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Analysis Techniques for Loop Qualification and Spectrum Management

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Abstract

The telecommunications industry has worked for over a decade to develop digital subscriber line (DSL) technologies to revitalize the embedded copper plant. Now the industry is on the threshold of reaping the benefits of this effort, bringing megabit-per-second connectivity to offices and homes. However, network providers must properly manage the introduction and application of these systems to the local network. Accurate engineering is critical to avoid incompatibilities and failed provisioning that would otherwise create customer disappointment, delay and higher costs.

An understanding of subscriber loop make-ups, including length, wire gauge and location of bridged taps, is key to the proper engineering of DSL systems. While some loop records exist, they may be inaccurate or out of date. Knowing the types of systems that are transmitting in a given cable is also critical, because of the resultant crosstalk and the potential need for spectrum management. In this paper, we describe techniques for obtaining precise loop make-ups, and for determining the current crosstalk profile in the loop plant.

1. Achieving the Full Potential of DSL Technology

Among the new techniques being used to upgrade the public network are access technologies that use embedded copper plant to support higher bandwidth services. These technologies include ISDN, HDSL, ADSL and others for which carriers have announced aggressive deployment plans.

The new DSL technologies have the potential to become strategically important to an operator's business strategy. While they have been robust in trials, any new technology, no matter how powerful and reliable, must be properly applied. This involves several engineering tasks, the two most important of which are:

- Loop qualification - knowing what type of DSL system and what bit-rate can be successfully and reliably provisioned on a given customer's loop.
- Spectrum management - an engineering process that allows an operator to place new DSL systems into the plant in compliance with spectral compatibility guidelines and standards, and to troubleshoot field problems suspected of being caused by crosstalk from other systems.

Maintaining accurate records of the loop plant is important to many aspects of an operator's business. Beyond supporting traditional voice services, even more accurate and detailed loop records are needed when deploying DSL-based services. These technologies are typically engineered to operate over a class of subscriber loops, such as Revised Resistance Design (RRD) loops (up to 18 kilofeet), or Carrier Service Area (CSA) loops (up to 12 kilofeet). In fact, the need to be able to qualify a loop for use with one of these technologies is becoming critical as the technologies emerge and deployment begins. The ability to easily and accurately qualify loops will allow operators to offer a range of new services. Conversely, problems and high expenses associated with qualifying loops could inhibit deployment, thus lowering or eliminating associated new revenues.

Several approaches and tools are being developed to facilitate loop qualification. The most common is mining existing data in loop databases, checking it for accuracy, and then bulk-provisioning loops that are candidates for DSL-based service. Sometimes a combination of loop records and engineering information about feeder route topology is used to obtain an estimate of loop length. Another technique uses loop loss measurements from traditional POTS loop testing systems to estimate loop length.

These approaches use good engineering judgement and result in large populations of loops that are likely candidates to support advanced services. However, a typical approach is to minimize customer disappointment by biasing the techniques toward low probabilities of false-positive results. This is done at the expense of increasing the probability of false-negative results. In other words, the approaches are conservative, and some loops that might support DSL service remain unused.

Other loop qualification methods use the adaptation settings of a modem operating over the subscriber loop of interest. For example, if a DSL system is operational, the adaptive filter settings contain useful information about the loop. This approach has the decided disadvantage that a DSL system must first be in operation on the loop which one hopes to qualify. Yet another technique called the Sapphyre[SM] technique uses standard dial-up modems that operate over any subscriber loop to glean voice-band information about the loop, in order to predict performance at higher frequencies of interest to DSL.

It would be desirable to have a technique that could identify and qualify all nonloaded subscriber loops in a mechanized and highly accurate manner without the need for special equipment or intervention at the subscriber's location. In the following section, such a system is introduced.

Historically, local exchange carriers have carefully controlled systems that they place in the distribution network. T-carrier, used to support digital loop carrier remote terminals and private line services, is a highly engineered transmission system with carefully controlled power levels and pulse templates. ISDN Basic Rate Access and 2B1Q-based HDSL were carefully engineered for spectral compatibility assuming worst case scenarios of long loops with bridged tap and high binder group fills. A similar philosophy was initially proposed for ADSL. However, ADSL standards deliberations were more vendor-driven, and more aggressive. In particular, the option to use a historically high transmit power level was allowed. Simulations show that, under certain conditions, such systems could result in spectral incompatibilities, wherein crosstalk from one type of system interferes with another type of system.

Part of the rationale used to approve more aggressive ADSL standards was that local telephone companies could pick and choose among technologies and set power levels via software provisioning to control the spectral environment. However, several issues now complicate an operator's ability to deal with the situation. First, multiple technologies are being developed by equipment manufacturers, including DMT, CAP and QAM. Second, these systems run at multiple bit rates. Finally, and perhaps most importantly, the Telecommunications Act of 1996 includes loop unbundling provisions that make it possible for competing operators, often referred to as Competitive Local Exchange Carriers (CLECs), to gain access to individual loops. This activity was initially POTS-focused, but several operators are already offering ADSL-based unbundled services. This trend has been tremendously accelerated by the November 1999 FCC "line sharing" ruling, under which a CLEC can return the POTS connection and service to the incumbent, and retain the DSL bandwidth to offer only data services, such as high-speed Internet access.

[SM] Sapphyre is a service mark of Telcordia Technologies, Inc.

Over time, the competitive local environment may lead to several providers gaining access to the copper distribution plant, with each having a significant customer base. The customer base will be randomly dispersed in an area, driven by marketing forces and consumer choice. The competitive environment is expected to yield churn rates significantly higher than current churn rates for POTS. All this means that the spectral environment in a cable will be difficult to predict, and will be constantly changing.

In recognition of the importance of spectral compatibility in the loop plant, American National Standards Institute (ANSI) Working Group T1E1.4 initiated a project in 1998 to develop relevant standards. The group has been responsible for DSL standards on ISDN Basic Access, HDSL and ADSL, and is an excellent forum in which to foster industry consensus on spectral compatibility requirements.[1]

The deliberations have been well attended by industry players, including new equipment manufacturers and operators focused on market niches. This has led to a number of proposals for new DSL systems, for example the class of symmetric DSLs (SDSL). Unfortunately, this creativity complicates the problem of spectrum management, as is apparent from Table 1, which shows the currently agreed classes of DSL systems.

Table 1. Spectrum Management Classes

Spectrum Management (SM) Class	Deployment Guideline, max loop length EWL 26 gauge kft	Included DSL Technologies
Class 1	all nonloaded loops	ISDN SDSL < 300 kbps 2-line & 4-line DAML
Class 2	11.5 kft	SDSL < 512 kbps
Class 3	9 kft	HDSL and 784 kbps SDSL
Class 4	10.5 kft	HDSL2 (single-pair HDSL)
Class 5	all nonloaded loops	ADSL, CAP/QAM RADSL, G.lite (partial-overlapped)
Class 6	Not defined	VDSL
Class 7	6.5 kft	SDSL < 1568 kbps
Class 8	7.5 kft	SDSL < 1168 kbps
Class 9	13.5 kft	Overlapped, echo-canceled ADSL

Figure 1 shows currently proposed power spectral density (PSD) templates for each of these spectrum management classes. There are several ways to comply with the standard, the simplest being that the PSD of the signal transmitted by a piece of equipment fall under the template at all frequencies. This will generally be verified during manufacture, but if problems arise in the field the local operator will need to resolve incompatibilities and complaints, possibly including identification of systems that are transmitting in violation of the standard.

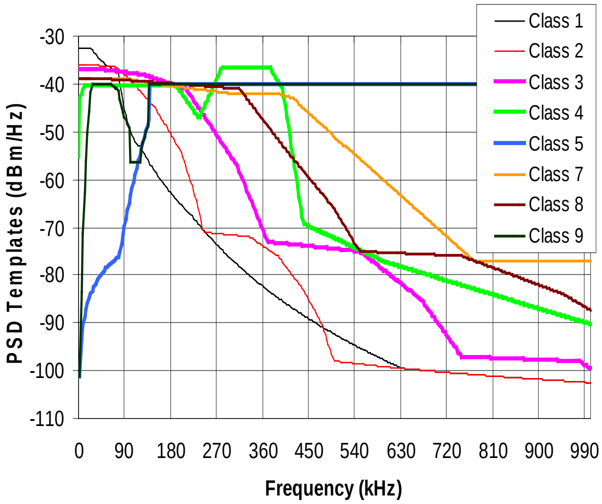


Figure 1. Spectrum Management Class PSDs

It would be desirable to have a technique that could characterize the crosstalk environment on a loop-by-loop basis, in a mechanized and highly accurate manner without the need for special equipment or intervention at the subscriber's location. In the following section, the same system used to identify and qualify loops will be extended to support spectrum management.

2. The Broadband Test Head

The mainstay of the telephone company local network is the local loop plant. Nearly all residential customers and many business customers are served by metallic twisted pair cables connected from a local switch in the central office to the subscriber's telephones. When customers request service, request a change in service or drop service, these facilities must be appropriately connected or rearranged in the outside plant by specially-trained craft dedicated full-time to this task. Obviously, an operator must understand its subscriber loops and know where they are connected, where the flexibility points such as junction boxes are, etc. Loop make-up records have been kept on paper and, more recently, have been manually entered into a computer database. Whether on paper or stored in computer memory, there have been questions about the accuracy and currency of these records.

One way to improve existing records is to examine and update them manually if they are missing or inaccurate. This method is expensive and time consuming. Furthermore, new technologies such as DSL require additional information that was not previously kept for voice services, so new information must be added to the existing records. Test set manufacturers offer measurement devices that can greatly facilitate this process, but this typically requires a remote craft dispatch and two-ended testing.

A highly mechanized, highly efficient and almost universally deployed loop testing system already exists. Originally developed by the Bell System, one of the most important elements of this system is the Mechanized Loop Testing (MLT) system that was retained by (now) Lucent Technologies at divestiture. This system uses a metallic test bus and full-splitting metallic access relays on line card electronics. By these means, a given subscriber loop can be taken out of service and metallically connected to a centralized test head where single-ended measurements can be made on the customer's loop. The test head runs a battery of tests aimed at maintaining and diagnosing the customer's narrowband (4 kHz) voice service.

Telcordia has invented key technology to upgrade this infrastructure. The intent is to replace the narrowband test head with a new, broadband test head. This test head would be able to interface with a switch to connect to a specified loop, apply a set of test pulses to that loop and record the response of the loop. The results would then be analyzed using sophisticated signal processing algorithms to determine the complete loop make-up. This approach has many uses. First, it can be used to check existing records; the loop make-ups can be methodically obtained and compared with existing database records. Because we expect the information to be more accurate and detailed than the existing records, the new data will often replace existing data and populate the database. Thus, through an entirely mechanized process, an operator can completely update its loop records.

The updated loop make-ups can be used by another system to calculate and qualify the ability of a given loop to support advanced DSL services. A computer system will take the loop make-ups, models of the various DSL systems and standards for spectral compatibility, and determine very precisely what service the customer’s loop can support. Such determination should be achievable in real-time, for example in response to a service agent query while on a different phone line with a customer.

In addition to determining the loop make-up, additional information can be determined regarding the noise environment a particular loop is exposed to. By means of additional spectrum analysis algorithms this noise may be identified, further facilitating the service provisioning process, identifying noise sources exceeding spectral compatibility requirements, and generally facilitating maintenance and administration.

3. An Example of Loop Identification

Most solutions for qualifying a loop for DSL services do so without unveiling the exact make-up of the loop. Recent work has demonstrated the feasibility of a technique that can achieve precise loop make-up identification via single ended measurements. The availability of the exact make-up of the loops in the local plant will not only solve the problem of qualifying loops for DSL-based services, but will also support other important loop plant engineering functions.

The approach used for determining the loop make-up is in the time-domain. Special probing pulses are launched onto the loop via the local metallic test bus. If a discontinuity is present (gauge change, bridged tap, end of loop), a signal (echo) travels back to the CO corresponding to the discontinuity. Such echoes are collected in the CO and are then processed. The solution employs a combination of advanced reflectometry and signal processing techniques. The advanced reflectometry allows the detection of very weak echoes generated at the ends of long loops, while additional signal processing is necessary to resolve overlapping echoes and identify discontinuities.

Several problems have to be solved in order to achieve the capability of exact loop make-up identification, especially those related to the limitations of current Time Domain Reflectometers (TDRs). First of all, today's TDRs have an effective range of some number of kilofeet (kft) and are not sufficient to allow detection of echoes generated by far discontinuities. Secondly, today no commercial TDR has the capability of detecting echoes generated by gauge changes. Moreover, even when all echoes can be detected it is not trivial to resolve them. In fact, the available observations consist of an unknown number of echoes, some overlapping in time and frequency, some not, some *real* and some *spurious*[1], that exhibit unknown amplitude, unknown time of arrival and unknown shape. The problem of resolving the above observations on the basis of a *single-sensor experiment* is a very complex problem that is seldom addressed in the literature.

An example of a TDR trace is given in Fig. 2, for the case of a 12 kft AWG-24 cable with a 1 kft bridged tap located either at 1 kft (Case A) or at 10 kft (Case B). The typical negative-positive sequence characterizing a bridged tap is manifest for Case A, but not for Case B where there is no sign of the presence of an echo. However, by using special signal processing on the waveform of Case B, it is now possible to see the negative positive echoes of the bridged tap (Case B + Processing).

[1] We define "spurious" echoes as echoes resulting from multiple back-and-forth reflections, as opposed to the "real" echoes that are the echoes that immediately return to the CO when generated by a discontinuity in the cable. The presence of spurious echoes is due to the fact that each discontinuity generates both a reflected and a refracted signal, so that a part of the signal travels back and forth on the line, bouncing between discontinuities, before it ultimately arrives at the Central Office (CO).

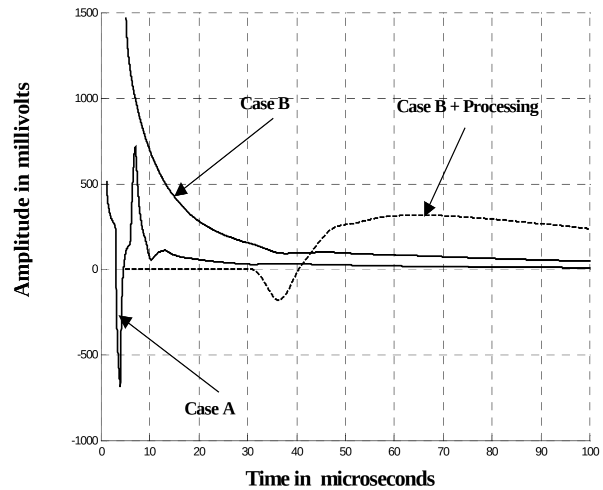


Figure 2: Effectiveness of signal processing on a TDR trace (bridged tap case)

With the use of special signal processing techniques, it is also possible to see gauge changes. The fact is that the echoes generated by a gauge change cannot normally be seen, not because they are too weak to be detected, but because they are hidden. An example is given in Fig. 3, where the TDR trace of a 3 kft AWG-26 cable spliced to a 12 kft AWG-24 cable is shown. The normal trace of a TDR does not reveal the presence of any echo, but the processed trace clearly shows a negative echo that indicates the transition from a medium with higher characteristic impedance to a medium with a lower one.

Finally, very good results have been obtained with a newly developed algorithm that uses sophisticated signal processing to perform loop make-up identification. Preliminary tests indicate that the algorithm is able to precisely identify loop make-ups, whatever topology they may have.

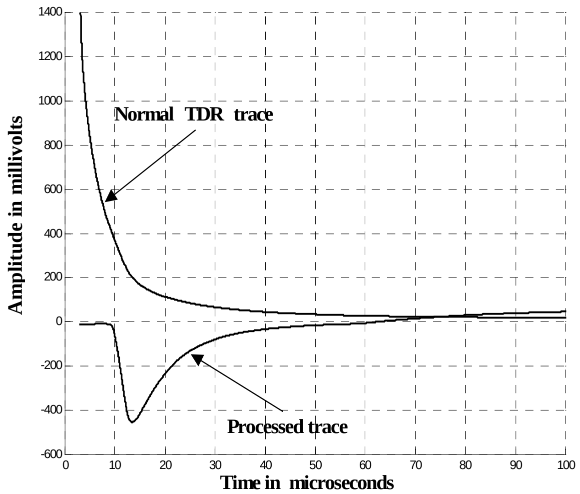


Figure 3: Effectiveness of signal processing on a TDR trace (gauge change case)

4. An Example of Crosstalk Identification

Spectral compatibility is the property whereby crosstalk among different systems transmitting on different pairs in the same twisted-pair cable does not cause significant degradation to the performance of any of the systems. Spectrum management is the process of deploying DSLs in the loop plant in a manner that ensures spectral compatibility. Figure 4 below depicts crosstalk in a typical loop environment, including near-end crosstalk (NEXT) and far-end crosstalk (FEXT).

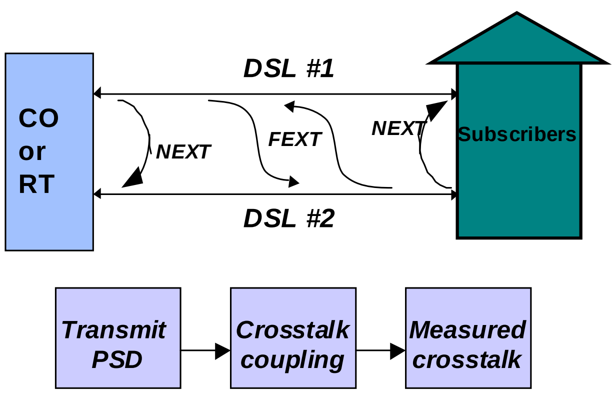


Figure 4. Crosstalk: transmitted signal, coupling, and received crosstalk

Current techniques for spectrum management apply relatively rigid rules uniformly across the entire loop plant, as embodied in the draft spectrum management standard currently under development by ANSI committee T1E1.4. These rules do not take into account the individual types of crosstalk sources or crosstalk couplings related to a particular pair in a cable, which may be considerably different than the near worst-case couplings that are assumed in the draft standard. Thus, a system that can characterize crosstalk on a loop-by-loop basis has the potential to yield a much more granular crosstalk characterization of the plant. This data, entered into a new loop spectrum management database, in turn has the potential to be mined, correlated and exploited to provide more optimal performances for individual subscriber loops.

To see how such a database might be created, we give the following example in which the crosstalk noise on a given pair is analyzed and characterized. NEXT from an upstream ADSL source is measured for a number of pair-to-pair combinations. These NEXT PSDs are correlated with the PSD crosstalk templates of some known sources. As can be seen from the calculated results in Table 2, each measured NEXT is highly correlated with the template NEXT from upstream ADSL. The unknown NEXT source is correctly identified.

Table 2. Correlations of measured NEXT from unknown source with known crosstalk templates

Measured NEXT	BRI NEXT	HDSL NEXT	T1 NEXT	ADSL Down NEXT	ADSL Up NEXT
5 -> 4	0.218	0.790	-0.276	-0.221	0.975
6 -> 15	0.194	0.798	-0.269	-0.215	0.992
11 -> 20	0.183	0.792	-0.269	-0.214	0.957
10 -> 21	0.153	0.808	-0.258	-0.204	0.994
4 -> 25	0.201	0.784	-0.267	-0.214	0.983
3 -> 12	0.071	0.768	-0.223	-0.174	0.938
13 -> 15	0.088	0.770	-0.227	-0.179	0.952
9 -> 20	0.230	0.791	-0.279	-0.223	0.962
14 -> 24	0.213	0.806	-0.276	-0.220	0.983
8 -> 18	0.120	0.802	-0.246	-0.194	0.976
2 -> 22	0.106	0.771	-0.233	-0.184	0.969
12 -> 4	0.085	0.735	-0.216	-0.171	0.935
1 -> 5	0.130	0.798	-0.247	-0.195	0.975
7 -> 18	0.066	0.790	-0.231	-0.177	0.896

5. An Advanced Loop Provisioning and Maintenance System

Let us consider a system that analyzes the responses of subscriber loops to probing signals to perform loop identification, and measures crosstalk and identifies the types of systems that are the sources for that crosstalk. The data is collected and used by a provisioning and maintenance system to enable more efficient engineering, provisioning, spectrum management, and maintenance of the copper loop plant.

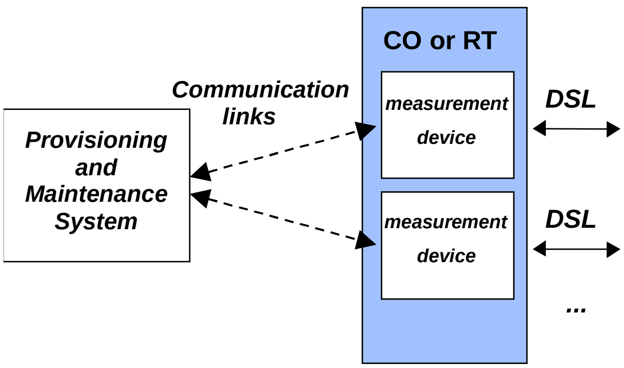


Figure 5. An advanced DSL Operations Support System

The loop make-ups, and types and numbers of crosstalkers in a cable can be measured, recorded, and tracked. This database can be coordinated with a DSL provisioning system to allow the highest possible service rates while ensuring spectral compatibility. Rather than using broad-brush loop estimates and spectrum management rules based on worst-case assumptions, precise loop make-ups and accurate noise characterization along with the actual powers of DSLs transmitting in the cable can be coordinated by the system.

This system is useful for network monitoring and maintenance. A DSL may experience significant degradation when signal to noise ratios (SNRs) are inadequate, perhaps when another source transmits a PSD that is too high. The system can isolate the causes of failures such as long loops or bridged taps, identify crosstalk sources, and help mitigate problems by techniques such as power back-off or lowering transmitted bit-rates. The system can also determine if an unbundled loop is receiving crosstalk levels that are within specifications.

6. Conclusions

We have introduced techniques for determining loop make-ups and for obtaining a spectrum analysis on a loop-by-loop basis. These techniques are not the only methods for obtaining such information, but they have the advantage of being applied in a mechanized, single-ended fashion from the central office. Thus, a new "brodaband test head" can be installed in the office that will automatically and routinely provide current information on loop make-ups and crosstalk. Using sophisticated signal processing and analysis approaches, we hope to be able to precisely determine loop make-ups for the entire nonloaded loop plant, including section lengths and bridged tap composition. The same approach can be used to gather and characterize crosstalk for each of the loops.

This information can be input to a provisioning and maintenance system that will retain and correlate the records. This database can in turn be used for a number of important functions, such as loop plant engineering, loop qualification and provisioning of DSL-based services, spectrum management, and maintenance of the loop plant. We believe that such a capability is required to fully exploit the power of emerging DSL technologies, and to effectively deal with the increasingly complex and dynamic unregulated local loop environment.

References

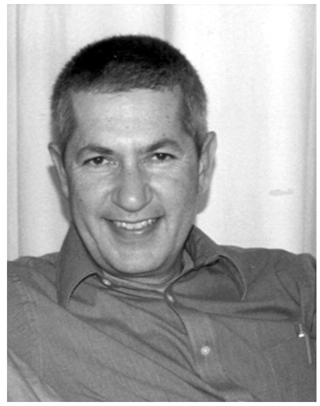
[1] Draft proposed American National Standard, Spectrum Management for Loop Transmission Systems, Committee T1 – Telecommunications, Working Group T1E1.4, T1E1.4/2000-002R3, Vancouver, Canada, August 14, 2000

Authors

Stefano Galli received the Ph.D. in "Information Theory and Communications" from the University of Rome "La Sapienza" (Italy) in 1998. Stefano's main research efforts are devoted to the problem of automatic loop qualification and, more recently, to the analysis and performance assessment of wireless home networks and power line carrier systems. His research interests also include detection and estimation, channel equalization and coding, personal wireless communications and, more recently, DSL system and crosstalk modeling. Dr. Galli is a Member of the IEEE and has authored over 30 technical papers.

Dr. Kerpez received his Ph.D. in Electrical Engineering systems from Cornell University in 1989. He has analyzed, invented, and helped standardize new transmission systems, modulation techniques, codes, equalizers, multiplexing and networking techniques for digital local access telecommunications systems. Dr. Kerpez worked extensively on high-bit-rate digital subscriber lines (HDSL), and he was instrumental in the invention and subsequent definition of asymmetric digital subscriber lines (ADSL). He has been active in the T1E1.4 DSL standards committee since 1989. He has authored over 100 technical papers. Dr. Kerpez is a Senior Member of the IEEE.

John Lamb received a Master of Electrical Engineering degree from Stevens Institute of Technology in 1982. He began his career at Bell Laboratories designing integrated circuits for telephone systems. At Telcordia, he has been responsible for many phases of conformance testing for various types of DSL hardware, including test system design, test plan development and physical layer testing. He has authored over 50 analysis reports on DSL equipment ranging from chip sets to routers to line cards for switches and digital loop carrier systems.



Dr. Valenti received a Ph.D. in Physics from the City University of New York in 1977. He has contributed to the development of physical layer requirements for digital subscriber line (DSL) and Fiber in the Loop (FITL) systems. Much of Dr. Valenti's recent work has focused on the measurement and characterization of crosstalk, impulse and background noise in the copper loop access network. He has provided leadership for many years within the ANSI T1E1.4 Working Group where he is currently serving as Editor of the Spectrum Management standard.

David L. Waring received a Master of Science degree in Electrical Engineering from Georgia Tech in 1978. He began his career at Bell Laboratories designing subscriber loop electronics. He moved to Bellcore at its inception in 1984, where he worked on a number of projects including early Metropolitan Area Network field trials. He led teams that proposed requirements for HDSL and ADSL. He was project manager of several industry-leading interactive digital video trials. Dave currently leads research into "last mile" broadband local access and customer premises networks. Dave is a Senior Member of the IEEE.