VDSL Technology Issues—An Overview

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Abstract

The very-high-speed digital subscriber-line (VDSL) technology makes possible delivery of information to speeds up to 52 Mb/s. The high-frequency band used (up to 20 MHz) raises many challenges not existing in the present DSLs, among them spectral allocation, transmission in a FEXT (far-end-crosstalk) noise environment, RF interference sources. We discuss here the issues pertinent to the deployment of VDSL technology.

INTRODUCTION

VDSL is capable of delivering data rates comparable with cable modems. Optical fiber is used to transport data to the residential area; from there data is transmitted over the existing copper infrastructure. Efforts to establish standards for this technology are currently under way in the US (ANSI T1E1), Europe (ETSI) and the International Telecommunication Union (ITU). The wide frequency bandwidth used (up to 20 MHz) raises several technical challenges. The most important ones are presented below, as they are discussed in the standardization committees.

VDSL DEPLOYMENT CONFIGURATIONS

Due to the large attenuation of high-frequency signals on twisted-pair lines, the deployment of VDSL is limited to a loop length of less than 4500 feet from the signal source. Figure 1 shows two possible configurations. For customers close to the central office (CO), VDSL can be deployed over copper wiring from CO (Figure 1a); this configuration is called fiber to the exchange (FTTEx). For more-distant customers the fiber is run to an optical network unit (ONU), from which the data is distributed using the existing infrastructure (Figure 1b). This configuration is called fiber to the cabinet (FTTCab).

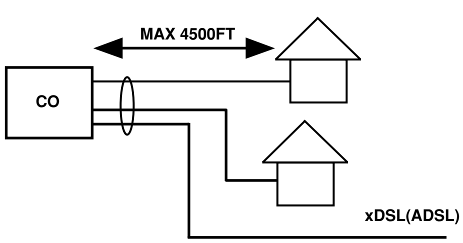

Figure 1a. FTTEx configuration.

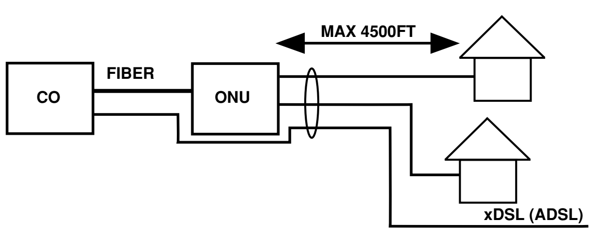

Figure 1b. FTTCab configuration.

The present spectrum allocation proposals use the ADSL downstream frequency band for VDSL downstream as well. From the point of view of the crosstalk between ADSL and VDSL, there is a subtle difference between the two configurations of Figure 1. In the FTTEx case, the presence of the VDSL does not affect ADSL performance because VDSL power spectral density (PSD) is less than ADSL PSD. Conversely, the presence of ADSL in the same binder may have a serious impact on VDSL performance. In FTTCab configuration the situation is reversed. VDSL signals from the ONU may generate unacceptable noise levels for the ADSL downstream signal, as it becomes heavily attenuated along the path from CO to ONU. (Reference 1)

DATA RATES AND SPECTRUM ALLOCATION

Table 1 depicts some of the data rates considered in the US for standardization at one time or another.

Table 1. VDSL Data Rates

	Asymmetric Services Data Rate		Symmetric Services
Profile	Downstream Mb/s	Upstream Mb/s	Each Direction Mb/s
Short Loop	51.84	6.48	25.96
(1500 ft.)	38.88	4.32	19.44
Medium Loop	25.92	3.24	12.96
(3000 ft.)	19.44	2.43	9.72
	12.96	1.62	6.48
Long Loop	6.48	1.62	
(4500 ft.)			

The asymmetrical services expected to dominate in the US market include video distribution—including HDTV—and Internet applications. In Europe there is more interest in the symmetrical services, which are directed towards business applications. Within each category of services, the data rate depends on the distance from the customer premises to the ONU (CO).

Frequency-division multiplexing (FDM) was chosen as the multiplexing method for separating the upstream and downstream data transmission. For asymmetrical services the ratio between the downstream and upstream data rate is close to 10:1, thus most of the bandwidth should be allocated for downstream. For symmetrical services the bandwidth should be allocated equally to the two directions. A requirement of the standards is that both types of services should coexist on the same cable. Under these conditions, no spectral allocation method can simultaneously optimize both the asymmetrical and symmetrical services data rates.

One solution is to define two spectrum allocations: One is optimized toward the asymmetrical services, while accommodating certain symmetrical data rates as a secondary goal; the other is geared more towards symmetrical services. Also, because the short loop profile requires considerable bandwidth, it was recognized that it will be difficult to accommodate them in the same binder with the rest of the services. This is why the standardization effort is presently focused on medium loop profiles; this spectral allocation is also suitable for the long loop case. An agreement in principle was reached within ITU for a spectrum allocation that contains four bands (two downstream and two upstream) in the 138-kHz-to-12-MHz frequency range. An example of such a spectrum allocation for North America (Reference 2) is shown in Figure 2. The reach is 2500 ft for 22/3 Mb/s asymmetrical services and 1700 ft for 13/13 Mb/s symmetrical services. For lower data rates on longer loops the first upstream/downstream bands can be used. Future allocation of the spectrum above 12 MHz will allow the transmission of higher data rates on short loops.

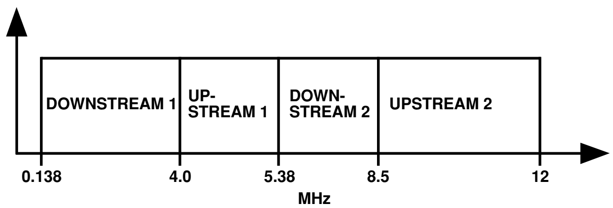

Figure 2. VDSL frequency plan for North America.

BRIDGED TAPS

Figure 3 shows a loop with a bridged tap and its attenuation for different tap lengths, $L = 0, \lambda/4, 5\lambda/4, 101\lambda/4$, where λ is the wave length. The shortest bridged tap creates a deep null in the channel characteristic. For the VDSL spectral plan, from Figure 2, such a bridged tap will significantly reduce the data rate in the Downstream 2 channel. The ratio between downstream and upstream data rates will be significantly affected by short bridged taps. The longer bridged taps have less of an impact because the reflected wave is attenuated by the losses in the line. There is still an SNR loss because the transmitted signal power is split between the line and the bridged tap at the insertion point. The difference is that on long bridged taps the SNR loss is evenly distributed between the two directions. This is the reason why the ETSI standard does not have provisions for bridged taps; however, they are still part of US standard requirements.

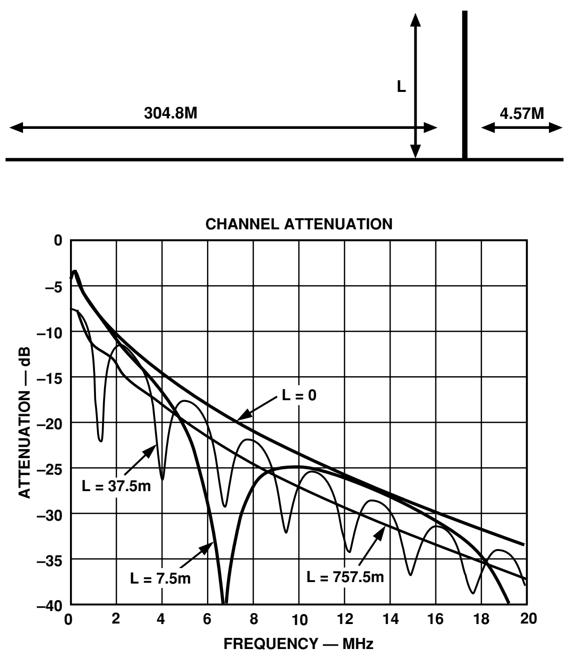

Figure 3. Magnitude response of a bridged-tap loop.

CROSSTALK NOISE SOURCES

Figure 4 illustrates the crosstalk noise sources on a twisted-pair wire. The near-end crosstalk (NEXT) noise is generated between signals travelling in opposite directions. NEXT is proportional to frequency at power 1.5. Because the incoming signal is attenuated at the receiver input, only one such interferer will reduce the VDSL performance significantly. This noise source can be contained by allocating different frequency bands for upstream and downstream direction (Figure 2).

The far-end crosstalk (FEXT) noise is generated between signals travelling in the same direction in a cable. FEXT is the dominant crosstalk noise source in VDSL. Its power spectral density:

$$PSD_{FEXT} = k\,Lf^2\,|H_{ch}(f)|^2 \cong kLf\,e^{-(2\,L\alpha(f))}$$

depends on the frequency, f, the length of the cable segment, L, that the two signals run in parallel, and the channel transfer function $H_{ch}(f)$. Because the channel transfer function is an exponential function of L, the power spectral density of the FEXT noise is small for large values of L and is relatively high for low L. In the upstream direction (Figure 4), transmitter Tx4US is much closer to ONU than Tx2US and Tx3US. Tx4US will inject a relatively high level of FEXT noise in pairs 2 and 3. The upstream signals from these pairs are heavily attenuated at the point where the FEXT noise is injected. The result is that in the upstream direction the FEXT noise from sources close to the ONU (CO) will degrade significantly the SNR of the sources far away from ONU, collocated in the same binder. The solution consists in reducing the transmit power, depending on the distance from the transmitter location to the ONU (CO). This problem does not exist in the downstream direction (all the transmitters are located at ONU/CO).

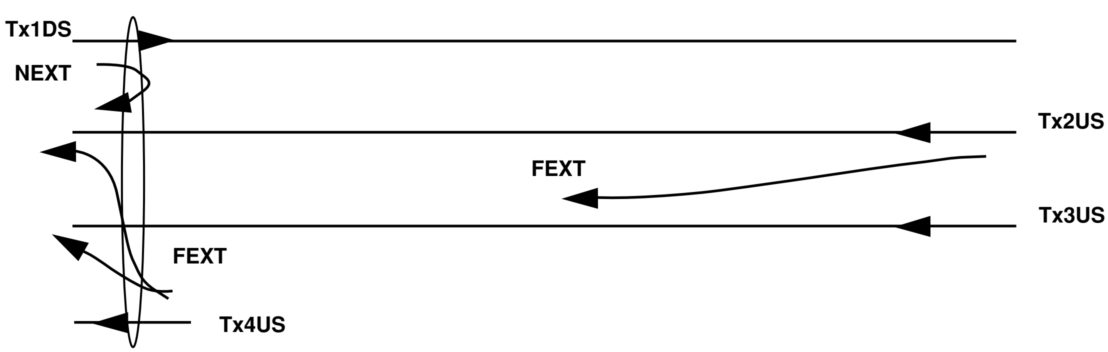

Figure 4. Twisted-pair crosstalk noise sources.

RF INTERFERENCES

Both the European and US standards allow six relatively narrow (100 kHz–200 kHz) amateur radio bands within the VDSL spectrum. Significant interference can exist between the VDSL signal and signals from amateur radio stations. Causes include improper (lack of) shielding, decrease in the balance of the phone line at high frequencies (it can go as low as 10 dB–30 dB), and use of untwisted drop wires. There are three problems manifested by these interference sources:

- *egress suppression*. VDSL interference in the radio amateur bands can be restricted by limiting the power spectral density of the VDSL signal in these bands to 80 dBm/Hz.
- *ingress suppression*. The amateur-radio signal interference can be as high as 0 dBm at the VDSL receiver input. It is highly desirable to attenuate such interference before converting to digital, otherwise a high-resolution ADC able to handle both the signal and the interfering signals is necessary.
- the amateur radio signal is a non-stationary signal, characterized by ON/OFF periods. Eliminating the effects of this signal (even attenuated) in the digital domain is not a simple task.

LINE-CODE

Three proposals for the line-code were submitted to the standards organizations:

- *single carrier modulation (QAM)*, the input data is split into two streams that modulate an in-phase and a quadrature sine wave; this method is presently used in most of the modems. It must be noted that with a frequency band allocation such as that in Figure 2, two such systems are necessary for each upstream and downstream direction.
- *discrete multitone modulation (DMT)*, the frequency band is split into a large number of channels; each individual channel uses QAM modulation. An efficient method for coding/decoding makes use of the IFFT at the transmitter and FFT at the receiver; it also ensures orthogonality between the carriers. This modulation method is used in ADSL.
- *filtered multitone (FMT) modulation* (Reference 3), can be viewed as a combination of the other two methods. The modulation is achieved by splitting the data into several streams, each of them applied to one of the inputs of a filter-bank. Because of implementation complexity, the number of channels is considerably less than in DMT. The sharp filters allow the elimination of guard bands used in QAM. Linear or decision-feedback equalizers are necessary for eliminating inter-symbol interference (ISI).

QAM and DMT modulation are compared below in the light of VDSL's specific problems. In most of the cases the reader will be able to extrapolate the results for FMT.

- The DMT signal has a Gaussian amplitude distribution. A peak-to-average ratio (PAR) of 15 dB is necessary to reduce the clipping to an acceptable level. Accommodating such high signal peaks requires an extended range for the transmitter buffer and increases the power consumption in the analog front end. Some of the single-carrier modulation's advantage is lost, because the line signal is the sum of two QAM channels (see Figure 2).
- Two QAM transmitters/receivers are necessary in each direction for single-carrier modulation; the DMT requires frame synchronization and supervision, and timing recovery is more difficult. As a result, the complexity is about the same for the two methods.
- The data rate losses due to cyclic prefix/suffix (DMT modulation) and guard bands (QAM) are similar.
- *RF egress*. In order to reduce the transmit PSD to –80 dBm/Hz for each of the radio amateur bands falling within the transmit band, notch filters are necessary for single modulation systems. These filters make the equalization more difficult. In DMT systems, the bins falling within amateur radio bands are not used. As a general observation, DMT modulation's greater flexibility in controlling PSD across the VDSL spectrum may translate into higher performance.

CONCLUSION

VDSL allows the transmission of high data rates, up to 52 Mb/s, using the existing twisted-pair wires. An agreement was reached in the standards organizations on using frequency division multiplexing with four frequency bands (two for upstream and two for downstream) in the 138-kHz-to-12-MHz frequency range. The details of the spectrum allocation are yet to be determined. The FEXT noise is the major crosstalk impairment. It requires power-backoff in the upstream direction. Short bridged taps can significantly alter the ratio between the upstream and downstream data rate, which is the reason they are not specified in the ETSI standard; however, they are still part of the US standard. Finally, T1E1 and ETSI agreed to include all three line codes in the present standards. In the long term the standards may evolve to the line code most capable of facing the difficult technical problems posed by VDSL.

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