DSL Spectrum Management Standard

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ABSTRACT

Different digital subscriber lines transmitting on loops in the same telephone cable generate crosstalk into each other. Two different DSLs are spectrally compatible if they can both use the same cable with low probability of significant degradation from crosstalk. Spectrum management is the process of ensuring spectral compatibility while optimizing the loop plant. Spectrum management requires knowledge of cable plant characteristics extending into higher frequency spectra (~ 1 MHz), the different DSL types, and how to compute the impact of crosstalk. Also, definitions of the level of crosstalk from one DSL type that significantly degrades another DSL type is needed, which can only reach broad acceptance through industry-wide agreements. In the United States, DSL Access Standards Committee T1E1.4 has created a technical definition of spectral compatibility, the Spectrum Management Standard T1.417-2001. The details of DSL spectral compatibility and compliance with the standard are presented in this article, as well as a brief history of the standard and some possibilities for the future.

INTRODUCTION

Digital subscriber line (DSL) technology enables Internet access and other digital services over existing copper telephone loops at high speeds, up to multiple megabits per second. Each DSL signal traverses a single twisted pair from a central office (CO) to a subscriber. Many twisted pairs, sometimes thousands, are bundled together in a single cable. Electromagnetic coupling between the different twisted pairs creates crosstalk between them. The twisting of the pairs keeps the crosstalk coupling between the balanced circuits on each pair to a low level at voice frequencies. Twisted-pair cabling was invented by Alexander Graham Bell, and, besides the telephone itself, was probably his greatest invention, allowing many circuits to share a single cable.

Crosstalk generally increases with increasing frequency, and since DSL frequencies extend into the megahertz region, crosstalk becomes the major limitation to high-speed DSL transmission [1–3]. Early DSL technologies, such as basic-rate integrated services digital network (ISDN) and high-bit-rate DSL (HDSL), were considered to be limited by self-near-end crosstalk (self-NEXT): the crosstalk between the same types of systems at the same end of the cable. The impact of self-NEXT was controlled by using low-frequency baseband transmission. Later, asymmetric DSL (ADSL) avoided most self-NEXT by transmitting upstream and downstream signals in different frequency bands, using frequency-division duplex (FDD). The fact that ADSL and other emerging systems were not limited by self crosstalk, coupled with an increasing number of different DSL types, caused *alien* crosstalk to become a limiting impairment, where alien crosstalk is crosstalk originating from a different type of DSL. DSL spectrum management involves controlling alien crosstalk to ensure spectral compatibility.

Competition in the local loop has caused a need to standardize DSL spectrum management. In the past, a service provider could choose to deploy only a set of loop transmission technologies that were spectrally compatible and ignore all others. This is still true in some locales. Now, however, many loop plants are unbundled, and a competitor may lease any loop and deploy a number of different systems. In the United States, many competitive local exchange carriers started providing broadband Internet access in the late 1990s by deploying DSL types that were potentially incompatible with existing services. A national standard emerged to provide a technical definition of spectral compatibility and allow competition to progress in an orderly fashion.

A common misunderstanding of many individuals who have recently become involved with DSL is that there is a "crosstalk problem" for only a few DSLs on only a few loops. However, every DSL has been designed and built, and runs with crosstalk limitations. For example, crosstalk limits HDSL to 1.5 Mb/s on two pairs up to 9 kft 26 gauge. With no crosstalk, approximately 10 Mb/s is achievable with almost the same technology on one pair of this length. Other DSL bit rates, loop reaches, and reliability would also increase dramatically without crosstalk. As time progresses more DSLs will be deployed and crosstalk will increase, which will cause failures if the plant is not engineered to function with crosstalk.

The received crosstalk power spectral density (PSD, the power as a function of frequency) equals the PSD transmitted by a crosstalk disturber plus the crosstalk power coupling in decibels. Spectral compatibility is often enforced by limiting the transmitted PSD to be below some defined PSD mask at all frequencies, which in turn limits the received crosstalk PSD. Different

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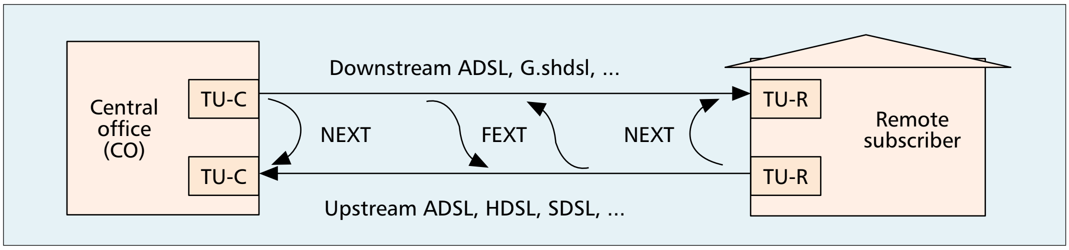

Figure 1. *NEXT and FEXT.*

PSD masks are defined for different classes of technologies and different loop reaches.

There are other impairments to DSL transmission besides crosstalk: impulse noise, radio frequency interference (RFI), and so on. However, these are almost totally independent of the generally dominant crosstalk impediment, and are not usually explicit in spectrum management. This article describes different DSL types and the crosstalk between them. A brief history of spectrum management, spectrum management standard compliance, and some future directions are also presented.

Digital Subscriber Line Technology

DSL transmits relatively high bit rates, from hundreds of kilobits per second to tens of megabits per second, on ordinary copper telephone loops. This is done by using much wider bandwidth than can be passed through a voice switch. Telephone loops are very dispersive at high frequencies, creating intersymbol interference. DSL transmission is enabled by adaptive transceiver techniques that overcome intersymbol interference: decision feedback equalization (DFE), discrete multitone modulation (DMT), or other techniques [2, 3].

DSL Alphabet Soup

Spectrum management requires knowledge and coordination of all DSL types, so a summary of common DSLs is given in Table 1. Symmetric systems send the same bit rate and PSDs upstream (from the customer) and downstream (to the customer), and are often baseband pulse amplitude modulated (PAM). Symmetric systems include single-pair high-speed DSL (G.shdsl), symmetric DSL (SDSL), high-bit-rate DSL (HDSL), and ISDN. ISDN, HDSL, and SDSL all use two binary, one quaternary (2B1Q) modulation, which is uncoded 4-level PAM. G.shdsl uses more bandwidth-efficient 16-level trellis coded PAM.

Asymmetric systems, including ADSL and very-high-bit-rate DSL (VDSL), send different PSDs upstream and downstream, and may be modulated with DMT, a type of orthogonal frequency division multiplexing, quadrature amplitude modulation (QAM), or PAM. There are also a number of proprietary DSL technologies that are not included in Table 1.

DSL Standards Bodies

A number of standards bodies are involved with DSL. In the United States, committee T1E1.4, DSL Access, is sponsored by the Alliance for Telecommunications Industry Solutions (ATIS) and accredited by the American National Standards Institute (ANSI). T1E1.4 has written standards for spectrum management, VDSL, splitters and in-line filters, HDSL4, HDSL2, ADSL, HDSL, ISDN, T1 lines, and so on.

The International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) Study Group 15 Question 4 (SG 15 Q 4) has written global standards for VDSL, G.shdsl, G.lite, G.dmt.bis, HDSL2, and so on. Many regional standards bodies use ITU standards for DSL by creating "pointer" standards that mainly reference the pertinent ITU standard and add a few regional parameters such as using the 2.048 Mb/s E1 rate in Europe or the 1.544 Mb/s T1 rate in North America.

The European Telecommunication Standards Institute (ETSI) Transmission and Multiplexing 6 (TM6) writes European DSL standards. The Japan Telecommunication Technology Committee (TTC) formulates Japanese standards. The Full Services Access Network (FSAN) group does not write standards per se, but has been active in defining VDSL. The DSL Forum addresses end-to-end system aspects of DSL, typically at layers above the physical layer. A new committee is IEEE 802.3ah, Ethernet in the First Mile (EFM), which is looking at DSL for carrying Ethernet traffic [4].

Crosstalk Impact

Spectral compatibility is an old subject, having been investigated for plain old telephone service (POTS), analog carrier, and other loop technologies deployed in the past. Particular concern has always been on characterizing telephone subscriber loop signaling and crosstalk in the frequency domain, hence the designation spectral compatibility.

NEXT and FEXT

Near-end crosstalk (NEXT) is defined as the crosstalk that couples between a receiving path and a transmitting path of DSL transceivers at the same end of two different subscriber loops within the same twisted pair cable (Fig. 1). Far-end crosstalk (FEXT) is the noise detected by the receiver located at the far end of the cable from the transmitter that is the noise source. FEXT is typically less severe than NEXT because FEXT is attenuated by the cable.

If $S(f)$ is the transmit PSD of the crosstalker in milliwatts per hertz, and $X(f)$ is the dimensionless [1, 5, 6] 1 percent worst-case crosstalk power coupling, then $S(f)X(f)$ is the received 1 percent worst-case crosstalk PSD. The 1 percent worst-case crosstalk power coupling is a model that is likely to be exceeded in no more than 1 percent of all telephone cables. Engineering to the 1 percent worst case is a standard industry

Asymmetric systems, including ADSL and very-high-bit-rate DSL (VDSL), send different PSDs upstream and downstream and may be modulated with discrete-multi-tone modulation, a type of orthogonal frequency division multiplexing, or with quadrature amplitude modulation (QAM), or PAM.

Acronym	Description	Standard(s)	Modulation	Number of pairs	Line bit rate	Approximate passband frequencies
ADSL	Asymmetric DSL	ANSI T1.413, ITU G.992.1	Discrete multitone (DMT)	One	Up to ~1 Mb/s upstream, up to ~8 Mb/s downstream	25–138 kHz upstream, 25–1104 kHz downstream
G.lite	"Splitterless" ADSL	ITU G.992.2, ANSI T1.419	DMT	One	Up to ~1 Mb/s upstream, up to ~1.5 Mb/s downstream	25–138 kHz upstream, 25–552 kHz downstream
ISDN, BRI, or BA	Integrated services digital network (ISDN) basic-rate (BRI) or basis access (BA)	ANSI T1.601 ITU G.961	2B1Q	One	160 kb/s symmetric	0–80 kHz
RADSL	Rate adaptive DSL	ANSI T1.TR.59	Carrierless amplitude/ phase (CAP), a type of QAM	One	Up to ~1 Mb/s upstream, up to ~8 Mb/s downstream	25–138 kHz upstream, 25–1104 kHz downstream
HDSL	High-bit-rate DSL	ITU G.991.1, ETSI TS 101 135, ANSI T1.TR.28	2B1Q	Two	1.544 Mb/s symmetric	0–370 kHz
HDSL2	High-bit-rate DSL, 2nd generation	ANSI T1.418 ITU G.991.2	16-level trellis coded (TC) PAM	One	1.544 Mb/s symmetric	0–300 kHz upstream, 0–440 kHz downstream
HDSL4	4-wire high-bit-rate DSL 2nd generation	ITU G.991.2, ANSI T1.418	16-level trellis coded (TC) PAM	Two	1.544 Mb/s symmetric	0–130 kHz upstream, 0–400 kHz downstream
SDSL	Symmetric DSL	ETSI TS 101 524	2B1Q	One	Up to 2320 kb/s symmetric	0–700 kHz
G.shdsl	Single-pair high-speed DSL	ITU G.991.2, ANSI T1.422	16-level trellis coded (TC) PAM	One	Up to 2320 kb/s symmetric	0–400 kHz
VDSL	Very-high-bit-rate DSL	ANSI trial-use standard T1.424, ITU G.vdsl, ETSI TS 101 270	DMT or QAM	One	Up to ~13 Mb/s upstream, up to ~22 Mb/s downstream	25 kHz–12 MHz
T1 line	T1 line	ANSI T1.403	Alternate mark inversion (AMI)	Two	1.544 Mb/s symmetric	0–1.544 MHz
E1 line	E1 line	ITU G.703	High-density bipolar (HDB3)	Two	2.048 Mb/s symmetric	0–2.048 MHz

Table 1. *Common broadband copper loop transmission systems.*

practice that ensures low probability of service failure. The 1 percent worst-case NEXT and FEXT power couplings are shown in Fig. 2 along with some individual measurements [6].

The 1 percent worst-case crosstalk power coupling $X(f)$ varies as $6\log_{10}(n)$ dB, where n is the number of crosstalk disturbers in the cable binder. It is difficult to count or control n, so it is typically assumed that the binder is filled with crosstalkers and $n = 24$ or $n = 49$, which is at most 10 dB pessimistic compared to $n = 1$ disturber. The received noise is the sum of all crosstalk, NEXT and FEXT, plus low-power –140 dBm/Hz flat background noise. NEXT, and separately FEXT, from different crosstalker types is summed with the FSAN crosstalk summation method [7].

Spectral Compatibility Calculations

The amount of degradation of a DSL's performance caused by crosstalk from another DSL can be accurately forecast by a computer simulation calculation. A statistically worst-case environment is simulated using the 1 percent worst-case crosstalk coupling, highest probable number of crosstalk disturbers, and long loops. Then the transmission performance (i.e., bit rate) is accurately calculated with computer programs. If the performance meets some target, nearly all deployed DSLs (at least 99 percent) will also meet that target. This is more efficient than lab testing many combinations of two DSL types in a cable until 99 percent have passed. Furthermore, there are many different DSL types that need to be crosschecked. Moreover, computer simulation is repeatable, and simulation parameters have been standardized so that results from multiple parties are in agreement. The simulation parameters have been calibrated with lab measurements.

Generally, there are three types of DSL performance calculations: total crosstalk power, single-carrier equalizer equations, and multicarrier "water filling." For specific details of these calculations see Annex A of the Spectrum Management Standard [1]. Spectral compatibility with POTS and other narrowband services is calculated simply by determining if the total received crosstalk power is above or below a certain threshold.

Wideband single-carrier DSLs almost universally employ a receiver with a decision feedback equalizer (DFE), and, if trellis coded, the feedback portion is implemented in the transmitter with a precoder. Spectral compatibility with single-carrier baseband PAM and passband QAM DSLs is determined by calculating the signal-to-noise ratio (SNR) at the output of the DFE with the modified Wiener-Hopf equations derived by Salz [2, 3]. The SNR margin is the computed SNR minus the SNR required for 10^{-7} bit error rate (BER). A positive SNR margin, usually 6 dB or more, is needed to ensure reliable service with unknown impairments and temperature variations [1–3].

ADSL and G.lite are modulated with DMT, which transmits up to 255 orthogonal QAM subchannels at tones with 4.3125 kHz spacing up to 1104 kHz. Receivers generally incorporate a front-end pre-equalizer, and it is safe to assume that each subchannel is flat across its narrow 4.3125 kHz bandwidth. The Shannon capacity of each tone is computed assuming 6 dB margin, 3 dB coding gain, and 9.75 dB SNR gap; then these are all summed to compute the system bit rate.

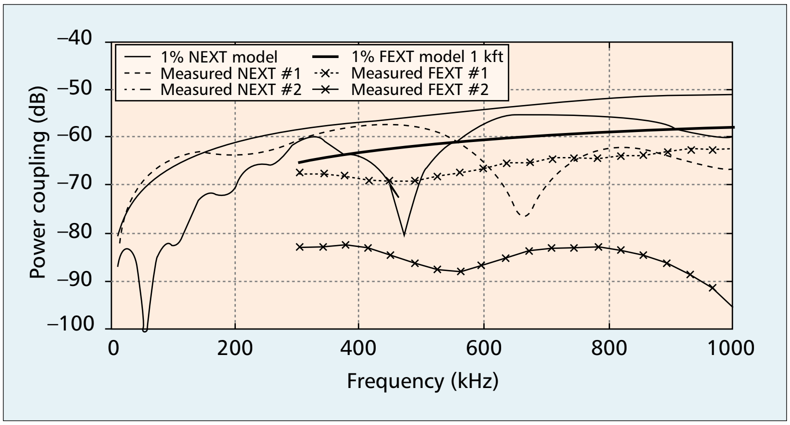

Figure 2. *1 percent worst-case single crosstalk disturber crosstalk power coupling models and measurements of pair-to-pair NEXT and FEXT. FEXT is on a 1 kft 24 gauge loop.*

An Example: HDSL Crosstalk into Downstream ADSL

Figure 3 shows an example of downstream ADSL transmitted on a 15 kft 26 gauge loop with two types of crosstalk: self-FEXT from other ADSLs, and alien-NEXT from HDSLs. The HDSLs would be repeatered on such a long loop. The upper left plot shows the transmit PSDs of HDSL and downstream ADSL. The lower left plot shows the power couplings (power transfer functions) of the 15 kft loop, and the 1 percent worst-case 24-disturber NEXT and FEXT for the 15 kft loop. Adding the ADSL transmit PSD to the loop coupling (in decibels) gives the received ADSL PSD in the upper right plot. Adding the ADSL transmit PSD to the FEXT coupling gives the received FEXT PSD from ADSL, and adding the HDSL transmit PSD to the NEXT coupling give the received NEXT PSD from HDSL, in decibels. Subtracting the appropriate crosstalk PSD from the received ADSL signal PSD gives the lower right hand plot, the received SNR.

Downstream ADSL has a passband extending from about 138 kHz to 1104 kHz. At a frequency in the ADSL passband, as the SNR increases more bits can be transmitted by using a constellation with more signal points at that ADSL frequency. The minimum constellation is QPSK,

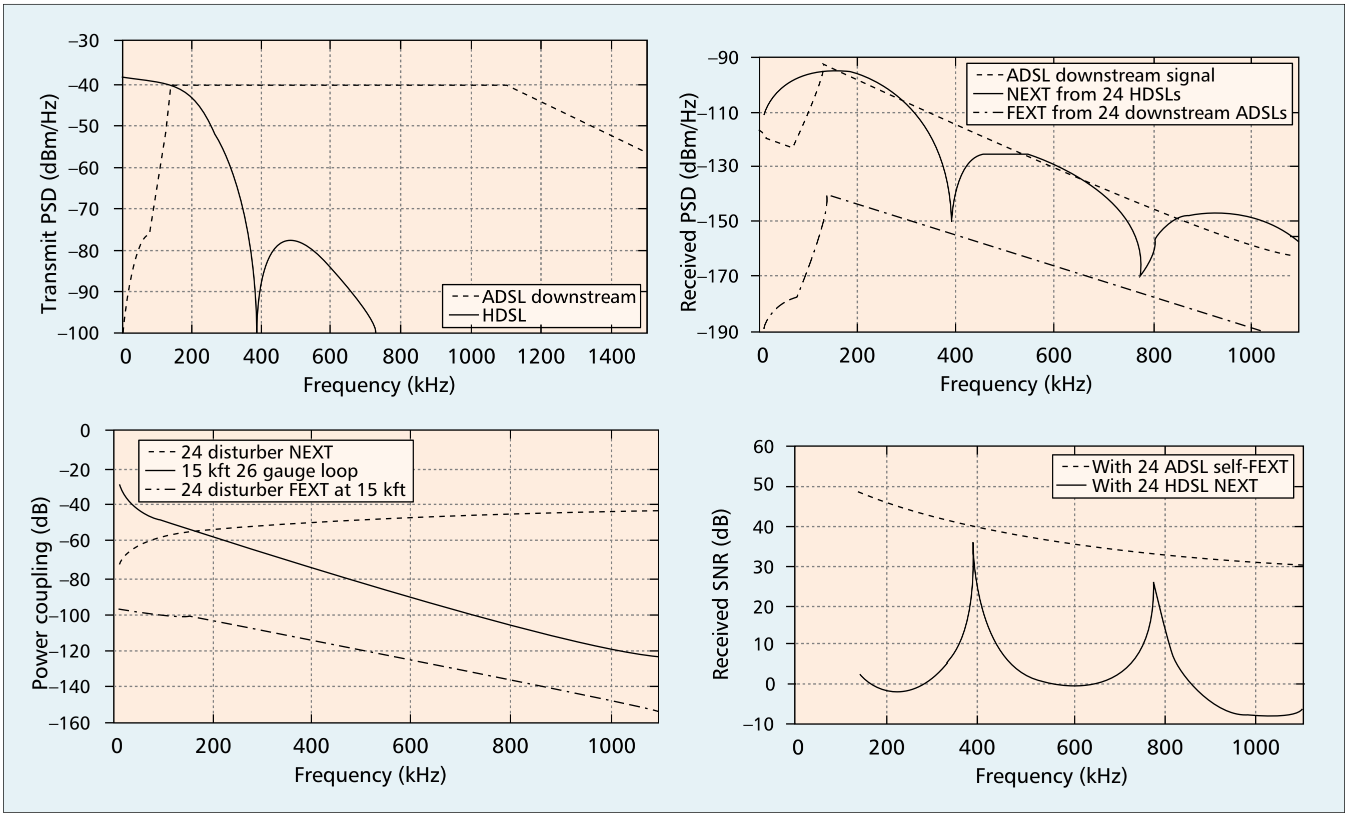

Figure 3. *Downstream ADSL performance with self-FEXT from 24 other ADSL crosstalk disturbers, and with 24 HDSL NEXT disturbers on a 15 kft 26 gauge loop.*

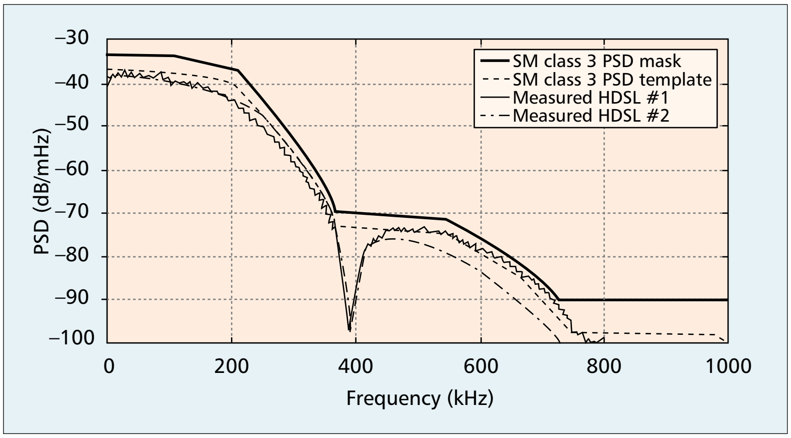

Figure 4. *Spectrum management class 3 (SM3) PSD mask, PSD template, and a couple of measured HDSL transmit PSDS.*

requiring at least about 17.5 dB to be useful [1]. The bottom right plot in Fig. 3. shows that few frequencies are at all useful with HDSL NEXT, whereas with self-FEXT all ADSL frequencies are useful. Adding –140 dBm/Hz background noise to the crosstalk, and performing the calculations in the spectrum management standard [1]; ADSL can transmit 1102 kb/s downstream on the 15 kft 26 gauge loop with self-FEXT, but it can only transmit 96 kb/s downstream with HDSL NEXT.

HDSL generates strong levels of crosstalk relative to the weak received ADSL signal on this loop. This results in poor ADSL performance compared to ADSL self-crosstalk, so HDSL can be said to be incompatible with ADSL on such a long loop. HDSL is compatible with ADSL on loops no longer than about 9 to 12 kft [1].

Creation of a Technical Definition of DSL Spectral Compatibility

Spectral compatibility was a study project in DSL access standards committee T1E1.4 in the mid-1990s. An early definition, in 1997, of DSL spectral compatibility was conformance to one of three "composite PSD masks": one for all downstream transmissions, one for upstream within CSA range, and one for upstream beyond CSA range [8]. This approach was very coarse-grained.

In the United States, the 1996 Telecommunications Act created an environment to foster competition by unbundling the local loop, allowing competitive carriers to provide broadband DSL services. Incumbent local exchange carriers could no longer control which technologies were deployed in their loop plant. Operators desired an industry-wide standard to allow DSL deployments by all parties without incompatible technologies causing service outages. Committee T1E1.4 took on the task of creating a technical definition of spectral compatibility, starting a standards project in 1998.

The concept of spectrum management classes first appeared in late 1998, was documented in many standards contributions in early 1999 [9–11], and is still in use. There are nine separate spectrum management (SM) classes. A class represents a set of technologies whose spectra and crosstalk impact are approximately the same, and membership within a class is proven through conformance with the PSD template specific to that class. For example, spectrum management class 3 (SM3) represents HDSL systems from all different vendors.

In mid to late 1999 the Internet bubble was full blown, and numerous new DSL service providers began to attend committee T1E1.4 spectrum management meetings. Some parties viewed many of the assumptions in calculating spectral compatibility as overly pessimistic. Others countered that performance in the field was often worse than the calculations predicted. Meetings became highly contentious.

A major conflict was defining spectral compatibility between asymmetric ADSL and symmetric SDSL. Most DSLs are limited to some performance level by self-NEXT and this performance should be maintained with alien NEXT. But ADSL has no self-NEXT and no such naturally defined performance level. Some operators deploying ADSL were concerned that crosstalk from high-speed SDSL lines would greatly lower ADSL bit rates. Some other operators deploying SDSL thought that overly pessimistic assumptions led to overprotection of ADSL and overly restrictive spectrum management limits on SDSL. This impasse was broken through in January 2000 by the "Fort Lauderdale Agreement" that SDSL is allowed at the SDSL 49-disturber self-NEXT reach, and then the performance of ADSL cannot be degraded beyond that with the resulting level of SDSL crosstalk. This definition of spectrally compatible SDSL was ensconced as a new method of spectrum management standard conformance, "technology-specific" guidelines. SDSL was categorized with 20 different bit rates and spectrally compatible loop deployment guidelines in 500 ft increments. This fine-grain structure allows, for example, 320 kb/s SDSL at 15.5 kft, whereas the nearest spectrum management (SM) class is allowed only to 11.5 kft. Technology specific guidelines for G.shdsl and HDSL4 were subsequently added to the standard.

Another issue was the list of systems with which new technologies need to demonstrate spectral compatibility, at times called "protected" services, then "guarded" sy stems, and finally "basis systems." At one point T1 lines were taken off this list.

After settling the major issues, defining all classes, test procedures, PSD conformance criteria, and other specifications, the spectrum management standard was balloted several times, issue 1 was finished in November 2000, and became Standard T1.417-2001 in January 2001. In order for this timely completion, issue 1 only addressed systems that are CO-based, and deferred defining spectral compatibility of deployments from remote terminals and repeatered lines, which are discussed further in a later section of this article.

Spectrum Management Standard T1.417-2001

This section gives a simple explanation of what it takes to comply with Spectrum Management Standard T1.417-2001 [1], but only the standard itself can be used to demonstrate compliance.

Compliance with the standard only determines the spectral compatibility of a system, and does not determine if a system can or cannot be legally deployed in any particular jurisdiction.

BASIS SYSTEMS

The general concept of the Spectrum Management Standard is to require spectral compatibility with all members of the set of "basis systems." Basis systems are usually standardized, and are expected to be widely deployed. The basis systems are:

- Voice grade services
- Enhanced business services (P-Phone™)
- Digital data service (DDS)
- ISDN BRI
- HDSL
- HDSL2
- ADSL, nonoverlapped
- RADSL
- Splitterless ADSL (G.lite)
- G.shdsl
- VDSL

SDSL was a basis system in issue 1 of the Spectrum Management Standard, replaced by G.shdsl in issue 2; and VDSL will probably be added in issue 2.

A new DSL technology must not generate crosstalk that significantly degrades the performance of *any* basis system. Ideally, crosstalk from all the basis systems should not significantly degrade the new DSL technology's performance, but this is not required. The definition of a fixed set of basis systems allows a new technology to demonstrate spectral compatibility without requiring potentially unobtainable knowledge of all other new technologies. Being a basis system in no way ensures conformance with the standard, and basis systems themselves may not be spectrally compatible on many loops.

PSD MASKS, TEMPLATES, AND CONFORMANCE

A system cannot transmit more power at any frequency than the PSD mask to which it conforms. To include as many systems as possible, the PSD mask of a given class should be loose, allowing relatively high power levels. But to ensure the best spectral compatibility, the PSD mask should be tight. This led to the definition of a PSD template [9–11], illustrated in Fig. 4. The PSD template approximates the actual PSDs of the systems it represents, and crosstalk is modeled as arising from the PSD template. The PSD mask is usually defined to equal the PSD template plus 3.5 dB and sets a hard upper limit to transmit PSDs, but is relatively loose. To offset this looseness, a sliding window normalized power constraint must also be satisfied: that $10\log_{10}$ of the sum of the ratio of the measured power (in milliwatts) divided by the PSD template (in milliwatts) cannot exceed 1 dB, in any 100 kHz sliding window. Some classes and technologies have slightly different PSD conformance criteria; for example, HDSL2 and G.shdsl need only comply with a hard PSD mask that is about 1 dB above the PSD template.

Section 6 of the Spectrum Management Standard defines PSD template conformance criteria, and Annex M explains why the particular sliding window constraint is used. It is based on equivalent noise, which was derived using the fact that channel capacity is directly proportional to signal power in decibels, and inversely proportional to noise power in decibels [11].

The total average transmit power across the entire bandwidth of a system is also limited. This limit is often a decibel or so below the total average transmit power of the PSD template, and then the template cannot be entirely filled. Compliance with the Spectrum Management Standard has generally been demonstrated analytically so far, but complete lab measurement procedures are contained in [1, section 6].

DEPLOYMENT GUIDELINES

Some technologies and classes are spectrally compatible only within a certain radius from a CO. For example, HDSL, HDSL2, and high-bit-rate SDSL or G.shdsl have wideband upstream spectra which create NEXT that can debilitate downstream ADSL on long loops. Telephone loops often have unterminated sections attached to them between the normal endpoints, called bridged tap. The working loop length (the length of all loop sections excluding bridged tap) on which a crosstalker transmits is sometimes limited so that it may not disturb the highly attenuated signals of basis systems on very long loops. This length, rounded to the nearest 500 ft, is a deployment guideline. Bridged tap is ignored because what matters is the loop of a basis system that receives crosstalk, which usually has about the same working length as the loop of the crosstalker, but not the same bridged tap. There are other deployment guidelines, such as not allowing reverse ADSL.

Loop length deployment guidelines are expressed in equivalent working length (EWL). In issue 2 of the Spectrum Management Standard, EWL = $L_{26} + (0.75)L_{24} + (0.60)L_{22} + (0.40)L_{19}$, where L_{26}, L_{24}, L_{22}, and L_{19} are the working lengths of 26-, 24-, 22-, and 19-gauge cable in the loop. The attenuation of a loop's working length approximately equals that of a pure 26 gauge loop of length EWL.

TIME DOMAIN REQUIREMENTS

By definition, a PSD is a long-term time average. Startup signals and instantaneous transmit voltages are not explicitly limited by the Spectrum Management Standard. Crosstalk samples are usually well approximated by a Gaussian probability distribution [12], and this is assumed in the Spectrum Management Standard.

There are some systems that transmit bursts of data and are quiet in between. These are known as short-term stationary (STS) systems, and their PSDs are measured while the transmitters continuously transmit. There are some requirements in the Spectrum Management Standard for STS systems: intentional synchronization is not allowed, the minimum duration of each burst is 246 μs, and systems must transmit at least 1 percent of the time in any 4 s. At startup, ADSL modems measure noise for 4 s, and the 1 percent requirement helps enable adaptation to STS crosstalk.

A DSL may adapt while STS crosstalkers are off, and then the DSL may be mis-adapted while the STS crosstalkers are on, potentially causing many dB of degradation compared to stationary crosstalk. However, STS vendors have presented extensive results showing that STS crosstalk only

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SM class or technology	Deployment guideline, EWL 26 gauge kilofeet (kft)	SM class members
SM class 1 (SM1)	Any non-loaded loop	ISDN, SDSL ≤ 300 kb/s, 2- and 4-line pair gain
SM class 2 (SM2)	11.5	SDSL < 520 kb/s
SM class 3 (SM3)	9	HDSL, SDSL < 784 kb/s
SM class 4 (SM4)	10.5	HDSL2
SM class 5 (SM5)	Any non-loaded loop	Non-overlapped ADSL
SM class 6 (SM6)	13 kft	VDSL
SM class 7 (SM7)	6.5 kft	SDSL < 1568 kb/s
SM class 8 (SM8)	7.5 kft	SDSL < 1168 kb/s
SM class 9 (SM9)	13.5 kft	Overlapped ADSL
Technology:		
2B1Q SDSL	20 different, vary with bit rate	2B1Q SDSL < 2320 kb/s
G.shdsl	19 different, vary with bit rate	G.shdsl < 2320 kb/s
HDSL4	Any non-loaded loop	TC-PAM 776/784 kb/s asymmetric PSD

Table 2. *Spectrum management (SM) classes and spectrally compatible technology specific guidelines. Nonloaded loops have no load coils.*

causes minor degradations. STS may be modeled with many different assumptions about traffic and victim systems' adaptation mechanisms, and the impact of STS crosstalk is still under study. Recent findings [13] show that typical STS crosstalk may cause a few decibels more degradation than stationary crosstalk, and a single STS disturber appears to have a worse effect than many STS disturbers — the opposite of stationary crosstalk.

OTHER REQUIREMENTS

In addition to PSD conformance, compliant systems must meet defined limits of transverse balance and longitudinal output voltage. The frequencies for which these requirements apply are defined for each class or technology in an earlier section, with testing methodology in a later section of the Spectrum Management Standard. Transverse balance and longitudinal output voltage requirements ensure that the signal transmitted on a pair is balanced so that the metallic voltage between the two conductors of the pair only weakly couples into longitudinal voltages from a conductor to ground. Transverse balance is a ratio relative to the transmit metallic signal, and longitudinal output voltage is an absolute measure [2].

THREE METHODS OF SM STANDARD COMPLIANCE

There are three methods of complying with the Spectrum Management Standard:

- Belong to one of nine SM classes
- Satisfy technology-specific guidelines
- Pass all analytical evaluations defined in Annex A

The first two methods are very similar, involving conformance to predefined PSD templates, and are summarized in Table 2. SDSL and G.shdsl have PSD templates and deployment guidelines that vary with transmitted bit rate. Recall that the deployment guidelines in Table 2 only ensure that crosstalk impact will be acceptable, and the SM class or technology will function within loop lengths only in rough correspondence.

Annex A compliance, also known as "method B," involves running a well defined set of computations to analytically demonstrate spectral compatibility with each basis system. Annex A conformance can be difficult to verify. Members of the standards committee worked to ensure that all calculation parameters were fully specified and generated repeatable results, but people who have not gone through this process could get different results. There is a publicly available tool, at http://net3.argreenhouse.com [14], that can perform all Annex A computations, but this or other software must be properly used to demonstrate compliance, and other requirements must also be satisfied.

Annex A assumes full binders and 1 percent worst-case crosstalk. Typically a reference crosstalker type is defined (e.g., SM class 3 is the reference for compatibility with HDSL) and two crosstalk scenarios must pass: 49 or 24 "new technology" crosstalkers, and 24 or 12 "new technology" crosstalkers plus 24 or 12 reference crosstalkers. SNR margins must be within delta (typically 0 to 1 dB) of the margins with 49 or 24 reference crosstalkers. If the evaluation initially fails, loop lengths of both the crosstalkers and the basis system may be decreased until it passes. Evaluations are performed separately for each basis system, and the deployment guideline is the minimum loop length for which all evaluations pass.

Using a DSL's exact PSD in Annex A calculations will often allow a longer deployment guideline (maybe 1 kft) than using its PSD template, since the exact PSD is often below the PSD template with which it conforms.

FUTURE POSSIBILITIES OF DSL SPECTRUM MANAGEMENT

NEAR TERM: ISSUE 2 OF THE SPECTRUM MANAGEMENT STANDARD

Issue 1 of the Spectrum Management Standard, T1.417-2001, specifies only CO-based systems. At the time of writing, work on issue 2 focused on VDSL, systems deployed from remote terminals (RTs), and repeatered lines. An agreement has been reached for repeatered lines: to relax evaluations with crosstalk from repeatered lines by 1.8 dB, equal to halving the number of disturbers, because repeatered lines are sparsely deployed; and to evaluate every possible repeater location in 500 ft increments.

At the time of writing, there is no broad agreement on RT-based DSL. ADSL or VDSL deployed from an RT can generate FEXT into CO-based DSL that is almost as powerful as NEXT if the distance from the RT to the CO-based remotes is a few kilofeet or less. While debilitating to CO-based ADSL, this is not a likely event.

Work on issue 2 has also defined spectrum management class 6 for VDSL, and analytical criteria for spectral compatibility with VDSL and G.shdsl.

Longer Term: Dynamic Spectrum Management

Longer-term research is generally focused on dynamic spectrum management (DSM), which incorporates parameters of the loop plant environment and loop transmission systems that are time- or situation-dependent.

DSM may be centrally coordinated at a digital subscriber line access multiplexer, with characteristics of individual crosstalk couplings and crosstalking transmitters extracted from DSL transceivers, automated tests, or loop databases. These measurements would then all be fed into a centralized spectral maintenance center (SMC), which stores and processes the data, and then possibly issues commands to coordinate DSL transmissions. The centralized DSM apparatus could also be used by a service provider to enhance DSL monitoring, diagnostics, and maintenance.

DSM may also be performed autonomously by individual transmitters. Total average transmit power levels may be preset, and then DSL transceivers adapt not only to optimize their own performance, but also to minimize the impact of their crosstalk on other DSLs. Recent work [9] has shown that autonomous DSM can achieve much of the gains possible in the near term. Centralized DSM is more likely at small fiber-fed remote terminals in the long term.

DSM coordination may evolve in three phases:

- Stage 0: Uncoordinated, current practice — 1 Mb/s. Some improvement may be possible by using measured crosstalk instead of always assuming worst-case.
- Stage 1: Spectrum balancing — 10 Mb/s. Transmit PSDs of DSLs are jointly or autonomously optimized to lower crosstalk. For example, two DSLs could use distinct frequency bands, eliminating crosstalk entirely.
- Stage 3: Vectoring, from a fiber-fed remote terminal — 100 Mb/s. Multi-user techniques are used to jointly optimize all transmit symbol streams and joint receiver structures. DSM operates in real time.

Much work on DSM has been conducted at Stanford University. Current work on DSM [9, 15, 16] is somewhat exploratory and focuses on autonomous adaptation, jointly optimizing transmit spectra and signals, crosstalk identification, and crosstalk cancellation.

Conclusions

DSL spectrum management requires knowledge of all DSL types and how their crosstalk effects other systems. Spectrum management also requires defining the level of degradation from crosstalk that is spectrally compatible or not. This can be hard to define when some DSL types are favored by some companies and not by others, such as was the case with SDSL and ADSL.

In the United States, committee T1E1.4 has overcome these obstacles and has issued the Spectrum Management Standard T1.417-2001 [1], containing a detailed definition of spectral compatibility that has broad industry consensus. This standard was forged at a time of much competition in the local loop, and represents a compromise between incumbent and competitive carriers. This standard provides an unambiguous yardstick for determining how new DSL technologies may coexist in the loop plant.

There are many near-term issues that were not addressed by the first issue of the Spectrum Management Standard, including RT-based DSL, repeatered lines, VDSL, and some aspects of short-term stationary (STS) systems. These are progressing in draft issue 2 of the Spectrum Management Standard. Beyond that, dynamic spectrum management (DSM) holds the possibility of greatly increased bit rates and reliability, by treating crosstalk as manmade interference that can be measured, understood, and mitigated with multi-user transceiver techniques.

Longer-term research is generally focused on dynamic spectrum management (DSM), which incorporates parameters of the loop plant environment and loop transmission systems that are time or situation dependent.

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Biographies

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