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White Paper

De-Mystifying Spectral Compatibility of Bonded Copper Systems - Why DMT is Superior to SHDSL

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Abstract

This paper compares the spectral impact of symmetric DMT and SHDSL systems and provides clear evidence as to why DMT systems provide superior spectral compatibility, especially when they're enhanced with MIMO on DMT functionality. It discusses the major technical reasons behind their differences and provides illustrative examples of why simplicity, performance and predictability are the fundamental reasons why DMT systems provide superior performance.

Introduction

Service providers are continually faced with how to maximize bandwidth to customers, both residential and business, while maintaining the integrity of their networks. A key solution that they're using to maximize bandwidth with their existing facilities is copper bonding. In fact, copper bonding technology is being used so prevalently throughout service provider networks, that it has quickly become a critical element of many service provider's fiber migration strategies.

However, as carriers use the same copper facilities to serve both residential and business customers, spectral compatibility is an increasingly important consideration. The goal of this paper is to shed additional and very valuable light on this topic by comparing the spectral impact of symmetric DMT and SHDSL copper bonding systems. It provides concrete evidence for why DMT systems provide superior performance and are significantly more spectrally friendly, particularly when they've been enhanced with MIMO on DMT functionality. It shows that simplicity, performance, and predictability are the three fundamental reasons behind DMT's superiority over SHDSL.

Today's DSL modems are capable of transmitting signals over a wide bandwidth, but the telephone copper pairs were not originally designed to transport such signals. The resulting pair-to-pair crosstalk can seriously damage the throughput of every service in the binder and threaten the integrity of the network unless strict spectral rules are adhered to. This issue has resulted in deployment guidelines developed by each carrier, an ANSI spectral management standard (T1.417) of several hundred pages providing more guidance, and a lot of heated discussions on how to best contain crosstalk and maximize the utility of the copper asset.

The introduction of bonded copper business access systems into the network, has brought renewed interest on the question of spectral compatibility of those systems with residential ADSL2/VDSL2 systems. Bonded copper systems available today rely on two different and distinct technologies:

- DMT-based systems (with MIMO), which utilize the same transmission technology as the ADSL2/VDSL2 systems.
- HDSL2/SHDSL-based systems, which utilize variants of the legacy HDSL technology.

It is therefore natural to wonder what the spectral compatibility implications of each technology are, and which one provides the best performance for the same level of spectral impact. This question is typically clouded in an impenetrable fog of convoluted technical arguments, exhaustive parade of special cases, and conflicting information from different vendors. The reality is actually not that bad. The spectral impact of a new service is explained by very basic principles that are easily understood. And the difference in impact of the different technologies is also explained by the very basic way they utilize the transmission spectra. Once the basic mechanism of spectral impact is clear, the various plots of impact and performance make more intuitive sense.

This paper compares the spectral impact of DMT-based and SHDSL-based bonded systems and explains the basic differences in impact based on the fundamentally different ways they utilize the transmission spectrum. It shows that the more modern DMT based transmission scheme is inherently spectrally friendlier than the legacy SHDSL systems for three reasons:

- DMT systems do not impact the upstream of any service (symmetric or asymmetric, ADSL of HDSL)
- DMT systems do not impact the downstream of any symmetric service (DMT or HDSL)
- The DMT impact on the downstream of ADSL2 can be controlled to a target level by spectral mask selection ahead of time and independently of the provisioned rate. The SHDSL impact cannot be predictably controlled and will vary with varying conditions in the binder (depending on the rate and modulation the SHDSL modem will train to)

The Basic Mechanism of Spectral Impact

Copper pairs travel great distances and in close proximity to each other in binder groups and cables in the access plant. Crosstalk is generated because of electro-magnetic coupling among the pairs and can be due to near-end (NEXT) or far-end (FEXT) transmissions as shown in Figure 1 and Figure 2, respectively.

NEXT is by far the strongest type of crosstalk and the one that should be scrutinized in the context of bonded copper systems. FEXT becomes important for very high bandwidth systems deployed in short loops (e.g., less than 2-3 Kft) but is not the main concern in this paper. For reasons of simplicity and clarity of presentation, we will not discuss FEXT any further in this paper.

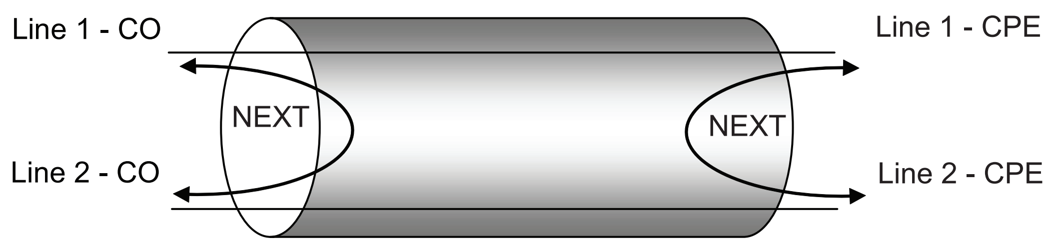

Figure 1: Example of NEXT Interference Between Two Pairs

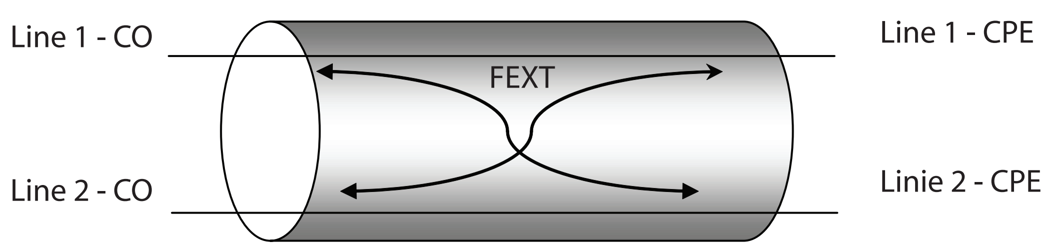

Figure 2: Example of FEXT Interference Between Two Pairs

Legacy HDSL/SHDSL Systems Confined by Overlap Spectra Design

In order to understand the spectral impact of each system, it is necessary to discuss the transmission spectrum it utilizes. Figure 3 depicts the upstream and downstream spectrum (or power spectral density – PSD) of legacy HDSL/SHDSL type systems. These systems utilize the same spectrum for upstream and downstream transmission as shown in the figure. For this reason they are often called "overlap spectra" systems, or "echo cancelled" systems. This type of spectral design is the worst possible from a self-spectral impact standpoint for the following reasons:

- Upstream and downstream transmissions are in the same band and interfere with each other
- NEXT crosstalk is generated into other similar systems both in the upstream and the downstream
- Especially for bonded systems this design is undesirable because the performance of the system is reduced the more pairs are added to the bonded group or the more bonded groups are deployed in the binder

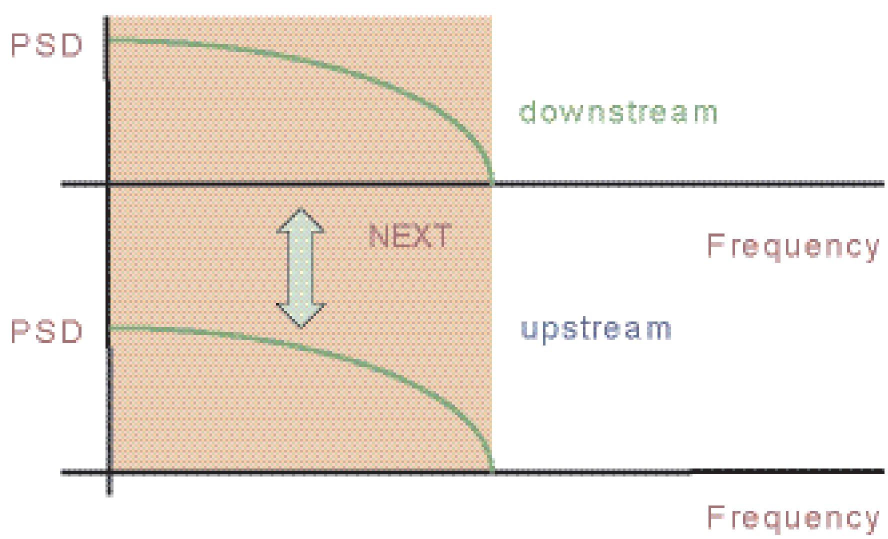

Figure 3: Overlapping Upstream and Downstream Spectra Create NEXT Crosstalk

This “overlap spectra” technology has its roots in the older ISDN modems, which used a narrow spectral band in the low frequencies, where NEXT is not a great concern. Later HDSL and especially SHDSL modems however, take this approach to wider bandwidths where NEXT is of great concern and “overlap spectra” is not a recommended spectral design. Fortunately, newer technology DMT modems (e.g., ADSL/ADSL2, VDSL/VDSL2) do not take this approach.

Starting with the advent of ADSL modems, the spectral design changed from “overlap spectra” to “band separation” or “frequency division multiplexing”. This is shown in Figure 4 where the upstream and downstream transmissions utilize different bands. This spectral design is far superior from a self-spectral impact standpoint for the following reasons:

- Upstream and downstream transmissions are in different bands and do not interfere with each other
- NEXT crosstalk is generated only “out of band” both in the upstream and the downstream
- Especially for bonded systems this design is desirable because the performance of the system is not negatively affected when more pairs are added to the bonded group or more bonded groups are deployed in the binder
- If these systems are equipped with MIMO, then the performance is actually improved when more pairs are added to the bonded group

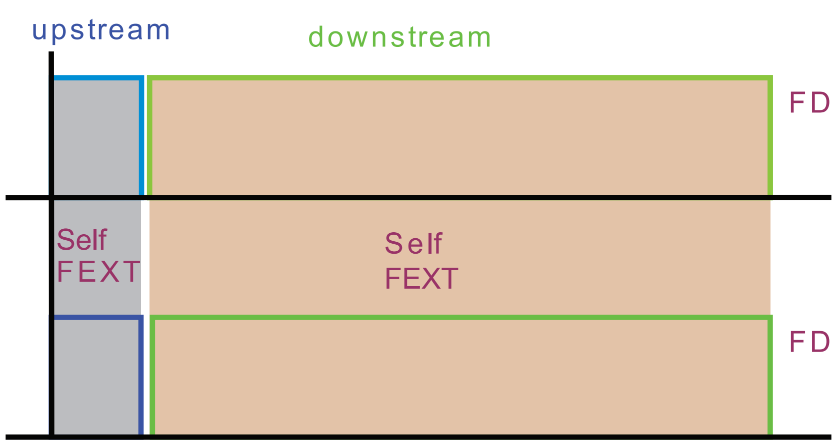

Figure 4: Frequency Band Separation Eliminates NEXT

The above observations on self crosstalk apply to DMT systems that are asymmetric as well as symmetric. The only difference between the two is the location of the breakpoint between the upstream and downstream bands. Asymmetric systems give more bandwidth to the downstream band while symmetric systems use a more balanced spectral design.

The situation is somewhat more complicated when there are mixtures of symmetric and asymmetric systems in the binder. This case is depicted in Figure 5. Notice that the upstream/downstream breakpoints are not aligned in this case and a band of overlap between upstream and downstream does appear. In this band, NEXT crosstalk is introduced into both the symmetric and asymmetric systems.

The natural question in this case is how the NEXT impact from symmetric DMT systems compares with the NEXT impact from symmetric HDSL/SHDSL systems. This question is addressed next.

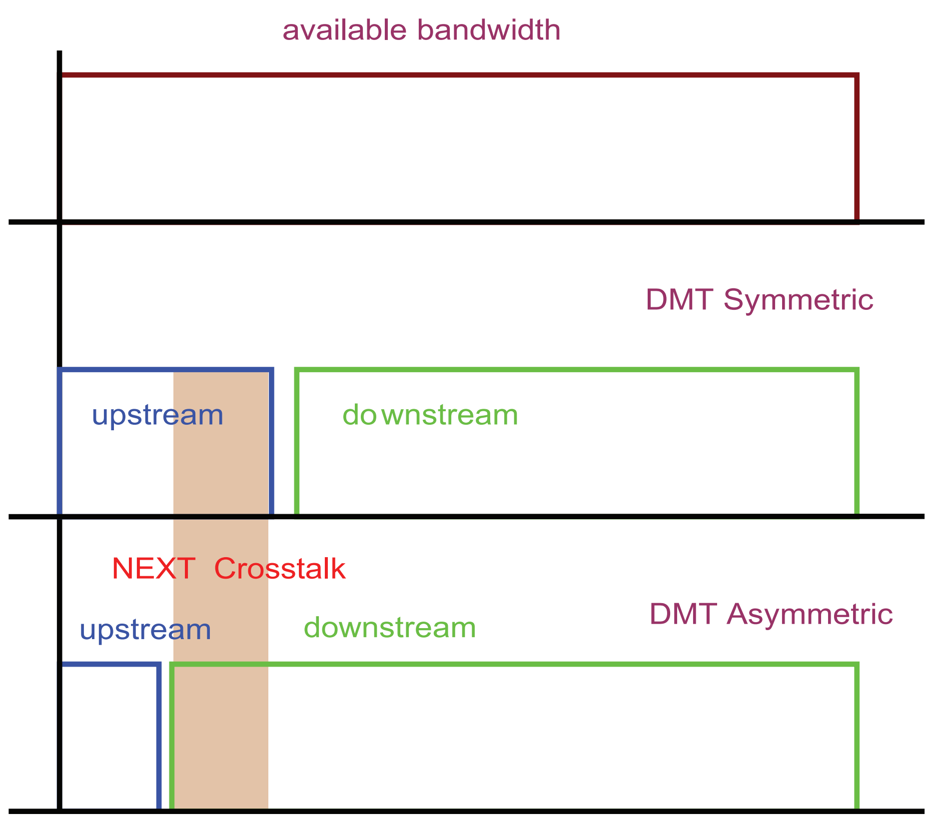

Figure 5: NEXT between Symmetric and Asymmetric DMT System

DMT's Simplicity, Performance and Predictability Mitigate It's Impact on ADSL/ADSL2+

Figure 6 shows the spectrum of an ADSL victim and the bands of NEXT overlap with:

- A symmetric DMT system (top)
- A symmetric HDSL/SHDSL system (bottom)

Notice that both systems overlap and affect ADSL downstream while only the HDSL/SHDSL system overlaps/affects ADSL upstream.

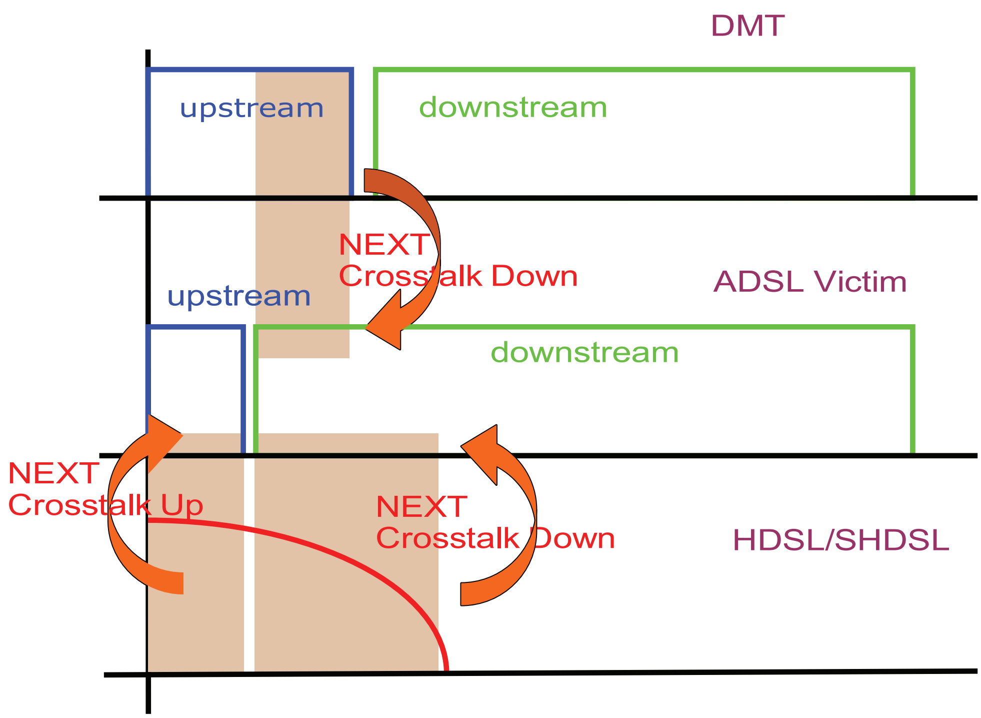

Figure 6: NEXT Crosstalk from DMT and SHDSL Systems

The degree of interference into ADSL downstream depends on how wide the up-stream band is. Both the DMT and the SHDSL based systems can vary the width of the upstream band and trade off performance for spectral friendliness. For this reason, it is easy to create special cases and unfavorable comparisons for either system, if one is not careful to compare apples to apples, that is, systems with similar upstream bandwidths.

In this paper we will avoid obfuscation and will not tire the reader with parades of special case performance graphs showcasing one technology but providing little intuitive understanding. Instead, we will explain the key reasons why the DMT technology is spectrally superior to SHDSL, and will provide some limited and general case performance plots to illustrate the difference.

The DMT system is superior to SHDSL for the following reasons:

- **Simplicity**: DMT spectral masks are set at startup time and are ndependent of the data rate. SHDSL spectral masks depend on the rate the modem syncs at and may actually change when conditions in the binder change. One cannot be sure beforehand how much impact an SHDSL system is going to have to a victim ADSL. The situation is even worse with enhanced SHDSL where the transmit spectrum depends not only on the data rate but also on the modulation the modem chooses (16 PAM of 32 PAM).

- **Performance**: Because of less self-interference and because of MIMO capabilities, DMT systems have higher performance. Therefore, DMT systems can achieve the equal of superior data rate while utilizing less bandwidth. Figure 7 shows some examples of DMT upstream spectra and HDSL/SHDSL spectra. Notice how wide the bandwidth of the 2.3 Mbps SHDSL system is, while the DMT systems can achieve more than that rate with less available spectral bandwidth.

- **Predictability**: DMT systems have predictable performance regardless of future changes, including adding more pairs to the bonded group or adding more bonded services in the binder. Enhanced SHDSL systems are unpredictable. When more bonded services are deployed in the binder, SHDSL system performance will deteriorate resulting in either failure to maintain the service or in retraining and expanding the bandwidth (and associated spectral impact).

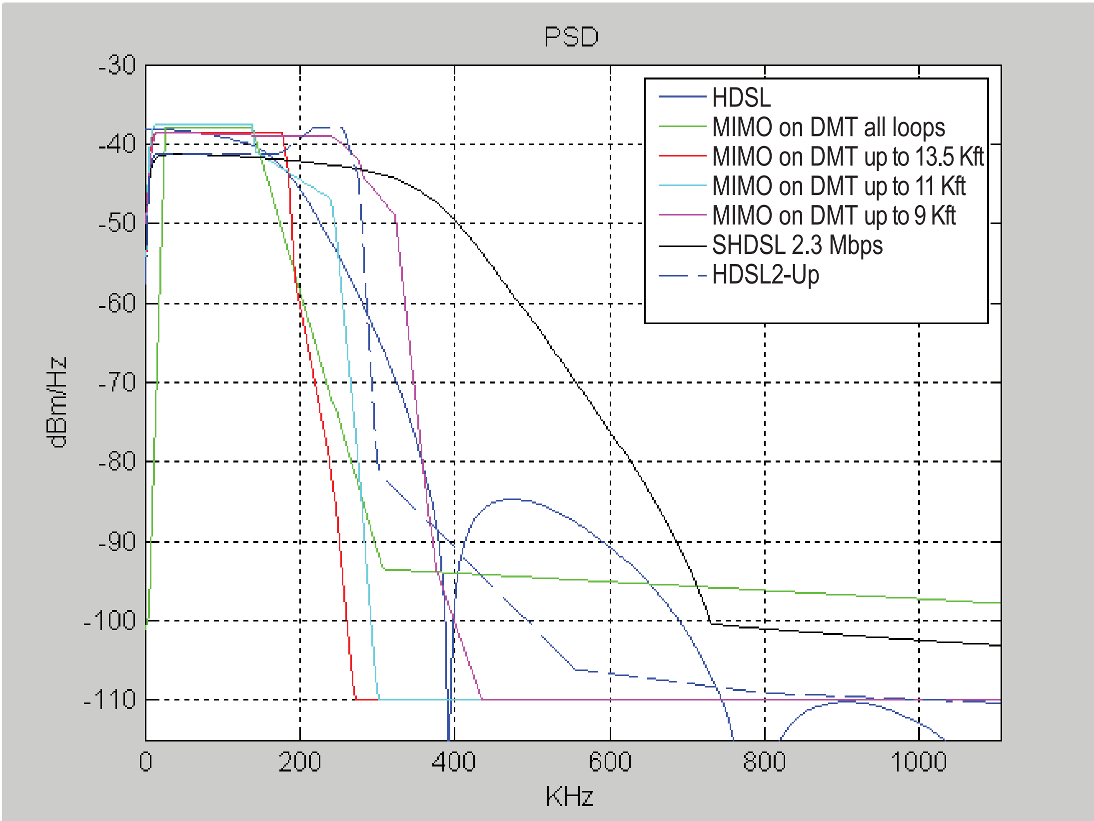

Figure 7: DMT Upstream Spectral Masks and HDSL/SHDSL Spectral Masks

These spectral drawbacks of SHDSL systems are well known. They are part of the reason the industry has moved away from the SHDSL spectral design in newer standards (ADSL2/VDSL2) and in recent deployments (residential DSL, IPTV etc). There have been some arguments however, that enhanced SHDSL addresses some of those spectral deficiencies. This issue deserves some more explanation and is the topic of the next section.

Why Enhanced SHDSL also Falls Short

Standard SHDSL modems transmit 3 bits per symbol (per Baud) using 16-PAM modulation. Enhanced SHDSL modems can also transmit 4 bits per symbol (or even sometimes 5 bits per symbol) using 32-PAM and even 64-PAM modulation respectively. The way this has been tied to spectral compatibility is by arguing that with enhanced SHDSL one can achieve the same data rate using lower Baud rate and more bits per Baud. Since the transmission spectrum is tied to the Baud rate, this results is narrower transmit spectrum and less interference.

This situation is depicted in Figure 8 where the spectrum of various SHDSL systems is shown for a fixed data rate of 2.5 Mbps. Notice that by going from 16-PAM to 32-PAM and 64-PAM the same rate is achieved with smaller spectral bandwidths.

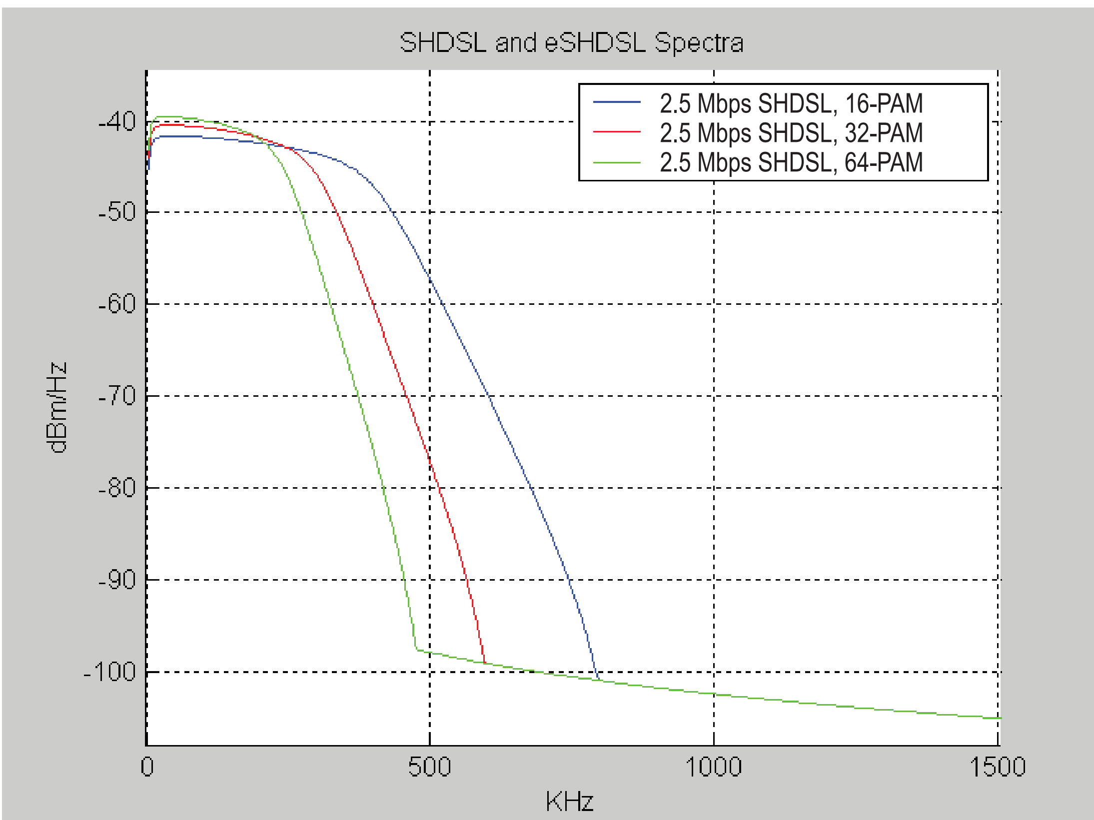

Figure 8: SHDSL and Enhanced SHDSL Spectra

This argument appears inviting, but it is too good to be true. It brushes aside the key issue of performance, that is, whether it is feasible in the first place to actually achieve the same data rate with a smaller bandwidth SHDSL modem. Unfortunately, the answer to this is negative.

Going from 16-PAM to 32-PAM does not change the SHDSL transmission method, spectral use or information encoding in any fundamental way. It does not increase the system's signal to noise ratio, or introduce any coding, MIMO or other performance gains. It only relaxes the maximum rate the modem is capped at (achievable for very short loops where the signal to noise ration is very high). It is therefore a dubious claim that the same SHDSL data rate can generally be maintained with smaller spectral bandwidth.

This objection has been articulated by many experts in the industry. In reference [2], a study from Infineon AG (a SHDSL silicon manufacturer) concludes that none of the enhanced SHDSL technologies (32-PAM or 64-PAM) can match the performance of the original SHDSL 16-PAM technology. For simplicity's sake, we've listed a copy of reference Table 1 from the Infineon paper where these results are summarized in terms of reach. The reach of various SHDSL technologies (in meters) is shown for a target service of 2.5 Mbps as well as 5 Mbps. Notice that the 16-PAM original SHDSL system has the longest reach.

	Loop Reach [m] (26 AWG, 13.5 dBm, 49 self-NEXT, -140 dBm/Hz noise floor, 5 dB margin, 1.6 dB implementation loss)	
	2.5 Mbits/s	**5 Mbits/s**
16 TC-PAM	1920	1200
32 TC-PAM	1700	1050
64 TC-PAM	1350	750

Table 1: Loop Performance of 16-, 32- and 64-TC-PAM SHDSL

It is not only dubious that higher performance can be achieved with enhanced SHDSL, it is actually dangerous for the network. By not having a fixed spectral mask, independent of the rate the modem will train at, its impact on ADSL and other services can not be accurately predicted. For example, an enhanced SHDSL system may take advantage of high SNR at the time of deployment and use a 32-PAM modulation. Later, when more similar SHDSL systems are deployed in the binder, the SNR drops due to crosstalk and the modem retrains back to 16-PAM, suddenly increasing the impact on ADSL in a way that cannot be predicted or planned.

The situation is worse with bonded SHDSL systems. Some manufacturers let the various SHDSL modems in the bonded group re-train several times, with varying spectral masks and PAM modulation to cherry pick the configuration that provides higher performance and the least self interference. Needless to say, the extra performance is achieved in an extremely precarious way and it’s not dependable enough to support SLAs. The moment a new service is deployed in the binder, this fragile arrangement of specially chosen masks will break down. The fundamental reason is that the SHDSL lines in the bonded group interfere with each other and this problem will not go away unless a frequency division band plan is used as in DMT modems.

Proving it with Numbers – Data Supporting DMT's Superiority

In this section we document the superior spectral performance of DMT bonded systems against SHDSL bonded systems. The target victim here is an ADSL2+ system and the comparison is between a MIMO on DMT based bonded system and an SHDSL bonded system as disturbers. Details on the exact values of all parameters used in the simulation are shown in Table 2.

Parameter	Value
Loop type	26 AWG
Noise floor	-140 dBm/Hz
Gap	9.8 dB
Margin	6.0 dB
Coding gain	5.0 dB
Frequency spacing	4.3125 KHz
Max bits per tone	15
NEXT and FEXT coupling	ANSI 1% worst case (See T1.417)
MIMO on DMT™ gains	10 dB
Symmetric DMT PSD level downstream	-43 dBm/Hz

Table 2: Simulation Parameters

Figure 9 focuses on the downstream performance of an ADSL2+ victim and depicts the rate-reach curve. The baseline performance is given by the blue solid line, where the victim operates in the presence of 24 self (ADSL2+) disturbers. The green solid line shows the performance if 12 of the ADSL2+ disturbers are replaced by 12 SHDSL- 2.56 Mbps disturbers. Notice the significant reduction in ADSL2+ rate especially at longer loop lengths. In order to be fair, we denote on the plot the maximum reach for a 2.5 Mbps SHDSL according to Table 1 (around 6300 ft). We extend the green line beyond that however, to show what the effect will be if one deploys SHDSL beyond that limit.

The red solid line indicates the ADSL2+ performance in the presence of 12 self and 12 DMT disturbers (mask M2 – magenta line in Figure 7). Notice the much improved ADSL2+ performance (compared to the green solid line) as well as the added benefits:

- No limitations on the range of the DMT system
- Choice of DMT mask independent of rate with predictable impact

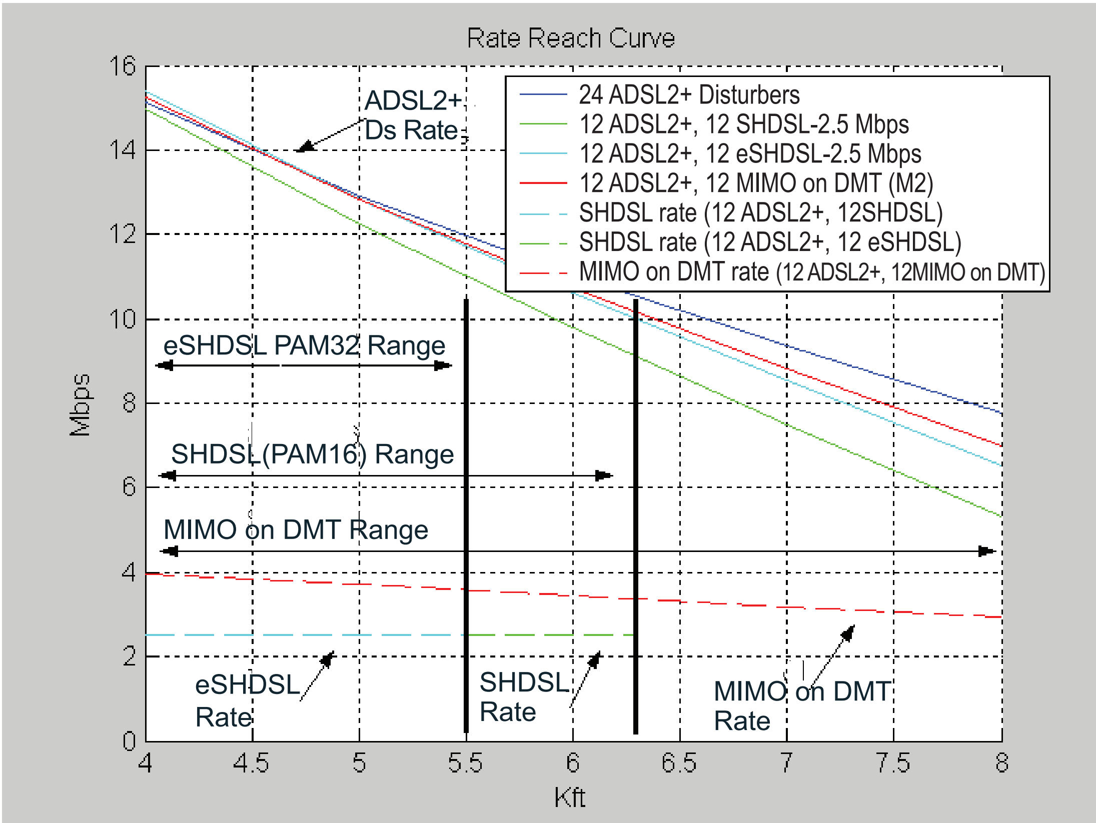

Figure 9: Impact on ADSL2+ Downstream Rates (solid) and Symmetric Achievable Rates (dashed)

The cyan solid line in Figure 9 shows the impact of enhanced SHDSL. Notice how the impact is reduced but still not as good as the DMT impact. Notice also the more severe range limitation of the eSHDSL system (around 5.5 Kft).

The issue of the unpredictability of SHDSL impact can be best explained in the context of this figure. If one deploys extended SHDSL beyond the 5.5 Kft and obtains impact according to the cyan line, there is no guarantee that in the future and when more disturbance is added into the binder the SHDSL system will not revert back to the higher performance and higher impact 16-PAM (green line).

Last but not least, the dashed lines in Figure 9 show the symmetric performance of the DMT and SHDSL systems. Notice that the performance of the DMT system (dashed red line) is much higher than the SHDSL system (dashed cyan and green lines) on top of its superior spectral friendliness. The reasons for that as mentioned before include the lack of interference among the bonded group pairs and the MIMO performance gains.

Figure 10 shows similar results for ADSL victim systems. It focuses on longer loops and compares the spectral impact of 1.8 Mbps SHDSL to the MIMO on DMT spectral impact. Similar conclusions of better performance and less spectral impact in favor of the MIMO on DMT system can be seen here as well.

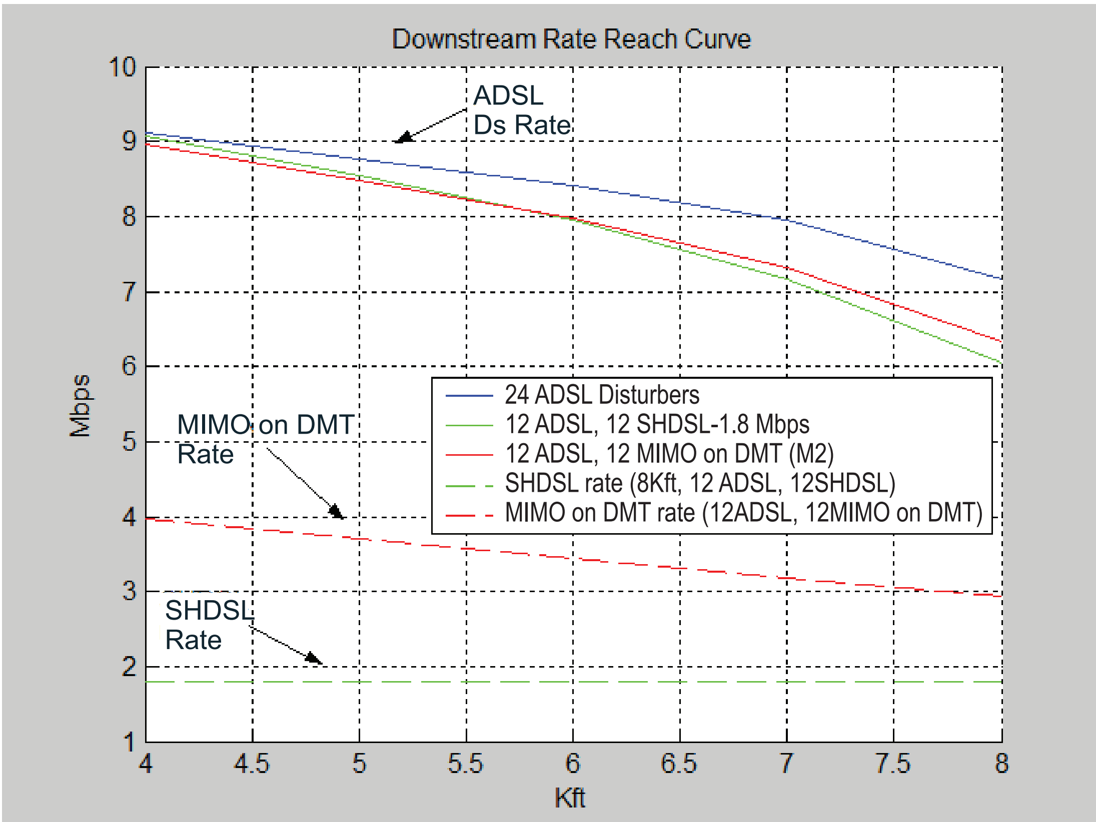

Figure 10: Impact on ADSL Downstream Rates (solid) and Symmetric Achievable Rates (dashed)

Conclusion

This paper explains why simplicity, performance and predictability are the fundamental reasons why DMT-based copper bonding systems are superior to SHDSL-based copper bonding systems, particularly when they are enhanced with MIMO on DMT functionality.

It also compares the spectral impact of symmetric DMT and SHDSL systems and provided clear evidence as to why DMT-based systems provide superior spectral performance and how SHDSL-based systems' spectral performance is confined by it's overlapping spectra design. It illustrates the unpredictable nature of the performance and spectral impact of SHDSL systems and how their performance depends on what type and how many other services are deployed in the same binder along with them. The paper also explains how in direct contrast to this, the predictable nature of DMT systems lays a foundation for superior performance, particularly as more and more bonded pairs are deployed in the same binder as one another or along with ADSL services. Additionally, these spectral drawbacks of SHDSL systems are identified as being well known and part of the reason the industry has moved away from the SHDSL spectral design in newer standards (ADSL2/VDSL2) and in recent deployments (residential DSL, IPTV etc).

This paper shows clear and convincing data that substantiates the superior performance of symmetric DMT copper bonding systems when compared to SHDSL systems along the three critical dimensions- rate, reach and reliability. The data illustrates just how superior DMT system performance could be, particularly when Positron's MIMO on DMT technology is used.

The superiority of DMT in spectral compatibility and in numerous other areas is not only demonstrated in this paper, but is also recognized by the standards bodies; DMT has been chosen as the foundation for most modern DSL standards (ADSL2/VDSL2) and has been by far the most widely deployed DSL technology. It has also been chosen by Positron Access Solutions as the basis for innovative high performance products that can provide up to 50 Mbps of symmetric bandwidth at Carrier Serving Area (CSA) range in adverse disturbance conditions. Consequently, Positron's products along with the standards bodies have been paving the way for a brighter future for DMT.

References

[1] T1.417 Spectrum Management Standard (Issue 2), Committee T1E1.4 Standard

[2] Infineon Technologies AG, "Spectral Compatibility of Enhanced SHDSL with ADSL", T1E1.4/2002-188, Working Group T1E1.4, August 19-22, 2002

Positron Access Solutions, a member of the Metro Ethernet Forum, develops and manufactures copper and fiber optic transmission equipment. Its portfolio includes copper bonding, Pseudowire and converged SONET/Ethernet products offering extensive solutions for access, backhaul and aggregation of business, wireless and triple-play services. The Aktino product line delivers Carrier Ethernet solutions of up to 100Mbps on bonded copper for Ethernet Business services and mobile backhaul. The AEX Pseudowire product line delivers converged Ethernet TDM/ATM services for both business applications and mobile backhaul. With offices in Irvine, CA and Montreal, QC, Positron's global footprint extends from the United States and Canada through Europe, Latin America and Asia.
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