TNO report

Evolution and prospects cable networks for broadband services

A technical perspective of the European and specifically the Dutch cable networks

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Management summary

European cable networks have played an important role in the development of broadcast television and broadband services. The delivery of Gigabit broadband services is considered to be the next access network challenge in the development of broadband services. In this whitepaper we have studied and analysed the technical capabilities of cable networks to deliver Gigabit broadband services.

This whitepaper comprises in-depth information regarding cable technology and cable network upgrading. To complement the knowledge that is readily available from earlier TNO cable research projects and assignments, public sources from the internet and conferences have been consulted and three players with an interest in the development of cable access technologies have been interviewed: Alcatel-Lucent, Huawei and Cable Europe Labs.

The scope of the study was limited to the technological options for expanding the cable network capacity. The broadband market demand was not assessed. Therefore, the study does not provide an indication of the timing of the network upgrades; however, using the results of an earlier study of Dialogic and TNO into the development of the broadband demand commissioned by the Dutch Ministry of Economic Affairs[*], we believe that cable networks can serve the market well beyond 2020, provided the capacity is properly expanded as discussed in this report.

To deliver Gbps services, the cable capacity has to be expanded. Basically, a cable network provider has three options for expanding broadband capacity:
- A rationalisation of the broadcast services: television programmes are only distributed in the most advanced digital video format and only when a customer is watching. Such a rationalisation can be achieved by switching off analogue services, using a single and the most efficient video coding algorithm and introducing switched digital video,
- Network upgrades to downsize the cable network segments and to extend and re-allocate the cable upstream and downstream frequency bands. These upgrades include deep fibre deployment up to, or beyond, an Fibre-to-the-last Amplifier (FttlA) architecture to create segments of 20 homes passed or less, the extension of the upstream band up to 200 MHz and the extension of the downstream band up to 1 GHz. In the long term, the spectrum above 1 GHz can be used, possibly for a second upstream band.
- The deployment of new, more efficient transmission technologies like DVB-C2, EuroDOCSIS 3.x, DOCSIS Ethernet over Coax (DOCSIS EoC) or EPON Protocol over Cable (EPoC).

The first objective of this study is to establish the maximum capacity of the cable network. Assuming that broadcast services are rationalised, the upstream and downstream bands are extended to 200 MHz and 1 GHz respectively, and that the cable segments are downsized to 20 homes passed using an FttlA architecture, the network will be able to deliver a 1600/250 Mbps premium broadband service and an estimated basic service of 1300/200 Mbps. Segmentation beyond an FttlA

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[*] "*Vraag en Aanbod Next Generation Infrastructures 2010-2020*", Dialogic and TNO, Delft, 2010

architecture, down to cable segments of 10 or even 5 homes is feasible, which will allow the delivery of a premium service of more than 1600/250 Mbps.

Technically, for a segment size of 1 home passed, a 6.5/1 Gbps broadband service can be delivered to each home using existing technologies and currently discussed cable network architectures. When assuming a sustained development of the transmission technologies up to QAM 64k modulation and a future use of the cable spectrum above 1 GHz for a second upstream band, a 10/2 Gbps capacity per cable segment will be feasible.
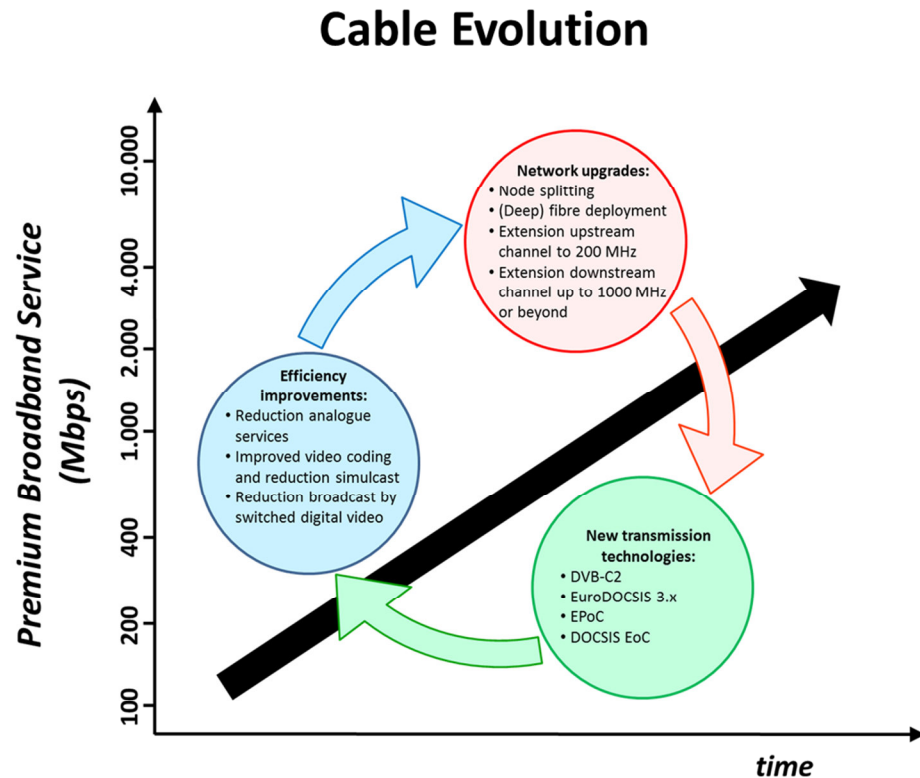

Figure   The overall cable evolution based on a cyclical process consisting of efficiency improvements, network upgrades and the deployment of new transmission technologies.

Cable operators can choose from the mentioned upgrade options; one allocates additional frequency channels to EuroDOCSIS, another one will choose further segmentation of the network, whereas a third operator may opt for DVB-C2 transmission technology with a higher throughput per 8 MHz frequency channel. Together, the upgrade options provide a cable toolbox from which a cable provider can craft its own, optimised cable evolution roadmap, applying all upgrade options in various combinations as and when appropriate as illustrated in the figure. Because of the different network and market situations, each cable provider will optimise its network strategy. The migration strategies of cable providers will look different; a common roadmap seems unlikely.

To summarise, European cable networks can progress towards Gigabit broadband infrastructures. Cable technologies provide the opportunity to develop an optimised network evolution strategy to expand broadband capacity.

Contents

1   Introduction

Cable has played an important role in the development of broadcast television and broadband services. In this whitepaper we have studied and analysed the technical capabilities of European cable networks to continue such a role by evolving towards Gigabit broadband infrastructures.

Currently, most European cable networks offer a premium broadband internet service with a downstream bit rate up to 100 Mbps and an upstream bitrate of 10 Mbps. However, in the future, operators foresee an even higher bandwidth demand, including a demand for higher upload speeds. Broadband is considered of crucial importance for social-economic development, which is reflected in the Digital Agenda for Europe of the European Commission[1]. In Europe, some 70 million homes have a cable network connection and, as such, cable could play an important role in reaching the goals set in the Digital Agenda. This raises the question to what extent can cable networks continue to meet the demand for higher bandwidths and contribute to the development of future broadband services.

The objective of this whitepaper is to provide an overview of the evolution and prospects of cable networks from a technological viewpoint. This overview encompasses three elements:
- What options does a cable provider have for expanding the cable network capacity?
- What is the ultimate bitrate per home that can be delivered using a coaxial cable with a fibre backhaul?
- How will the network roadmap look to reach this ultimate capacity?

This whitepaper comprises in-depth information regarding cable technology and cable network upgrading. To complement the knowledge that is readily available from earlier TNO cable research projects and assignments[2,3], public sources from internet and conferences have been consulted and three stakeholders with an interest in the development of cable access technologies have been interviewed: Alcatel-Lucent, Huawei and Cable Europe Labs.

The scope of the study was limited to the technological options for expanding the cable network capacity. The broadband market demand was not assessed. Therefore, the study does not provide an indication of the timing of the network upgrades; however, a clear indication of developments has been obtained, including the broadband capacity that can be created.

The whitepaper is organised as follows. In section 2, we present a brief overview of the architecture and design of a current state-of-the art cable network. This

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[1] The Digital Agenda for Europe is developed to ensure that, by 2020, (i) all Europeans have access to much higher internet speeds of above 30 Mbps and (ii) 50% or more of European households subscribe to internet access above 100 Mbps.
[2] TNO was one of the members of the 7th Framework project "*Research for Development of Future Interactive Generations of Hybrid Fibre Coax Networks (ReDeSign)*", www.ict-redesign.com.
[3] "*Vraag en Aanbod Next-Generation Infrastructers 2010 - 2020 (Demand and Supply Next Generation Infrastructers Infrastructers 2010 – 2020)",* TNO Report, Commissioned by the Dutch Ministry of Economic Affairs, February 2010.

overview is intended as an introduction to cable networks. Next, in section 3, we summarise the main technological developments that will define any cable network evolution. These technological developments provide a technical framework for the cable network roadmap. Basically, three distinct tools for improving the cable broadband capacity can be distinguished: *i)* adopting a more efficient use of the existing capacity, *ii)* upgrading the cable network itself and *iii)* deploying technology with an improved transmission efficiency. Each option is discussed in a separate section. To conclude, in section 7, we will elaborate on the capacity of the ultimate cable network and the network roadmap that will take us to this point.

2   The current cable architecture

A modern cable network is composed of fibre and coaxial cables, amplifiers and optical transmitters, and transmission and reception equipment. To ensure the correct appreciation of the following sections, we will give a brief description of the design of the cable system and its main subsystems.

2.1   Design

2.1.1   Topology

The most common design of a modern cable network is given in Figure 1. The network is composed of optical fibre rings connecting to coaxial branches at the periphery. Generally, this design is denominated as hybrid fibre coax (HFC) architecture.
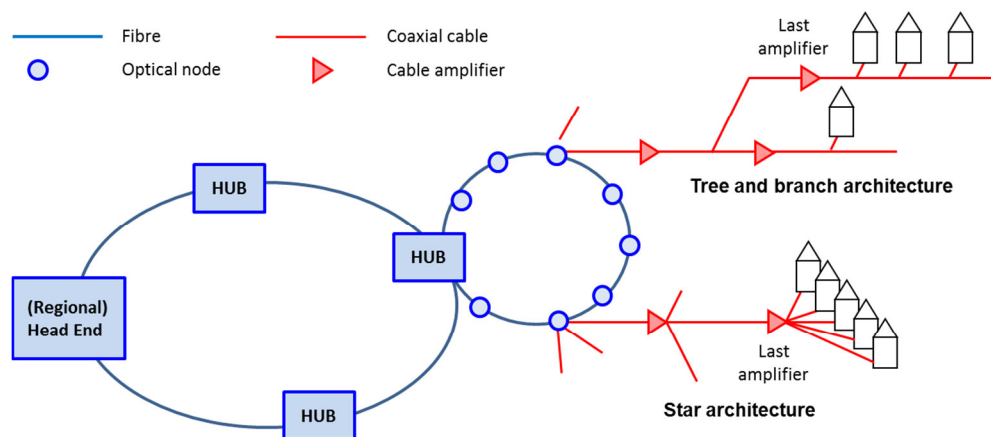
Figure 1 Topology of a modern hybrid fibre coax (HFC) network, showing the two main coaxial architectures: the tree and branch, and the star architecture. Although the figure shows both architectures, in reality the networks have either the tree and branch, or the star architecture.

The fibre part of an HFC network is designed primarily for transporting signals over long distances. The coaxial part distributes the signals locally to the homes. When distributing signals over this coaxial cable, the signals weaken due to the attenuation of the coaxial cable and the splitting of cables to serve each home. To compensate for these signal losses, broadband amplifiers are installed in the coax network. Generally, a number of amplifiers along the coaxial connection between the node and the customer's home are needed, thus forming a cascade (of amplifiers). In the European cable networks, two types of coaxial network architectures can be distinguished, a star or mini-star architecture and a tree-and-branch architecture. Both types are indicated in Figure 1. The length of the coaxial

cascade typically varies from 2 up to 20 amplifiers. In the Netherlands, the mini-star architecture with 2 amplifiers is most prevalent.

2.1.2 *Cable transmission services*

In a conventional cable network concept, RF modulated signals[4] are directly delivered to the customer so that a customer can connect any analogue television set or FM radio without the use of extra receiver equipment[5]. These RF modulated signals can be generated either in the network's (regional) head end or in the HUB. Dependent on the network level where the RF modulated signal is generated, a different transmission service is obtained:

Broadcast service:
Broadcasting is used to distribute a set of television and radio programmes to all homes in a region, whether analogue or digital. The RF signals are generated in the (regional) head end and distributed via fibre to each HUB. In the HUB, the signal is combined with (narrowcast) signals generated in the HUB and forwarded to the nodes.

Narrowcast service[6]:
This service is used for individualised services like telephony, internet access and video-on-demand. All services for customers connected to a specific node are multiplexed into one or a number of RF modulated signals. In the HUB, these node-specific signals are combined with the broadcast signals and sent to the specific node.

The concepts of broadcast and narrowcast are illustrated in Figure 2
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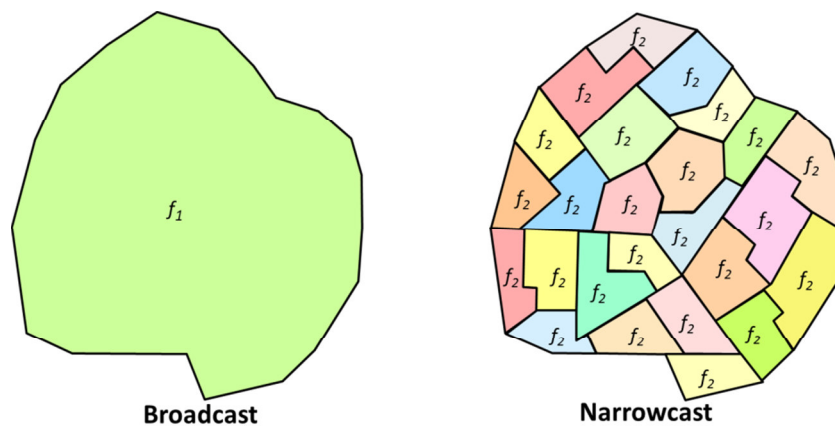
Figure 2 Concepts of broadcast and narrowcast. For broadcast, a signal with frequency f_1 is distributed in a larger area. In narrowcast, the area is partitioned in subareas and in each subarea the frequency f_2 is used to convey a different signal, as indicated by the colours.

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[4] Radio frequencies: frequencies used for radio transmission.
[5] Today, also television with an integrated digital receiver and CI+ interface can be directly connected to the cable network
[6] The term 'narrowcast' has different meanings. It is also used to refer to 'Digital Signage' such as the provisioning of customer information using electronic displays as often found in airports and railway station (time tables) or shops and restaurants (advertisements etc.). Evidently 'narrowcast' is not used in this sense in this report.

Each node is connected to the HUB by at least two fibres, one for downstream signals and the other one for upstream signals. In the node, the optical downstream signals are converted to electrical signals and inserted in the coaxial part of the network, for conveyance to the customer. Electrical return signals from the customer are converted to an optical signal and sent upstream to the HUB.

An overview of the typical size of the cable network at the different hierarchical network levels, expressed in homes passed, is given in Table 1.

Table 1 Typical size of the network at the different hierarchical network levels[7]

	Netherlands	**Europe**
(Regional) Head End	200.000	100.000 – 600.000
HUB	10.000	10.000 – 50.000
Optical node	800[8]	400 - 2000[8]
Last amplifier	208	20 - 50[8]

2.1.3   Electrical design

Since electrical amplifiers are needed in the coaxial part of the network, the cable network relies on the concept of frequency division duplex (FDD): different parts of the spectrum are allocated for downstream and upstream services. For technical reasons, both bands are separated by an unused band. The downstream band starts at a frequency of 85 MHz and thus supports the delivery of FM radio services in the appropriate 87 – 107.5 MHz FM radio band and television and internet services in the higher frequencies up to 862 MHz. The upstream frequency band is allocated from 5 up to 65 MHz, though in practice the spectrum below 20 MHz cannot be used because of an excessive noise level[9]. This frequency design is illustrated in Figure 3.
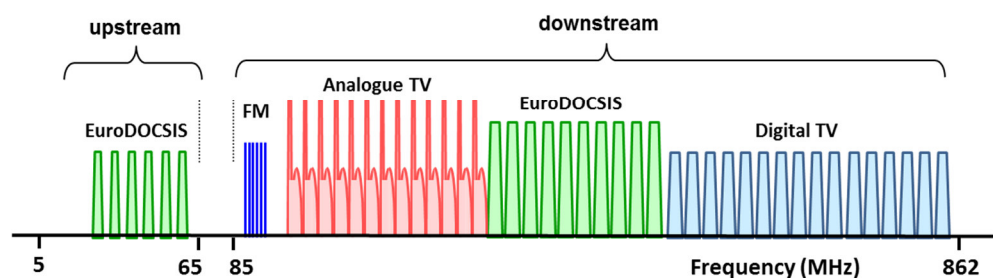
Figure 3 Frequency allocation of a modern hybrid fibre coax (HFC) network

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[7] ReDeSign Reference Architecture Report, October 2008, www.ict-redesign.eu, Table 8 and Table 9.
[8] The figure gives the average number of homes passed by a node or last amplifier of an operator's networks. Thus, smaller and much larger nodes will occur within a network.
[9] S.Pfletschinger, "*Multicarrier modulation for broadband return channels in cable TV systems*", PhD Thesis University of Stuttgart, 2003

Although all Dutch networks and various European networks support the 862 MHz downstream frequency edge, there are various European networks where the downstream band is limited to a lower frequency, such as 750 or even 650 MHz.

Text Box 1 Cable broadband services

For economic reasons, any modern communication infrastructure is designed as a shared infrastructure, whenever possible, including DSL and fibre networks. As a rule, sharing an infrastructure or part of an infrastructure minimises the cost per user or per service delivered. Thus, in any network the metro and core networks and all the routers, switches and gateways are shared and handle the traffic of thousands of customers. Sharing an infrastructure, however, requires special measures to warrant the proper delivery of the services. In general there is no, or only a limited control of the capacity demand of the individual customers and as such there is a risk that the cumulative demand exceeds the capacity of a network link or of a network node. Therefore, sharing parts of an infrastructure requires specific operational and technical measures to minimise congestion and to manage the traffic fairly in the event of congestion. In the case of the core and metro networks, the traffic of each link and each router, switch etc. is monitored, and when necessary extra capacity is quickly added.

Like mobile networks, a cable infrastructure's access network is shared and, as such, all appropriate technical and operational measures to warrant the quality of the services are applied.

Traffic management
Degradation of the service for one customer as a result of the bandwidth demand of other customers will only occur during instances of congestion. In commercial cable and mobile access networks, measures are implemented to avoid congestion or to manage the traffic fairly in the event of congestion. These measures include:

- Full and appropriate management of all user data packets
  Advanced traffic management protocols are implemented as part of the access technology. The delivery of all data packets of all customers is fully scheduled by the system. Services are classified; specific services like premium telephony or films on demand are distinguished from best-effort internet services. The traffic management protocols distinguish between the premium services and best-effort services. Premium service data packets receive priority treatment. In the event of congestion, packet delay and packet loss are assigned fairly to the best-effort services whereas the service quality of premium services is not degraded.
- Appropriate and timely system capacity management
  Congestion only affects the best-effort services; however, best-effort services also have to be market compliant. Therefore, the network capacity demand is continuously monitored. To warrant a market compliant best-effort service, an appropriate capacity threshold is specified and when this threshold is surpassed, the network capacity is expanded. In the operational organisation the necessary processes are implemented to add capacity quickly, thus preventing unacceptable degradation of the best-effort services.
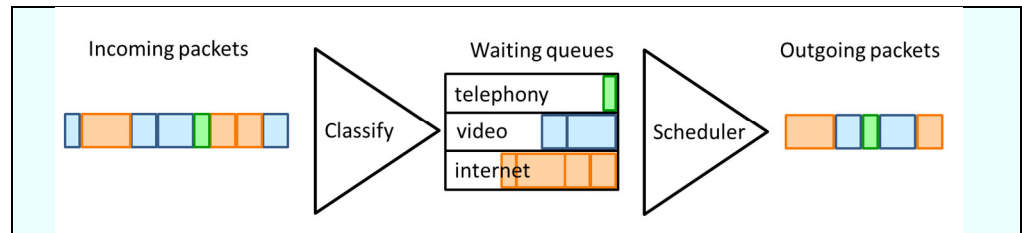
Figure 4   Illustration of the packet management in the access networking technology for a shared medium. Dependent on the service type, the arriving packets are temporarily stored in type-specific waiting queues. The scheduler draws packets from the waiting queues and forwards them. Scheduler rules are applied, for example at any moment, telephony packets will be forwarded first. When there are no telephony packets, then video packets will be handled. When there are no telephony and no video packets, internet packets will be forwarded. The CMTS supports such scheduling mechanisms

Service bitrates

In an unshared access network like DSL, the full capacity of the connection is only available for the customer served by that connection. The capacity cannot be handed over to another user. In contrast, in a shared medium, the total capacity is available for all customers. In reality though, not all users are active, and even if active, many applications produce an intermittent stream of packets. Statistically, a fixed ratio is found between the maximum bitrate and the averaged bitrate during 10 minutes of a service's peak hours. This ratio is called the overbooking factor. Today, an overbooking factor of about 20 applies. For a shared medium, this overbooking allows cable providers to offer broadband services with a bitrate 20 times larger than the available capacity per customer. For example, in the case of a EuroDOCSIS 3.0 service with 8 bonded channels of 416 Mbps together and 416 customers, there is a capacity of 1 Mbps available per customer. Thus the cable provider can deliver a 20 Mbps basic broadband service to all 416 customers.

Broadband service differentiation: basic, medium and premium services

Apart from this statistical bitrate multiplier, a shared medium offers another attractive feature. Like any market, the broadband market can be seen as a pyramid with an upper, middle and bottom tier. The bottom tier comprises the many customers that chose a basic service whereas the upper tier is made up of the few customers that desired a premium service. Stated differently, the broadband market is characterised by a mix of many customers receiving a basic service and a few customers receiving a premium service. For such a market, a shared infrastructure offers the advantage of being able to deliver premium, medium and basic services in an efficient way. EuroDOCSIS 3.0 technology supports channel bonding to create access pipes with multiple 52 Mbps capacity that is used to serve tens or hundreds of customers. Today, bonding four or eight channels with 208 or 416 Mbps total throughput is common practice. If we assume that the 416 Mbps capacity is used to serve 416 customers, the operator can deliver an average service of 20 Mbps to all the connected customers. To serve the different tiers, the operator can offer a basic broadband service with a bit rate of less than 20 Mbps along with medium and premium services with a bit rate larger than 20 Mbps. Today, 100 and 120 Mbps market compliant subscriptions are delivered using a EuroDOCSIS 3.0 network with 8 bonded channels.

2.2   Signals and services

To deliver the complete service package, the cable networks transport different signals in the up and downstream bands, with each signal being assigned its own frequency channel. Since the signals contain the services, they are referred to as carriers. Currently, cable networks convey the following carriers and services

Analogue television
PAL and SECAM television are the European standards for analogue broadcasting. A single television programme is transmitted in a 7 or 8 MHz frequency channel. Today, most European networks deliver some 25 – 40 channels, depending on the market situation.

Analogue FM radio
Standard FM radio services are delivered in the 87 – 107.5 MHz frequency band.

DVB-C
DVB-C is the first European standard for the transmission of digital television over cable networks. A DVB-C carrier has an 8 MHz bandwidth and it supports two modulation modes - QAM 64 and QAM 256 modulation with 38 and 52 Mbps throughput respectively.
DVB-C is used to deliver radio and television programmes but in digital. A number of programmes are multiplexed in a digital transport stream. Each DVB-C carrier can contain a single transport stream. Aside from digital radio and television, DVB-C is also used for video-on-demand services. For this service, a number of video-on-demand programmes for customers connected to a single node are multiplexed in a single transport stream. The transport stream is then narrowcasted in the node serving the customers using the network narrowcast service, see paragraph 2.1.2.

In the Netherlands, DVB-C is used to deliver *i)* about 140 - 200 television programmes, whereof 20 – 45 are in high-definition quality and *ii)* a large assortment of films and catch-up television from Dutch public and commercial stations.

EuroDOCSIS
For cable telephony and internet services, a dedicated technology - Data Over Cable Systems Interface Specification (DOCSIS) - has been developed by Cable Labs in the US. During the development of this technology at the end of the last century, European operators abandoned the idea of an own two-way technology, EuroModem, in favour of a Europe optimised DOCSIS technology, EuroDOCSIS.

For the downstream, in EuroDOCSIS the regular DVB-C carrier is applied. For the upstream, more robust modulation technologies are applied to handle the more severe noise environment, with a smaller throughput of 30 Mbps in a 6.4 MHz channel at most[10]. Because of the 65 MHz frequency limitation of the upstream band, operators can deploy 6 upstream carriers of 6.4 MHz in the upstream frequency band.

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[10] In the upstream band, each customer home network acts as an antenna that receives all kinds of distortion signals. All homes in a network node contribute to this ingress noise.

Currently, EuroDOCSIS release 3.0 is commonly deployed throughout the European cable networks. The most relevant features supported by EuroDOCSIS are:

1. By bonding a number of downstream and/or upstream carriers, high bitrate services can be delivered. Thus, bonding 4 or 8 downstream channels yields a bit pipe of 208 and 416 Mbps respectively. Similarly, higher upstream bitrates can be delivered by bonding the upstream channels. Apart from the limited downstream and upstream cable spectrum, there is no inherent technical limitation to the number of channels that can be bonded, as demonstrated by the recent 4.7 Gbps bitrate record recently realised in a network trial of Kabel Deutschland,[11]
2. Mature and proven security solutions to protect customer privacy and data integrity, and to control network access,
3. Mature quality-of-service mechanisms to deliver services with a guaranteed quality of service like telephony alongside best-effort services like broadband internet access,

To deliver EuroDOCSIS services, a EuroDOCSIS modem is needed at the cable customer location. A cable modem termination system (CMTS) that controls all customer modems and manages the capacity of the bonded down and upstream channels is needed within the network.

Over the years, the initiative to develop (Euro)DOCSIS technology has yielded a mature product and a mature industry. EuroDOCSIS is standardised by CableLabs and Cable Europe Labs. The market comprises products from Motorola, Cisco, Arris, Harmonic and Casa, amongst others. Mandatory certification warrants interoperability among products and components from different manufacturers.

Today, all large Dutch cable providers deliver a 120 Mbps premium broadband service based on the bonding of 8 downstream carriers throughout their networks.

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[11] Press Release "*Kabel Deutschland erzielt Weltrekord: 4,700 Mbit/s Downloadgeschwindigkeit im Feldtest*", 31 May 2012

3   The high-level cable network roadmap

To contribute to the further development of broadband services, the cable providers need to expand their network capacity; however apart from a bare capacity expansion, they have to align their network evolution with the general high-level technology and business trends. In this section we will discuss some of the main high-level trends.

3.1   Changing market and business environment

The changing market and business environment is the most elementary driver for the cable evolution. Dependent on these changes, a cable provider will decide whether to invest in network improvements or not. History shows that cable providers anticipate market trends such as the development of commercial television, HD television and broadband internet, and manage to prepare their networks in readiness. For the future, larger bandwidth including higher upload speeds are foreseen.[3] Cable-based services for small and medium sized businesses are expected to develop further whereas new services like e-Health and e-Learning may need a differentiated access proposition alongside consumer and business propositions.

3.2   Migration to all-IP networks

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 design and build this triploid service architecture themselves using separate components, often from different vendors. In 2008, engineers from Comcast - a USA cable provider with a foot print of more than 50 million homes - proposed to develop a solution to integrate these three cable transmission technologies.[12] In the following year, the initiative received further support from Cox, CableVision, NTSC and Liberty Global amongst others. With support from CableLabs, a first consolidated solution, the Converged Cable Access Platform (CCAP), was developed and published in 2011. Cable Europe Labs has contributed a CCAP version for the European market. Vendors have announced that the first products will be available in late 2012 or early 2013.

Basically, CCAP integrates the systems for DVB broadcasting, DVB narrowcasting and IP/(Euro)DOCSIS in a single platform, see Figure 5. It doesn't eliminate the three subsystems, but it forges them together in an efficient and economic manner. In particular, it adds the flexibility to re-allocate capacity amongst DVB broadcast, DVB narrowcast and IP/(Euro)DOCSIS services. Moreover, CCAP is designed for classical cable TV head ends as well as for IPTV head ends.

Since CCAP brings new features, a new type of cable home gateway is needed at the customer side of the network to terminate the cable network and to feed the home network. This new home gateway will receive the content from the cable network, from either the DVB broadcast, the DVB narrowcast or IP/(Euro)DOCSIS

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[12] http://www.cedmagazine.com/articles/2012/01/ced-person-of-the-year-jorge-salinger
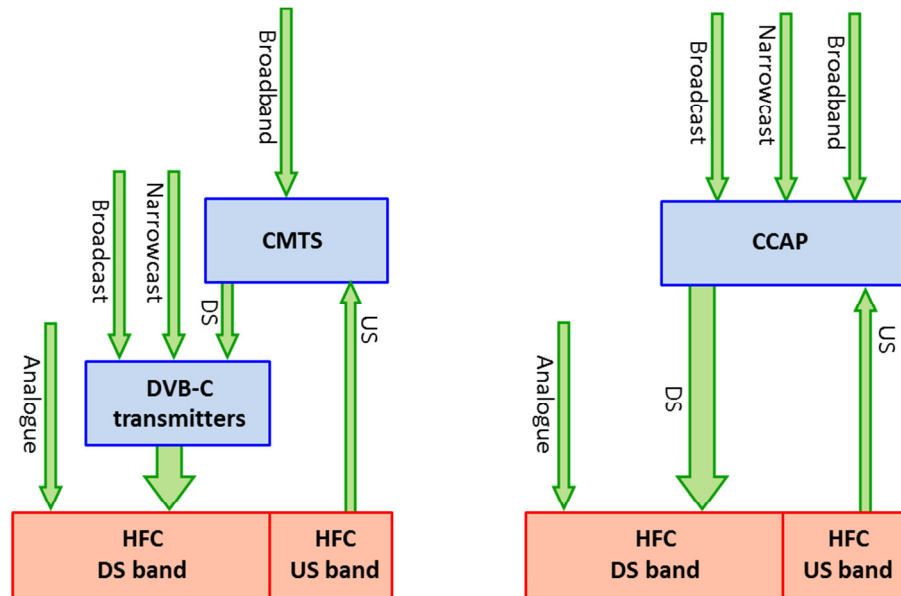
Figure 5. The existing system architecture (left) and CCAP system architectures (right).

service, and forward the service to any customer premises equipment with a conventional scart or HDMI connection or an IP connection. For the latter distribution mode, services received from the DVB broadcast or narrowcast are converted to IP services. Currently, this capability has been implemented in the latest generation of cable home gateways, such as the Horizon Media Box of UPC and the NETGEAR 802.11ac DOCSIS3.0 gateway.[13] The latter is equipped with 24 DVB-C receivers that can tune to either a DVB-C 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, is paving the way for the all-IP cable solution which, for example, will enable an easy migration of the programme delivery mode: television programmes can be reallocated from DVB broadcast to (Euro)DOCSIS, or similar, video on demand from DVB narrowcast to (Euro)DOCSIS. Currently cable providers are exploring these options to fully profit from the technical and economic benefits of IP[14].

3.3   The evolution of the home network

Rapid changes can be observed in the home environment in particular. For example:

- Increasingly, content is consumed throughout the home and using every kind of user terminal, ranging from the flat screen in the living room, the PC and tablet to the smartphone.

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[13] http://www.netgear.com/about/press-releases/2012/06122012.aspx
[14] Since 2011, a new conference "IPCable Worl Summit" is successfully organised by Informa.

- Hybrid broadband broadcast television[15] allows the full integration of conventional television, new video and audio over-the-top services from third parties and internet.
- New home networking solutions are developed or existing ones enhanced. New television sets are equipped with an IP port as well as the conventional coaxial, scart and HDMI ports. The IEEE 802.11 working group has started the specification of a new Wi-Fi technology, 802.11ac with 1 Gbps capacity, as a follow up to the current 802.11n with a throughput of 100 Mbps and more. For transmissions over the coaxial cable network in the customer's home, the Multimedia Over Coax Alliance (MoCA) provides technology with a throughput of 175 Mbps for release 1.1 whereas release 2.0 offers 800 Mbps. For the American market, Cisco has introduced a residential gateway with an 8x4 DOCSIS 3.0 modem and MoCA. Apart from deploying a new wireless (Wi-Fi) network or reusing existing coaxial cables, a customer may choose to install a new wired network, for example unshielded twisted pair or plastic optical fibre for standard 802.3 Ethernet.
- The home equipment is gradually changing from a dedicated set top box to connect to the television set with a dedicated scart or HDMI cable, to a home media gateway that may connect to any IP device using smart protocols, such as Universal Plug and Play and DLNA. The new Horizon Media Box of UPC illustrates this development.

Clearly, IP is rapidly replacing the conventional in-home coaxial distribution network to deliver services to the user terminal.

3.4   Power consumption and space limitations

Existing technical facilities like HUBs and nodes are limited in terms of space, power supply and cooling. Generally speaking, increasing the amount of space and improving the power and cooling capabilities of a location is difficult. Therefore, all network equipment has to fit in with these limitations, irrespective of the continuous growth of the capacity demand. Since the capacity demand doubles approximately every two years, such a growth is not sustainable unless the size, power consumption and cooling requirements shrink proportionally. In addition, an equal price erosion of the equipment is required as well since in many markets the broadband bandwidths do rise but the subscription rates not.

Although the above requirements may seem rather challenging, modern silicon technology can meet them. In silicon technology, circuit speed increases and power consumption decreases when using smaller technology. Moreover, integration of subsystems or subcomponents into a single chip further contributes to the reduction of equipment size and power consumption. This evolution of systems that combine increased processing capabilities with a smaller size and lower power consumption is best seen in consumer electronics like smart phones and tablet PCs. For these products, large volumes and competition drive this development. For network systems smaller volumes apply, although the volumes will increase proportionately to the market capacity demand. Moreover, competition and the limited space and power available in the HUBs and nodes forces vendors to take this road. For

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[15] www.hbbtv.org

example, one of the CCAP requirements concerns a substantial reduction of size, power consumption and cooling.

The success in reducing size, power consumption and cooling is illustrated by the newest cable solution. Casa, for example, has squeezed 8x96 downstream channels onto a single card for its 12 RU C10G CMTS, whereas until a few years ago 32 or 64 channels per card was considered state-of-the-art.

3.5 Summary

We have argued that some elementary developments are needed as an enabler for a sustained development of cable networks. The migration to an all-IP cable architecture that stretches into the home environment and a sufficient reduction to the size, power consumption and cooling of the network equipment are most crucial to the development of cable. From the analysis, we can conclude that appropriate solutions have already been put in place or they are well under development, thus providing the basic condition to deliver higher bitrates for consumer, business and new social services like e-Learning and e-Health.

4   Efficiency improvements

Broadcasting is a very basic concept for distributing the same signal to a (large) number of customers. In the early years of television broadcasting, there were a few television programmes, watched by many. In such a scenario, broadcasting is an efficient concept to distribute television. Today in contrast, there are (very) many television programmes that often are watched by a few people only[16]. Evidently, broadcasting programmes that are not or hardly watched represents a waste of capacity. For these services, narrowcast will offer distribution capacity savings. Moreover, digital technology has provided the capability to reduce the transmission capacity to convey television programmes and video services by smart coding algorithms like MPEG-2 and a successor H.264. In this section we will analyse the benefits of video coding and substituting broadcasting with narrowcasting for programme delivery.

4.1   Video coding

From the late fifties until the mid-eighties during the last century, television took off as a terrestrial service with a limited number of public television channels. From the second half of the eighties, commercial television gradually developed, a development that has continued until now. Today, a European cable operator typically distributes some 100 or more television programmes.

In the early nineties, there was sufficient spectrum on cable to accommodate from ten up to twenty channels in analogue. Anticipating larger numbers of commercial television programmes, the DVB project developed a digital television technology for cable, encompassing dedicated digital downstream transmission technology (DVB-C) in combination with MPEG-2 video coding. This technology was implemented from the second half of the nineties onwards, which over the years has resulted in the establishment of a large customer base. Irrespective of this offer, digital television didn't succeed in fully replacing the analogue services because of the good picture quality of the European analogue television standard and the convenience of analogue which makes it possible to connect several TV sets without additional equipment. More recently, the appearance of high definition flat screen television sets in the living room has created a sufficient customer base for the launch of high definition television (HDTV). HDTV requires a higher bit rate per programme and therefore cable providers introduced a more advanced video coding algorithm, H.264, for the HD programmes. Currently, a next technology for video coding is being developed, H.265 or High Efficiency Video Coding, which is targeted for the delivery of a ultra-high definition television (ultra-HDTV) with a resolution of 7680 × 4320 pixels.[17] H.264 and H.265 respectively yield a 50% and 67% bitrate reduction as compared to MPEG-2.[18]

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[16] The top 20 programmes account for 90% of the viewers, SPOT Televisierapport 2010.

[17] H.265 is the latest compression standard developed jointly by ISO/MPEG (Motion Picture Experts Group) and ITU-T/ VCEG (Video Coding Experts Group).

[18] Cliff Reader, "Technical Update on Developments and Dynamics in the field of Codecs", NABShow, April 2011, Las Vegas.

For the above historical reasons, almost all cable operators offer analogue television, standard definition digital television (SDTV) using MPEG-2 coding and HDTV with H.264 coding. The programmes watched most are distributed in all three formats: analogue, SDTV and HDTV. Therefore, the most straightforward option for improving the efficiency of a cable network would be to rationalise the broadcast services offered by *i)* applying digital coding with the best compression for all television services and *ii)* terminating the distribution in analogue and in inferior digital coding technologies.

To illustrate the spectrum gain, we show in Table 2 the impact of the above measure for a typical example[19]. We assume a 6 Mbps and 12 Mbps coding for SDTV and HDTV respectively and a capacity of 38 Mbps per DVB-C carrier. The table shows a large reduction from 53 cable channels down to 16 cable channels to distribute the same package, which corresponds to a 70% saving.

Table 2 Illustration of efficiency gains using (advanced) digital coding

	Programs	Number 8 MHz cable channels	
		Distribution analogue, MPEG-2 and H.264	Distribution H.264
Analogue	25	25	0
SDTV	140	23	11
HDTV	15	5	5
Total of 8 MHz channels	-	**53**	**16**

For various business considerations, such a drastic termination of analogue and MPEG-2 encoded services is not pursued by the cable providers. Conventional analogue television continues to be appreciated by the customer with a conventional CRTV because it combines good picture quality with convenience of use[20]. Moreover, as a rule, national media legislation mandates the conveyance of a number of analogue channels. To migrate from MPEG-2 coding to H.264 coding, digital receivers that only support MPEG-2 have to be replaced. Irrespective of these reasons for continuing analogue and MPEG-2 encoded services in the short and medium term, for the long term, such a rationalisation can be foreseen. CRTV televisions are taken out of production, whereas the good picture quality of analogue television is degraded when watched on a flat screen. Furthermore, modern flat screen displays with an increased resolution, television sets with a CI+ interface and the delivery of television services on tablets undermine the demand for analogue services[21]. Cable providers will reduce the analogue packages

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[19] This example is intended to illustrate the capacity gain. It does not necessarily reflect a real deployment of a cable provider.

[20] The European analogue PAL and SECAM television technologies have a good picture quality when watched using a CRT television set. As a rule, the PAL and SECAM picture quality degrades when watched on a modern flat screen display.

[21] *"A new breed of media? – Report on TV myth and truths"*, D. Witteveen and M. van der Donk, Deloitte, 2012.

gradually and once the installed base of H.264 receivers is sufficiently large MPEG-2 coding will be terminated.

4.2   Reduction of the broadcast package

Digital television has created the business opportunity to produce and distribute programmes targeted at smaller audiences like minorities or people with a special interest. Today, all these programmes are broadcasted all the time, irrespective of the number of people watching. Evidently, it would be more economical to only distribute programmes in cable segments where someone wants to watch the programme. The technology to only distribute a programme in cable segments in response to a specific customer demand and not throughout the entire network is known as switched digital video (SDV). It is quite similar to the video-on-demand service and it is already deployed in the USA cable networks[22]. Implementation of the IP cable architecture, as discussed in paragraphs 3.2 and 3.3 or adaptation of the video-on-demand platform, will enable an operator to migrate to a switched digital video solution.

One should note that with the gradual reduction of the cable network's node sizes, as discussed in subsection 5.1, the likelihood of a programme not being watched by anyone within that node will increase. Therefore, the efficiency gain of SDV will increase with the foreseen decrease of the node size.

4.3   Summary

Considering the current usage of cable resources, a substantial efficiency improvement can be foreseen. In the illustration of Table 2, currently 53 8 MHz channels are used to distribute a total of 140 television programmes. If the programmes are distributed using H.264 coding, only 16 channels are needed. A substantial further reduction of the required network capacity can be expected upon the roll out of switched digital video.

Today, in a cable network with an 862 MHz upper frequency edge some 90 channels of 8 MHz can be used.[23] This shows that when these measures are implemented, only a minor part of the cable spectrum will be needed for broadcast services, thus freeing up downstream spectrum for video-on-demand and internet services.

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[22] Press Release "BigBand Networks' Switched Digital Video Solution Deployed by Cox Communications", Redwood City, 22 August 2007.
[23] In practice not the full band from 85 – 862 MHz can be used. The band below 107,5 MHz is used for FM radio; the 108 – 128 MHz band often cannot be used because of the filter used to deliver TV and FM signals to separate ports, and in the 575 – 615 MHz band one or two 16 MHz channels are assigned to the use of VCR by the customer.

5   Network upgrades

In the previous section we have argued that when working towards an efficient use of broadcast services, most of the cable spectrum can be freed up for narrowcast services. Here, we will analyse the possibilities for expanding the capacity of the cable network itself. In most cable networks today, each optical node represents a narrowcast segment. By splitting the nodes, the same narrowcast channels are shared by fewer homes and thus fewer customers. In the current cable frequency plan, the upstream band is limited and likely to be insufficient to support future upstream capacity demands. Moreover, coaxial cable can convey signals at frequencies above 862 MHz, today's European upper frequency edge, albeit not as efficiently. Thus, extending the frequency spectrum and reallocating the upstream and downstream bands may provide more and properly balanced capacity. Below, we will analyse the options of node splitting and frequency re-arrangements.

5.1   Node splitting

In most European cable networks, each optical node is currently associated with a narrowcast segment. Stated differently, all narrowcast carriers are shared by all homes connected to that specific optical node and not with homes connected to other nodes. In general, the narrowcast capacity is shared by 400 – 20008 homes, see also Table 1.
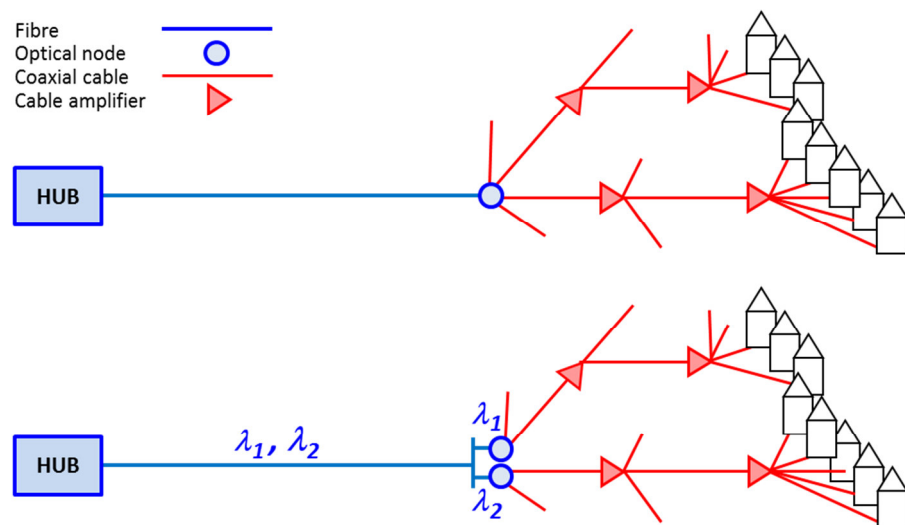
Figure 6 The concept of node splitting.

As a rule, the optical node is located at the centre of a neighbourhood. To serve all homes, typically 4 to 8 coaxial branches originate from the node, each feeding part of the neighbourhood. A straightforward method for expanding the capacity per home is to reduce the narrowcast segment size. Part of the branches is disconnected from the existing node, connected to a second, newly installed, optical node, as shown in Figure 6. The second node is fed by a new set of narrowcast transmitters and receivers. Thus, the narrowcast segment size is (approximately) halved or the capacity per home is doubled. This process of node splitting can be repeated until each branch is fed by its own node.

Manufacturers have already anticipated this development. They have added modular node solutions to their product portfolio that support node splitting by inserting one or more extra downstream and/or upstream modules.

5.2   Fibre deployment

Once an optical node is fully split while a continuous growth of the broadband demand is foreseen, a cable provider can further expand the network capacity by extending the fibre from the existing node to a branching point off the coaxial network closer to the homes, as shown in Figure 7. Thus the segments can be reduced to several hundreds of homes passed or even less. At first sight, fibre to the last amplifier that feeds some 20 up to 40 homes, see Table 1, can be considered as an ultimate cable network upgrade. However, from a technical viewpoint, even these segments can be split. In some networks, like the Dutch networks with their star-topology, segments of a few homes or even a single home can be created.
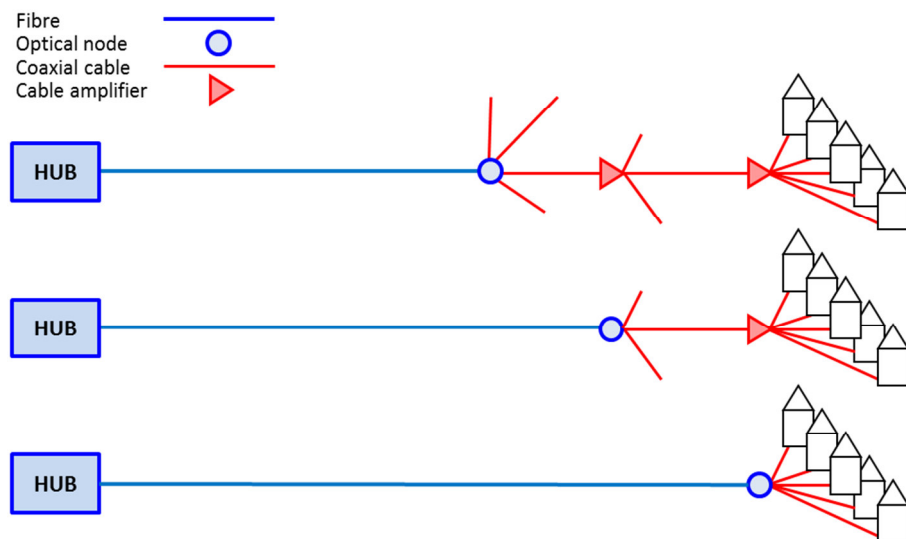
Figure 7 Replacement of coaxial trunk cable by fibre

5.3   Extension and re-allocation of the cable spectrum

Cable spectrum is defined by the cable design and can be changed. In particular, cable providers and equipment manufacturers are considering an extension of the upstream frequency band and an extension of the downstream band.

5.3.1   *Extension of the downstream frequency band*
Today, in the European networks, cable spectrum is used up to a frequency of 862 MHz. In various networks, the downstream band is limited to a lower frequency of, for example, 750 MHz. This frequency limitation is historical. Higher frequencies are less attractive to use because of the increased signal attenuation, among other reasons, but there are no principal reasons obstructing such usage. In practice though, extension of the frequency edge up to 862 MHz or beyond will have a large impact and as such is considered as a major network upgrade.

For a good network performance, a minimum signal level is required at the next amplifier. When increasing the frequency, the signal attenuation will increase as well. Therefore, either the distance to the next amplifier has to be reduced or the output level of the amplifier has to be increased. The first solution requires a repositioning of the street cabinets. The second option, increasing the output level of the amplifiers, is also not easy to implement since amplifiers already operate at their appropriate maximum output level. Therefore, the output level cannot be simply raised. As a rule, a cable provider will have to install new amplifiers. However, amplifier improvements and, in particular, the recent development of amplifiers with a GaN[24] final stage with a double output power, offer the possibility to expand the frequency range. Thus, extension of the frequency edge is feasible, however, from the business perspective, it will require appropriate network planning.

5.3.2   *Extension of the 5 – 65 MHz upstream band and creation of a second upstream band*

The existing 5 - 65 MHz allocation of the upstream band is a design choice from more than a decade ago and based on commercial considerations of that time. To change the upstream – downstream band split, all diplex filters in the amplifiers and optical nodes have to be replaced. Modern components have a diplex filter in a separate module that can be easily replaced, but older components with an integrated diplex filter have to be replaced.

Technically, a second upstream channel above the downstream frequency edge can be created as well. To do so, all existing amplifiers must be equipped with an additional upstream amplifier. Moreover, to use such a secondary upstream channel, manufacturers have to produce the necessary equipment, which will require general support for this solution from the cable society.

Text Box 2 Potential Interference from terrestrial mobile services

To facilitate the growth of mobile broadband services, the European Union and its member states have decided to allocate the 790 – 862 MHz band of the former 470 – 862 MHz band for terrestrial broadcasting to mobile services[25]. Further spectrum re-assignment of this 470 – 862 MHz band, amongst others of the 700 MHz band, are under discussion.

The use of these frequencies for mobile services is expected, under worst-case conditions, to interfere with cable services delivered using the same frequencies. This interference is caused via ingress of the radio transmit signal of the mobile terminal in the customer's home domain. An insufficient shielding of *i)* the coaxial cables and other coaxial home networking components and of *ii)* receiver equipment provide the ingress path.

So far, there are no indications that interference of cable services by terrestrial mobile radio signals via the cable network of the cable provider provides a third ingress path. Therefore, from the formal viewpoint, this interference is not a cable

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[24] Gallium Nitride is a novel semiconductor material with better electrical properties as compared to Silicon or Gallium Arsenide.
[25] Often, this band is referred to as the "Digital Dividend" of terrestrial broadcasting.

network issue, but a customer home network and equipment problem.

The interference can be attributed to a co-existence problem between the mobile and cable services using the same frequencies. To address this problem all stakeholders (cable customers, cable providers, manufacturers of consumer electronics, mobile operators and the national administrations) must take responsibility[26]. It will take several years for these mobile networks to develop, thus granting the stakeholders time to develop and implement a satisfactory solution.

There are several options for controlling this interference in the customer's home domain, amongst others: *i)* the customer improves the shielding of its home coaxial network and replaces its cable receivers by equipment with better shielding, *ii)* reduction of the mobile signal level or *iii)* the cable provider installs a network termination unit at the home network interface (HNI) where the coaxial cable enters the home. This network termination unit should receive cable services delivered via the channels that suffer from the interference and forward them using other home networking technologies like Wi-Fi, Ethernet, MoCA etc, as pointed out in subsection 3.3. Solutions are currently being developed. An updated mandatory standard for the shielding of cable receivers like television sets and cable modems has been developed[27]. Shielding requirements for cable networks have been raised[28]. Deployment of mobile femto cells and Wi-Fi off load respectively can contribute to a lower LTE transmission level and a reduction in the use of LTE in the home environment. Furthermore, the on-going development of the home network towards a fully-fledged broadband IP environment using other home networking technologies like Wi-Fi, Ethernet and MoCA will also help to relieve the interference problem. As pointed out in paragraphs 3.2 and 3.3, cable is currently undergoing a transition from an architecture with different platforms for broadcast, video-on-demand, catch up services and broadband internet to a seamless all-IP architecture for all services. In this development, the customer home domain will also migrate to an all-IP architecture. Therefore, we believe that this problem will be solved in the medium term.

5.4   Summary

Cable networks offer various upgrade opportunities for expanding the network capacity for broadband services: splitting the nodes, in the medium and long term, along with the extension of the fibre to reduce the narrowcast segments and the possibility of adding frequency spectrum and reallocating spectrum from the downstream band to the upstream band.

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[26] "*Co-existentie Kabel- en Mobiele Netwerken - Behoud van een ongestoorde relatie*", TNO, Report 35374, October 15, 2010.
[27] Comité International Spécial des Perturbations Radioélectriques, Subcommittee I – Electromagnetic compatibility of information technology equipment, multimedia equipment, and receivers, CISPR-35, May 2012.
[28] EN 50083 – 2: 2012, "Cable networks for television signals, sound signals and interactive services - Part 2: Electromagnetic compatibility for equipment".

6   Transmission technologies

Apart from rationalising the usage of cable capacity as discussed in section 4 or upgrading the cable network as argued in the previous section, operators may deploy more efficient transmission technologies. In this section we provide an overview of the developments of DVB-C for broadcasting (Euro)DOCSIS services and of new alternative transmission systems for Ethernet services.

6.1   Development of second generation DVB-C technology

Under the umbrella of DVB, Kabel Deutschland and cable equipment manufacturers have developed a second generation DVB transmission technology for cable networks with a higher throughput. The DVB-C2 specification was published in March 2011[29]. DVB-C2 supports different modulation schemes, each corresponding to a specific capacity of an 8 MHz cable channel. To deploy DVB-C2, a minimum signal level (P_{min}) and a minimum signal-to-noise ratio (SNR_{min}) is needed. Table 3 shows the capacity of an 8 MHz channel and the P_{min} and SNR_{min} for the different modulation schemes. For comparison purposes, the DVB-C figures are also listed. The data indicate a 30% capacity gain at the same signal level and even 60% gain provided the signal level can be sufficiently increased.

Table 3   Bitrate per 8 MHz channel and minimum signal level DVB-C and DVB-C2 modulation schemes

Technology	Modulation scheme	SNR_{min} (dB)	P_{min} (dBμV)	Throughput (Mbps per 8 MHz)
DVB-C[30]	QAM 64	26	48	38
	QAM 256	32	54	52
DVB-C2[31]	QAM 256	23	38	55
	QAM 1024	29	44	69
	QAM 4096	35	51	83

Currently there are several manufacturers of DVB-C2 network side transmitters including Arris[32], amongst others. Sony has introduced television sets with an integrated DVB-C2 receiver onto the market[33]. Kabel Deutschland is considering s the launch DVB-C2 services.

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[29] ETSI EN 302 769 V1.2.1 (2011-04), "*Digital Video Broadcasting (DVB);Frame structure channel coding and modulation for a second generation digital transmission system for cable systems (DVB-C2)*"
[30] Performance requirements are copied from IEC-60728 part 1.
[31] Signal requirements are copied from ETSI TS 102 991 V1.2.1 (2011-06).
[32] ARRIS D5® Universal Edge QAM can support DVB-C2 broadcast and VOD solutions
[33] Sony KDL-46HX755 is the first model with integrated DVB-C2 tuner

In the existing cable networks, for DVB-C QAM 256 a signal level *P* and an *SNR* are found for 55 dBµV and 36 dB respectively.[7, 34] Comparison with the required SNR_{min} for DVB-C2, see Table 3, shows that DVB-C2 QAM 1024 will operate equally well, but that DVB-C2 QAM 4096 deployment will be critical.

Like the migration of video coding from MPEG-2 to the more advanced H.264, migration from DVB-C to DVB-C2 requires new customer equipment. Because of the need of a new receiver, cable operators will wait for the appropriate business opportunity.

6.2   Developments (Euro)DOCSIS and new alternatives

Over the past decade, the market for (Euro)DOCSIS technology has been served by the traditional cable vendors like Cisco, Motorola, Arris and Casa. Vendors of fixed access networking technologies like Alcatel-Lucent, Huawei and ZTE, however, have limited or no cable access products in their portfolio. Although the worldwide market for cable access technology is smaller than the market for DSL or FttH technology, a mature cable product would be of strategic value to them. Currently these non-traditional cable manufacturers are studying and developing alternative two-way cable transmission solutions that fit in with their existing portfolio. Amidst this development, China is believed to provide a stepping stone for an innovative cable technology. China offers a large cable market, see Table 4, dominated by multitenant buildings in the large cities. To address this market, vendors have taken the initiative to develop Ethernet Passive Optical Network (PON) technology adjusted to coaxial networks. This initiative is launched under the umbrella of the Institute of Electrical and Electronics Engineers (IEEE) 802 LAN/MAN Standards Committee, known for the standardisation of Ethernet and Wi-Fi technologies. Besides this initiative, CableLabs and its supporting vendors are pursuing a new (Euro)DOCSIS release 3.x[35]. In what follows, we will give an overview of the main cable access technologies considered by the vendors.

Table 4 The main cable markets

	Homes Passed
Europe	70 million
USA	130 million[36]
China	187 million[37]

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[34] These are the signal-to-noise ratio and signal level at the receiver
[35] Jeff Baumgarten, Cisco Hints at What Comes After Docsis 3.0, Cable Show,14 May 2012.
[36] Info NCTA (www.ncta.com)
[37] Italian Trade Commission, China Television Industry Market Report, June 2011.

6.2.1   *DOCSIS Ethernet over Coax / miniCMTS*

With the large Chinese market in mind, Broadcom has developed a dedicated DOCSIS Ethernet over Coax (DOCSIS EoC) chipset.[38] This solution has been derived from the standard (Euro)DOCSIS 3.0 technology by removing some features that are less relevant for the Chinese market, thus reducing complexity and costs. Currently, Broadcom has a 1 Gbps system in its portfolio.[39] DOCSIS EoC is intended for integration with EPON backhaul technology whereas the customer can use a DOCSIS cable modem. The first large-scale role out has been announced[40].
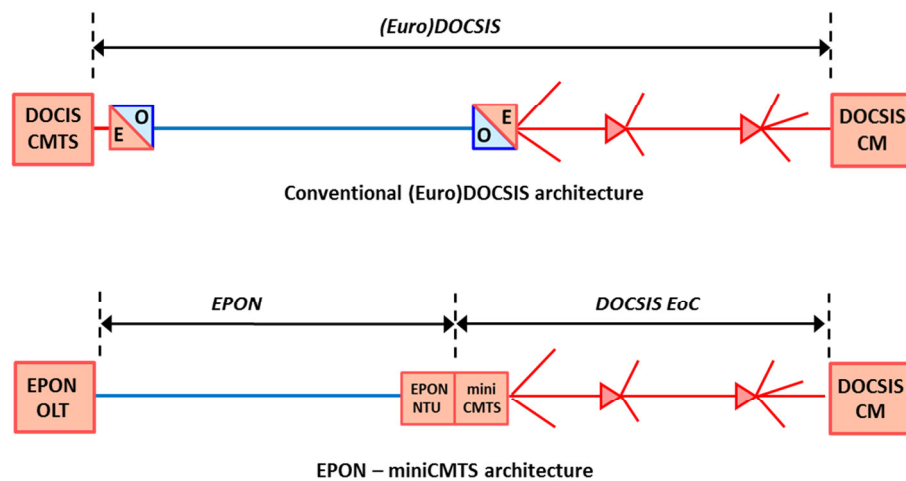
Figure 8.   Conventional (Euro)DOCSIS (top) and EPON/DOCSIS EoC (bottom) architectures.

At the cable network's transition between the fibre and coax, the so-called miniCMTS takes care of the conversion of the EPON signal to a DOCSIS EoC signal and vice versa, as shown in the left window of Figure 9. In this architecture, an end-to-end Ethernet solution with QoS is obtained using the EPON and DOCSIS QoS mechanisms.
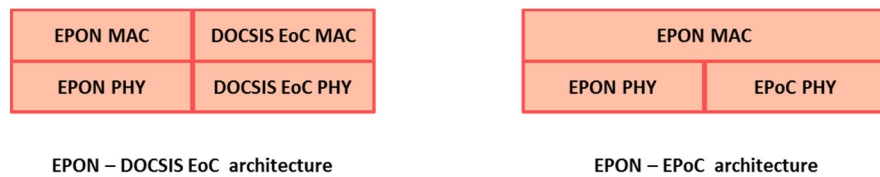
Figure 9   System architectures of EPON/DOCSIS EoC and EPON/EPoC

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[38] Broadcom, DOCSIS® EoC for EPON in China,

[39] Press Release, "*Broadcom Boosts Speed for DOCSIS®-based EoC Cable Architecture Solution - 1 Gigabit per Second Broadband Performance Supports New Services Including TV Video Conferencing and IPTV", Broadcom*, BEIJING, 20 March 2012

[40] Press Release "*Sumavision Deploys Broadcom DOCSIS®-based EoC Cable Architecture Solution in China - High Volume Deployment to Chinese Cable Operators Opens the Way to Network Convergence*", BEIJING, 20 March 2012

6.2.2   EPON Protocol over Coax

EPON Protocol over Coax (EPoC) can be considered as a next step in the evolution of an end-to-end Ethernet solution for hybrid fibre coax networks. As indicated earlier, EPoC is an initiative launched under the umbrella of IEEE 802. A study group is currently developing the project allocation request (PAR) that, when approved, demarcates the start of the development of a standard. This PAR is relevant to the discussion here because it defines the objective and scope of a new IEEE 802 technology. The study group considers two EPoC options:

- A time division duplex (TDD) solution
  This solution can only be used in coaxial networks without signal amplifiers. It offers the advantage of full flexibility of upstream – downstream capacity allocation. Since amplifiers cannot be applied in the coaxial networks, this solution requires deployment close to homes, in a fibre-to-the-last Amplifier (FttlA) architecture.
- A frequency division duplex (FDD) solution
  This solution is targeted for cable networks with amplifiers, thus supporting a (more extended) coaxial network with amplifiers. The drawback of this solution is the conservation of fixed capacity compartments for up and downstream.

Roughly, the TDD solution is targeted more for the Chinese market whereas the FDD solution appears more appropriate for the European and American markets.
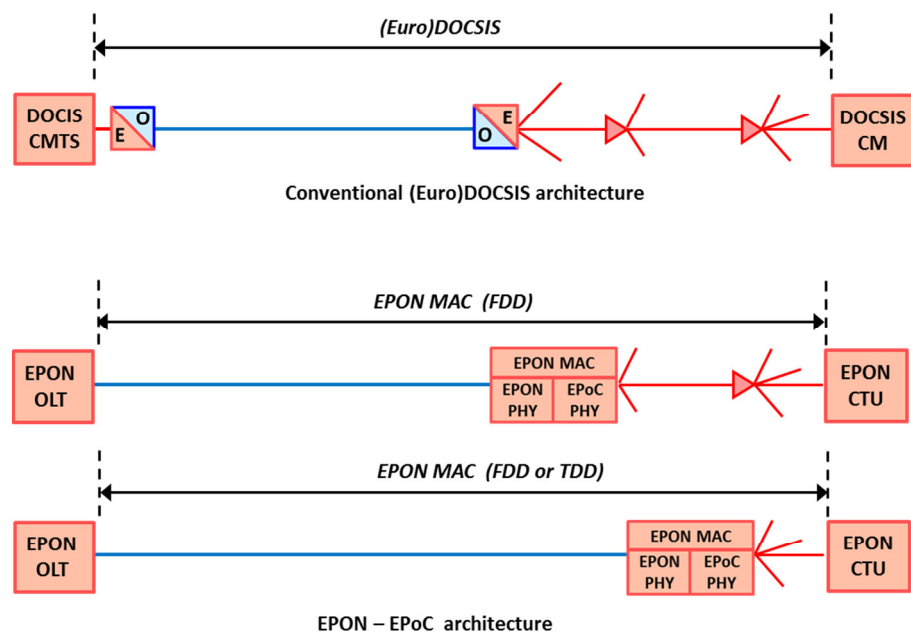
Figure 10. Conventional (Euro)DOCSIS and EPON – EpoC architectures.

Irrespective of the FDD or TDD technology to be used, both options will support co-existence with the current design of the cable networks. In the TDD solution, a dedicated frequency band above the current downstream frequency edge will be allocated to EPON over Coax. The FDD solution will support the existing 5–65 MHz band by default, although an extension of the return channel beyond 65 MHz and/or

the allocation of a second upstream band above 862 or 1000 MHz are considered as well.

On 16 May 2012, the study group adopted a motion to develop a system with "A data rate higher than the 1 Gb/s baseline data rate and up to 10 Gb/s when transmitting in assigned spectrum and in channel conditions that permit"[41]. Assuming that *i)* the full frequency spectrum is allocated for EPoC and that *ii)* the upstream and downstream frequency edge are placed at 200 MHz and 1 GHz respectively, this yields a system with an estimated bitrate of 1 Gbps upstream and 6 Gbps downstream.

As stated by the name, EPON Protocol over Coax is intended to provide an EPON service over a coaxial network. In this concept, as shown in Figure 10, the MAC layer of EPON is used from one end of the system to the other; there is no conversion of the MAC layer at the fibre-coax transition like in the case of Ethernet over DOCSIS. However, because of the different nature of fibre and coax, a conversion of the PHY layer is needed. Standardisation will thus focus on the cable PHY layer, leaving other parts of EPON intact.

For cable providers, EPoC offers various attractive features. The required functionality of the EPON to EPoC converter is kept to a technical minimum, co-existence with the current cable network design and services is conserved, multi-Gbps capacity can be added to the network and the solution will support the full EPON quality-of-service protocol set.

6.2.3   (Euro)DOCSIS 3.x

The next release of (Euro)DOCSIS technology, called (Euro)DOCSIS 3.x, is being developed by CableLabs, supported by Cisco, Motorola and Arris amongst others[35]. Since (Euro)DOCSIS 3.0 can already support high bitrates by channel bonding of, for example, 64 downstream channels and 6 upstream channels corresponding to 4 Gbps downstream and 180 Mbps upstream, the improvement focusses on an improved spectral efficiency of the transmission technology and an extension of the upstream frequency band edge. When implemented, these improvements yield a system with a capacity comparable to EPoC.

6.3   The bonus of a digital backhaul and short cascades

As argued in subsection 6.1, in the current HFC networks with a SNR value of 36 dB7, DVB-C2 QAM 4096 modulation is critical. The question thus arises whether the SNR can be improved to support this modulation scheme and possibly even higher modulation schemes like QAM 16k and QAM 64K modulation?

In the current architecture, optical transmission is used to convey the RF signals over large distances. Since all cable signals are generated and received by electrical systems, the signals have to be converted from the electrical domain to the optical domain and vice versa for the fibre transport. In the whole cascade composed of the optical link and the coaxial part with amplifiers, the optical link

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[41] Minutes of the meeting of the IEEE 802.3 EPoC study group, Minnneapolis,15-16 May 2012

generates most of the noise signals. Elimination of the RF optical link thus will contribute to the improvement of the *SNR*. In addition, the *SNR* will improve further when reducing the number of amplifiers in a cascade, which of course requires deployment of more fibre. A conservative estimation indicates that a 5 dB improvement of the *SNR* (up to 41 dB) should be feasible when eliminating the optical link[42] and a further 6 dB improvement (up to 47 dB) when eliminating the optical link and the cascade apart from the last amplifier.

In the column "Network" of Table 5 we show some capacity estimates for the above-mentioned 5 dB and 11 dB improvement of the signal-to-noise ratio[43]. The figures show that elimination of the optical link and reduction of the number of amplifiers in a cascade allow the use of transmission systems with bitrates beyond 83 Mbps per 8 MHz channel as supported by DVB-C2 QAM 4096 modulation.

Table 5 Potential cable network capacity and transmission systems requirements. See also the footnote 43.

	Network			Transmission technology	
	SNR_{min} (*dB*)	Capacity[43] (Mbps)		Modulation scheme	P_{min} (*dBμV*)
		8 MHz	720 MHz		
Current HFC record[11]	-	52	4.700	QAM 256	-
Current HFC networks	35	83	7.500	QAM 4096	51
Cascade of amplifiers	41	98	8.800	QAM 16k	58
One amplifier	47	112	10.000	QAM 64k	65

Currently, QAM 4096 modulation is the highest modulation scheme supported by any cable transmission technology. Hence, to capitalise on the higher *SNR* when eliminating the optical link and reducing the cascade length, a transmission technology with a QAM 16k modulation scheme or higher is needed, as shown in Table 5. The column "Transmission technology" shows the minimum carrier signal level required for this modulation scheme. Clearly, there is sufficient head room to apply higher modulation schemes; however, the key to release this capacity lies in mastering the higher modulation schemes, not in the cable network.

In the miniCMTS and EPoC solutions, the optical back haul already relies on digital EPON transmission technology and thus are already prepared for higher modulation schemes with improved spectral efficiency.

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[42] Current amplifiers with a full digital load have a SNR of 53 dB or better. One can cascade up to 16 of such amplifiers before the SNR is reduced to 41 dB, 5 dB higher than the 36 dB *SNR* found in today's cable networks.7
[43] The capacity estimates are obtained from the Shannon theorem, taking an implementation margin into account.

6.4   Summary

Taken together, the above new technologies offer plenty of choice for the cable providers. On the one hand, EuroDOCSIS 3.x and DOCSIS EoC offer an evolutionary upgrade whereas on the other hand, EPoC supports a full upgrade to an FttlA network. Intermediate options like fibre to the curb (FttC) are supported as well. Moreover, the new technologies support co-existence with the current cable service design, thus allowing an operator to choose an optimal blend between new and existing services and technologies.

7 The cable roadmap

In the previous sections 4, 5 and 6 we have discussed the elements considered for cable network improvements:

- A more efficient use of the cable capacity by rationalisation of the broadcast offer, migration to a single video coding algorithm and introduction of switched TV,
- Network upgrades to reduce the node size and to expand and/or re-allocate the cable frequency spectrum. These measures are intended to create a sufficient and appropriately balanced up and downstream capacity at the HFC network level,
- Introduction of new transmission systems with greater capacity and better performance.

In this section we will illustrate how these improvements can be applied to develop the cable network. In subsections 7.1 and 7.2 respectively, we will discuss the cable evolution up to a fibre to the last amplifier architecture and beyond the last amplifier. In particular, we will depict the capacity that can be created. In the last subsection 7.3, the practical implementation aspects are considered.

7.1   Segmentation up to the last amplifier

From all the upgrade options, network segmentation has the largest potential to expand the cable capacity. In the European cable networks, often segments of 2000 homes are found. These segments can be split down to a Fibre-to-the-last-Amplifier (FttlA) architecture, with only the last (small) coaxial part remaining. As pointed out in subsection 5.1, the segment size can be reduced down to about 20 homes. Thus, the cable capacity can be expanded by a factor 100.

Text Box 3 The cable broadband proposition: basic and premium services

The broadband market and the cable broadband proposition
As elaborated in Text Box 1, the broadband market is characterised by an upper, a mid and a bottom tier. In response, the cable provider offers a basic service, a medium service and a premium service. In a cable network the upstream and downstream broadband capacity per segment is defined by the number of upstream and downstream channels and the throughput per channel. Given this network concept of segments with a limited capacity, the basic and premium service bitrates can be defined as:

- Basic service bitrate: a broadband service with a peak bitrate (sufficiently) less than the average capacity per customer multiplied by the overbooking factor,
- Premium service bitrate: a broadband service with a peak bitrate corresponding with a (substantial) part of the capacity of the segment. For example, today cable providers offer a 120 Mbps premium service using 8 bonded EuroDOCSIS 3.0 channels with a capacity of 416 Mbps per segment.

Premium service bitrate

Considering the above-mentioned, the premium service is a rather challenging market offer, in particular when considering the universal trend towards higher bit rates. To develop the premium service, an operator can *i)* split the segments and/or he can *ii)* expand the capacity per segment. When splitting the segments, he can deliver more premium services but since the capacity of the segments doesn't increase; there is not much room to increase the peak bitrate of the premium service. When expanding the capacity per segment, the operator can increase either the peak bitrate proportionally or he can deliver the same premium service to more customers. Thus splitting the segments and expanding the capacity per segment provide the tools to match the market development of the premium service and the network capacity.

Dependent on the market and network, every operator will have to specify a maximum ratio between the premium bitrate and the capacity per segment. This ratio has to provide an appropriate balance between the number of customers with a premium service per segment, the risk of service degradation or failure and the manageability of the network and customers. Because of this, in this whitepaper we assumed that an operator can deliver a premium service with a peak bitrate of 25% of the segment capacity, in agreement with the current Dutch practise. This figure of 25%, however, is not a theoretical or practical maximum; provided that the capacity is properly managed, a provider may well offer a premium service with a peak bitrate larger than 25% of the capacity of a segment.

Basic service bitrate

The bitrate of the basic broadband service that can be offered to the user will be slightly less than the product of the network capacity per home multiplied by the overbooking factor. As a rule, an overbooking factor of 20 is appropriate.

Small segments

The possibility to specify a broadband proposition consisting of a basic, a premium and optionally a medium service, is based on the statistical nature of the broadband traffic in combination with large segments to serve many customers. For small segments with few customers, the size reduction will have an impact on the broadband proposition. Because of the fewer customers, the statistical advantage of sharing the capacity will reduce, which can be modelled as a gradual decrease of the overbooking factor down to 1 for a segment with only one customer. Similarly, the ratio between the peak bitrate of the premium service and the capacity of the segment will gradually increase from the 25% up to 1 for a segment with one customer.

In the current networks, most downstream capacity is used for broadcasting, thus limiting the spectrum available for narrowcast services. Similarly, the upstream band can accommodate 6 channels of 6.4 MHz at most because of the 65 MHz upper band edge. So, the creation of more downstream and upstream spectrum may boost the capacity. Such a boost can be accomplished by the deployment of switched digital video and the extension of the upstream band from 65 MHz up to

200 MHz. Implementing both measures will expand the downstream and upstream capacity by a factor of 4 or more.

Last but certainly not least, expansion of the downstream spectrum from the current 750 or 862 MHz up to 1 GHz or beyond, and the application of transmission technologies that support QAM 4096 modulation, will double the cable capacity.

So, segmentation will be the work horse for expanding cable capacity. Therefore, to properly value the broadband potential of a cable network, it makes sense to distinguish between segmentation and all other upgrades. As an illustration of the cable evolution, we have defined 4 conceivable system upgrade levels. Combined with a cable segment size, the upgrade levels give an indication of the broadband capacity. In this example, the initial cable network corresponds to a representative European cable network. Furthermore, in the upgrades, only currently available technologies and network concepts are introduced or ones that are already under consideration by the cable community. The objective of the illustration is to provide a realistic picture of cable's potential for the short and medium term. One should note that the upgrade levels do not correspond with a cable network roadmap of a specific operator, they are purely intended as an illustration.

System Upgrade Level 0 (current cable architecture)
A network with a 750 MHz band edge is assumed. Most downstream spectrum is used for broadcasting. For our illustration we assume that a cable provider has allocated 8 channels of 8 MHz each for broadband services, corresponding to a downstream capacity of 400 Mbps. In the upstream, the use of 6 channels of 6.4 MHz and with a capacity of 20 Mbps each is assumed.

System Upgrade Level 1
The broadcast package is reduced by the introduction of switched digital video and the phasing out of analogue services. Considering the limited upstream capacity, it doesn't seem logical to boost the downstream capacity without expanding the upstream capacity as well. Therefore, the upstream band is extended up to 200 MHz. When applying an improved modulation, the band up to 200 MHz can convey 1 Gbps. However, the extended upstream channel is retained from the downstream band. Taking a new guard band into account, the downstream band will start at a frequency of 250 MHz. For a cable network with a 750 MHz upper frequency edge and with 120 MHz allocated for the remaining broadcast services, only 380 MHz will be available for narrowcast services. This 380 MHz corresponds with a capacity of about 2.5 Gbps.

System Upgrade Level 2
For this level, the downstream band edge is extended from 750 MHz up to 1 GHz. The broadcast package is not reduced, so that now 630 MHz, or 4.1 Gbps, can be used for the broadband services. The upstream channel is not changed

System Upgrade Level 3
The DVB-C QAM 256 modulation is fully replaced by DVB-C2 QAM 4096 modulation or by an equivalent technology. Thus, the capacity is increased from 4.1 Gbps up to 6.5 Gbps.

The above upgrade levels are, as pointed out before, defined independently of the segmentation size. Given the upgrade level and the segmentation size, one can make a rough estimation of the basic and premium service bitrates, see Table 6.

Table 6 Estimated bitrate of a premium and basic broadband service for different segment sizes and for the 4 system upgrade levels, assuming a 100% penetration. See the text for an explanation

DS and US capacity per segment		Premium broadband service (Mbps)	Basic broadband service (Mbps) Size cable segment & overbooking factor[44]						
			2000	1000	500	200	100	50	20
			20	20	20	12,7	9,0	6,4	4,1
Upgrade Level 0									
DS	400 Mbps	**100**	4	8	16	26	36	51	-
US	120 Mbps	**30**	1,2	2,4	4,8	7	11	15	-
Upgrade Level 1									
DS	2.5 Gbps	**625**	-	50	100	158	225	320	-
US	1 Gbps	**250**	-	20	40	63	90	128	-
Upgrade Level 2									
DS	4.1 Gbps	**1000**	-	82	164	260	370	520	840
US	1 Gbps	**250**	-	20	40	63	90	128	200
Upgrade Level 3									
DS	6.5 Gbps	**1600**	-	-	260	410	585	830	1300
US	1 Gbps	**250**	-	-	40	63	90	128	200

The estimations of Table 6 show the evolution of the basic and premium broadband service that a cable provider can offer when rationalising its broadcast services and upgrading its network as specified by the levels 0 to 3, in combination with the segmentation of the network from 2000 homes per segment down to 20 homes per segment. This latter segmentation corresponds to a fibre-to-the-last Amplifier architecture. In this illustration, an operator could currently offer a basic service with a bit rate from about 4/1.2 for segments of 2000 homes passed up to basic service of 1300/200 Mbps when implementing the level 3 FttlA architecture. Similarly, the premium service can be increased from a 100/30 Mbps service up to a 1600/250 Mbps service, provided that the cable provider will manage the network capacity properly as pointed out in the Text Box 3**.**

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[44] To include the effect of the smaller segments on the statistical averaging of the customer traffic, as modelled by the overbooking factor, we have assumed that the overbooking factor declines linear with the square root of the segment size for segments smaller than 500 homes passed.

For completeness we have to remark that the 6.5/1 Gbps capacity per cable segment of upgrade level 3 is not the theoretical and technical limit. Once the optical link is eliminated and the cascade is reduced down to a single amplifier, as pointed out in subsection 6.3, transmission technologies with a higher spectral efficiency and capable of delivering 10 Gbps using 720 MHz of cable spectrum can be deployed. Furthermore, the cable spectrum can be extended to frequencies (well) above 1 GHz. Amongst others, the spectrum above 1 GHz can be used for a second upstream band. Clearly, the potential of a cable network is not exhausted at 6.5/1 Gbps, but can be even boosted up to a 10 / 2 Gbps on the long term.

7.2   Segmentation beyond the last amplifier

From the technical viewpoint, a cable network can be segmented beyond the last amplifier.

In case of a star architecture, see Figure 1, each home is connected by its own coaxial cable to the last amplifier. In this architecture, an operator can create segments ranging from all homes connected to the last amplifier down to one home. He can offer an unshared cable (segment of one home) as a premium service whereas customers with a basic service are combined into one larger or several smaller segments. In fact, the cable operator can fully optimise the segment size to the service demand of the customers. In the upgrade example of Table 6, he can offer a 6.5 /1 Gbps premium service.

In the tree-and-branch architecture, two or possibly more coaxial branches depart from the last amplifier; each coaxial branch runs along the street and each home is connected by a dedicated drop cable. In this architecture, an operator can deploy fibre up to the last amplifier and define each coaxial branch as a separate cable segment; however, he can also choose to split the existing coaxial branches, thus creating even smaller segments, for example by splitting each coaxial branch somewhere in the middle, thus creating two branches. To do so, fibre has to be deployed beyond the last amplifier. Evidently, the tree-and-branch architecture does not offer the same flexibility to create arbitrary small segments up to segments of one customer like the star architecture; however, small segments of 10 homes or even less are feasible.

Text Box 4 The Dutch cable networks

The Netherlands has a most excellent cable infrastructure:
- A cable penetration of 97%,
- Networks with short cascades, 65 MHz and 862 MHz upstream and downstream band edges and a star architecture and predominantly an optical node and two amplifiers,
- A full service package of 25-35 analogue TV programmes, 140 – 200 SDTV programmes, 20 – 45 HDTV programmes, premium telephony and broadband internet with a premium 120 Mbps service.

Figure 1 and Table 7 give a specification of the network. The figures indicate that the networks provide a comfortable position for network upgrading. Without any new fibre deployment, the cable segments can be reduced to 100 up to 250 homes passed with an average of about 130 homes passed. When allocating say 32 DS

channels and 6 US for broadband services, a 120/14 Mbps basic subscription can be offered to all homes passed, whereas a 400/45 Mbps premium service can be offered to a limited number of customers[45]. In the Dutch market with a national DSL infrastructure and regional and local FttH networks, cable broadband will not have 100% penetration, thus creating room for a basic subscription beyond 120/14 Mbps.

Table 7 Average size and range of the service areas in The Netherlands in homes passed

	Average (HP)	Range (HP)
Optical node	800	400-2000
Group amplifier	130	100-250
Last amplifier	25	20-50

When demanded by the market, Dutch cable providers could consider rationalising the broadcast service package, expanding and re-allocating the up and downstream frequency bands and deploying EuroDOCSIS 3.x to use the 65 – 200 MHz upstream frequencies. This yields a basic broadband service of about 520/80 Mbps assuming 100% market share.

Considering the star architecture with a last amplifier serving some 20 – 50 homes, the deployment of an EPoC solution may appear attractive when the market demands a Gbps basic service. Technically, a number of EPON/EPoC converters can be installed in a street cabinet. Customers with a basic subscription can share a converter whereas customers with a premium service can have an own converter with the full 6.5/1 Gbps throughput or more.

7.3   Implementation of cable upgrades

From an historical viewpoint, cable operators have a tradition to upgrade their networks when the market offers a sufficient business prospect. Most cable networks were built as a full coaxial network with long cable trunks. About two decades ago, when the first optical solutions became available and when commercial television developed rapidly into a flourishing business, cable providers started upgrading their networks. Neighbouring networks were interconnected whereas the coaxial trunks were shortened. At the end of the 20th century, when internet developed into a consumer service, cable networks were upgraded to a 2-way network. Next, the introduction of EuroDOCSIS with its quality-of-service features created the possibility of offering premium telephony services. This process of cable upgrading still continues.

From a business viewpoint, every cable network upgrade represents a capacity stock: capacity is created, but is not immediately and fully delivered to the

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[45] In the upstream band, QAM 64 modulation can be applied for smaller segments instead of QAM 16. Thus the capacity of the upstream band can be increased from 120 Mbps up to 180 Mbps per segment.

customers. After the upgrade, the operator can increase the capacity delivered to the customers gradually by installing additional transmission systems, like EuroDOCSIS and VoD servers, in the network. After a period, when all newly created capacity has been consumed, the operator runs out of stock and he will need to implement the next upgrade. Like every grocer, an operator will manage this cyclical process; on the one hand stocks should be limited whereas on the other hand a stock should be sufficient to warrant tomorrow's service delivery.

In subsection 7.1, we argued that the different options for expanding cable's capacity can be ranked by capacity gain as follows:
1. Segmentation of the network,
2. The combination of switching off analogue, deploying switched digital video and extending the upstream band from 65 up to 200 MHz,
3. The extension of the downstream frequency edge up to 1 GHz,
4. The introduction of QAM 4096 and equivalent modulation technologies.
Below we will briefly discuss the practical implementation of these upgrades.

7.3.1   *Segmentation of the network*

Most cable networks result from an aggregation of local networks, often built for smaller communities, with a disparate design and/or dimensioning. When upgrading these networks to a two-way hybrid fibre coax architecture, this disparity in the coaxial parts is not eliminated; it is conserved. Thus, current large operators often have a network with some local variation, such as, for example, a node size difference. As a result, the possibility of offering higher data rates to all customers is limited by a small number of network sections with a minor design or dimensioning. Upgrading these bottlenecks thus offers the possibility to increase network capacity. Telenet in Belgium, for example, has upgraded its networks in this manner[46]. Node splitting was implemented throughout the network, however, where necessary, existing coaxial branches were shortened, replacing the coaxial cable by fibre. The upgrade reduces the node from 1400 homes per node down to 500 homes.

For segmentation down to a segment size of 200 homes passed, fibre will have to be deployed up to the last but one amplifier; for segments of 20 homes or less, fibre up to the last amplifier is needed. Evidently, such upgrades will require a substantial amount of fibre and trenches, though less than for a full FttH network.

7.3.2   *Switch-off analogue, deployment of switched digital video*

From a purely technical and practical viewpoint, analogue services can be terminated but every television set without an integrated digital receiver must be equipped with a standalone receiver or set-top box (STB). However, as pointed out in subsection 4.2, analogue television is still appreciated by customers with a CRTV.[20] Often media legislation demands the distribution of a minimum (must carry) package in analogue. Therefore, switching off analogue services is not a technical but primarily a business and regulatory issue. Nevertheless, digital penetration on cable increases from year to year, fuelled by HDTV, flat screens with a CI+ interface and new devices like tablet-PCs and offers operators the possibility to drop analogue programmes, thus gradually approaching a full switch-off.

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[46] The Telenet program "Digital Wave 2015", Press release Mechelen, 3 March 2010

The introduction of switched digital video will not affect the television service to the customer; however, a new interactive digital receiver is needed. The operator will have to re-engineer and expand its narrowcast capacity and the switched digital video technology has to be installed in the head end. Possibly, the upgrade of the digital receiver may turn out to be the most complicated part of the upgrade. Non-interactive receivers have to be replaced. Interactive receivers need a software upgrade. Modern television sets with an integrated digital receiver, an IP port and a CI+ interface need a software upgrade, but for these upgrades the cable provider is dependent on the manufacturer. In practise, these problems are manageable provided that the technology is introduced gradually. For example, a cable provider may start with the digital programme packages with the smallest number of subscribers and step-wise migrate more programme packages to the switched digital video platform.

7.3.3 *Extension of the upstream band from 65 up to 200 MHz*

The extension of the upstream frequency band will require a re-engineering of the upstream channel. Usually the optical upstream transmitters in the node and the optical receivers in the HUB already support frequencies up to 200 MHz and do not need replacing. All amplifiers need a new split band filter and it is likely that an upstream band amplifier with a higher output level has to be installed. Evidently, as long as there is no (Euro)DOCSIS or EPoC equipment in the market that supports higher upstream frequencies, frequency extension is not an option. However, current initiatives to develop new EuroDOCSIS 3.x and EPoC technologies that support upstream frequencies above 65 MHz demonstrate the urgency felt in the market to expand upstream capacity.

7.3.4 *Extension of the downstream frequency edge up to 1 GHz*

Although the cable spectrum is used up to 862 MHz, some cable operators have an upper frequency edge of 750 MHz or below. As pointed out in subsection 5.3, the extension of the frequency edge requires the replacement of the amplifier and possibly even a repositioning of street cabinets. Smart deployment, and in particular the right timing, may reduce the investment. The replacement of amplifiers that have surpassed their depreciation period, offers the opportunity to deploy amplifiers with an increased output power. In addition, considering the disparate design and dimensioning of the coaxial trucks, an operator may trace those coaxial links that limit the use of higher frequencies most and reposition only those. Evidently, reducing the node size and in particular shortening the coaxial trunks contributes to lowering the implementation costs of extending the downstream frequency edge.

7.3.5 *New transmission technologies*

The deployment of a new transmission technology can be considered to be a most disruptive option. A new transmission technology will bring substantial advantages along with various challenges. For example:
- The customer will need a new modem or cable terminating unit,
- In case of a FDD technology, possibly the cable network must be upgraded to extend the upstream and or downstream frequency band,

- Some solutions require replacement of the RF optical backhaul by an optical digital backhaul, possibly EPON,
- Some solutions require deep fibre like FttC or FttlA.

As discussed in subsection 6.2, the manufactures are considering various new technologies like EuroDOCSIS 3.x, DOCSIS Ethernet over Coax, EPoC FDD and EPoC TDD. These technologies offer different network solutions ranging from an evolutionary one based on EuroDOCSIS 3.x up to a most revolutionary solution based on EPoC TDD, and with two intermediate options DOCSIS Ethernet over Coax and EPOC FDD. Depending on this ranking, the options will require a more limited or a more extended re-design of the cable network; however, they will yield a smaller capacity for an evolutionary technology and a larger capacity for the revolutionary solution. The different options will offer operators the choice between a small step, a big leap or an intermediate upgrade.

Text Box 5 The Gigabit broadband market

In this study we see developments that provide cable networks with the potential to support Gbps in the future. A question commonly asked, however, is "When is a sufficient market demand for such high bandwidth broadband services foreseen?"

In this study we have not addressed this question. The scope of the study was limited to the technological options for expanding the cable network capacity. The development of market demand for bandwidth over time was not assessed and therefore the study doesn't provide an indication of the timing of network upgrades.

However, it is clear that since the advent of internet during the 1990s, the demand for bandwidth has continuously grown. Market researchers expect bandwidth demand to keep growing. Furthermore, significant investments in many countries in FTTH can be viewed as an indication that these investors believe in the future demand for very high bandwidth services.

In early 2010, Dialogic and TNO made an analysis of the broadband market development.3 In this study, a large number of publicly available estimates of the expected bandwidth growth were analysed. Based on this analysis, an optimistic annual growth rate of 40% and a pessimistic rate of 30% were deduced. In addition, the bandwidth usage at that time was assessed, which yielded a high and low average bandwidth estimate. To conclude, the bandwidth usage and the annual growth rate were combined to predict the bandwidth demand in 2020. The combination of the 40% growth rate and the high average bandwidth yielded a 400/100 Mbps estimate for 2020 whereas 75/15 Mbps was found for the 30% growth rate with the low average bandwidth. Thus, these figures provide an upper and lower estimate of the broadband bandwidth demand in 2020.

The bandwidth that can be delivered by a cable network is shown in Table 6. To deliver the 400/100 Mbps services at that time, an upgrade level 1 combined with a segmentation of 50 homes per segment is needed; for the 75/15 Mbps, the same upgrade level is needed with segmentation of 500 homes. The table also shows that the potential capacity of the cable network is not exhausted at this point. Therefore, we believe that cable networks can serve the market well beyond 2020.

7.4   **The cable evolution roadmap**

In the above subsections we have discussed the implementation of the various options for expanding the cable capacity, ranging from smaller evolutionary improvements up to large intrusive upgrades. From a technical viewpoint, all the mentioned upgrades can be implemented provided of course that there is sufficient market development to convince the vendors to develop and fabricate the technology. Depending on the regional market conditions and network status, a cable provider can choose between an evolutionary network roadmap and a more revolutionary upgrade to an FttlA or beyond. The evolutionary upgrades offer the operators the opportunity to gradually follow the bandwidth demand of the market and postpone an FttlA upgrade until the appropriate time. When properly planned, the evolutionary upgrades can be used to prepare the cable network for the upgrade to an FttlA architecture. Like a grocer, every operator will develop the most economic cable upgrade roadmap, with efficiency improvements, network upgrades and new transmission technologies as ingredients, providing an optimum balance between growth of the bandwidth demand and network investments. This evolution is illustrated in Figure 11.
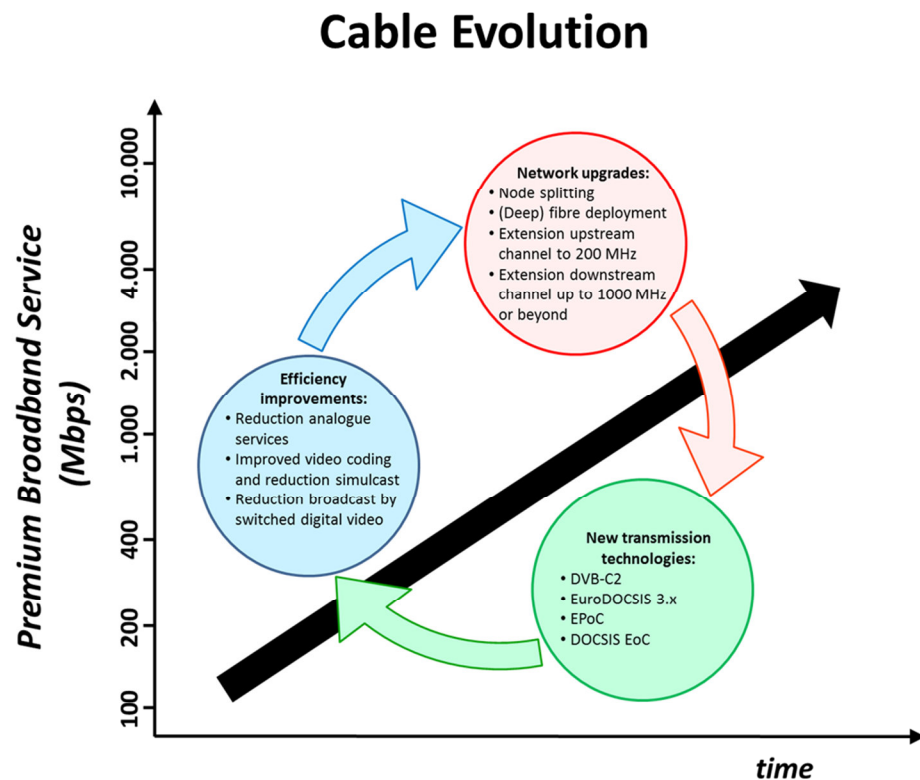

Figure 11 The overall cable evolution as a cyclical process consisting of efficiency improvements, network upgrades and the deployment of new technologies.

7.5 Conclusion

To add broadband capacity, an operator has the option to rationalise the broadcast services, to further segment the network, to expand and re-allocate the upstream and downstream spectrum and to deploy new transmission technologies.

Assuming that all upgrade options are implemented and that the cable segments are downsized to 20 homes passed, the network can deliver a 1600/250 Mbps premium broadband service for the upper market tier and a 1300/20 Mbps basic service. However, 20 homes segments is not a fundamental limit of a cable network; splitting the segments down to 10, 5 or even less homes is technically feasible. For a segment size of 1 home passed, a broadband service of 6.5/1 Gbps can be delivered when applying currently available transmission technologies and network concepts. However, from a technical viewpoint, even a 10/2 Gbps capacity per network segment can be created when the optical link is eliminated, the cascade is reduced to a single amplifier, QAM 64k modulation technology is developed and the spectrum above 1 GHz is used.

Taken together, the upgrade options provide a cable toolbox from which a cable provider can craft its own, optimised global cable evolution roadmap. Because of the different network and market situations, the migration strategies of cable providers will look different; a common roadmap will not exist.

List of abbreviations

CCAP	Converged Cable Access Platform
CI+	Common Interface Plus
CMTS	Cable Modem Termination System
CNU	Cable Network Unit
DLNA	Digital Living Network Alliance
DOCSIS	Data over Cable Systems Interface Specification
DVB	Digital Video Broadcasting
EPoC	EPON Protocol over Coax
EPON	Ethernet Passive Optical Networks
FDD	Frequency Division Duplex
GaN	Gallium Nitride
HDMI	High-Definition Multimedia Interface
HDTV	High-definition Digital TV
FttC	Fibre-to-the-Curb
FttlA	fibre-to-the last Amplifier
MoCA	Multimedia over Coax Alliance
MPEG	Moving Picture Experts Group
QAM	Quadrature Amplitude Modulation
QoS	Quality-of-Service
OLT	Optical Line Terminator
ONU	Optical Network Unit
PAR	Project Allocation Request
PON	Passive Optical Networks
RU	Rack Unit
SDTV	Standard-definition Digital TV
SDV	Switched Digital Video
TDD	Time Division Duplex
VCR	Video cassette recorder
VoD	Video-on-Demand
Wi-Fi	Branding name for 802.11 wireless home technology