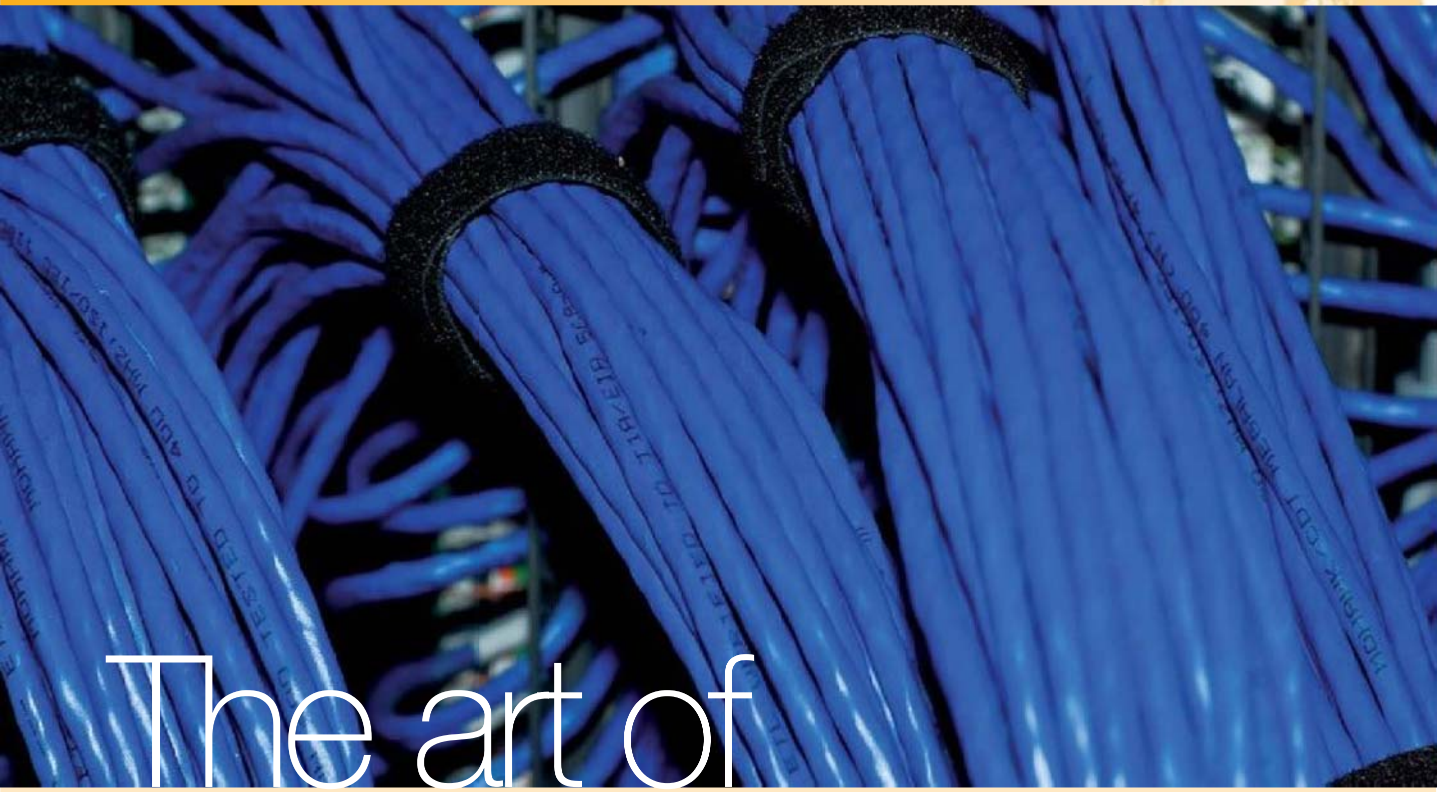

The art of deploying DSL, Broadband via noisy telephony wiring

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The huge spread in crosstalk coupling between the individual wire pairs of a telephony cable makes it a significant challenge to deploy systems such as ADSL and VDSL2 in high volumes. More careful planning is required to deliver Triple Play services. This article explains the effects and consequences of spread in crosstalk coupling between wire pairs and discusses an initial strategy for deploying VDSL2.

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Since 1996, he has played a very prominent role in DSL standardisation in Europe (ETSI, FSAN), has written more than 100 technical contributions to ETSI, and took the lead within ETSI-TM6 in identifying / defining cable models, test loops, noise models, performance tests and spectral management. He is the editor of an ETSI-TM6 reference document on European cables, and led the creation of the MUSE Test Suite, a comprehensive document for analyzing access networks as a whole. He also designed solutions for Spectral Management policies in the Netherlands, and created various DSL tools for performance simulation (SPOCS, www.spocs.nl/en) and testing that are currently in the market.

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Introduction

The transmission characteristics of twisted-pair telephony cables bring many challenges for DSL operators who need to deploy thousands or millions of xDSL lines. Their customers often ask, "What bit-rate can you offer me with your DSL solution?", but this cannot easily be answered. Nevertheless, customers request a certain bit-rate and, if the subscription is accepted, they expect to get what was promised. Additionally, the "performance" of operators is often tested in consumer magazines by comparing the promised bit-rates with those delivered.

However, the bit-rate received by customers is not straightforward to calculate. The huge spread in crosstalk coupling between the individual wire pairs causes many differences in attainable bit-rate, even to neighbouring customers. DSL operators have to cope with that when they define their deployment rules. Trial-and-error deployment strategies with adaptive bit-rates may have worked well for offering an "elastic" service, such as Internet Access, but more careful planning is required to deliver Triple Play services.

This article explains the effects caused by cross-talk coupling and the consequences for operators with respect to DSL deployment. First, ADSL examples are presented to explain the impact of different crosstalk levels on the bit-rate in individual wire pairs. Second, the consequence of crosstalk on the network as a whole (i.e. millions of wire pairs) is evaluated.

Based on this, the severity of spread in cross talk (for which a given bit-rate can be achieved in practice) is investigated. The observed ADSL bit-rates are all based on measurements in KPN's access network in the Netherlands. Finally, an intial strategy for deploying VDSL2 is outlined based on past ADSL experience and the findings presented. A good understanding of expected bit-rate uncertainties due to spread in crosstalk is valuable for evaluating the business case for VDSL2 before any VDSL2 system is being deployed.

Bit-rate limits on a single wire pair: crosstalk

Broadband services via ordinary twisted-pair telephony cables strain DSL modems to their limits. Modems such as ADSL(2) transmit signals with frequencies of up to 1.1MHz, and ADSL2plus up to 2.2MHz. A signal with a strength of only a fraction of its original level will arrive at the customer premises. For instance, the attenuation of a 1MHz signal component in a Dutch telephony cable that is 4km long (using 0.5mm copper wires) is in the order of 75dB. This figure is higher for 0.4mm cables used in other European countries [4]. Although the received signal is weak, it can still be recovered by DSL modems.

However, a modem not only receives the attenuated signal, but also receives noise. This noise comes from other DSL systems using the same cable (and also from sources outside the cable, especially when the cable is not shielded). The electro-magnetic coupling between individual wires causes a transmitted signal in one such wire pair to induce a weak signal into all the other wire pairs of the same cable.

If multiple DSL modems use different wire pairs in the same cable, then all their signals will mutually contribute noise, and all wire pairs will receive a mixture of weak signals that behave like noise. This is called crosstalk noise, or simply crosstalk. A typical Dutch distribution cable packs 900 of these wire pairs in one binder, and when hundreds of wire pairs are connected to other DSL systems, the cumulated crosstalk noise can be significant.

Figure 1 illustrates the crosstalk noise for a randomly selected individual wire-pair for all relevant frequencies. Curve 1 shows the signal spectrum being transmitted by an ADSL2plus modem. Curve 2 shows what fraction of it will arrive after 4km of attenuation in a twisted-pair cable.

If the quality of the wire pair is excellent (and only weakly coupled with other wire pairs), then the cumulated crosstalk noise from all other DSL systems in that cable will be very small. Curve 3 illustrates this for a typical mix of 300 DSL systems using 300 wire pairs in a 900 wire pair cable. The shaded green area indicates how much higher the received signal level is compared to the received noise level. This is indicative of the signal-to-noise ratio at the receiver. DSL modems can cope with it, and can recover data under noisy conditions if the bit-rate does not exceed a certain maximum.

Calculations according to [2,4] have shown that an ADSL2plus modem can transport up to 7.5Mb/s under these particular stress conditions (the maximum bit-rate), if the noise from sources outside the cable is ignored. In a realistic deployment however, it is recommended to account for sufficient safety margin, and not to exceed 6.5Mb/s (in this example). It will make the transmission more robust so that even an increase in noise of 6dB will not cause the transmission to fail (the so called attainable bit-rate at 6dB noise margin).

Figure 1: Spectra of ADSL2plus in a 4km wire pair, and the received crosstalk noise from other DSL systems.

In practice, however, most wire pairs are not as good as assumed above. The spread in crosstalk coupling between individual wire pairs in the same cable is significant.

Measurements conducted by the former KPN Research (now merged with TNO) on a Dutch cable demonstrated a spread in crosstalk coupling of more than 60dB. This behaviour is typical, dominated by the physical construction of telephony cables, and may hold for cables used in several different countries.

If multiple DSL systems use the same cable, then the cumulative crosstalk level in each wire pair will be the power sum of what each of these modems contributes. These power sums will therefore increase with the cable fill (the number of DSL systems sharing the same cable), and will be different for each wire pair. The spread in these power sums will be lower than the spread in individual contributions (weak contributions are dominated by the strong ones). Nevertheless, the spread is still significant since variations in noise level of more than 20dB are not uncommon at high cable fill.

Figure 2 quantifies the consequence of higher crosstalk levels for another wire pair that is assumed to be near worst case. In this second example, it is assumed that the cumulative crosstalk noise level is 20dB higher than in the first one. Under these conditions, the signal components cannot be decoded above 1.3MHz since their levels are below the noise levels.

The result is that an ADSL2plus modem can no longer recover the high data rate that was feasible under the conditions shown in Figure 1. However, if we allow the modem to drop its bit-rate below a certain value, then the modem can adjust its transmission signal in such a manner that the lower bit-rate can be recovered. Such a bit-rate limit is related to the signal-to-noise ratio (SNR).

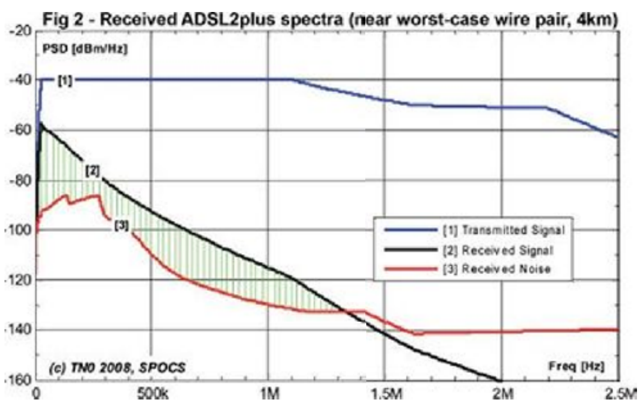

Figure 2: Spectra of ADSL2plus in a 4km wire pair, when the crosstalk noise is 20dB above the level used in Figure 1.

Calculations according to [2,4] showed that an ADSL2plus modem can transport up to 3.2Mb/s under these particular stress conditions (maximum bit-rate), but in this example it is recommended not to exceed 1.7Mb/s (attainable bit-rate) to facilitate the 6dB noise margin.

Current DSL systems recover data from noisy signals with a quality that is near the edge of what is theoretically possible: the “Shannon limit”. The SNR determines this bit-rate limit. Expanding a bit-rate limit by increasing the transmit power works on individual wire pairs, but not for a cable as a whole: if all systems double their power, then the crosstalk noise will double too, and the SNR remains the same for all modems.

The Shannon limit is approximated to be 6-8dB for modern DSL modems [2]. This means that if such a modem handles the same bit-rate as a hypothetical DSL modem (operating at the Shannon limit), the noise should be 6-8dB lower to enable this. This high quality is achievable for all commonly used line codes: DMT, CAP, QAM and PAM, and has been demonstrated for HDSL, SDSL, all flavours of ADSL, for VDSL and it will probably hold for future DSL products as well.

Deployed modems should never be pushed up to their maximum bit-rate, whether it is a real or a hypothetical modem. Lowering the bit-rate provides a noise margin for keeping the link working at the selected bit-rate when the noise increases by ‘x’dB. Reducing the bit-rate to a value that offers 6dB noise margin is a much better choice and is called the “attainable bit-rate”.

Bit-rate limits in cables: spread in crosstalk

A DSL operator would like to know what bit-rate is attainable with a certain technology for all of its customers; not only for all wire pairs in a cable of 4km, but also for all cables between 0 and 6km in an access network. These bit-rates can be predicted with proper simulation tools, such as SPOCS [5], and proper simulation models [2], by assuming that crosstalk dominates the noise environment.

These tools can predict the bit-rate for a system under well-defined stress conditions (loop length, crosstalk coupling, cable loss, DSL disturber mix): a so-called scenario. If the bit-rate is evaluated for a realistic scenario, at multiple loop lengths and at multiple crosstalk assumptions, then the result is indicative for what happens in an access network as a whole.

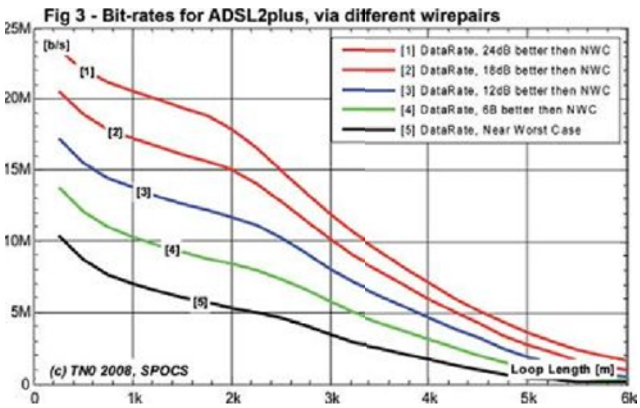

Figure 3: Bit-rate, predicted for ADSL2plus in noisy wire pairs, for different levels of crosstalk.

Figure 3 illustrates such a prediction of the maximum bit-rate that can be offered with a typical ADSL2plus system (FFD, over POTS) under various crosstalk conditions. It shows the attainable bit-rate in different wire pairs of the same cable, ranging from a near worst-case wire pair (high crosstalk levels) to an excellent wire pair (low crosstalk levels). Near worst case means in this context that 99% of the wire pairs are better and less than 1% of the wire pairs are worse.

The upper prediction curve (1), belongs to a wire pair of outstanding quality (24dB better than in the near worst-case wire pair); a customer, connected via a 4km cable, can receive up to 7.1Mb/s when connected to such a high quality wire pair. However, his (unfortunate) neighbour, who happens to be connected to a near worst-case wire pair of that cable, can receive no more than 1.7Mb/s.

All these prediction curves have been evaluated at 6dB noise margin, meaning that the crosstalk noise should increase by at least 6dB before the systems will fail. Such a safety margin enables the delivery of reliable bit-rates. Furthermore, this example assumes that ADSL2plus shares the cable with a mix of 300 xDSL systems, ranging from various flavours of ADSL, SDSL, HDSL and ISDN.

The scatter plot in Figure 4 shows what really happens on operational wire pairs, in conjunction with the curves of Figure 3. Each dot represents the combination of the attainable bit-rate and the length of an individual wire pair, as reported by an operational DSL modem on that wire pair. The measured performance, represented by each dot, is limited by a combination of crosstalk and impulse noise, while the simulated performance represented by each curve is based on crosstalk only.

The plot shows only a few thousand of these dots, but the originating “cloud” of dots was extracted from performance parameters reported from approximately one million operational DSL lines in the Netherlands. Similar scatters may exist for lines in other countries, but that information is not available.

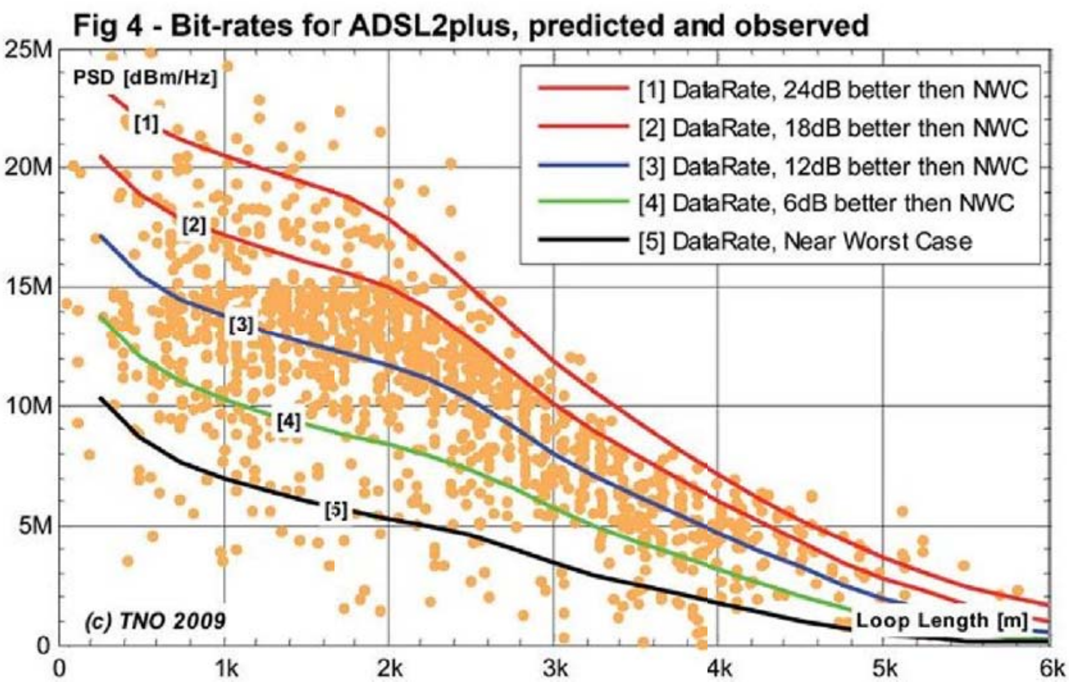

Figure 4: A significant spread in attainable bit-rate will be observed when monitoring millions of operational ADSL2plus lines. The correlation between looplength and bit-rate is very weak (may range from 1 to 22Mb/s at 2km). A set of bit-rate predictions are indicative for large deployment volumes only, and not for individual wire pairs.

These modems can estimate the attainable bit-rate and loop length from the received signal-to-noise ratio at their inputs and the insertion loss between the modems at both ends of a wire pair. If estimated on a wire pair, inside a cable that is filled significantly with DSL modems (say >20%), then the reported attainable bit-rates are very good indicators for the real value.

Figure 4 illustrates how high the spread in attainable bit-rate can be for a given loop length. On some wire pairs it is even better than the most optimistic prediction curve of the plot, and on others even worse than the most pessimistic prediction curve. In extreme situations, these wire pairs can be in the same cable, to two neighbouring customers. For instance: one customer can get more than 7Mb/s (on 4km distance), while his neighbour cannot exceed 1Mb/s. Similarly, offering 10Mb/s may work well for one customer at a distance of 3.4km, but may fail for another that is at a distance of only 300m. This behaviour is typical and is dominated by the physical construction of telephony cables.

This spread in crosstalk made it necessary to equip DSL modems with special features to deal with it. Today's systems are rate-adaptive at start-up, and can switch back to lower bit-rates if the signal-to-noise ratio becomes too poor.

If too many errors are detected, they interrupt the link for a while and retrain the modem parameters. This at least brings the connectivity back up. But before retraining, and thus shortly interrupting the service, the modem will first try to cope with the new noise situation by means of a variety of advanced mechanisms: swapping bits to other frequency bands, forward error correction etc. This is all done automatically.

Summary

The maximum bit-rate that can be offered via DSL lines to customers is restricted by crosstalk and its level is wire-pair specific. The spread in crosstalk is too significant to be ignored, and has consequences for the deployment rules.

Simple deployment rules, based only on loop length, are not optimal but valuable as an initial approach. The associated curves can be evaluated with proper simulation tools for arbitrary scenarios (service mix, cable characteristics, topologies etc).

During the introduction of VDSL2, the use of such a simple length-based deployment rule is a good option. However, as soon as more information becomes available from operational VDSL2 modems, the use of a wire-pair specific deployment rule needs to be considered. This is where dynamic line management techniques become valuable, but are not applicable when defining the service offer to justify the business case for VDSL2 deployments and at the start of their roll-out.

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[2] ETSI TR 101 830-2, "Spectral Management, part 2: Technical methods for performance evaluations", 2008.
[3] ITU-T, Recommendation G993.2 "Very high speed Digital Subscriber Line Transceivers 2 (VDSL2)" (including all corrigenda).
[4] Rob F.M. van den Brink, "Cable reference models for simulating metallic access networks", ETSI/STC TM6 permanent document, June 1998 [5] SPOCS, a simulation tool compliant with ETSI TR 101 830-2, www.tno.nl/spocs

Other White Papers in this series:
[6] Rob F.M. van den Brink, "The art of deploying DSL; Broadband via ordinary telephony wiring", TNO 35090, White Paper on DSL, Oct 2009 (revision from June 2008)
[7] Rob F.M. van den Brink, "The art of Spectral Management; Access rules for VDSL2"; TNO 35091, White Paper on DSL, Oct 2009.
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