily overwhelmed by transfer function changes of the AFE itself.
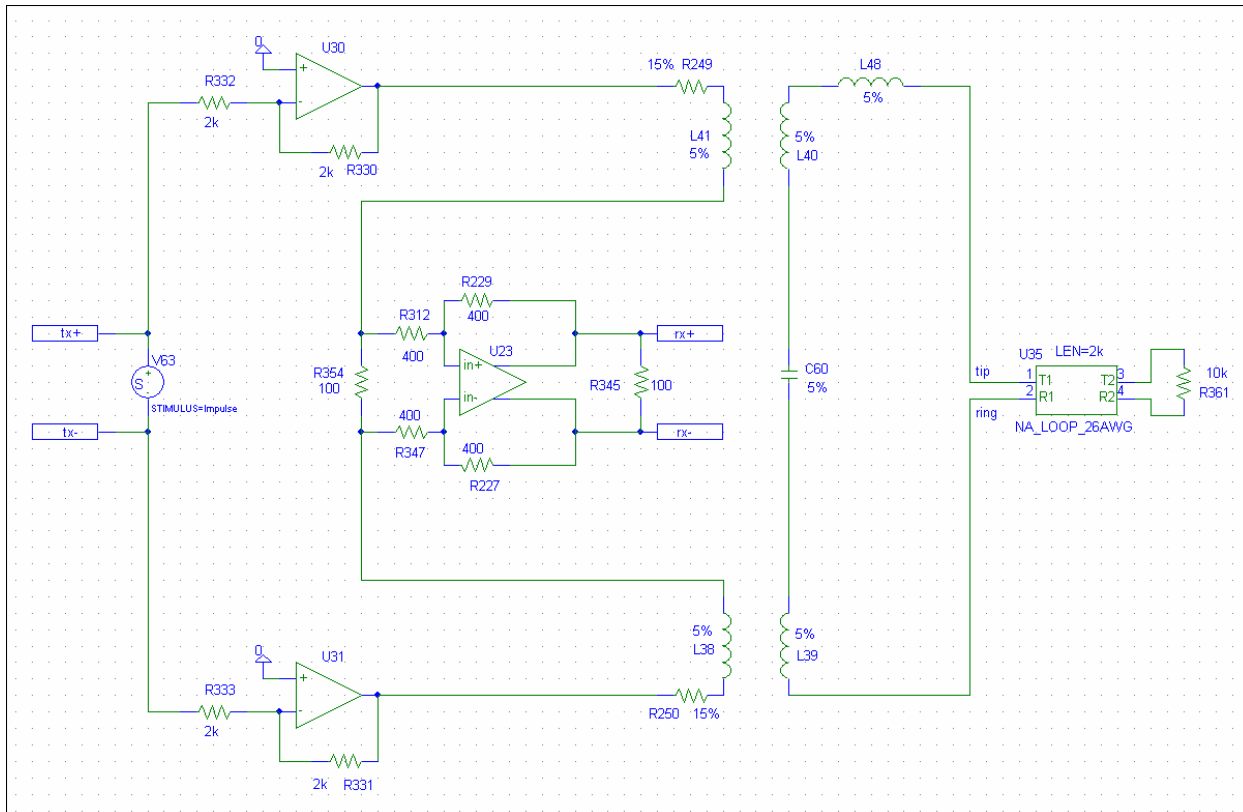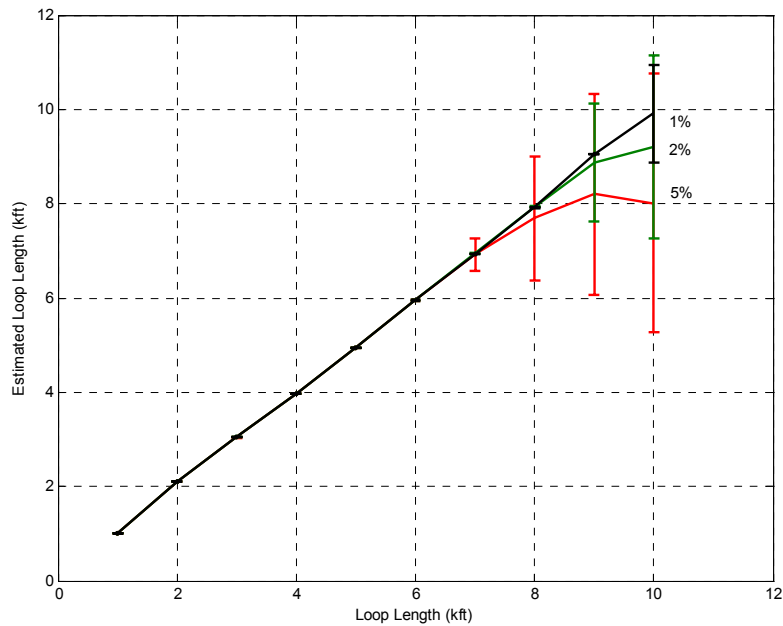
Figure 4: Simplistic AFE Schematic

**Figure 5: Estimated Loop Length (mean and standard deviation)
across 200 Monte-Carlo runs for each loop length, 10k termination**

A few comments about the simulation assumptions provide additional insight into the behavior and limitations of SELT. In all simulations, the remote termination impedance was assumed to be 10k ohms (representing an on-hook phone). Results were also run for different high (relative to the line impedance) impedance values, including 900 ohms. The results were not materially different from those shown in Figure 5. In all simulations it was assumed that the termination impedances were known. Again, this is a somewhat idealized assumption in that it assumes that the operator can determine that all remote phones are on-hook (high impedance state), that those phones truly represent high impedance in the ADSL band, and that if an ADSL modem is present at the remote, there is some means to force it into a high-impedance state.

As expected, if simulations are run assuming the presence of a low impedance remote termination, the results degrade significantly. For example, for TDR algorithms, when the termination matches the loop impedance, the size of all reflections is significantly reduced, and the effect of component variations can exceed the difference in reflection location and size at even shorter loops.

In all simulations, it was assumed the loop topology (i.e., single straight segment) and gauge (i.e., 26AWG) is known. It should be obvious that when these parameters become additional unknowns, the performance of loop estimation will necessarily degrade. Consequently, 8-9 kft appears to represent a fundamental working loop length limitation without calibration.

Finally, the simulations included no internal AFE components or circuitry. It was assumed that the responses of these blocks and component values were known exactly. Certainly, if these blocks were included in the simulation and their component tolerances included, the results would have been further degraded. However, in a properly architected DSL chip that incorporates SELT, it is simple to remove these internal component variation effects and hence remove the associated degradations on SELT performance. As such, the components of most concern are the external components that, as will be shown, are costly to calibrate.

In the second example, an S11-based calibration methodology was simulated to illustrate the improvements possible through calibration of the transformer and line coupling. This methodology is commonly used in network analyzers where a probe (or circuit) is connected to the device under test (DUT). In such a method, the DUT is removed and is replaced sequentially with a short, an open, and a 100 ohm load. The network analyzer takes measurements with each of these loads and uses the results to determine the two-port properties (i.e., S11, S12, S21 and S22) of the probe. Thus, when the DUT is reconnected, the network analyzer can accurately report only the properties of the DUT. For SELT on a DSL line card, the DUT is the loop and the probe is the DSL AFE. Figure 6 shows a simple schematic of how this technique can be achieved on a DSL line card. Of particular note is the addition of two relays per port. Again assuming a known loop topology (26AWG), known termination impedance (10k ohm), and noiseless conditions, Figure 7 compares the SELT performance without any calibration and with S11 calibration. The plot clearly illustrates the benefits of calibration. Whereas without calibration accurate results are achieved only on loops of length 8 kft and shorter, with calibration SELT provides accurate results on loops up to 18 kft in length.
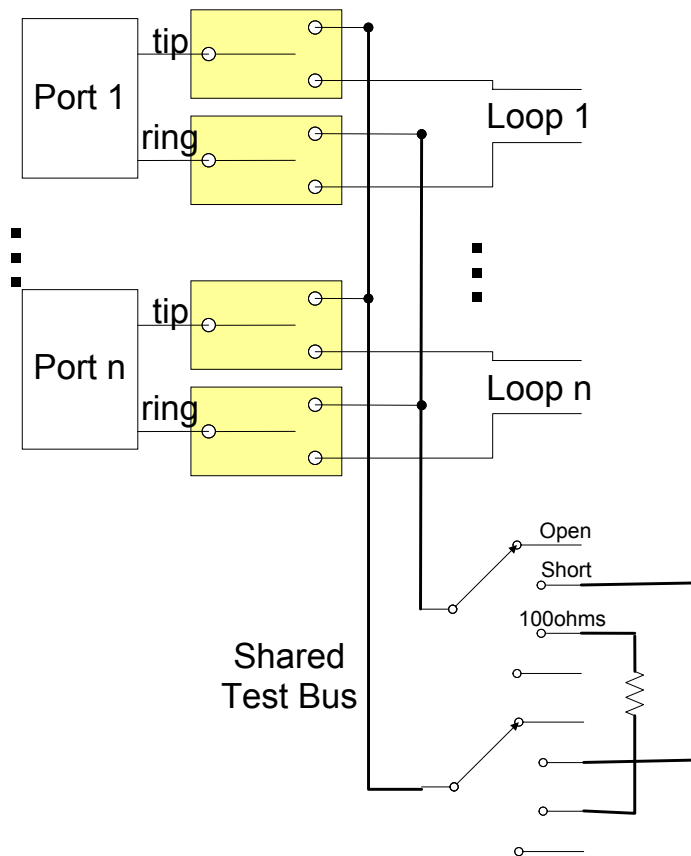
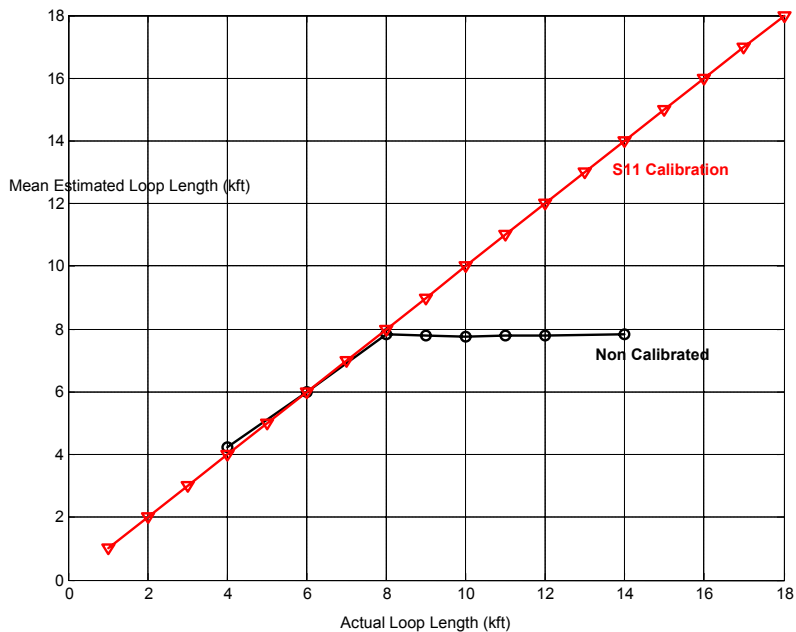**Figure 6: Basic Schematic to Realize S-parameter Calibration**

Figure 7: Un-Calibrated vs. S11 Calibrated SELT Performance

4. Summary

This white paper described the need for SELT and discussed the trade-off between accuracy and implementation complexity. Although much of the information SELT can provide can also be provided by external test equipment such as an MTAU, operators have been strong supporters of providing SELT through the line card to reduce expenses.

SELT was described, from a functional perspective, as comprised of three steps: data gathering, data analysis and data distribution. This layered model facilitates a good correspondence between actual implementation and standardization. Given the expectation that SELT will be realized across multiple devices, standardization is key to ensuring consistency of performance and interoperability.

The accuracy of SELT is dependent on the implementation constraints; conversely, the implementation dictates the level of SELT accuracy that can be achieved. As simulations showed, if the loops on which SELT measurements are desired are short enough, then existing line cards should be capable of providing adequate SELT performance without a significant increase in complexity or cost. However, when loops are this short, DSL performance is typically quite high – often higher than the desired level of service – and the value of SELT may be questionable in some scenarios. If longer loops are to be addressed, some sort of line card calibration is required. One way to accomplish calibration is by adding two relays per port to the line card. Unfortunately, adding two relays per port will increase cost, area and failure rate; whether these penalties are acceptable to operators in return for highly accurate SELT measurements on long loops is not yet clear. If calibration is not acceptable, SELT usefulness is realistically limited to deployment scenarios where loops are short and the deployment of an MTAU would not make sense. Unfortunately, physics dictates that SELT simply cannot be provided for free on a line card with full range and accuracy.

SELT is a technology that potentially will be important to accelerate the growth of DSL technologies worldwide. SELT can reduce operators' costs and thereby the customer's subscription cost. It will also help to increase customer satisfaction with DSL. Clearly, the motivation for SELT in DSL is high.