Vectored DSL: Benefits and Challenges for Service Providers

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ABSTRACT

Service providers are facing a two-dimensional challenge in deploying broadband access networks: the evolution of service demand and competition. The demand for content-rich services including high-definition multicast and unicast video is increasing. Also, telephone companies are facing fierce competition from cable companies, especially in the North American market. In areas where fiber to the home is not cost effective, vectored DSL is a cost-effective solution for achieving downstream data rates of 100 Mb/s over 500 m by leveraging the existing copper infrastructure. This article outlines the key market driving forces behind the need for high-speed DSL and specifically vectored DSL. This article also describes many vectoring features and capabilities, and highlights the key considerations for service providers in terms of vectored DSL planning, operation, and management.

INTRODUCTION

With the demand for data-intensive services increasing, service providers must adapt to not only quench the current demands but to also meet future needs. In the wireline realm, telephone companies (telcos) and cable companies (cablecos) are in competition to provide services including high-speed data, multicast and unicast video, HDTV, and 3D TV, as shown in Fig. 1. Cablecos make use of the DOCSIS 3.0 standard for delivering these services at very high rates. In order to maintain a competitive advantage, telcos must deliver new applications and content while ensuring an appropriate quality of experience (QoE). For telcos to support more sophisticated data services, higher data rates are required.

Fiber to the home (FTTH), where an optical fiber wire directly connects each customer premises (CP) to the central office (CO), can provide higher data rates than twisted-pair copper wire. However, deploying FTTH can require costly investments, especially in buried-cable areas. Instead, telcos who are already heavily invested in digital subscriber line (DSL) technologies are making use of hybrid optical-fiber-copper-wire networks to deliver services at a lower cost. One such hybrid network is known as fiber to the node (FTTN), where a node is used to interface between the optical fiber link from the CO and the existing copper wire link to each CP. With the combination of hybrid networks with short loop lengths (e.g., up to 1000 m) and power allocation techniques, telcos are currently able to offer downstream speeds in the 10–60 Mb/s range without vectoring. For even higher data rates, telcos are looking at vectored DSL as the vehicle to deliver very-high-speed (e.g., 100 Mb/s over 500 m [1]) to customers while cost-effectively leveraging the existing copper network investment.

Current DSL networks use cable binders consisting of bundles of twisted copper pairs in order to transmit data to and from various CPs. The interference between neighboring copper pairs, known as crosstalk, is the main adversary to the achievable data rate in DSL networks. Thus, to improve the achievable data rate, crosstalk must be reduced or, ideally, removed entirely.

There are two types of crosstalk associated with DSL networks: near-end crosstalk (NEXT) and far-end crosstalk (FEXT). NEXT is the crosstalk seen by neighboring pairs at the near-end receiver, and FEXT is the crosstalk seen by neighboring pairs at the far-end receiver. Newer DSL technologies use frequency-division duplexing to remove the NEXT, thus leaving the FEXT as the only significant form of crosstalk. Hence, higher data rates can be achieved by minimizing or removing the FEXT.

VECTORED DSL OVERVIEW

Vectored DSL [2] is a transmission technique that attempts to entirely remove the FEXT interference between neighboring lines. The vectored DSL crosstalk cancellation technique is standardized by the International Telecommunication Union Telecommunication Standards Sector under ITU-T G.vector (G.993.5) [3].

FEXT in DSL systems has the strongest impact on short loop lengths at high frequencies. As such, VDSL2 profiles 12a and 17a, which make use of up to 12 MHz and 17.6 MHz, respectively, are good candidates for vectoring. The results of several tests have shown that data rates of 100 Mb/s over 500 m are achievable [4].

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Vectored DSL uses multi-user signal coordination to cancel the FEXT interference between pairs. For downstream transmission, the transmitters are collocated at the DSL access multiplexer (DSLAM), and the transmitted signals can therefore be predistorted such that the signals arriving at the CPs are crosstalk-free. For upstream transmission, the receivers are collocated at the DSLAM, and the received signals can be processed in order to remove the crosstalk component. In both cases, once the crosstalk is removed, each pair can ideally achieve its interference-free data rate.

In addition to providing higher data rates, vectored DSL provides several significant benefits over previous DSL technologies. In particular, the vectored DSL system requires knowledge of the pair-wise crosstalk between each pair in the system. These values are also known as the FEXT coupling coefficients (Xlogps). In addition to allowing multi-user signal coordination, knowledge of the Xlogps enables more advanced network maintenance tools for system managers by identifying lines that generate large amounts of crosstalk. Abnormally large crosstalk can be due to line imperfections; as such, identifying it can assist with locating network faults and long-term network maintenance. Also, knowledge of the Xlogps can provide more accurate estimates of the network performance.

The vectored DSL system also allows system managers to prioritize some customers over others (e.g., corresponding to higher-end service users). Each pair is specified by a target data rate, line priority, maximum data rate, and minimum data rate. Vectored DSL introduces the notion of line priority. As described in G.993.5, when resources are limited, the vectored DSLAM might not be able to mitigate all of the FEXT sources for every line in the vectored group. As such, a line priority (e.g., low, high, or no priority) could be configured for each line in the vectored group. This feature enables the use of different tiered service adapted to customer needs and inherently targets a wider customer base for a quicker transition to vectored DSL.

DSL PHANTOM MODE

Beyond vectored DSL, the future of DSL technology is the combination of vectored DSL and DSL Phantom mode technology [5]. DSL Phantom mode technology is a method for theoretically transporting three channels worth of data over two channels. In particular, coordination using only two physical channels is able to achieve performance as good as up to three independent physical channels. The information on the "phantom," or virtual, channel is split over the physical channels and can be recovered at the receiver side after processing. This process generates excess crosstalk. Therefore, by combining Phantom DSL with vectored DSL, the excess crosstalk can be removed, and the overall system can gain the performance benefits of Phantom DSL without the consequence of increased crosstalk. Furthermore, the concept can be generalized to more than two physical channels to gain additional performance benefits; that is, if N physical channels are used, there can be up to $N-1$ additional phantom channels.

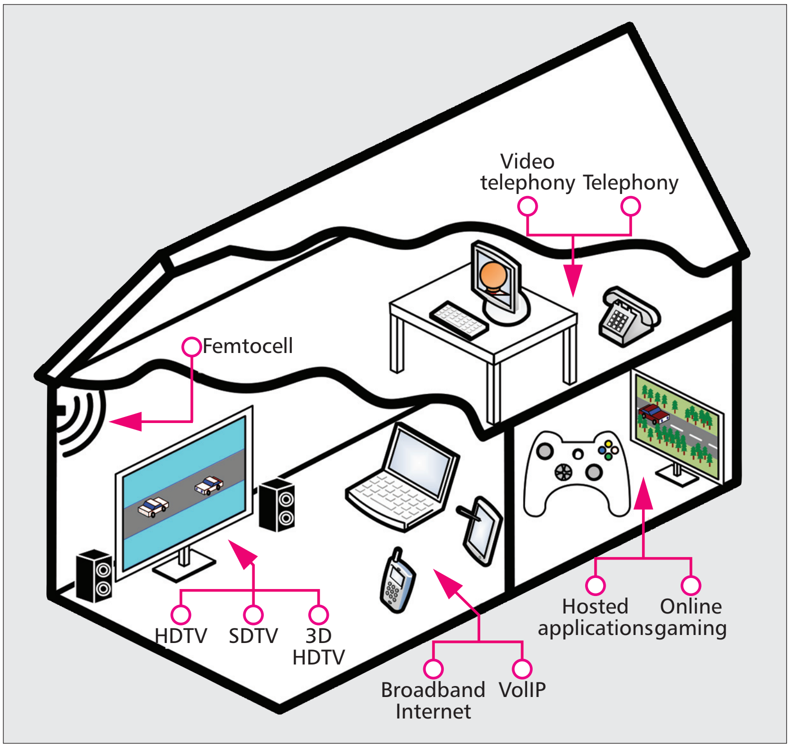

Figure 1. *Application and services offered by telcos.*

DSL Phantom mode also provides some challenges from an implementation perspective. More specifically, Phantom mode requires a sophisticated modem capable of supporting multiple-pair bonding. In particular, it needs a modem that can recover the three channels worth of data from the two physical channels. As well, the DSL modem's chipset must be sophisticated enough to vector the two physical and the phantom channels. Furthermore, the multiple-line requirement for Phantom mode may require infrastructural changes in locations where consumers are only provided a single line. Finally, thus far, DSL Phantom mode results have only been obtained within a laboratory setting.

Table 1 summarizes the achievable downstream speeds of three companies using Phantom mode and vectoring for various numbers of pairs and line lengths. Alcatel-Lucent showed that combining Phantom mode and vectoring can achieve downstream speeds of 390 Mb/s over 400 m using two pairs or 910 Mb/s over 400 m using four pairs [6]. Alcatel-Lucent also showed that it was capable of achieving 100 Mb/s at 1 km using two pairs [7]. Nokia Siemens Networks showed that when combining Phantom mode and vectoring, it can achieve 825 Mb/s over 400 m using four pairs [6] and 750 Mb/s over 500 m using four pairs [8]. Huawei showed that with Phantom mode and vectoring, it can achieve 700 Mb/s over 400 m using four pairs [6].

Given the substantial gains offered by Phantom DSL, it is important for telcos to plan future vectored DSL networks with multiple-pair bonding in mind. This would have the benefit of reducing the investment cost for transitioning from single-pair vectoring to phantom DSL.

Company	Number of pairs	Downstream speeds (Mb/s)	Line lengths (m)
Alcatel-Lucent	Two	100	1000
	Two	390	400
	Four	910	400
Nokia Siemens Networks	Four	825	400
	Four	750	500
Huawei	Four	700	400

Table 1. *Downstream speeds achieved in a laboratory setting by various companies using Phantom DSL.*

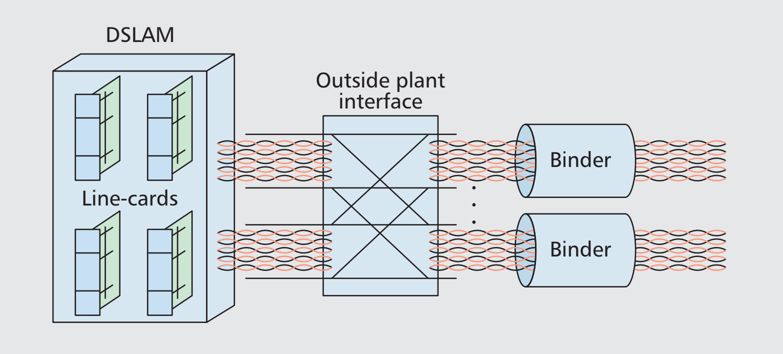

Figure 2. *DSLAM level vectoring with 2 binders and 4 line cards.*

VECTORING LEVELS

The vectoring process can be applied at various levels characterized by the number of pairs that are included in the vectoring process. Every DSLAM can service up to 192 or 384 or more customers, depending on the size of the shelf. Within each DSLAM are line cards that can each service 24, 48, or more customers, depending on the card density. The computational and memory complexities for vectoring increase with the number of pairs vectored. Thus, performing vectoring for all 192 or 384 pairs in the DSLAM is more difficult than vectoring the 24 or 48 pairs sharing the same line card.

Line-card-level vectoring applies vectoring only to the 24 or 48 pairs it services. Since the vectoring is only applied within the line card users, the vectoring processing engine can be embedded into the line card.

DSLAM-level vectoring applies vectoring over every pair connected to the DSLAM, as shown in Fig. 2. This provides the maximum data-rate gain because it allows the system to dynamically cancel the crosstalk between any pairs connected to the DSLAM; however, DSLAM-level vectoring presents several DSLAM and chip engineering design challenges including inter-line-card communication, large memory and computational complexities, and training time.

Finally, multi-DSLAM-level vectoring applies vectoring across multiple DSLAMs. This can be used in some instances of high-density areas where two or more DSLAMs are deployed side by side. Multi-DSLAM-level vectoring can apply vectoring across many more pairs, depending on the size of the shelf.

SERVICE PROVIDER DEPLOYMENT SCENARIOS

While using FTTH might yield higher data rates (e.g., downstream speed of at least 100 Mb/s [9]), it is still not cost effective to deploy in buried-cable areas. Thus, the ability to offer similar data-rich services using hybrid optical fiber and copper wire networks is particularly interesting. Telcos are looking to vectored DSL as a means to deliver comparable downstream content-rich services using the hybrid network.

FTTN is one example of a hybrid optical fiber and copper wire network. The family of hybrid networks is known as FTTx. Other examples include fiber to the curb (FTTC), fiber to the building or basement (FTTB), fiber to the premises (FTTP), and fiber to the office (FTTO). The FTTx networks differ in the transmission length covered by the copper wire network. Figure 3 shows the deployment scenarios for FTTN, FTTC, and FTTB. As well, the vectoring levels, VDSL2 profiles, and DSLAM port capacities for the FTTx shown in Fig. 3 are given in Table 2.

The FTTN architecture is deployed to cover an entire distribution area, as shown in Fig. 3a. In North America, FTTN loops can contain up to 1.5 km of twisted-pair copper wire, although it is rare for FTTN loops to be that long. In high-density distribution areas, multiple DSLAMS at the same node might be required. As such, the FTTN architecture is a good candidate for DSLAM or multi-DSLAM-level vectoring. In particular, FTTN loops of less than 500 m will benefit the most from the vectoring process and are therefore of particular interest.

For FTTC deployment scenarios, the DSLAM is deployed much closer to the customers than FTTN (i.e., up to 500 m of twisted copper pair wire), as depicted in Fig. 3b. FTTC has the ability to deliver very high data rates since it operates on significantly shorter line lengths; however, due to the shorter lengths, each DSLAM's service area is reduced, and more than one DSLAM are required to cover the entire distribution area. As such, each DSLAM covers a sub-distribution area and services a smaller number of subscribers. A small DSLAM in the FTTC architecture could simply be a sealed module including one line card (e.g., 48 ports). Hence, line-card-level vectoring would be the most appropriate level for the FTTC architecture, as shown in Table 2.

The FTTB architecture in Fig. 3c services an entire building or a multi-dwelling unit. In this case, a DSLAM is deployed inside the building. Depending on the size of the building, a small DSLAM with a single line card or a larger DSLAM can be required. As such, depending on the size of the building, line card or DSLAM-level vectoring would be most appropriate, as shown in Table 2.

FTTx networks are used all around the world. For example, Japan deployed asymmetric DSL (ADSL) services and was beginning to expand to very-high-rate DSL (VDSL) services as of November 2005. In the United States, AT&T deployed a VDSL service under the AT&T U-verse moniker to provide the triple-play services of Internet, TV, and phone through an FTTN network architecture covering 2 million customers across 22 states as of December 9, 2009. Similarly, Bell Canada services over 1.8 million homes with VDSL2 through their FTTN networks in Montreal and Toronto as of February 4, 2010 [9].

VECTORED DSL ADOPTION REQUIREMENTS

The adoption of vectored DSL by telcos and the pace at which it is adopted will depend on many factors that are critical to the success of delivering IPTV and other triple-play services to their customers. More specifically, it will depend on the ease of deployment, the ability to deliver IPTV while ensuring a QoE, and how it affects line stability. These factors are discussed in the following section. Interested readers are referred to [10] for more information on deployment factors and line stability.

DEPLOYMENT FACTORS

The rate at which vectored DSL is adopted will depend on the ease of deployment, implementation, and transitioning from current systems. In particular, if it is possible to easily deploy new DSLAMs close to customers (e.g., FTTC), it will be easier to achieve higher data rates and offer data-rich services. Moreover, the ease of transitioning a customer's line from non-vectored to vectored is also a factor as it can require a service interruption, modem replacement, and potential upgrade of the copper wires at the dwelling. Furthermore, there will be scenarios where a vectored DSLAM shares a cable binder with a non-vectored DSLAM (e.g., VDSL2, ADSL, ADSL2plus). Such situations must be dealt while still ensuring high enough data rates on both the vectored and non-vectored lines.

LINE STABILITY

In a vectoring context, the stability of the lines requires increased attention. Since vectoring removes the crosstalk, other noise sources become more dominant including impulsive noise and non-stationary noise (e.g., radio frequency interference [RFI], particularly for Phantom DSL). These noise sources were masked by the more dominant crosstalk prior to vectoring. However, after the removal of crosstalk, these noise sources can cause line stability issues. The main issue is how effectively current protection mechanisms can stabilize the line in the presence of dominant impulsive noise in order to avoid the need for resynchronizations.

Deployment scenario	Vectoring level	VDSL2 profile	DSLAM capacity (# of ports)
FTTN	DSLAM or multi-DSLAM	12a or 17a	192+
FTTC	Line card	17a	48
FTTB	Line card or DSLAM	17a or 30a	48+

Table 2. *Properties of various FTTx networks.*

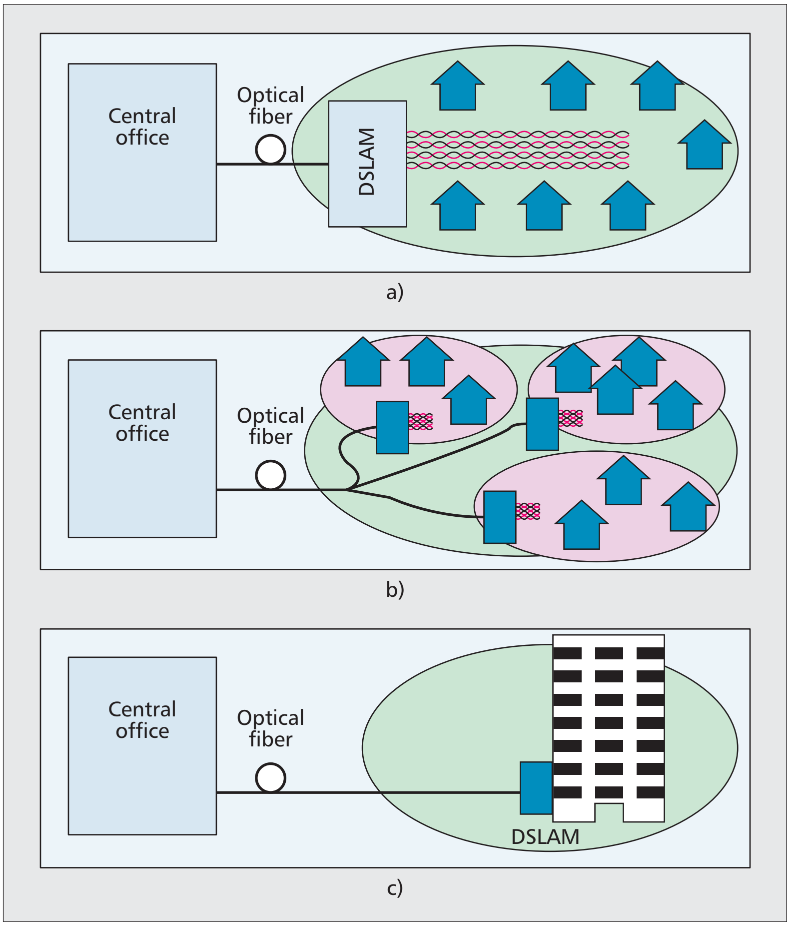

Figure 3. *Various FTTx scenarios: a) FTTN; b) FTTC; c) FTTB.*

IPTV DELIVERY AND QOE

From an IPTV perspective, any service disruption, such as resynchronizations, video pixelization, frozen screens, or audio hiccups, can negatively affect the customer's QoE. From a service provider's point-of-view, it is essential to make sure that vectored DSL will still be "well behaved" under poor noise conditions. More specifically, after crosstalk cancellation, vectored DSL must be able to overcome the effects of both the now-dominant repetitive electrical impulsive noise (REIN) and single high impulsive noise event (SHINE) by reducing the likelihood of packet loss and errors in their presence while delivering IPTV. In particular, it is essential that vectored DSL meets the QoE requirements associated with IPTV services as defined in the Broadband Forum technical report TR-126 [11].

An ideal configuration would be to place lines which have been jointly-vectored adjacent to one another and to place lines which have not been jointly vectored further away from one another within the binder or within different binders inside the cable. However, the rewiring of the lines within a binder (i.e., binder rearrangement) is challenging, costly, and impractical.

Deployment Planning, Operation, and Management Considerations

This section will discuss five main considerations regarding the deployment, operation, and management of vectored DSL in practical systems. Interested readers are referred to [10] for more information.

Consideration 1: Managing Non-Crosstalk Noise

After applying vectoring, nearly all the crosstalk is canceled. Consequently, other sources of noise, including REIN and SHINE, which were previously hidden by the crosstalk become more relevant. There are two ways to mitigate the impact of these sources of noise. The first method involves a combination of configuration tools such as:

- Seamless rate adaption (SRA), which could be used in a slow-changing noise environment or to provide more stability in the case of fluctuating crosstalk.
- Impulsive noise protection (INP), interleaver delay, or physical layer retransmission (i.e., G.998.4) to properly handle impulsive noise.
- Save Our Showtime (SOS), to prevent the line from retraining and service from being disrupted. SOS can also be used in situations where the crosstalk increases suddenly (e.g., impulsive noise) and could be important in the context of IPTV where service interruption could impact the QoE.
- Other tools such as virtual noise and erasure decoding, which could provide additional line stability and more protection against other noise sources.

The second method leverages the dynamic line management (DLM) and dynamic spectrum management (DSM) capabilities in monitoring and optimizing the settings for interleaved forward error correction (FEC) and the transmitted power spectral density (PSD).

Consideration 2: Managing Non-Vectored Lines and Legacy CPE

It is possible for DSL binders to contain mixed lines (e.g., a mix of VDSL and ADSL) connected to common or different DSLAMs. Similarly, there may be DSL binders consisting of a combination of vectored and non-vectored DSL lines. As a result, the crosstalk from non-vectored lines onto the vectored lines cannot be canceled. The non-canceled crosstalk will cause some degradation to the vectored line's performance. One method for addressing this issue is to treat the non-vectored crosstalk interference as noise and apply some spectrum management techniques to mitigate the remaining crosstalk (e.g., DLM and DSM), as in consideration 1. An alternative approach would involve the service provider moving the non-vectored lines to the vectored DSLAM and upgrading the respective customer premises equipment (CPE) to vectoring-capable CPE.

Similarly, in areas where outdated services are already being provided (e.g., ADSL, VDSL, VDSL2), if the telcos would like to deploy vectored DSL to provide higher-speed services, the vectored DSLAM should be able to support vectored DSL lines in addition to providing the same "old services" to legacy customers with their existing CPE modems. As discussed in consideration 2, mixed binders of non-vectored and vectored lines will lead to non-canceled crosstalk. To address this issue, the ITU has developed a mechanism called "vectoring-friendly" CPE, which can be downloaded as a firmware for the CPE modem to operate in vectoring-friendly mode. In this mode, the legacy lines would continue to operate with the same performance as before, but the crosstalk generated by those lines to the vectored lines is canceled as well.

Consideration 3: Managing Unbundled Lines

The issue of unbundled lines arises when competing service providers share a binder. This issue is relevant in regulated environments where loop unbundling is mandated. A common situation involves two vectored DSLAMs from different service providers sharing the same binder. Due to the lack of vectoring coordination between the two DSLAMs, interference between the clusters cannot be canceled. One possible solution to this situation is for the service providers to cooperate in order to take advantage of vectoring and the higher data rates it enables. For example, this cooperation could be achieved through an external coordination vectoring engine. If cooperation is not possible, each service provider can implement vectoring across their own lines, while treating the other lines as alien crosstalk. Moreover, from a practical perspective, when lines from competing service providers share a binder, an issue that arises is the physical location of the lines within the binder. More specifically, within a binder, the crosstalk between lines in close proximity is significantly stronger than the crosstalk between lines that are far apart. Hence, an ideal configuration would be to place lines that have been jointly vectored adjacent to one another and those that have not been jointly vectored further away from one another within the binder or within different binders inside the cable. This would maximize the benefits of vectoring in an unbundled environment by allowing the vectoring process to remove the effects of large crosstalk and minimize the effects of alien crosstalk; however, the rewiring of the lines within a binder (i.e., binder rearrangement) is challenging, costly, and impractical.

Consideration 4: Managing Disorderly Shutdown Events

Disorderly shutdown events are caused when a power failure occurs or the customer shuts down their modem inappropriately. It has been shown through several tests by manufacturers that these events can cause a significant change in the signal-to-noise ratio and may therefore lead to a retraining of the vectored lines. In general, retraining the lines should be avoided since it requires a few minutes to remeasure the crosstalk channel gains. Clearly, that is not desirable from a service provider's point of view. The ITU is working on a mechanism called "Fast Channel Tracking" to report any changes in the crosstalk state to the vectoring processor so that the impact of these events can be mitigated.

CONSIDERATION 5: MANAGING BINDER GROUPS

The final consideration deals with the management of clusters of lines sharing a binder. This consideration may not exist when DSLAM or multi-DSLAM-level vectoring is applied. However, in some instances, telcos may deploy vectoring at a small DSLAM with only one line card in a distribution area. As demand grows, a second vectored DSLAM may be required. Customers may be connected to this new DSLAM through the same binder as the original DSLAM. Without vectored coordination between the two DSLAMs, there will be non-canceled crosstalk. The non-canceled crosstalk can be mitigated by using spectrum management techniques as discussed in consideration 2 or canceled entirely using separate dedicated binders for each vectored DSLAM. Binder dedication is expensive and not desirable from a service provider's point of view, and simply mitigating the crosstalk leads to suboptimal performance. As such, binder management should be carefully planned to ensure that an appropriately sized DSLAM is initially deployed.

CONCLUSION

Vectored DSL is the new copper-based access technology breakthrough. It allows for significant data rate increases through crosstalk cancellation and allows service providers to deliver very-high-speed data services in a cost-effective manner. Vectored DSL products are expected to soon become commercially available. Performance results from several manufacturers show that speeds of 100 Mb/s per line is achievable. Service providers will be faced with planning, operation, and management of vectored DSL considerations. However, the use of vectored DSL features and the leveraging of the DLM/DSM capabilities can ensure that necessary line stability and desired QoE to customers are achieved.

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REFERENCES

[1] V. Oksman ET AL., "The ITU-T's New g.vector Standard Proliferates 100 Mb/s DSL," *IEEE Commun. Mag.*, vol. 48, no. 10, Oct. 2010, pp. 140–48.

[2] G. Ginis and J. Cioffi, "Vectored Transmission for Digital Subscriber Line Systems," *IEEE JSAC*, vol. 20, no. 5, June 2002, pp. 1085–1104.

[3] ITU-T Rec. G.993.5-2010, "Self-FEXT Cancellation (Vectoring) for Use with VDSL2 Transceivers," 2010.

[4] E. Karipidis *et al.*, "Capacity Statistics for Short DSL Loops From Measured 30 MHz Channel Data," *6th IEEE Wksp. Signal Proc. Advances in Wireless Commun.*, June 5–8, 2005.

[5] B Lee *et al.*, "Gigabit DSL," *IEEE Trans. Commun.*, vol. 55, no. 9, Sept. 2007, pp. 1689–92.

[6] M. Ricknäs, "Vendors Closing in on 1 Gb/s Using DSL," Oct. 26, 2010, http://www.pcworld.com/article/208790/vendors_closing_in_on_1g_bps_using_dsl.html.

[7] S. Vanhastel, The Investment Required to Upgrade DSL is Quite Small, Alcatel-Lucent, Apr. 27, 2010, http://www.gazettabyte.com/home/2010/4/27/dsl-will-phantom-channels-become-real-deployments.html.

[8] D. O'Shea, BWF: Vendors' DSL Ambitions Moving Full Speed Ahead, Oct. 29, 2010, http://connectedplanetonline.com/residential_services/news/BWF-Vendors-DSL-ambitions-moving-full-speed-ahead-1029.

[9] Bell Canada, "Bell High Speed Fibre Rollouts Enable New Internet and TV Services," http://www.bce.ca/en/news/releases/bev/2010/02/04/75344.html

[10] G. Ginis, M. Goldburg, and J. Cioffi, "The Effects of Vectored DSL on Network Operations," *J. Telecommun. Management*, vol. 3, no. 2, July 2010, pp. 107–17.

[11] DSL Forum Technical Report TR-126, "Triple-Play Services Quality of Experience (QoE) Requirements," Dec. 2006.

BIOGRAPHIES

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