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Cable and DSL: a Comparison of their Capabilities and their Upgrade Roadmaps

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Customer	KPN

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Summary

Situation

Over the past two decades, twisted-pair copper and cable networks have evolved from single service analogue networks (POTS and analogue TV) to digital broadband infrastructures for all electronic services. For both networks substantial upgrades are needed to meet the foreseen demand for higher service bit rates.

Request KPN

KPN has asked TNO to provide an overview of the technical developments of twisted-pair copper and cable networks. In particular, KPN has asked TNO to provide an outlook to the future evolution of the transmission technologies, the network capacity and the service bit rates of copper and cable networks.

Research questions

This request is elaborated into the following research questions which are addressed in this paper:

- what are the technical options of upgrading twisted pair copper networks with DSL transmission technology, and what are the bit rates associated with the upgrades,
- what are the technical options of upgrading cable networks with EuroDOCSIS and DVB-C transmission technologies, and what are the bit rates associated with these upgrades,
- how do copper and cable infrastructures compare in terms of upgrades and bit rates that can be delivered?

Approach and sources

In order to address these questions, TNO has performed desk research and predominantly used publically available sources, like technical standards, reports of industrial meetings, press releases. TNO has combined this information with her own background expertise in copper networks with DSL technology, and in cable networks with their technologies.

Conclusions

For DSL, the upgrade roadmap is more or less straightforward: from ADLS2+ and VDSL services from the central office, via VDSL2 services from the street cabinet to G.fast from the curb or basement of a building. For cable, the technical elements of the upgrades can be defined, but the order and the extend in which these elements will be used cannot be indicated.

The comparison of copper and cable networks shows that copper and cable infrastructures and their upgrade roadmaps are different and therefore difficult to compare. Without the detailed upgrade strategy knowledge of the

cable operator and without knowledge of the future consumer bit rate demand, it is not feasible to develop a cable roadmap.

Although TNO is not in a position to specify or even provide an indication of the upgrade roadmap of a Dutch cable network, the following statements are defensible:

- DSL services from the central office have been overtaken by the broadband services from the Dutch cable networks,
- Dutch cable networks have a strong position as compared to VDSL2 from the street cabinet:
  - VDSL2 with vectoring from the street cabinets can deliver 100 Mbps at most, with vectoring and bonding 200 Mbps,
  - With the current EuroDOCSIS 3.0 technologies, cable networks already can deliver 100 - 200 Mbps services with an about nation-wide coverage. These services can be delivered in large volumes by further segmentation. There is no need to bring fiber to the group amplifier or an upgrade of the cable frequency plan,
  - With EuroDOCSIS 3.0 and DOCSIS 3.1 technologies and an upgrade of the cable frequency plan but without the need to bring fiber to the group amplifier, cable networks can deliver broadband services with a bit rate beyond 200 Mbps services in large volumes,
- The Dutch cable and DSL infrastructures can deliver bit rates of (several) hundreds of Mbps up to Gbps to customers, although different upgrades are needed,
- The ultimate FttLA amplifier upgrade, and possibly FttGA too, results in a cable network that can deliver services with a higher bit rate than a copper network with G.fast, assuming that cable would pursue these upgrades in the future.

Apart from the technological differences, TNO notes a difference of the infrastructures from the viewpoint of the nature of the service:

- Cable networks offer the possibility of a homogeneous product (bit rate) throughout the service area whereas for DSL the bit rate depends on the length of the copper pair. In addition, DSL bit rates show a large statistical variation caused by cross talk albeit that in VDSL2 this variation can be eliminated using vectoring; the length-dependency is not repaired.
- To offer a (substantially) higher downstream and upstream bit rate to a customer, a DSL operator must use a different technology. In contrast, cable operators can increase the bit rate without introducing a new

transmission technology by adding frequency channels. Because of the currently limited upstream frequency spectrum, the maximum cable upstream bit rate is limited. Once the market demands higher upstream bit rates, cable providers will have to extend the upstream frequency band and introduce DOCSIS 3.1 technology to increase the bit rate. TNO has found no indications on the point in time when the cable operators will have to do so.

Dutch cable networks can deliver high bit rates in limited volumes to serve the top market segment without the immediate need of an extensive upgrade of the network. In contrast, for the delivery of a substantially higher bit rate via twisted pair, the DSL network has to be fully upgraded first.

1 Introduction

The past two decades, twisted-pair copper and cable networks have evolved from single service analogue networks (POTS and analogue TV) to digital broadband infrastructures for all electronic services. For both networks substantial upgrades are needed to meet the foreseen demand for higher service bit rates.

In the above situation, KPN has asked TNO to write a paper focusing on the questions:

- what are the technical options of upgrading twisted pair copper networks with DSL transmission technology, and what are the bit rates associated with the upgrades,
- what are the technical options of upgrading cable networks with EuroDOCSIS and DVB-C transmission technologies, and what are the bit rates associated with these upgrades,
- how do copper and cable infrastructures compare in terms of upgrades and bit rates that can be delivered.

In order to address these questions, TNO has performed desk research and predominantly used publically available sources, like technical standards, reports of industrial meetings, press releases. TNO has combined this information with her own background expertise and experience in copper networks with DSL technology, and in cable networks with their technologies.

In Chapter 2, DSL technology and roadmaps are discussed. Chapter 3 covers this for cable networks. Chapter 4 contains a comparison between both types of infrastructures. References are contained in Chapter 5.

2 Twisted-pair copper network technologies and their capabilities

This chapter describes the various generations of DSL transmission technologies and their main properties.

2.1 DSL technologies and performance

2.1.1 Digitizing the copper access network

The Dutch telephony access network consists of twisted copper wire pairs bundled together in cables (see Figure 1). Large cables containing many hundreds of wire pairs originate at the main distribution frame (MDF) in the central office (CO). Because of the historic evolution of the telephony network over the last hundred years, many different cable types have been deployed. Therefore the cables that are currently in use show a large spread in type, age and quality.

Figure 1: A typical cable in use in the Dutch copper access network. These cables contain many hundreds of individual wire pairs. Source: TNO

The large cables from the CENTRAL OFFICE typically fan out into smaller cables at sub loop distribution frames (SDF) in cabinets and in underground splices as depicted in figure Figure *2*. In this way, almost all buildings in the Netherlands are connected with one or more twisted wire pairs.

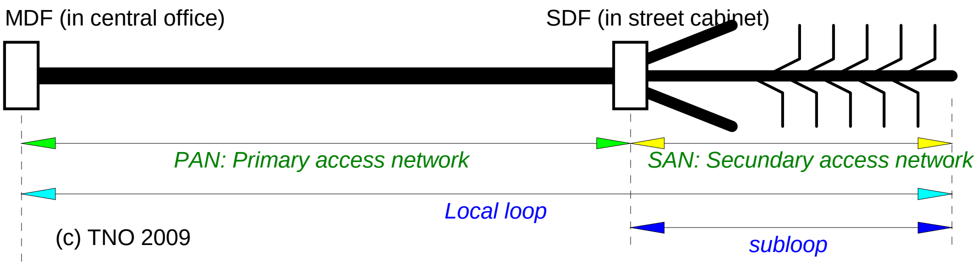

Figure 2: Structure of the twisted pair copper access network. Source: TNO

Figure 3 below shows a photo picture of the MDF at the central office and of a typical SDF in a street cabinet.

Figure 3: A part of the main distribution frame in a central office (left) and a small cabinet with its sub loop distribution frame inside (right). Source: TNO

Traditionally, these copper wire pairs were used for telephony and other analogue services. To transform this analogue network into a modern, digital access network, a variety of so-called DSL (Digital Subscriber Line) technologies has been developed and deployed over the years. See Figure 4 for an overview of these technologies and a classification in terms of access speeds. More on this can be found in [1].

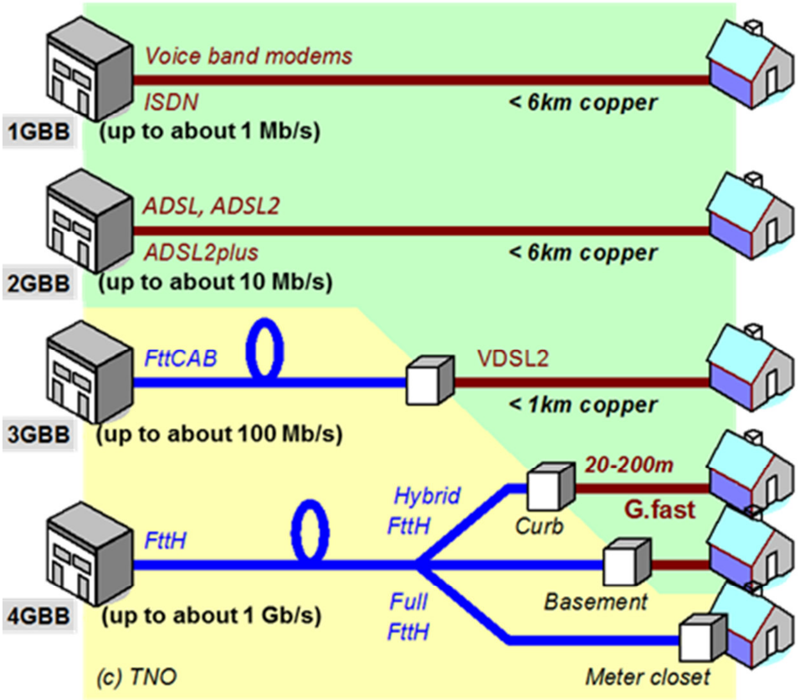

Figure 4: Systematic categorisation of the DSL Broadband Generations (1st Generation Broadband, 2nd GBB, 3rd GBB and the 4th GBB) and their maximum bit rate. Source: TNO

Figure 4 illustrates that over the generations of copper access technology, the big leaps in the access speeds have been achieved by reducing the copper distance that has to be bridged by the DSL solution. Reducing the copper distance reduces the electrical attenuation, which is the main limitation for DSL at higher frequencies. A reduced copper distance thus allows a wider physical spectrum to be used, and therefore implies more bit rate. Reducing the copper distance requires a deeper penetration of fibre into the access network.

The important trend of deeper fibre penetration implies that the physical location where the copper innovations takes place is moving from the central office to the cabinet and to other locations closer to the end-customer. All 2GBB transmission techniques can be considered fully developed by now: there is not much innovation taking place anymore in these techniques. In contrast, important 3GBB innovations such as vectoring are currently being deployed in the network and 4GBB technologies are still in their standardisation phase.

The economies of scale for deployment from the cabinet (and other locations close to the customer) are considerably less than for deployment from the central office. The number of customers that can benefit from the upgrade of xDSL equipment in a street cabinet or basement is substantially smaller than in the case of an upgrade of central ofice equipment. Thus, the return on investment has to be obtained from a smaller number of customers. Table 1 gives the typical service area of the different hierarchical locations of the Dutch copper network.

Table 1: Typical service area of the Dutch copper network. Source: TNO

	Average Network size (homes passed)
Central office	5.500
Street cabinet	300
Distribution point (e.g. curb or basement)	10 - 40

2.1.2 Bit rate / reach performance of DSL

Before discussing the bit rate / reach performance of individual DSL technologies, it is important to understand that the performance of a certain xDSL technology is a statistical quantity and not a fixed value or a simple function of the loop length. The bit rate will show a large spread going from one line to the other, even for lines of the same loop length. The bit rate "performance cloud" in Figure 5 illustrates this statistical behaviour. Only statistical quantities such as the mean or the 10% worst-case bitrate may be expressible as proper functions of the loop length. Note that this statistical behaviour makes it challenging for an operator to predict or to guarantee a bit rate to a customer prior to deploying the service.

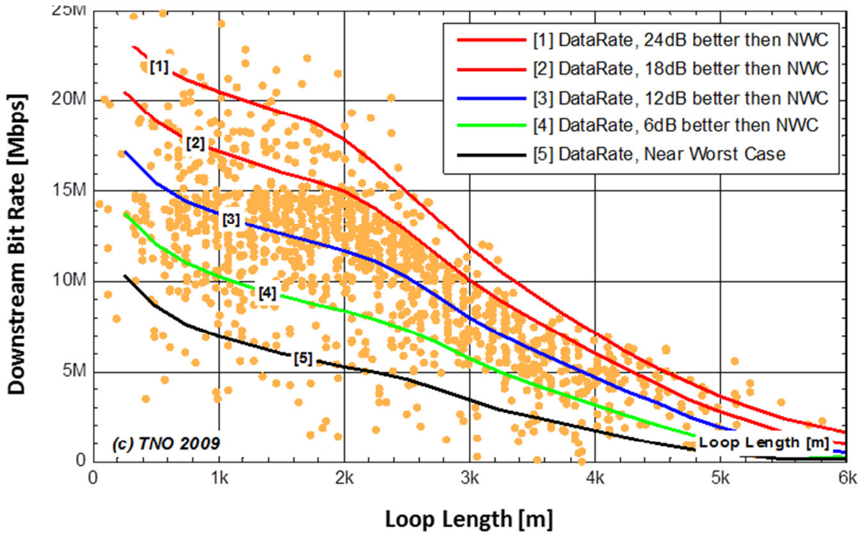

Figure 5: Measured downstream ADSL2+ bit rate of a large number of wire pairs as function of loop length. Each yellow-brown dot represents the bit rate of a wire pair. The results are obtained from cables of different quality. Source: [1]

The reasons for this statistical nature of the performance are as follows. Most modern DSL techniques try to squeeze as much bitrate performance out of the line as possible. This maximum possible bit rate is determined by the signal-to-noise ratio (SNR) at the receiver, which is the ratio of:

- The amount of received signal
  The received signal is determined by the used transmit power and by the attenuation in the cable. The longer the cable, the lower the received signal.

Since the attenuation in the cable is normally a well-behaved function of the loop length, the strength of the received signal is also a deterministic function of the loop length and of the properties of the cable type.

- The amount of noise
  The noise is dominated by the crosstalk noise picked up from other DSL systems present in the cable. This is determined by the amount and types of the crosstalk disturbers, but also by the crosstalk coupling within the cable. The crosstalk coupling within the cable is not a deterministic function of e.g. loop length: it is an inherent stochastical property of the cable, with a large statistical spread. As a result, the received noise at the receiver cannot be predicted based on e.g. loop length.

2.1.3 First Generation Broadband: Voice band modems and ISDN

The first generation technologies provided bit rates well below 1 Mbps. These techniques included voice band modems (up to 56 kbps) and ISDN. ISDN enabled 2 digital telephony channels (at 64 kbps) and one additional data channel (at 16 kbps). The reach of ISDN is such that it is able to deliver its maximum bit rate of 144 kbps to almost all the customers connected to a central office.

2.1.4 Second Generation Broadband: HDSL ,(E-)SDSL and ADSL variants

The DSL techniques that deliver 2GBB services are best divided in symmetric and asymmetric services. All second generation DSL techniques were designed and optimised for deployment from the central office, i.e. with a loop length range of typically 0 to 6 km[1]. The spectral usage of 1st and 2nd generations DSL technologies is depicted in Figure 6.

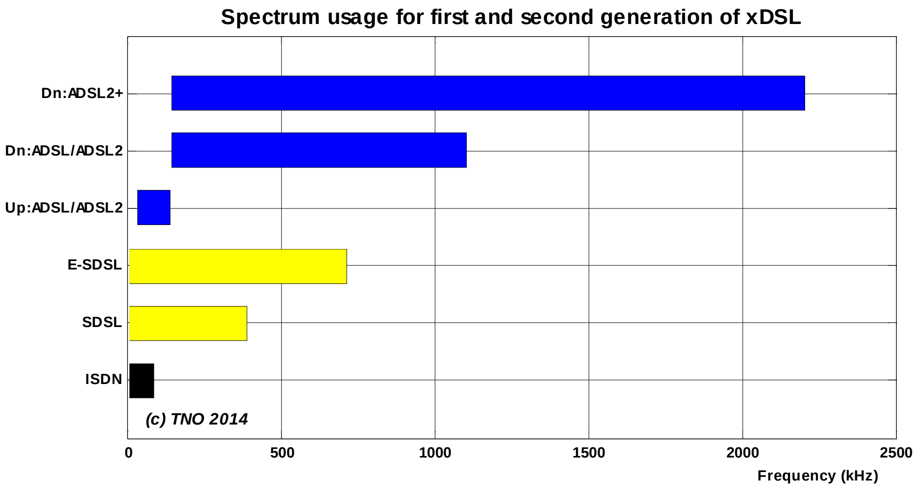

Figure 6: Spectrum usage of some first and second generation xDSL technologies. Source: TNO

[1] See relevant references in section 5 for further reading.

2.1.4.1 Symmetric DSL (SDSL/SHDSL)

For the business market, the focus has traditionally been on delivering symmetric services. In particular there has been a need for technologies to deliver 2 Mbps leased lines and for PABX connect. The second generation DSL technologies for these customer services are summarised in table Table 2.

Table 2: Symmetric DSL technologies. Source: TNO

Technology	Bitrate	Remarks
HDSL	2.3 Mbps	Fixed bit rate. Uses 2 or 3 wire pairs. Can use repeaters to extend the reach
SDSL/SHDSL	n * 64 kbps, up to 2.3 Mbps	Maximum bit rate is 2.3 Mbps
E-SDSL/E-SHDSL	n * 64 kbps, up to 5.7 Mbps	Maximum bit rate at short range 5.7 Mbps

2.1.4.2 Asymmetric DSL (ADSLx)

For the consumer market, the focus has been on delivering more downstream bandwidth than upstream. The range of asymmetric DSL (ADSL) technologies that were developed and optimised for this are summarised in Table 3.

Table 3: Overview of asymmetric DSL technologies. Source: TNO

DSL	Maximum Bitrate	Remarks
ADSL	Downstream: 8 Mbps, Upstream: 1 Mbps	Downstream bitrates may fall below 1 Mbps at end of the length range
ADSL2	Downstream: 12 Mbps Upstream: 1~2 Mbps	ADSL2 repairs a number of issues with ADSL1. In terms of bitrate/reach, ADSL2 is a modest improvement with respect to ADSL
ADSL2+	Downstream: 24 Mbps Upstream: 1~2 Mbps	Large downstream improvement with respect to ADSL2 on short loops. Similar performance as ADSL2 above 2~3 km

In case of ADSL2+, 10-15 Mbps (DS) and 1 Mbps (US) is delivered to the majority of the market[2]. In addition to the entries in the table, there exist various ‘flavours’ of ADSL2 and ADSL2+ with somewhat different properties. These flavours are defined in Annexes of the ITU standard, and are therefore often referred to by their Annex

[2] It is noted that the ADSL2+ 10 – 15 Mbps downstream bit rate range agrees with the data of Figure 5.

name. For instance, there exist “Annex A” and “Annex B” variants, intended to be combined with respectively POTS or ISDN telephony services in the baseband.

2.1.5 Third Generation Broadband: Very high bit rate DSL (VDSL)

To deliver many tens up to one hundred of Megabits per second, VDSL (and later VDSL2) were developed. These techniques are intended and optimised for cabinet deployment, and thus for loop lengths up to roughly 1000 m. It is also possible to deploy VDSL2 directly from central offices, but it will only benefit the customers that live nearby the CO.

For VDSL2, various profiles exist that differ in the frequencies being used (e.g. up to 8.5 MHz, 12 MHz, 17.664 MHz and 30 MHz)[3]. The more physical bandwidth used, the higher the maximum bit rates at short loop lengths. Typical numbers for the maximum possible bit rate at short loop lengths are more than 100 Mbps in downstream and 30 Mbps in upstream. However, due to the use of high frequencies, VDSL is strongly limited by crosstalk. Therefore, more realistic short loop (~100 m) bit rates for real-world VDSL2 are 50 Mbps downstream and 10 Mbps upstream, about half the maximum bit rate without cross talk noise. On longer loops, the performance goes down further: indicative values for 1 km loop length would be 20 Mbps downstream and 4 Mbps upstream.

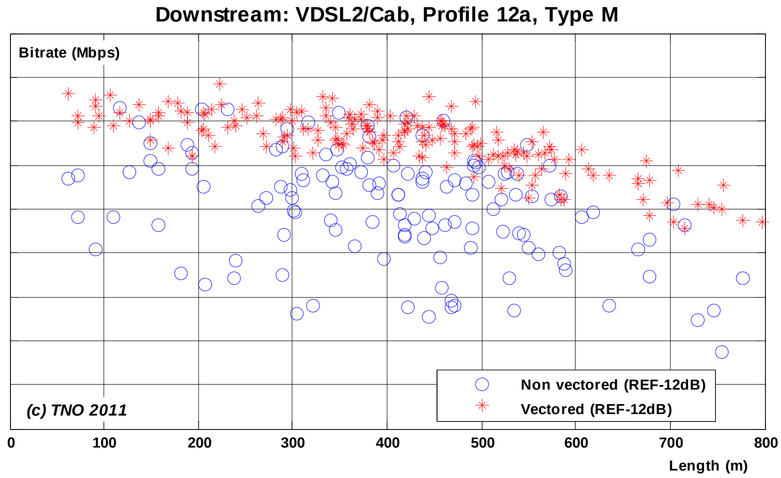

Figure 7: “Artist Impression” of the effect of vectoring: the bit rate performance cloud is moved up and gets compressed. Source: TNO

2.1.5.1 Vectoring

The higher the frequencies used by an xDSL system, the higher the crosstalk coupling in the cable becomes, and the more the performance becomes limited by the crosstalk from other systems in the cable.

[3] ITU-T G.993.2, *“Very high speed digital subscriber line transceivers 2 (VDSL2)”,* International Telecommunications Union, 12/2011.

The technique of vectoring was designed to overcome this crosstalk obstacle for VDSL2[4]. By using advanced signal processing and precoding of the transmit signals, it is possible to remove the detrimental effects of crosstalk almost completely. In this way, downstream bit rates around 100 Mbps per second on short loops become realistic, and a substantial part of the customers will in fact be able to get 80 Mbps. For the upstream, bitrates up to 30 Mbps become attainable at short loop lengths, with a substantial part of the customers able to get 16 Mbps. Vectoring repairs the halving of the bit rate caused by cross talk interference, or doubles the bit rate as compared to VDSL2 without vectoring [2]. In Table 4 the benefits of vectoring are summarized.

Table 4: Indications of VDSL2 bit rates in operational networks, with and without vectoring. Source:TNO

DSL		**Downstream (Mbps)**	**Upstream (Mbps)**
VDSL2	Short loop (~100 m)	50	10
	Majority of market	40	8
	Long loop (~1km)	20	4
Vectored VDSL2	Short loop (~100 m)	100	30
	Majority of market	80	16

Two benefits of vectoring are, as illustrated by Figure *7* and Figure 8:

- Vectoring increases the bit rates substantially. In many cases, the bitrate on the line can be doubled,
- Vectoring increases the predictability of the bit rate as function of the loop length, since vectoring reduces the spread in the bit rate performance.

In particular the second property makes it easier for an operator to guarantee a bit rate to a customer, prior to delivering the service.

For the vectoring scheme to work, all the VDSL2 lines in a cable must be connected to the same ‘vectoring group’ in which the coordination of all the transmit signals takes place. It is widely accepted in the xDSL industry that the presence of even a few lines not connected to the vectoring group (so-called “alien” lines) can destroy most of the vectoring benefits [3] [4]. This property makes vectoring very hard to combine with sub-loop unbundling, i.e. a situation where different operators have their own DSLAMs located at the cabinet. A few companies claim that their solutions can mitigate this impact somewhat, but the general industry consensus is that the impact of alien systems will remain very large [5] [6].

[4] ITU-T G.993.5, *“Self-FEXT Cancellation (Vectoring) for use with VDSL2 transceivers”,* International Telecommunications Union, 04/2010.

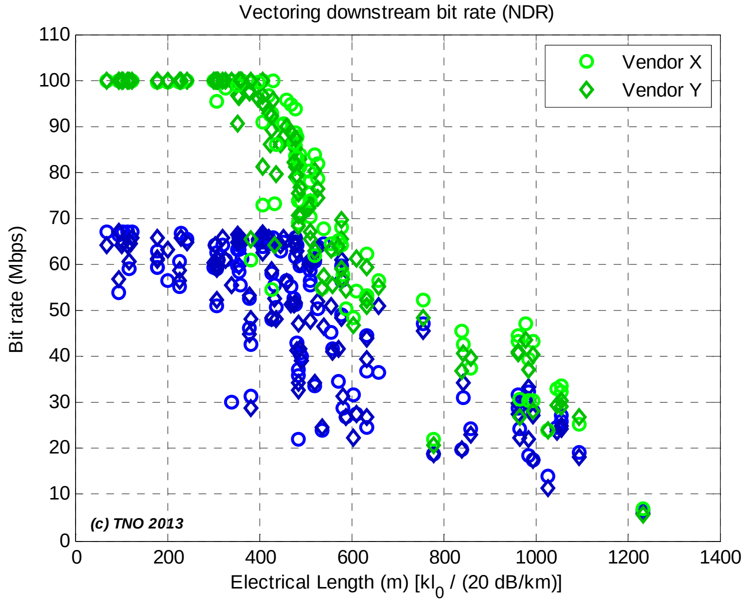

Figure 8: Rough impression[5] of the vectoring gains for VDSL2. The blue markers denote non-vectored performance, the green markers denote vectored performance. Source: KPN technical vectoring trial.

A challenge of vectoring is the large processing capacity to predict the real-time distortion signal on each copper line. For cables as deployed from the street cabinet with up to 200 wire pairs at most, the vendors have mastered the technology[6]. However, the required processing power increases quadratic with the number of wire pairs and therefor it will be an even larger challenge to develop vectoring for DSL technologies deployed from the central office.

2.1.6 Fourth Generation Broadband: G.fast

The latest generation of xDSL technology is called G.fast, and is intended to deliver many hundreds of Mbps to customers. This technology is optimised for bridging the last 100 meter or so of copper loop to the customer, and is therefore intended to be deployed from a point close to the end-user, e.g. in a fibre-to-the-Basement (FttB) or a fibre-to-the-Curb (FttC) topology.

The first version of the G.fast technology will be using the frequencies up to 106 MHz (see Figure 9), and aims for a maximum aggregate bit rate (the sum of up- and downstream) of 1 Gbps at short loop lengths. At 100 meter, the design target is to deliver an aggregate bit rate of at least 500 Mbps. An interesting novelty of G.fast is that it is not optimised for symmetric or asymmetric services: the operator can configure the required upstream/downstream ratio per DSLAM based on the service requirements.

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[5] This plot is based on a limited technical field trial, and is not necessarily representative for the gains of vectoring in general. In particular, the plot shows bit rate caps at short loop lengths, which are artefacts due to the chosen configuration used in the technical field trial.

[6] "*VDSL2 Vectoring Explained*", Paul Spruyt, Alcatel Lucent, November 9 2012.

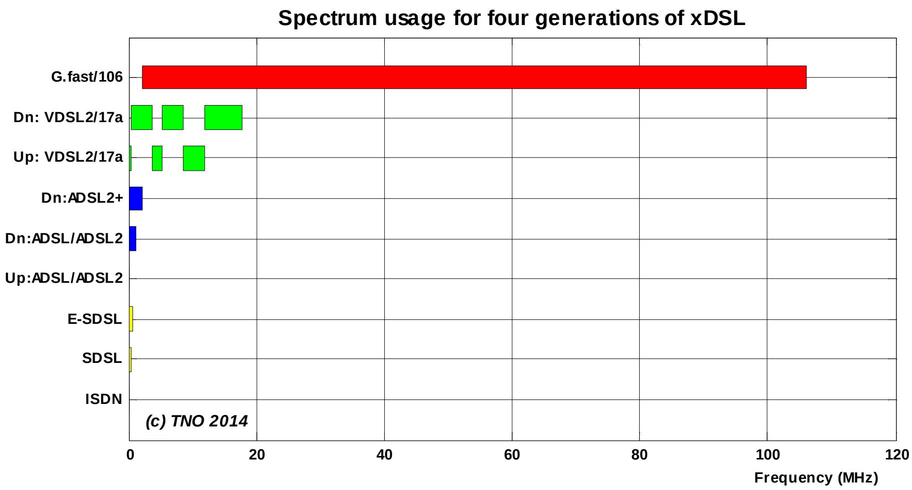

Figure 9: Spectrum usage of G.fast depicted together with the preceding generations of xDSL technologies. On this scale the spectrum used by ISDN and upstream ADSL is no longer visible. Source: TNO

For G.fast deployment, the vast number of DSLAMs needed will become a major challenge. It is therefore widely accepted that G.fast must support a number of operational features like:

- Zero-touch Operation (e.g. the use of automated distribution frames to minimise truck-roll to the distribution points),
- Reverse Power Feeding, to avoid the need for electrical power at each distribution point,
- Rugged, climate-hardened cases.

Standardization of G.fast (Recommendation ITU-T G.9701) in the ITU-T Study Group 15 is progressing. The working group members have reached agreement on all most relevant protocol aspects and G.fast has obtained first-stage approval [7]. Next, working group 15 will develop the full recommendation. The first-stage approval is important in the technology development process because it allows manufacturers to design and test first chip sets. First equipment can be expected in 2015 [8]. To finalize the development of the technology, production has to be ramped up and interoperability of the equipment of different vendors has to be secured. Therefore, G.fast will be available for large-scale deployment by 2016 – 2017.

2.1.7 Bandwidth Boosters for xDSL

Two add-on techniques for DSL must be mentioned in this overview, since they enable higher bit rates and/or higher stability.

2.1.7.1 Bonding

Except for HDSL, all the technologies discussed above need only a single wire pair to work. However, most of the technologies allow to exploit the presence of more than one wire pair by using the standardised functionality of bonding. This allows the use of two (or more) wire pairs, to deliver the sum of the bit rates that can be transported over each of the constituent wire pairs[7].

Many customers in the Dutch access network are connected by two wire pairs, and bonding is therefore an attractive option in the Netherlands, either to increase the maximum possible bit rate to a customer, or to extend the reach of a particular service bit rate of interest.

2.1.7.2 G.inp: DSL layer retransmission

A technique that has been added relatively recently to xDSL is DSL-layer retransmission[8]. The purpose of retransmission is to combat the effects of impulse noise that is present in the twisted-pair copper access network. Impulse noise can cause the loss of data packets, and it affects in particular delay sensitive services and high-quality streaming services in which there is not enough time to have the application request a resend of a lost packet.

Before the availability of retransmission at the DSL layer, it was necessary to use a robust error correction protocol that requires a substantial overhead, thus reducing of the maximum throughput of the line.

2.2 Homogeneity and flexibility of the DSL broadband offer

Although an DSL operator can deliver service profiles with different bit rates, the DSL service offer has some specific characteristics:

- The bit rate decreases with increasing length of the wire pair,
- Without vectoring, the bit rate of wire pairs of the same length shows a large variation from line to line, with a minimum bit rate of less than 25% of that of a good wire pair. Vectoring “repairs” wire pairs with a bad performance, thus reducing the variation and improving the predictability. Vectoring does not “repair” the length dependency,
- The statistical behaviour makes it challenging for an operator to predict or to guarantee a bit rate to a customer,
- Currently, as shown in Figure 10, the service bit rate that DSL operators offer is limited by the specific DSL technology. The figure shows that KPN can only deliver a 80/8 Mbps service with VDSL2 from the street cabinet, and that Tele2 and KPN can only deliver the 40/4-5 Mbps service from the central office using VDSL2. To offer a (substantially) higher service bit rate, the operator must use a different technology.

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[7] Minus a small overhead associated with the bonding protocol.
[8] ITU-T G.998.4, *“Improved Impulse Noise Protection (INP) for DSL Transceivers”*, International Telecommunications Union, 06/2010.

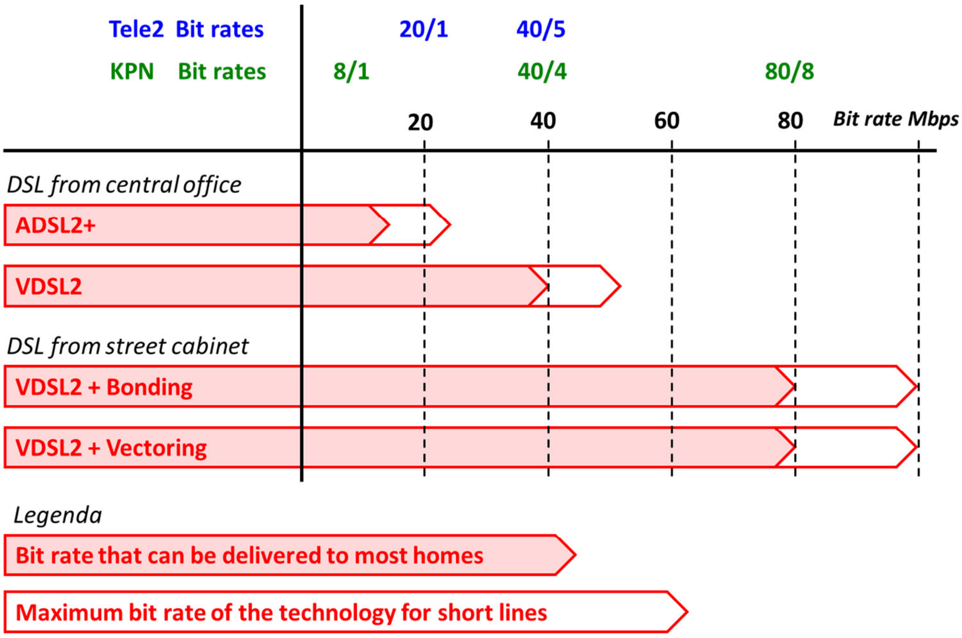

Figure 10: Match of KPN[9] and Tele2[10] subscription bit rates (march 2014) and the bit rates of the different DSL transmission technologies. Source: KPN&Tele2.

[9] http://www.kpn.com/prive/internet/internet-voor-thuis/tarieven.htm
[10] https://www.tele2.nl/shop/thuis/internet-abonnement/

3 Cable network technologies and their capabilities

This chapter contains an overview of cable networks and of cable technologies. Additional technical information on cable networks and their design can be found in references [9] and [10].

3.1 The modern HFC network

To deliver the broadband services, cable networks have been upgraded to two-way hybrid fibre coaxial (HFC) networks. In the Netherlands most cable networks have a star architecture with two amplifiers in the coaxial part as shown in Figure 11.

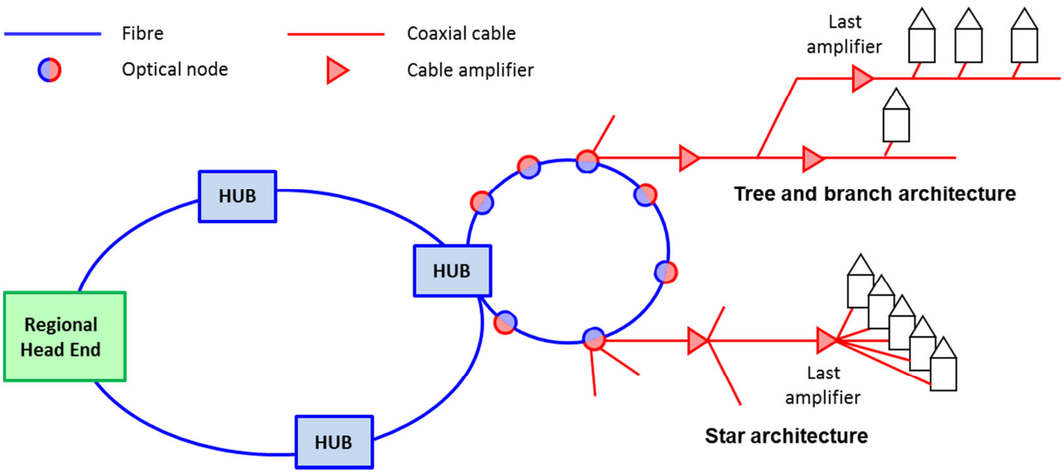

Figure 11:The standard topology of an HFC network. Source: TNO

The basic purpose of the HFC network is the distribution of radio frequency signals from the network to all connected homes and the aggregation of radio frequency signals from the home. For this distribution and aggregation of the signals a branching coaxial network with a fibre back haul connection to a HUB is used, as shown in Figure 11. Typically the coaxial part in the Netherlands encompasses some 800 homes. Table 5 summarizes the typical size of the different hierarchical levels of the network shown in Figure 11. Figure 12 gives an impression of the street cabinets of the coaxial part of the cable network.

The current HFC networks have a frequency arrangement with 8 MHz channels in the downstream band. In the upstream band there is not necessarily a regular channel arrangement. Because of high distortion signal levels in specific parts of the 5 – 65 MHz upstream band, the lower part of the band, say below 25 MHz, cannot be used [6][7][8][12]. In the useable part, a number of 3.2 or 6.4 MHz channels are defined. Part of the downstream channels distribute the same signals to all homes in the service area of the so-called head end. These channels are used for the broadcast services. Some channels are used to distribute signals in a single coaxial segment of the network. In an adjacent coaxial segment the channels can be used to distribute other signals; the channels can be reused in every coaxial segment. This reuse is called narrowcasting, and it is used to deliver personalized services like (broadband) internet, telephony, VoD and catch-up TV services.

Table 5: Typical size of a Dutch cable network at the different hierarchical network levels. Source: [7]

	Network size (homes passed)
Regional Head End	200.000
HUB	10.000
Optical Node	800[11]
Group Amplifier	150[11]
Last Amplifier	20[11]

Figure 12: A typical Dutch street cabinet for an optical node (left) and last amplifier (right). Source: TNO

The digital and analogue radio and television broadcasting signals are generated in the head end, and distributed via the HUBs to all optical nodes using optical transmission, as illustrated in Figure 13[12]. All narrowcast DVB-C signals are generated in the HUB and combined on a per cable segment basis, and conveyed to the optical node as well[12]. For each cable segment, a dedicated optical transmitter is used. In the optical node, the cable broadcast and narrowcast signals

[11] The figure is copied from [10]. The reference gives a typical number of homes passed by a node or last amplifier of an operator's network. Thus, smaller and larger nodes will occur within a network.

[12] For the transmission RF-over-fibre technology is used. So, in fact, an analogue optical transmission technology is used.

are combined to create the full cable spectrum, converted to an electric signal and distributed to the homes.

Because of the limited capacity of the optical transmitters used for the narrowcast services, the number of 8 MHz frequency channels for narrowcast services is limited.

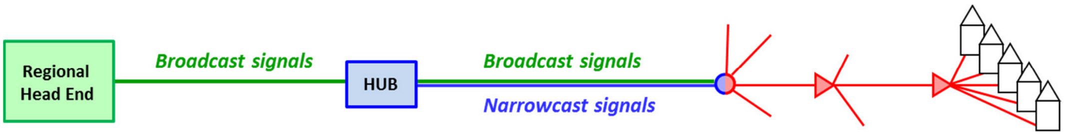

Figure 13: HFC broadcast and narrowcast service architecture. Source: TNO

The capacity available for broadcasting is simply determined by the number of 8 MHz frequency channels allocated for broadcasting. The capacity for narrowcasting, though, is determined by the number of frequency channels allocated and by the number of customers of the coaxial segments. Thus, while the frequency band for narrowcast is a limited resource, the capacity for narrowcasting can be expanded by reducing the number of customers per segment. The number of customers per segment can be reduced by splitting the coaxial segments. Such a segmentation or splitting is implemented at the optical node. Actually, the process of adding capacity is similar to cell splitting in mobile networks.

At the optical node the optical broadcast and narrowcast signals are combined whereas from this point a number of coaxial branches emanate. In case of splitting a segment, an additional optical backhaul for the narrowcast signals is created and the coaxial branches are (re)distributed over the available optical backhauls, as shown in Figure 14.

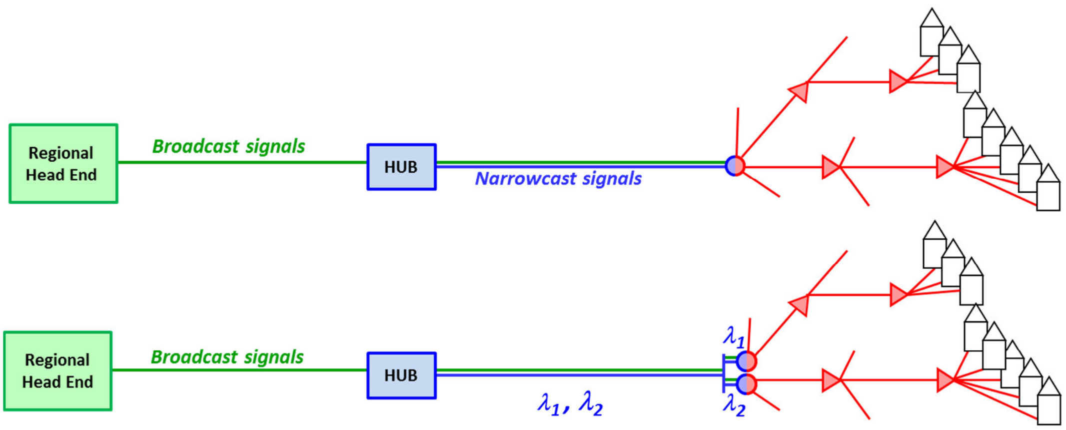

Figure 14:The principle of cable network segmentation. Source: TNO

3.2 Cable transmission platforms

In cable networks, three transmission technologies are used to deliver the services to the customer:

- Analogue PAL[13] for television and FM for radio,
- DVB[14] Broadcasting technology for managed digital radio and TV broadcast services, VoD and catch-up television services,
- EuroDOCSIS for best-effort internet services, streaming video to PCs, tablets and smart phones and managed telephony services.

3.2.1 Analogue technologies

The analogue PAL television and FM radio services still have a specific market value, but customers are watching more and more digital television. CAIW and REKAM, two smaller local Dutch cable providers, have already switched off their analogue services some years ago.

3.2.2 Broadcasting technologies

DVB is the technology suit developed by the DVB project for broadcasting services[15]. This suit specifies technologies for coding of video and audio, multiplexing of programmes, digital right management and transmission via satellite (DVB-S), the ether (DVB-T), cable (DVB-C) and IP (DVB-IP). All key DVB technologies have been developed in the past. In the past years, 2nd generation transmission technologies DVB-S2, DVB-T2 and DVB-C2 have been developed.

In all Dutch cable networks, DVB-C is the workhorse for the delivery of managed digital television services. DVB-C needs an 8 MHz frequency channel of the cable network. Using QAM[16] 256 modulation DVB-C delivers a so-called transport stream (TS) with a throughput of 35 or 52 Mbps per 8 MHz channel. This depends on the signal level used in the HFC network (and subsequent level of intermodulation interference). Each transport stream carriers a number of television programs.

DVB-C2 has been specified in 2012 and brings a 30% or even a 60% larger throughput as compared with DVB-C QAM 256. The technology is used and available in the German market, but to the best current knowledge of TNO, Kabel Deutschland is the only cable operator that so far has deployed DVB-C2 in parts of its networks.

3.2.3 VoD and catch up television

Apart from broadcasting, the DVB technology typically is used in cable networks for VoD and catch up television. The content is stored on servers at a regional network level. The servers have a connection to dedicated DVB-C transmitters in the HUB, the so called EdgeQAMs, that feed the narrowcast network with a signal.

VoD and catch-up television typically require a bit rate of a few Mbps, with possibly different bit rates for different content types, like for instance catch up television and HD video-on-demand. Thus, the capacity to deliver VoD and catch-up television per

[13] PAL is the abbreviation of Phase Alternating Line
[14] Digital Video Broadcasting (DVB)
[15] DVB Project, www.dvb.org
[16] QAM is the abbreviation for Quadrature Amplitude Modulation

coaxial segment is limited to a fixed number of 8 MHz channels and therefore to a limited number of simultaneous programs.

3.2.4 EuroDOCSIS technology

EuroDOCSIS is the European version of the DOCSIS two-way transmission technology developed in the late nineties of the past century. Currently EuroDOCSIS releases 2.0 and 3.0 are widely deployed. The EuroDOCSIS high-level architecture exists of a cable modem termination system (CMTS) in the cable network that serves a number of customers cable modems. The CMTS can be considered as the equivalent of the DSLAM in DSL. The available EuroDOCSIS capacity is shared using time division multiple access (TDMA). The technology includes protocols to manage the quality of service and the data security. In EuroDOCSIS 2.0 only a single upstream channel with a maximum bandwidth of 6.4 MHz and a maximum throughput of 20 – 30 Mbps and a single 8 MHz downstream channel with a 35 or 52 Mbps throughput are used. In EuroDOCSIS 3.0 multiple upstream and downstream channels can be bonded together to deliver higher bitrates. The newest cable modems have 24 receivers combined with 8 upstream transmitters, corresponding to a technical bit rate limit of 1 Gbps / 240 Mbps. A time line of the introductions of the EuroDOCSIS technologies in the Netherlands is shown in Figure 15.

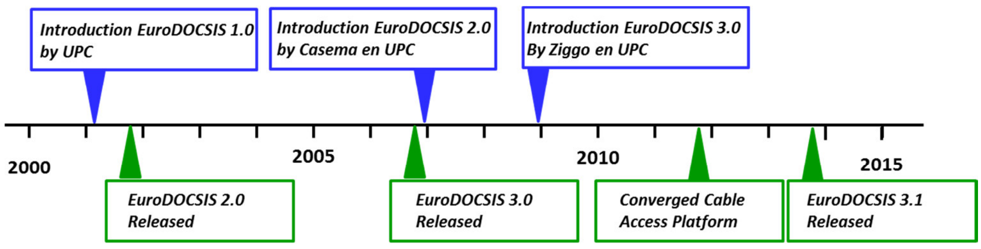

Figure 15: Overview of EuroDOCSIS Cable technology releases and of their introductions in the Netherlands. Source: TNO

3.3 Innovations in the cable technology

3.3.1 Migration to a cable all-IP architecture

For historical reasons, digital services from cable are delivered by a combination of DVB broadcasting, DVB narrowcasting and IP/(Euro)DOCSIS technology. The service providers designed and built this triploid service architecture themselves using separate components, often from different vendors. In 2008, the initiative was developed to integrate these three cable transmission technologies in to a single Converged Cable Access Platform (CCAP), as shown in Figure 16. In 2011, the CCAP technology was finalized and published as s standard. First products are on the market since 2012 / 2013.

CCAP integrates the conventional DVB and EuroDOCSIS cable subsystems in such a way that the capacity for DVB broadcast, DVB narrowcast and IP/(Euro)DOCSIS services can be easily reallocated. Secondary objectives of CCAP were a substantial reduction of the power consumption and of the form factor, thus reducing operational and investment costs.

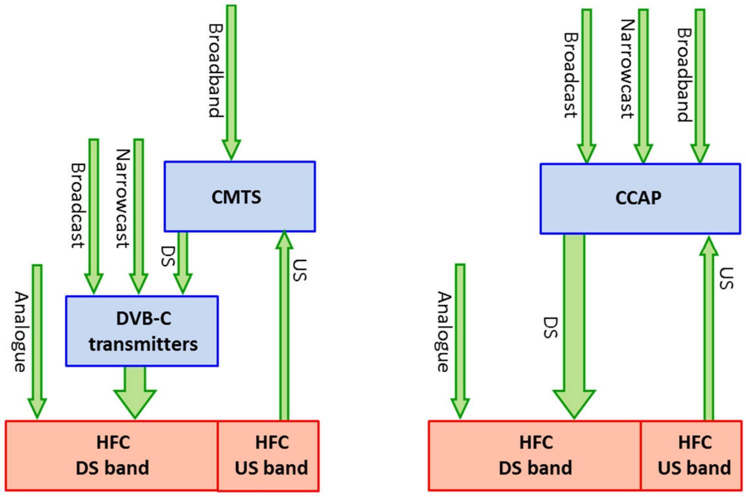

Figure 16. The conventional cable system architecture (left) and CCAP system architecture (right). Source: [7]

To make full use of the CCAP benefits, a new type of cable home gateway is needed as well. This new home gateway receives the content from either the DVB broadcast, the DVB narrowcast or IP/(Euro)DOCSIS service, and forwards the service to any customer home equipment with a HDMI or IP connection. For the distribution of a service in the home via IP, services received from the DVB broadcast or narrowcast are converted to IP services. Currently, this technology is implemented in new home gateways such as the Horizon Media Box of UPC or the NETGEAR[17] gateway. The latter is equipped with 24 receivers that can tune to either a DVB carrier with a television programme or to a number of bonded (Euro)DOCSIS downstream carriers.

Thus, CCAP, together with a new generation of cable home gateways, brings a cable all-IP solution. Such a cable all-IP solution will have a large added value for the cable. For instance, it will enable the evolution from DVB broadcasting technology to IP for the delivery of managed television, VoD and catch-up television services.

3.3.2 DOCSIS 3.1

In 2012 Cable Labs in the USA initiated a project to develop a next release of DOCSIS technology (DOCSIS 3.1) targeted at a system with a 10/2 Gbps (down/up) capacity. In 2013 the specifications were finalized and approved. The main DOCSIS 3.1 features are [13], [14]:

- Fully compatible and interoperable with EuroDOCSIS 2.0 and 3.0 releases,
- Completely new physical layer for upstream as well as downstream using the currently most advanced transmission technologies. DOCSIS 3.1 uses

[17] http://www.netgear.com/about/press-releases/2012/06122012.aspx

a superior modulation technology (OFDM[18]) as well as improved error coding (LDPC[19]) as compared to EuroDOCSIS 3.0,

- Support for extended upstream and downstream frequency bands,
- A DOCSIS 3.1 CMTS must be able to serve a mixed population of EuroDOCSIS 2.0, 3.0 and 3.1 modems, DS: FDM, US TDM.

Table 6: Improvement of EuroDOCSIS 3.1 compared to EuroDOCSIS 3.0. Source: TNO

	EuroDOCSIS 3.0	**DOCSIS 3.1**
Downstream		
Modulation Technology	Single Carrier modulation	Orthogonal frequency division modulation
Frequency band	108 – 1000 MHz	258 MHz – 1.218 GHz (mandatory) 108 MHz – 1.750 GHz (optional)
Throughput per 8 MHz of spectrum	64 QAM: 38 Mbps 256 QAM: 52 Mbps	256 QAM: about 50 Mbps 512 QAM: about 57 Mbps 1024 QAM: about 63 Mbps 2048 QAM: about 69 Mbps 4096 QAM: about 75 Mbps
Upstream		
Modulation Technology	Single Carrier modulation	Orthogonal frequency division modulation
Frequency band	5 – 65 MHz	5 – 204 MHz
Throughput per 6.4 MHz of spectrum	16 QAM: 20 Mbps 32 QAM: 25 Mbps 64 QAM: 30 Mbps	64 QAM: about 30 Mbps 128 QAM: about 35 Mbps 256 QAM: about 40 Mbps 512 QAM: about 45 Mbps 1024 QAM: about 50 Mbps 2048 QAM: about 55 Mbps 4096 QAM: about 60 Mbps

Briefly summarized, this new DOCSIS technology has been designed to use the full capacity of the cable network in the most efficient way. To make maximum use of its capabilities, the operators will have to upgrade the cable network too: they will have to extend the upper frequency edge of the upstream band from the current 65 MHz, possibly up to 204 MHz and similarly the downstream band has to be extended as well.

[18] Orthogonal Frequency-Division Modulation
[19] Low-Density Parity-Check code

3.4 The cable options to create capacity

The main challenge for the cable is create more capacity for broadband services in an economical manner. As discussed in an earlier report [10], there are three elementary options to expand the cable capacity: *i)* a more efficient use of the spectrum for broadcasting, *ii)* upgrade of the network and *iii)* deployment of transmission technologies with improved spectral efficiency. All three options are discussed below.

3.4.1 A more efficient use of the cable frequency spectrum

For legacy reasons, the same television channels are delivered using analogue transmission, digital transmission with a first generation video coding technology (MPEG-2) for standard definition television and more advanced H.264 coding for high-definition television. Currently Ziggo and UPC Netherlands distribute 25 or more television channels in analogue, which requires 25 8 MHz channels or 200 MHz of downstream spectrum. In addition they offer some 150 television channels in digital, whereof 20 or more in high-definition, which, taken together, requires another 25 channels of 8 MHz at least.

Moreover, in practice a smaller number of channels is viewed the most. Stated differently, most of the 150 channels are viewed by a smaller number of customers, and as such it would be more spectral efficient to distribute a channel only if somebody is watching. Technically it is possible to distribute a television channel in a single coaxial segment if a customer in that segment is watching, and switch it off when nobody is watching. Thus, all of the 150 television channels that in a segment are not watched can be switched off. Once the segments serve some 100 homes or less, this can bring a substantial additional spectrum saving. The technology for this switched television is already available. Moreover, once the cable network is evolved to all-IP, switched television based on IP technology can be easily implemented. Of course, channels that are watched in each cable segment can be broadcasted from the head end.
The switch-off of analogue television and of digital television using MPEG-2 coding, and the migration to a switched television solution, all have a large impact in the market. Analogue television still is used by many customers. Switch-off of MPEG-2 coding and the introduction of switched television requires a new interactive receiver. As such, the cable operators have a preference to improve the use of the cable spectrum gradually, in an evolutionary approach.

3.4.2 Network upgrades

To boost the capacity of the network cable providers can *i)* split the cable segments further, possibly with deployment of fibre to the group amplifier (GA) or last amplifier (LA) and/or *ii)* expand the upstream and downstream frequency bands.

3.4.2.1 Segmentation and deep fibre

The principle of segmentation has already been explained in subsection 3.1 and shown in figure Figure *14*. At the optical node, the coaxial branches of the cable network can disconnected and provided with a particularized narrowcast signal. As illustrated in figure Figure *17*, this segmentation can be used in combination with the deployment of new fibre to the GA or the LA. In the Netherlands, full splitting of the current optical nodes results in a segments of about 150 homes. A segment size of say 20 homes is feasible if fibre is deployed to the GA, see Table 7.

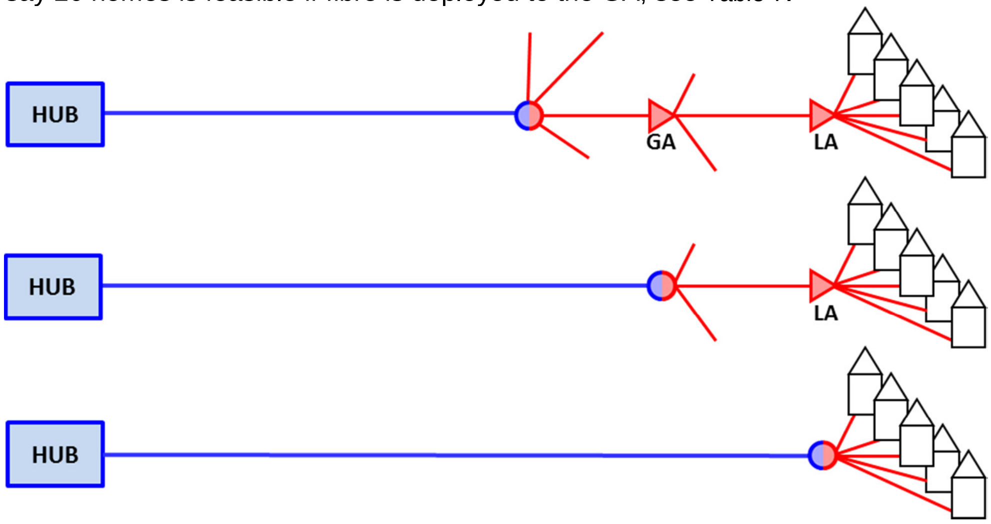

Figure 17: Deployment options of deep fibre in the Dutch cable networks. Source: TNO

Table 7: Typical service area size at the different coaxial network levels and the minimum segment size in the Dutch cable networks. Source: [7]

	Service area size (homes passed)	
	Aggregated	**Minimum segment**
Optical Node	800[11]	150[11]
Group Amplifier	150[11]	20[11]
Last Amplifier	20[11]	1

3.4.2.2 Extension of the upstream and downstream frequency bands

The spectrum use of the cable basically is fully defined by filters in the signal amplifiers and as such a design issue. Moreover, fundamentally there is no limitation of the spectrum that can be used. Higher frequencies, are more attenuated and as such the use of low frequencies is more economic. The current frequency design dates from the liberalization of the telecom market in the nineties of the past century which created for cable providers the opportunity to offer telephony and (narrowband) internet access services. At that time the upstream band was allocated just beneath the FM radio band.

To accommodate the foreseen growth of the broadband, a cable provider should have sufficient downstream and upstream capacity, and moreover, with a ratio in the range of 10:1 up to 5:1[20]. Considering the current frequency design, in particular

[20] "*Vraag en aanbod Next-Generation Infrastructures 2010 – 2020*", Dialogic and TNO, 2010.

the 65 MHz upper frequency edge of the upstream channel is too low for this range, and has to be extended to a higher frequency. As a result of this extension, the low frequency edge of the downstream band has to be repositioned to a higher frequency, which creates the need to compensate this frequency loss by extending the high frequency edge to a frequency beyond 862 MHz, to 1 GHz or even higher. A further issue concerns the FM radio service that cannot be distributed if the upstream band edge is extended to a higher frequency.

The developers of the new DOCSIS 3.1 technology have chosen a 5 – 200 MHz upstream band combined with a 240 – 1200 MHz for downstream. Change of the frequency design of the cable network requires replacement of amplifiers and optical equipment, and as such is costly. Moreover it will have an impact on the capability to transmit FM which is generally still considered a relevant service in the coming years.

3.4.3 Transmission equipment with an improved spectral efficiency

Today's cable transmission technologies all date from the late eighties of the past century or before. Only DVB-C2 and DOCSIS 3.1 technologies use state-of-the-art modulation and coding technologies, and as such currently the only candidates for the improvement of the spectral efficiency. Market support for DVB-C2, is rather limited in contrast to that for DOCSIS 3.1. Therefore, in this paper, we focus on the migration to DOCSIS 3.1.

As remarked, the interoperability of DOCSIS 3.1 with earlier technologies is most crucial for an economic migration. EuroDOCSIS 2.0 and 3.0 customer equipment currently in use represents a large value. Replacement of this equipment thus represents a large disinvestment and in addition a large and challenging operation. Similarly, replacement of the existing EuroDOCSIS technology in the network would be uneconomic. Therefore, DOCSIS 3.1 has been designed with the migration in mind. The foreseen implementation strategy is as follows[13], [14]:

1. First, the manufacturers will produce new DOCSIS 3.1 customer modems. Once these are in the market, the operators will only provide these new modems, thus they make a start building a population of DOCSIS 3.1 enabled customers. The new modems are expected for late 2014.
2. Second, the new DOCSIS 3.1 network equipment, the CMTS, will become available, likely in 2015. Once available, DOCSIS expansion is realized with this new 3.1 technology though it is operated in the 3.0 mode only. Given the vast broadband growth, the EuroDOCSIS 3.0 capacity thus can be replaced by DOCSIS 3.1 in a few years.
3. Third, DOCSIS 3.1 services are activated. So far, all new DOCSIS 3.1 equipment operates in single carrier DOCSIS 3.0 physical (PHY) mode. To start DOCSIS 3.1 services, the new DOCSIS 3.1 PHY must be activated, but for the operation of the EuroDOCSIS 3.0 modems, transmissions with the DOCSIS 3.0 PHY cannot be terminated. This dilemma is solved as follows:
   - In the downstream band extra frequency channels for the new 3.1 PHY are allocated, next to the downstream frequency channels used for DOCSIS 3.0 PHY. Thus, as illustrated in figure Figure *18*, a hybrid situation is created where the new DOCSIS 3.1 modems can be served using the full downstream bands of the DOCSIS 3.1 and

EuroDOCSIS 3.0 channels whereas the EuroDOCSIS 3.0 modems can use the EuroDOCSIS 3.0 channels only.

- In the upstream, the same frequency channels are shared for EuroDOCSIS 3.0 and DOCSIS 3.1 PHY transmissions in the upstream: all connected cable modems get dedicated time slots for their transmission allocated, and each modem can choose for EuroDOCSIS 3.0 or DOCSIS 3.1 PHY during its time slots.

In summary, the new DOCSIS 3.1 technology is positioned to create broadband capacity in an efficient manner, while protecting current investments.

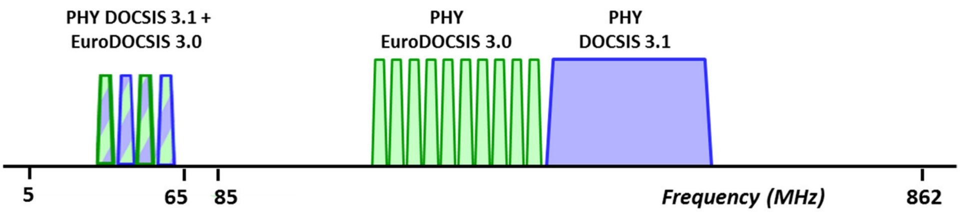

Figure 18: Hybrid EuroDOCSIS 3.0 / DOCSIS 3.1 spectrum use. The green and blue spectrum are used for EuroDOCSIS 3.0 and DOCSIS 3.1 respectively. In the upstream channel, both modulations are used intermitted in time (time division multiplexing). Source: TNO, [10], [11]

3.5 The cable upgrade strategy

Cable providers can combine all above upgrade option in a smart and flexible manner. Thus the upgrade roadmap can be optimized for their existing infrastructure, the availability of new cable technologies, and the foreseen market developments. In particular, they will:

- Protect past investments to avoid disinvestments, for instance, DOCSIS 3.1 is fully compliant to this asset management strategy,
- Align upgrades with replacement investments as much as possible,
- New equipment will be prepared for future upgrades. For example, if an operator has to replace amplifiers or optical transmitters, he will choose for components that can support the new frequency plan.

3.6 Homogeneity and flexibility of the EuroDOCSIS broadband offer

Provided the EuroDOCSIS capacity is properly managed, as pointed out in subsection 3.2.4, the platform can deliver the same bit rate to each connected home, irrespective of the length of the coaxial cables to connect a home. Moreover, to increase the bit rate of the broadband service, the operator can add frequency channels. A limitation here can be that all upstream channels may already be in use. To increase the downstream bit rate, a cable operator does not have to introduce a new transmission technology. The network upgrades are primarily needed to expand the capacity and to create more upstream frequency spectrum to obtain an appropriate balance between the upstream and downstream capacity. However, to use the extra upstream frequency spectrum, the cable provider has to introduce DOCSIS 3.1 technology as explained in subsection 3.4.3. TNO has no indications of the point in time when the cable operators will have to extend the upstream band and deploy DOCSIS 3.1 technology to serve the market.

Cable networks thus offer the possibility of a homogeneous product throughout the service area in combination with a flexibility to increase the downstream bit rate of the service on an individual customer basis. However, for higher upstream bit rates a new transmission technology is needed once there develops a marker demand for an upstream bit rate that cannot be delivered using the current upstream band with 65 MHz upper edge and EuroDOCSIS 3.0 technology.

The maximum bit rate from the cable, provided the segments are sufficiently small, is about a quarter (and more) of the aggregated throughput of the bonded channels [10]. Past year, for instance, Com Hem in Sweden has introduced a 500/50 Mbps cable service to more than 1 million customers using 16 bonded downstream channels with an aggregated throughput of slightly more than 800 Mbps[21]. So, even a maximum bitrate of more than 25% of the segment capacity is offered.

[21] Com Hem Revs Up 500-Meg Broadband Tier, Jeff Baumgartner, www.multichannel.com, Aug 21 2013. http://www.multichannel.com/news/distribution/com-hem-revs-500-meg-broadband-tier/261362

4 ”Comparison” of the copper and cable upgrade roadmaps

In the chapters 2 and 3 we have presented an overview of the design and technologies of twisted-pair copper and cable networks. In the following sections we discuss and compare the upgrade roadmaps.

4.1 The upgrade roadmap of the copper network

For the copper network, the upgrade roadmap is more or less straightforward because the bit rate that can be delivered is related to the length of the copper cable. Thus upgrade roadmap becomes predictable, though the exact timing of the upgrades not.

As described in section 2, first and second generation DSL technologies are currently delivered from the central office. Traditional central offices are well suited to house the DSL Access Multiplexers (DSLAM) because of the available space, the power and cooling facilities and the available fibre connectivity with the core network.

In some Dutch cities, VDSL2 is already deployed from the street cabinets. For the roll out of VDSL2 services from the cabinet, the copper network operator has to:

- Install a DSLAM in the cabinet which often requires extending the physical size of the cabinet (which may be subject to municipality permits),
- Arrange electrical power and possibly cooling,
- Bring fibre to the cabinet to connect the DSLAM to the core network.

It should also be noted that the number of cabinets is an order of magnitude larger than the number of central offices. Furthermore, installing active equipment such as DSLAMs in cabinets raises the number of locations where maintenance must be performed, increasing the operational complexity of running the network.

Because of all these drawbacks related to deployment from the cabinet, it has taken considerable time for the VDSL2 deployment from the cabinet to become substantial. This also explains why a technology that is intended and optimised for deployment from the cabinet has also been deployed from the central office where it benefits only customers close to the central office.

KPN already is deploying VDSL2 with bonding and VDSL2 with vectoring respectively from the central office and the street cabinet.

The subloop from the street cabinet to the homes consists of a few underground cables with many wire-pairs which are splitted into thinner cables and eventually into drop cables. To offer bonded VDSL2 services from the street cabinet, two wire pairs up to the home are needed. Most homes in the Netherlands have a twisted pair copper drop cable with two wire pairs (quads) between the home and the first underground distribution point. Part of these quad drop cable already has two preconfigured wire-pairs up to the street cabinet, whereas the other part only has a single wire-pair from the distribution point up to the street cabinet. In the first case, VDSL2 with vectoring and bonding can be directly deployed. In the latter case though, a second wire pair has to be connected to the unused wire-pair of the quad first, a rather costly process because of the underground location of the distribution point and the lack of a distribution frames in the distribution point.

The Netherlands is one of the few countries with twisted pair copper cables with quads drop cables. Because of the smaller market, VDSL2 equipment for bonding will be more expensive.

Simultaneous deployment of DSL from different points in the network (central office, street cabinet, distribution point) can lead to strong spectral interference between these techniques. This has impact on migration scenarios. In the migration from central office-based services (ADSL2+) to cabinet-based services (VDSL2), there may be a prolonged period where services have to be deployed from both locations. Especially in the case of service delivery by multiple operators via the established local loop unbundling at the central office, the migration to the cabinet can be complex and time-consuming. During such a prolonged transition period, certain spectral management measures may be necessary to protect the services from the central office and the street cabinet. For instance, to protect the (legacy) ADSL2+ from the central office services, it has been necessary to apply so-called power spectrum density (PSD) shaping to VDSL2/Cab, resulting in a performance penalty for the new service.

Once the market demands bit rates beyond the capabilities of VDSL2 from the street cabinet, the copper network operator could roll out G.fast. Although the standardization of G.fast is near finalization, the practical solutions to deploy G.fast have not been developed yet. G.fast deployment will require bringing the fibre deep into the neighbourhoods. Possibly a small street cabinet may be needed, or a hardened G.fast system has be placed under ground.

Table 8: Summary of the downstream and upstream bit rates for the various DSL technologies.

	Bit rate DS/US (Mbps)	
	Max	**Market Majority**
ADSL2+ / CO	24/(1-2)[22]	(10-15)[22]/1
VDSL2	50/10	40/8
VDSL2 plus Vectoring	100/30	80/16
VDSL2 plus Vectoring + Bonding	200/60	160/32
G.fast	About 1000[23]	About 500
G.fast plus Bonding	About 2000	About 1000

[22] Because of the statistical nature and various technical uncertainties, it is not possible to give a specific and undisputable value. Instead we indicate a typical bit rate range.
[23] The aggregate bit rate of the upstream and downstream is given.

The capabilities of the upgraded twisted pair copper network are fully defined by the DSL technology used, as summarized in table Table 8.

KPN has an obligation to offer unbundled local loop services. Third Parties like Tele2 and Online offer retail services using the KPN unbundled local loop service and an own network including a DSLAM in the central office. Evidently, KPN has the obligation to take the interests of these Third Parties into account, which could affect the upgrade of the copper network in terms of timing and costs.

4.2 The upgrade roadmap of the cable network

For cable networks the maximum service bit rate depends on the number of carriers that is bonded, and not on the length of the coaxial cables. To increase the bitrate, a cable operator adds frequency channels for extra carriers. Considering the downstream band up to 862 MHz, the number of downstream channels for broadband services can be increased at the expense of the channels used for other cable services. Currently, the upstream frequency band is limited to 65 MHz, and there is no or only limited unused upstream frequency spectrum to add channels. So, it is difficult to increase the maximum bitrate.

Irrespective of the possible need of a higher upstream bit rate, the cable operator will have to upgrade its network to expand the broadband capacity of the network in order to deliver higher service volumes.

As pointed out in subsection 3.4, there are many options to upgrade a cable network whereby the choice is made on economic considerations. As such, we cannot give a roadmap. Only the cable operator will be able to define the roadmap.

Nevertheless, to give an impression of the upgrade possibilities and capabilities of a cable network, we will discuss some progressive cable upgrade options:

1) Splitting of the optical node and reduction analogue
2) Deployment of DOCSIS 3.1 technology in addition to 1)
3) Redesign of the cable band plan in addition to 2)
4) Deep fibre

In this analysis, we assume a typical Dutch network as specified in subsection 3.1 .

4.2.1 Splitting of the optical node and reduction analogue

Using node splitting, the maximum node size in the Netherlands can be reduced to about 200 homes without the need to replace the coaxial cables by fibre. Assuming a market share of 50%, this corresponds with about 100 broadband customers per segment. Assuming that the Dutch cable providers can allocate 16 channels or a capacity of 800 Mbps per segment for the downstream in combination with 4 channels for upstream with 120 Mbps capacity per segment, there is about 8/1 Mbps available per customer. And assuming an overbooking factor of 10 – 20, the provider could offer a basic service somewhere in the ranch of 80/10 to 160/20 Mbps. For the top tier of the market, they can offer a managed service of 200/30 Mbps or possibly more.

In this scenario, the cable provider has to invest in additional optical transmitters, optical nodes and in EuroDOCSIS equipment.

4.2.2 Deployment of DOCSIS 3.1 technology (in addition to splitting the nodes)

A cable provider could deploy DOCSIS 3.1 technology. This migration can be economically implemented, provided that the cable operator makes an early start with the deployment of the DOCSIS 3.1 equipment (modems and CMTSs) and postpones activation of the DOCSIS 3.1 mode long enough, as explained in subsection 3.4.3.

This migration to DOCSIS 3.1 has no effect as long as it is operated in the EuroDOCSIS 3.0 mode. However, when activating the DOCSIS 3.1 mode, the operator could use higher downstream and upstream modulation schemes, for example 128 QAM instead of 64 QAM in the upstream and 1024 QAM instead of 256 QAM in the downstream. A further benefit of the superior DOCSIS 3.1 modulation technology could be that an operator can use a larger part of the upstream frequency band, and add a fifth upstream channel. With these improvements, the capacity per segment would increase from the mentioned 800/120 to 1000/175 Mbps. For a segment size with about 100 customers the cable provider could offer a basic service in the range of 100/17,5 – 200/35 Mbps and managed service of about 250/45 Mbps.

For this scenario, the cable operator has to invest in the full segmentation of the optical node as described in subsection 4.2.1 and replace all EuroDOCSIS 3.0 network and end user equipment by DOCSIS 3.1 equipment.

Conceivably, the cable provider could add extra downstream channels for DOCSIS 3.1, thus increasing the maximum downstream service bit rate. To do so, he has to reduce other services like for instance the analogue or digital television, or migrate all or part of the digital television from MPEG-2 coding to a more advanced and efficient video coding like H.264 or H.265 or introduce switched television. Obviously, such a rearrangement of the services and delivery platforms possibly requires investments as well, for example for the replacement of customer equipment like the STB.

4.2.3 Redesign of the cable band plan (in addition to splitting of the nodes and introduction of DOCSIS 3.1)

As pointed out in subsection 0, a redesign of the cable band plan is foreseen, for example from the current 0-65 / 85 – 862 MHz to a 5 – 200 MHz / 258 – 1000 MHz. This upgrade specifically will boost the upstream capacity and as such it is relevant only when deployed together with DOCSIS 3.1 Expanding the upstream channel up to 200 MHz, the operator adds 135 MHz to the 4 or 5 channels below the 65 MHz. In combination with the deployment of DOCSIS 3.1 and assuming 128 QAM modulation, this would boost the upstream capacity to about 900 Mbps per segment. If we further assume that the downstream capacity for broadband services is tripled from 16 channels of 8 MHz to 48 channels of 8 MHz, the operator creates a downstream capacity of about 3 Gbps. As pointed out in subsection 4.2.2, expansion of the broadband capacity will require accompanying measures to reduce the spectrum need of other services.

With about 100 broadband customers per segment, this 3 Gbps/ 900 Mbps capacity corresponds to basic broadband service with a bit rate of 300/90 up to 600/180 Mbps, and a managed service of 750/200 Mbps, or more.

For this scenario, the cable operator has to replace the optical transmitters in the HUB, the optical nodes and the amplifiers in the coaxial part of the network. In addition, the cable operator will have to invest in more DOCSIS 3.1 network equipment to feed the frequency channels.

4.2.4 Deep fibre cable upgrade

Considering the typical Dutch cable architecture, two deep fibre upgrades are conceivable, fibre to the group amplifier (FttGA) and fibre to the last amplifier (FttLA). From the group amplifier, small segments of a few final amplifiers can be defined or even segments of a single final amplifier serving say 20 homes or 10 customers. If fibre is deployed up to the final amplifier, the segments can be even further reduced, down to a single customer.

For these last upgrades, cable equipment manufacturers are considering a further improvement of the cable system architecture. To improve the performance of the cable network, and possibly to reduce costs as well, it is argued that the optical link carrying the RF modulated DOCSIS signals between the HUB and the optical node should be replaced by a digital optical link similar to optical Ethernet, but likely specifically designed for the DOCSIS system [15]. If so, the highest modulation schemes of DOCSIS 3.1 (2048 QAM and 4096 QAM) could be used.

When replacing the optical link with RF modulated signals by a digital link, changing the cable frequency plan only requires the change of the amplifiers, or the filters in the amplifiers. Moreover, since a digital optical link can carry DOCSIS signals only, the full cable spectrum can be used for broadband services. Assuming the frequency spectrum is extended up to 1200 MHz,, this would yield a bandwidth of 950/170 MHz for the downstream and upstream bands respectively, corresponding with a capacity of about 9,5/1,4 Gbps segment, to be shared by about 10 customers (FttGA) or less (FttLA).

To build an FttLA cable network, fibre has to be installed to each street cabinet. For FttGA, fibre to the group amplifier is needed. Conceivably, a larger cabinet has to be placed. Today, the street cabinets have a low voltage power supply from the coaxial network itself, and as such another power arrangement possibly is needed as well. Finally, the DOCSIS 3.1 technology with a digital optical link has to be deployed.

In the subsections 4.2.1 up to 4.2.4 we have presented several upgrade options. In Table 9 we summarized the capabilities of each of these progressive cable upgrades.

Table 9: Summary of capabilities of the progressive cable upgrades of subsections 4.2.1 up to 4.2.4. Source: TNO

	Customers / segment	**Channels DS/US**	**Capacity DS/US per segment (Mbps)**	**Range basic service DS/US (Mbps)**
Splitting nodes	100	16/4	800/120	80/12 – 160/24
DOCSIS 3.1	100	16/5	1000/175	100/17,5 – 200/35
Redesign cable frequency plan	100	48/26	3000/900	300/90 – 600/180
FttGA	10	950/170[24] MHz	9500/1400	>2000/>300
FttLA	<10	950/170 MHz	9500/1400	Up to 9500/1400

4.3 "Comparison" of the upgrade of the copper network and the cable network

In the subsections 4.1 and 4.2 we have given a description of the upgrade options of a copper network and an impression of the cable upgrades. Next, we would like to compare these upgrades capabilities of both networks. However, considering both sections, we notice that the technologies, the networks and the upgrade roadmaps are quite different. Moreover, upgrades will depend on previous investments, the existing local situation and market position and, for KPN, on its unbundled local loop obligations. Therefore we conclude that, like apples and oranges, the upgrade possibilities of both infrastructures are difficult to compare.

The upgrade possibilities of copper and cable networks in The Netherlands have too many aspects for a straight comparison. If we restrict these aspects to technical aspects of maximum bitrates, the expected availability of equipment and a qualitative indication that an upgrade step which requires new fiber and installation of new cabinets with new equipment is tougher than an upgrade without extension of the optical part of the network, we consider the following statements defensible:

- DSL services from the central office have been overtaken by the broadband services from the Dutch cable networks,
- Dutch cable networks have a strong position as compared to VDSL2 from the street cabinet:
  - VDSL2 with vectoring from the street cabinets can deliver 100 Mbps at most, with vectoring and bonding 200 Mbps,
  - With the current EuroDOCSIS 3.0 technologies, cable networks already can deliver 100 - 200 Mbps services with an about nation-wide coverage.

[24] In case of DOCSIS 3.1, one cannot speak of channels for a carrier because the whole frequency band is used. Therefore, we indicate the total frequency band available for downstream and upstream expressed in MHz.

  These services can be delivered in large volumes by further segmentation. There is no need to bring fiber to the group amplifier or an upgrade of the cable frequency plan,
  - With EuroDOCSIS 3.0 and DOCSIS 3.1 technologies and an upgrade of the cable frequency plan but without the need to bring fiber to the group amplifier, cable networks can deliver broadband services with a bit rate beyond 200 Mbps services in large volumes,
- The Dutch cable and DSL infrastructures can deliver bit rates of (several) hundreds of Mbps up to Gbps to customers, although different upgrades are needed,
- the ultimate FttLA amplifier upgrade, and possibly FttGA too, results in a cable network that can deliver services with a higher bit rate than a copper network with G.fast, assuming that cable would pursue these upgrades in the future.

Irrespective of the above statements, Dutch cable networks can deliver high bit rates in limited volumes to serve the top market segment without the immediate need of an extensive upgrade of the network. In contrast, for the delivery of a substantially higher bit rate via twisted pair, the DSL network has to be fully upgraded first.

5 References

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