FROM POTS TO VDSL - TECHNICAL ASPECTS OF A REASONABLE MIGRATION STRATEGY

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Abstract. This paper describes technical aspects in the development of the copper-access network. They include particularly those of compatibility of the ADSL- and future VDSL-transmission systems with the existing narrowband services like POTS and ISDN. Special emphasis is also laid on the compatibility of VDSL with other digital systems.

1. Introduction

Since the breakthrough of digital video encoding enabled by the MPEG standard and the rapid development of the Internet with its multimedia extension WWW (World Wide Web), a great number of manufacturers and network operators make every effort to establish a broadband access to offer future high bit rate multimedia services. The former idea of providing every customer with a fibre-based access cannot be put into practice because of the prohibitively high costs of installation and components. The most reasonable solution from an economic point of view is to upgrade existing networks with modern transmission and switching technology. This paper outlines the technical aspects of this upgrade.

2. Migration from narrowband to broadband services

The network which appears to be well suited to bring individual services to the customer is the copper-based telephone subscriber line network consisting of unshielded twisted-pair lines originally designed for speech transmission up to 4 kHz. Narrowband services are the Plain Old Telephone Service (POTS) and the Integrated Services Digital Network (ISDN).

High bit rate transmission systems like Primary Rate Access (PRA) and subscriber-line multiplexer (German abbreviation AslMx) have already been installed. Meanwhile, systems for bi-directional transmission of 2 Mbit/s over 1, 2, or 3 pairs up to 3 km (HDSL = High bit rate Digital Subscriber Line) and bit rate asymmetric transmission of up to 8 Mbit/s in downstream direction and 640 kbit/s in upstream direction (ADSL = Asymmetric Digital Subscriber Line) are commercially available. Depending on the bit rate, ADSL systems have a transmission range from 1.5 to 5 km. The ADSL-transmission technique is defined as a data-over-voice transmission on the existing telephone line so that no additional lines are necessary (unlike HDSL). Assuming a transmission range of 3.0 km, about 70% of all telephone subscribers (in Germany) can be reached via ADSL from the local exchange. Higher bit rates like 13, 26, and 52 Mbit/s as defined for the VDSL (Very high bit rate Digital Subscriber Line) technique can only be transmitted over shorter lines usually between the cabinet and the customer. In this case, a broadband fibre-based access has to be installed at the location of the cabinet, which means more initial investment compared with the use of ADSL.

A difficult and necessary task when migrating from narrowband to broadband services is to maintain the old narrowband services and their quality. In the following sections, solutions and specific migration problems concerning ADSL and VDSL will be discussed.

2.1 Coexistence of narrowband and broadband services on the same twisted pair

Since the number of free copper lines in the subscriber-line network is limited and the installation of new cables is very expensive, only such broadband services which use the same twisted pair together with the narrowband services have the chance of a large penetration. The coexistence can be ensured in two different ways. The first approach is that only one digital line signal carries both services. The other possibility is the spectral coexistence, where the narrowband signal remains unchanged and the broadband signal covers a high-frequency band above the narrowband signal (frequency division multiplex). The first possibility has the advantage that no analogue filters for the separation of the spectra are necessary, but the serious disadvantage that the narrowband transmission suffers from crosstalk problems in the same way as the broadband transmission. Therefore, the second possibility is preferred. The spectrum-separation filters have to meet the transmission requirements mentioned in Section 2.2.

In the following, the technical problems of the splitter-filter design will be explained. **Fig. 1** shows a basic block diagram of an xDSL system with splitter filters suited for POTS or ISDN. The lowpass filters block the noise, which originates from the broadband channel, whereas the highpass filters block the noise generated by the narrowband service terminal, e.g., by the dialling and hook-flash impulses of analogue telephone sets.

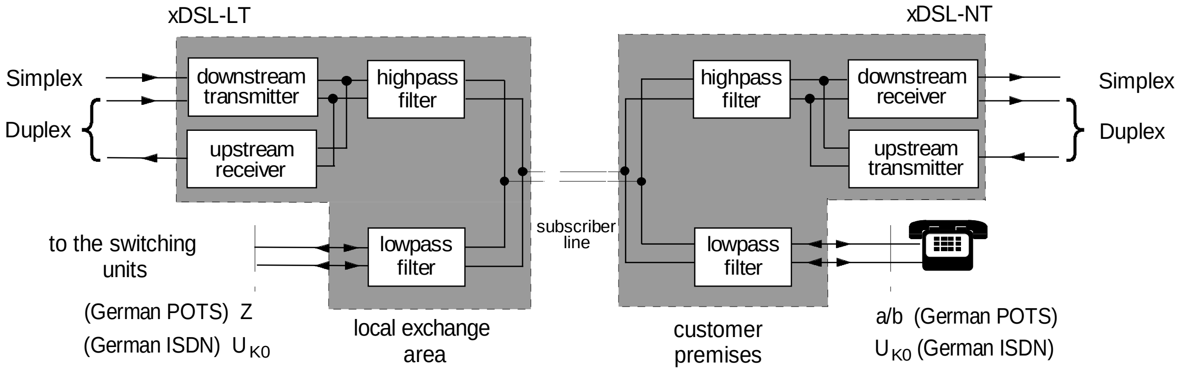


Figure 1: Principle of splitting and combining xDSL with POTS or ISDN

The complexity of the splitter filters depends mainly on the transmission bandwidth for the POTS or the ISDN signal and the required return loss values for the interfaces. For POTS, the line impedance at the *Z*-interface at the local exchange is complex with different values from country to country (see **Fig. 2**).

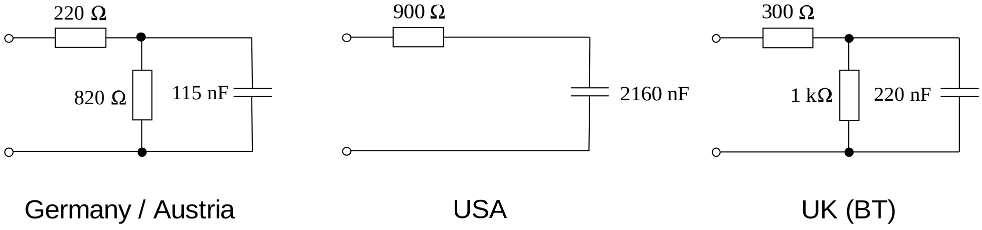
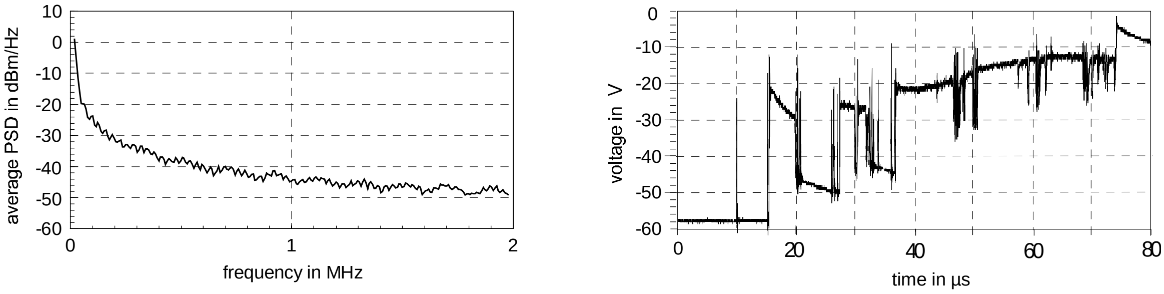


Figure 2: Model circuits for the complex line impedances in the voice band

For an ADSL system according to the ANSI standard, the digital transmission starts at roughly 25 kHz so that the edge frequency of the splitter-lowpass filter has to be somewhat lower. In this case, a passive filter design that meets the requirements in **Table 1** seems to be impossible. So the different ADSL manufacturers use passive base circuits with rather big coils together with an active part that performs the adaptation to the complex impedance of the line. A special drawback for POTS splitters is the high stop-band attenuation of the lowpass filter, which is necessary to limit the hook-flash crosstalk, covering a broad frequency range at high amplitudes. **Fig. 3a** shows the average power-spectral density (PSD) during impulse events. **Fig. 3b** depicts an example of a measured impulse event.



a) b)

Figure 3: a) Average power-spectral density of hook-flash impulses at 100 ohms
b) Measured hook-flash impulse event

In the ISDN case, no hook-flash impulses on the same line exist and the bandwidth is more than 40 times larger (120 kHz for MMS43 ISDN especially used inside Germany, 80 kHz for 2B1Q ISDN). The splitter filters for ISDN are significantly simpler than the ones for POTS. Thus, for POTS-ADSL, the lower edge frequency of the ADSL signal should be increased to above 120 kHz in order to reduce the complexity of the splitter filters. Therefore, in the case of ISDN-ADSL, one has to pay with a reduction of transmission reach which lies between 10 % and 15 % for 2 Mbit/s and 0.4-mm wires. This will be discussed in detail in Section 2.3. A universal splitter filter which meets the ISDN as well as the POTS requirements or a switchable filter could be used. The requirements for such a universal splitter filter are listed in a current ETSI contribution of Deutsche Telekom [1].

2.2 Technical requirements for POTS and ISDN services

To guarantee the specified quality of POTS and ISDN-based services, a large set of requirements has to be met. In the following, only the transmission requirements of the loop and the interfaces at the local exchange and the customer premises will be discussed. In the case of POTS, one has to distinguish between the *Z*-interface at the local exchange and the a/b-interface (Germany) at the customer premises. In the ISDN case, only the U-interface is defined. **Table 1** gives a survey of the most important transmission requirements for POTS and ISDN. For ISDN, the only quality-of-service requirement is the bit-error rate, whereas for ensuring the quality of speech in the POTS case, many different requirements are specified. Accordingly, different frequency-dependent tolerance schemes are defined. For simplification, only the maximum values are listed in the overview. There are fewer requirements in the ISDN than in the POTS case.

2.3 Interference of narrowband and broadband techniques on the same line

ISDN-ADSL results in a reach reduction of the ADSL system compared with POTS-ADSL. This is evaluated by simulating an approximately standard-compliant DMT-based ADSL system. The downstream and upstream channels are assumed to be separated by an ideal echo canceller. In this section, self-NEXT due to echo cancellation is neglected. The line attenuation is chosen according to the characteristics of the German subscriber-line network (wire diameter = 0.4 mm). Different NEXT disturbers are considered (HDSL, PRA, AslMx). No margin is taken into account because, here, only the differences in reach between POTS-ADSL and ISDN-ADSL are important.

	POTS (Germany)	2B1Q ISDN ETSI ETR 080	MMS43 ISDN 1 TR 220 (Germany)
frequency band	0.2 - 3.6 kHz 15.92 - 16.08 kHz	DC to 80 kHz	DC to 120 kHz
line impedance	Z_L (see Fig. 2)	135 ohms	150 ohms
return loss	> 18 dB	> 20 dB	> 16 dB
long. conv. loss	> 46 dB	> 45 dB	> 40 dB
max. group delay	750 µs	not defined	not defined
max. attenuation	10 dB	36 dB	42 dB
atten. distortion	0.7 dB	not defined	not defined
max loop resistance	1200 ohms	not defined	not defined
transmission reach	not defined	test loops with noise at BER 10^{-7}	0.4-mm cable 4.2 km / 5.0 km with / without noise at BER 10^{-7}

Table 1: Important transmission requirements for the line connection between customer premises and local exchange for POTS and ISDN

Fig. 4 depicts the dependence of the reach on the edge frequency of the ADSL signal, i.e., the 3-dB cut-off frequency of the highpass filter of the ISDN splitter. The carriers below this edge frequency are omitted. For POTS-ADSL, the reach is 4.1 km (edge frequency 25 kHz, 2.048 Mbit/s data rate, one AslMx as a disturber, Reed-Solomon code, bit-error rate < 10^{-7}). For ISDN-ADSL, the system achieves loop lengths between 3.88 (edge frequency 80 kHz) and 3.73 km (140 kHz). The difference in ADSL reach between 2B1Q and MMS43 ISDN line codes is only about 70 m (reach difference between 100 and 140 kHz), which can be neglected. Therefore, ISDN splitters for MMS43 could be applied for both 2B1Q and MMS43 ISDN. This enables an easier design of an ISDN splitter suitable for almost all countries (in contrast to POTS splitters).

If an edge frequency of 138 kHz is chosen, ISDN reduces the reach in comparison with POTS-ADSL by roughly 10 % to 15 %, i.e., 400 to 500 m, for 0.4-mm loops, 2.048 Mbit/s, and several disturbers. For a data rate of 8.5 Mbit/s, the reach is reduced by 500 m due to ISDN compared with 1.8 km of POTS-ADSL. Thus, for data rates of 8 Mbit/s and more, it is proposed to apply VDSL.

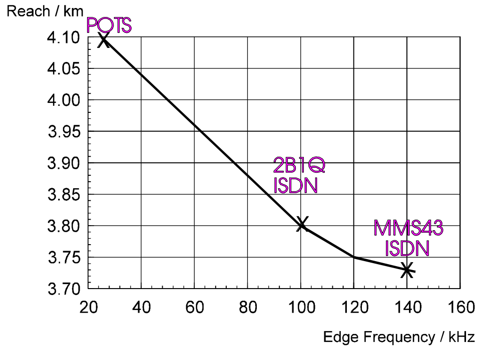


Figure 4: Reach of 2-Mbit/s ADSL dependent on the edge frequency (0.4-mm wire, 1 AslMx)

In the case of VDSL, reach reduction due to reserving the lower part of the spectrum for ISDN is not a critical issue. Because of compatibility requirements with other broadband transmission systems inside the same cable, VDSL is very likely to start far above the ISDN band, anyway (cf., Section 3.2). Further, VDSL is not limited to frequencies below 1.104 MHz as it is the case for ADSL.

3 Spectral compatibility of broadband systems on different lines

3.1 Spectral compatibility of installed broadband systems up to 8 Mbit/s

For the development of a reasonable migration strategy, the spectral compatibility between existing high bit rate transmission techniques has to be taken into account as well. The aim is to minimize interference of the systems in order to utilize the ‘copper resource’ in an optimal way, i.e., the maximum number of customers can be provided with services of maximum bit rate. The best spectral compatibility would be achieved if the systems were spectrally separated. The systems already installed in the network of Deutsche Telekom are PRA, AslMx, and, in smaller numbers, HDSL and ADSL.

The AslMx system is the most critical source of disturbance for ADSL and, vice versa, it is also affected by ADSL. Therefore, AslMx should be replaced by HDSL. PRA should be replaced by HDSL, too, because HDSL is an improved technique (higher reach) for typical PRA services. Further, the spectrum of HDSL (2B1Q) has a lower bandwidth than PRA (HDB3) and, thus, is more compatible with other systems. POTS-ADSL has the advantage that the downstream and upstream channels are spectrally separated which implies no self-NEXT (near-end crosstalk). In contrast to this, ISDN-ADSL suffers from self-NEXT due to echo cancellation (reach additionally reduced by about 100 m) since a spectral separation is not acceptable because of the higher reach reduction. Whereas the lower ADSL spectrum is limited by ISDN, the upper spectrum should be limited for better compatibility with VDSL, which both results in a degradation of the ADSL performance.

3.2 Spectral compatibility of VDSL with existing systems

Unlike ADSL and HDSL, which are quite mature techniques, VDSL is currently at the stage of definition and only a few lab systems have been available up to now. VDSL will represent the final copper-based technique that usually makes use of the last portion of the subscriber line only (distribution network), i.e., it is part of a fibre-to-the-cabinet architecture (see **Fig. 5**). The term VDSL includes bit rate symmetric as well as bit rate asymmetric transmission.

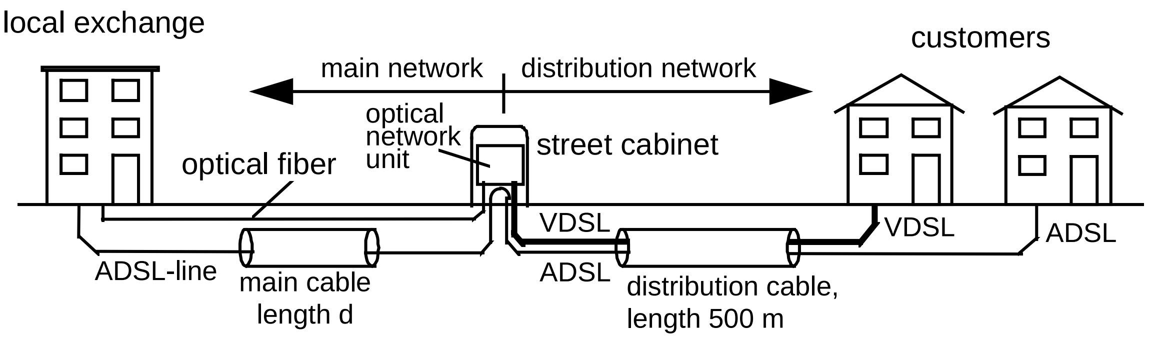


Figure 5: Topology of a typical xDSL scenario, comprising ADSL and VDSL.

Because of the smaller length of the distribution cables (90 % less than 500 m in Germany) compared with the total subscriber line, it is possible to transmit at very high rates and a wide frequency range will be occupied. Due to the high frequency components, radio-frequency interference is one of the major issues in the international standardization of VDSL. However, these topics are not addressed here, since in Germany almost all cables are buried. Therefore, radio waves are significantly attenuated. Instead, our interest shall be focused on the issue of spectral compatibility amongst xDSL systems in the same cable.

The limiting factor for the achievable bit rate of a particular VDSL link is crosstalk from other xDSL systems, including VDSL itself. There are two major effects resulting from the wider frequency range. First, attenuation is stronger. Second, crosstalk attenuation among adjacent lines inside a multipair cable becomes very low (20 - 30 dB).

Interestingly, most of the crosstalk problems with VDSL could have been avoided if years ago one had foreseen the increasing renaissance of the copper lines in the era of broadband access (instead of fibre to the home). At the time when the first broadband systems were designed, the focus was more on a simple and cheap transceiver design than keeping the out-of-band power low. More or less all systems like ADSL, HDSL, ISDN, and PRA emit significant signal energy in the VDSL band, e.g., PRA emits -73 dBm/Hz at 5 MHz. From the point of view of data-transmission theory this would not have been necessary. For PRA, about 3 MHz bandwidth would have been sufficient by far. Of course, views have changed now, but many systems have already been installed (cf., Section 3.1).

In the case of ADSL systems that have not yet been installed in large quantities, but are expected to be so in the near future, operators are currently interested in limiting their out-of-band energy in order to minimize the ‘spectral pollution problem’. As an example, the FSAN group of major European (and some American) operators has recently proposed to apply more stringent spectral masks to ADSL [2]. It is very likely that these more stringent requirements will be reflected in the procurement requirements of the individual operators even if they are not yet incorporated in the standards for the corresponding xDSL systems.

Fig. 6 is to give an impression of what is happening inside a multipair-copper cable. It shows power-density profiles over the frequency range envisaged for VDSL. As an example, only signal PSD at the cabinet side of the distribution cable are shown. In particular, you can see the PSD of the received VDSL upstream signal (where a transmit level of -60 dBm and 500 m length of the distribution cable has been assumed), far-end crosstalk (FEXT) of possible other VDSL links running on adjacent lines and crosstalk from ADSL downstream transmission (transmitter located at the local exchange). Also white background noise with a PSD of -140 dBm/Hz is considered.

The data rate that can be transmitted by a properly designed system depends essentially on the ratio of the received data signal power S to the receiver input noise power N. Owing to the cable properties and the PSD of disturbers, these quantities are not constant in frequency. An ultimate bound of the data that can be reliably transmitted in the VDSL band between 300 kHz and 30 MHz over such a linear channel is the Shannon channel capacity given by

$$C = \int_{300\text{ kHz}}^{30\text{ MHz}} \log_2\left(1 + S(f)/N(f)\right) df\,.$$

As a rough estimation of the data rate R that a practical system might be able to transmit at, we take here 60% of C (representing roughly losses due to roll-off, Reed-Solomon coding, guard bands or times, and overhead) and replace $S(f)/N(f)$ by $S(f)/N(f)\cdot 0.1$ (representing a transmission system without signal space coding and power shaping). Note that in order to obtain this data rate R, the whole frequency range up to 30 MHz is considered for one direction only. Treating duplex transmission is out of the scope of this short contribution. In the case of bit rate symmetric transmission, one may take $R/2$ as a rough estimation of possible transfer in one direction. **Table 2** gives examples for $R/2$ for several simple network scenarios corresponding to Fig. 5.

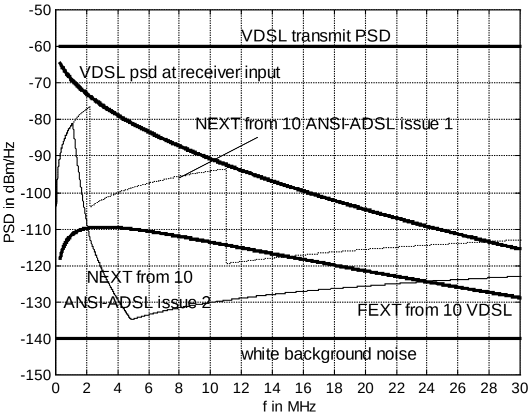


Figure 6: PSD at the VDSL up-stream receiver input for the special case of d = 0 m

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Assumed set of disturbers	$R/2$ (d = 0 m)	$R/2$ (d = 500 m)
White background noise only	99 Mbit/s	99 Mbit/s
Background noise plus 10 VDSL-FEXT	35 Mbit/s	35 Mbit/s
Background noise plus 10 VDSL-FEXT plus 10 ADSL-NEXT, issue 1	13 Mbit/s	31 Mbit/s
Background noise plus 10 VDSL-FEXT plus 10 ADSL-NEXT, issue 2	29 Mbit/s	33 Mbit/s

Table 2: Estimated achievable bit rates for symmetric VDSL

The dramatic impact of crosstalk becomes obvious. After adding further crosstalk sources that need to be considered in a complete network scenario (e.g., ISDN, PRA, HDSL), finally, bit rates in the range of 13 to 26 Mbit/s seem to be achievable for symmetric VDSL. Note also the severe performance penalty for the $d = 0$ m case, if ADSL systems according to the ANSI standard T1.413, issue 1 were installed.

4. Conclusions

The copper-based subscriber-line network originally destined for narrowband services is currently upgraded for providing broadband services. The compatibility of narrowband and broadband systems on the same line and, more important, the mutual spectral compatibility of all systems have to be considered. Especially for VDSL, the achievable bit rate depends enormously on noise contributions in the network which should be reduced wherever possible. Therefore, careful network planning by the operator is indispensable.

Bibliography

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