The art of deploying DSL, Broadband via noisy telephony wiring

Whitepaper on DSL – Rob F.M. van den Brink, TNO, The Netherlands, Oct 2009

Abstract[1]*: 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. Trial-and-error deployment strategies with adaptive bitrates may have worked well in the past for offering an "elastic" service such as Internet Access, but more careful planning is required to deliver Triple Play services. DSL operators who introduce VDSL2 can take advantage of the operational experience gained from millions of ADSL lines. This article explains the effects and consequences of spread in crosstalk coupling between wire pairs and discusses an initial strategy for deploying VDSL2.*

1. 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 bitrate can you offer me with your DSL solution?", but this cannot easily be answered. Nevertheless, customers request a certain bitrate, 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 bitrates with those delivered.
However, the bitrate received by customers is not straightforward to calculate. The huge spread in crosstalk coupling between the individual wire pairs causes many differences in attainable bitrate, even to neighbouring customers. DSL operators have to cope with that when they define their deployment rules. Trial-and-error deployment strategies with adaptive bitrates 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 paper 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 bitrate 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 bitrate can be achieved in practice) is investigated. The observed ADSL bitrates 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 bitrate uncertainties due to spread in crosstalk is valuable for evaluating the business case for VDSL2 before any VDSL2 system is being deployed.

2. BITRATE 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 up to 1.1 MHz, and ADSL2plus up to 2.2 MHz. 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 1 MHz signal component in a Dutch telephony cable that is 4km long (using 0.5 mm copper wires) is in the order of 75 dB. 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 behaves 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

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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 bitrate does not exceed a certain maximum.
Calculations according to [2,4] have shown that an ADSL2plus modem can transport up to 7.5 Mb/s under these particular stress conditions (the ***maximum*** bitrate), 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 6.5 Mb/s (in this example). It will make the transmission more robust so that even an increase in noise of 6 dB will not cause the transmission to fail (the so called ***attainable*** bitrate at 6 dB noise margin).

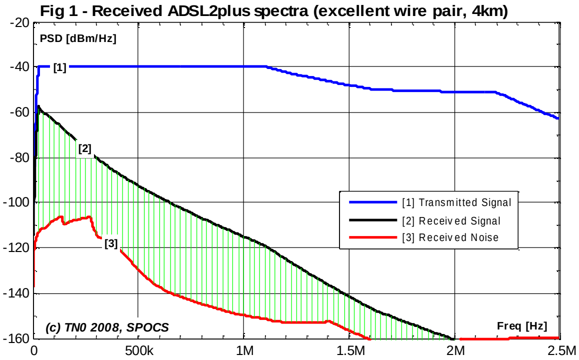

***Figure 1**: Spectra of ADSL2plus in a 4 km wire pair, and the received crosstalk noise from other DSL systems.*

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 60 dB. 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 cumulated 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 20 dB 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 cumulated crosstalk noise level is 20 dB higher than in the first one. Under these conditions, the signal components cannot be decoded above 1.3 MHz 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 bitrate below a certain value, then the modem can adjust its transmitting signal in such a manner that the lower bitrate can be recovered. Such a bitrate limit is related to the signal-to-noise ratio (SNR).
Calculations according to [2,4] showed that an ADSL2plus modem can transport up to 3.2 Mb/s under these particular stress conditions (maximum bitrate), but in this example it is recommended not to exceed 1.7 Mb/s (attainable bitrate) to facilitate 6 dB noise margin.

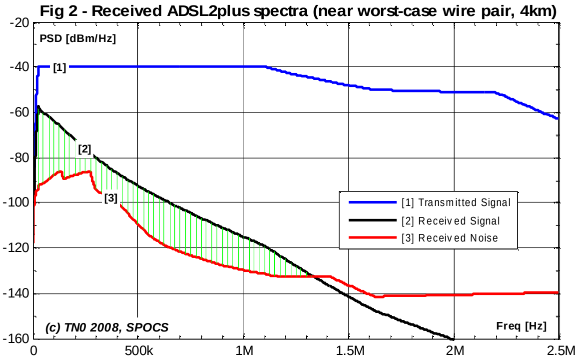

***Figure 2**: Spectra of ADSL2plus in a 4 km wire pair, when the crosstalk noise is 20 dB above the level used in Figure 1.*

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 bitrate limit.
Expanding a bitrate 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 6-8 dB for state-of-the-art DSL modems [2]. This means that if such a modem handles the same bitrate as a hypothetical DSL modem (operating at the Shannon limit), the noise should be 6-8 dB 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 bitrate, whether it is a real or a hypothetical modem. Lowering the bitrate provides a noise margin for keeping the link working at the selected bitrate when the noise increases by x dB. Reducing the bitrate to a value that offers 6 dB noise margin is a much better choice, and is called the "attainable bitrate".

3. BITRATE LIMITS IN CABLES: SPREAD IN CROSSTALK

A DSL operator would like to know what bitrate 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 6 km in an access network. These bitrates 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 bitrate for a system under well defined stress conditions (loop length, crosstalk coupling, cable loss, DSL disturber mix): a so-called scenario. If the bitrate 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.

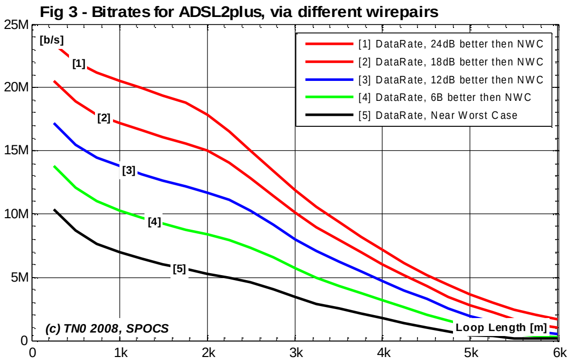

Figure 3: *Bitrate, prediceted for ADSL2plus in noisy wire pairs, for different levels of crosstalk.*

Figure 3 illustrates such a prediction of the maximum bitrate that can be offered with a typical ADSL2plus system (FFD, over POTS) under various crosstalk conditions. It shows the attainable bitrate 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 that less than 1% of the wire pairs are worse.

The upper prediction curve (1), belongs to a wire pair of outstanding quality (24 dB better than in the near worst-case wire pair); a customer, connected via a 4km cable, can receive up to 7.1 Mb/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 1.7 Mb/s.

All these prediction curves have been evaluated at 6 dB noise margin, meaning that the crosstalk noise should increase by at least 6 dB before the systems will fail. Such a safety margin enables the delivery of reliable bitrates. 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 bitrate 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.

These modems can estimate the attainable bitrate and loop

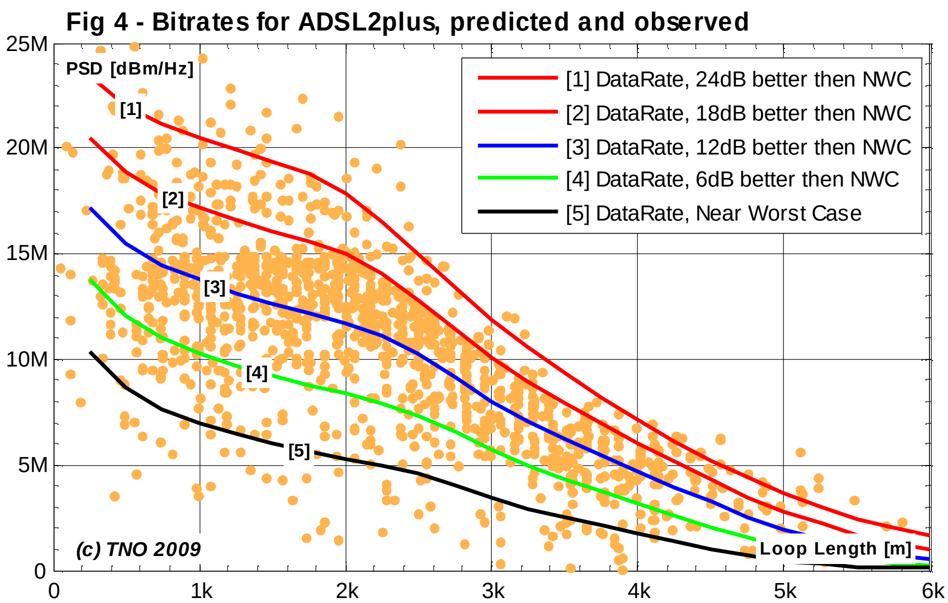

Figure 4: *A significant spread in attainable bitrate will be observed when monitoring millions of operational ADSL2plus lines. The correlation between looplength and bitrate is very weak (may range from 1 to 22 Mb/s at 2km). A set of bitrate predictions are indicative for large deployment volumes only,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

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 bitrates are very good indicators for the real value.
Figure 4 illustrates how high the spread in attainable bitrate 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 4 km distance), while his neighbour cannot exceed 1 Mb/s. Similarly, offering 10Mb/s may work well for one customer at a distance of 3.4 km, but may fail for another that is at a distance of only 300 m. 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 bitrates 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.

4. HOW TO DEPLOY VDSL2 IF THERE IS SIGNIFICANT NOISE SPREAD

Since a significant spread in crosstalk is a fundamental property of telephony cables, how should a DSL operator cope with it when deploying VDSL2? If the DSL operator's business case is based on a Triple Play service offer that includes offering *N* video channels in ***parallel*** to individual customers, how likely is it that the required bitrate is feasible for an individual customer? How many customers can be guaranteed these *N* video channels?
Trial-and-error deployment strategies with adaptive bitrates may have worked well in the past for offering elastic services, such as Internet Access, but more careful planning to deliver Triple Play services should be done. An inelastic service such as streaming video will fail when the attainable bitrate for *N* video channels in parallel is below a certain limit. An elastic service such as web browsing will remain operational under these conditions, and continues at lower speed only. In addition, inelastic services are more sensitive to all kinds of impulse noises than elastic services: retransmission of broken data is a build-in mechanism of the TCP/IP protocol and keeps elastic services like web browsing reliable.
Dynamic line management techniques, that optimize modem settings automatically by learning from performance parameters reported by operational modems, may also works well in loops with many DSL systems. But a large installed base is currently only available for deployments from the central office (ADSL) but not when ***starting*** VDSL2 deployments from street cabinets.
A solution is to learn from performance observations made for ADSL in the past (see Figure 4), and to apply that to VDSL2. This means starting from the safe side and deploying at pessimistic bitrates. As soon as the installed base is large enough to apply dynamic (or manual) line management techniques, the bitrate can be increased (or decreased) for individual customers.

4.1 START VDSL2 WITH LENGTH-BASED DEPLOYMENT RULES

Although crosstalk noise is not the only noise that stresses a VDSL2 modem, it is probably the only noise that can be predicted using the simulation techniques described in [2]. In practice, however, the noise environment has also all kinds of impulsive noises from sources outside the cable, and this is ignored in these simulations. A way of addressing that in simulations is to apply a significant reduction of predicted bitrate (typically 10-25%). It is common to improve the reliability of VDSL2 by adding forward error correction at the cost of a substantial amount of overhead, which reduced the payload bitrate significantly.
The curves in Figure 5 show the result of a simulation according to [2,4]. They predict the attainable VDSL2 bitrate under scenario assumptions that are meaningful for the Dutch access network. Assuming that crosstalk is the only noise of concern and that some loss occurs in the VDSL2 bitrate due to error correction, the prediction curves illustrate the attainable bitrate that can be offered via the various wire pairs of a cable. The loop length refers to the copper distance between the cabinet and the customer location. This example assumes that a mix of VDSL2 systems (from the cabinet) and ADSL2plus systems (from the central office, 3 km before the cabinet) shares the same cable beyond the cabinet. Furthermore, it assumes that the output signals of the VDSL2 systems are shaped according to national regulations ("NL access rules", see [1]). The assumed crosstalk coupling ranges from near worst-case coupling, towards excellent coupling (24dB better).

When starting VDSL2 deployments, it is impossible to compare these prediction curves with a scatter plot of observed bitrates. Such data does not exist at the start of something new. Therefore the plot in Figure 5 is combined with an educated guess of what might be expected on individual wire pairs as a consequence of spread in crosstalk coupling. The scatter points are an educated (random) guess of individual values, based on statistical experiences in Figure 4 with ADSL and on the prediction curves of the performance simulator. A considerable spread in attainable bitrate is assumed, similar to what has been observed for all kinds of ADSL deployments. Again, it is expected that the attainable bitrates on some wire pairs will even be better than the most optimistic prediction curve of the plot, and on others they will even be worse than the most pessimistic one.

VDSL2 operators, who evaluate such bitrate curves for their own networks, can use that information to select their initial deployment rule for rolling-out VDSL2. Based on ADSL experiences, it is a good strategy to start on the safe side by not exceeding the near worst-case curve or a curve assuming crosstalk noise that is 6 dB below the near worst-case level.

Note that you cannot blindly apply the curves in Figure 5 for arbitrary networks, since these curves are dedicated to KPN's network. The scenario assumptions are network/country specific, such as differences in topology, selected band plan, access rules, cable characteristics [4], technology mix, and selected PSD shaping. This can vary significantly among the cables used in different countries, and can change the curves in Figure 5 as well.

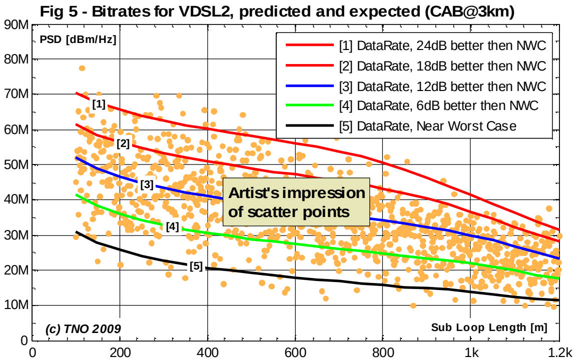

Figure 5: Artist impression on what bitrates will be observed in practice when deploying VDSL2. The solid lines are predicted bitrate curves for different crosstalk noise levels, and the dot markers what might be observed in the field.

4.2 IMPROVE VDSL2 WITH LINE-SPECIFIC DEPLOYMENT RULES

As soon VDSL2 is being deployed in loops with many VDSL2 systems, it makes sense to adjust the deployment rules when the operational performance is significantly better (or worse) than the initial deployment rule. A possibility is to select a more appropriate curve from Figure 6. Although a strategy of accepting/rejecting on the basis of *loop length* is simple to implement (and is used often), it is not an optimal deployment rule.

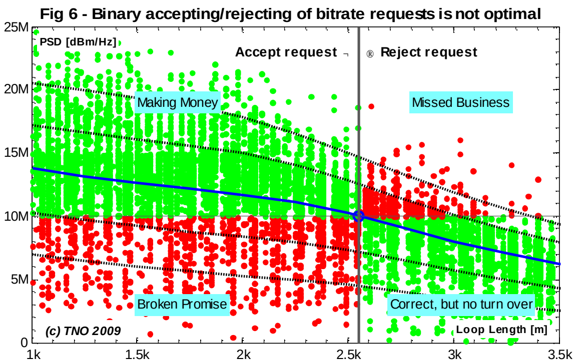

Figure 6: Consequence of using a fixed deployment rule (bitrate X up to distance Y): inefficient for most cases.

Due to the lack of sufficient VDSL2 data, we will illustrate this by means of the operational data obtained from an ADSL network. Figure 6 illustrates the consequence of such a simple deployment rule by comparing it with a scatter of attainable bitrates (reported by thousands of ADSL modems for individual wire pairs). The example assumes that all requests for 10Mb/s services are rejected when the loop length exceeds 2.6 km.

The following observations hold for Figure 6:

- Accepting the subscription request on wire pairs in the upper-left corner was a correct decision. These wire pairs have plenty of capacity, and customers will get the promised service.
- Rejecting the subscription request was also the correct decision for wire pairs in the lower right corner. They lack the quality to offer the requested bitrate.
- However the decision to reject was wrong for wire pairs in the upper-right corner. The number of scatters in that corner represents a significant portion of the market, so rejecting the request means less revenues.
- On the other hand, the decision to accept was also wrong for wire pairs in the lower-left corner, and this introduces unnecessary costs. These customers will complain that they do not get the service being promised, and the scatter plot illustrates that it will occur for a large number of customers.

This is a significant dilemma in practice, and justifies investments to increase the success rate of such reject/accept decisions. You can do it manually for each individual customer, but an automated approach by using dynamic line management techniques may be more appropriate.

5. SUMMARY

The maximum bitrate 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 beginning of their roll-out.

6. REFERENCES

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[2] ETSI TR 101 830-2, "Spectral Management, part 2: Technical methods for performance evaluations", 2008.

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[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 whitepapers in this serie:

[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)
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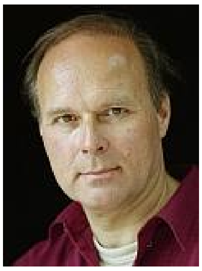

Since 1996, he has played a very prominent role in DSL standardisation in Europe (ETSI, FSAN), has written more than 100 technical contributions to ETSI, and took the lead within ETSI-TM6 in identifying / defining cable models, test loops, noise models, performance tests, and spectral management. He 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.

He has also been Rapporteur/Editor for ETSI since 1999 (on Spectral Management: TR 101 830), Board Member of the MUSE consortium (2004-2008, www.ist-muse.org) and Work Package leader within the Celtic 4GBB Consortium (2009-2011, www.4gbb.eu).