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FOREWORD

The CISP Working Party discussed this paper at its meetings in May and December 2007. The Working Party agreed to recommend the paper for declassification to the ICCP Committee. The ICCP Committee agreed to the declassification of the paper in March 2008.

The paper was drafted by Rudolf van der Berg from the Ministry of Economic Affairs, The Netherlands, while on assignment to the OECD.

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MAIN POINTS

The aim of this paper is to provide a broad overview of developments in optical fibre technologies in the last mile, that is, between subscribers' premises and telecommunication switches and in the backhaul part, from the switches to the core of the network. Issues related to the deployment of last mile fibre networks, their costs and related regulatory issues are also raised. The timeframe for the paper is the period between 2010 and 2020. This is the period when the new generation of hybrid fibre and all-fibre networks will have matured and rolled out on a large scale.

The significant increase in demand by users for higher broadband capacity is leading Internet Service Providers and telecommunication operators to place emphasis on how to meet the requirements for network capacity. In the last 20 years the focus was on using fibre in the backbone part of the network, up to the local Main Distribution Frames. In the coming years the focus will be on bringing fibre ever closer to the end-user in order to be able to deliver the desired bandwidth. For the period 2010-2020 speeds of 50 Mbit/s downstream and 10 Mbit/s upstream may be required to enable the parallel consumption of services (HDTV, radio, videoconferencing, security etc.) over the network. These speeds are significantly higher than the current OECD definition of broadband at 256 kbit/s, but are necessary to allow the end-user to enjoy a full range of services in parallel and to allow competition between the providers of these services over the network.

The paper evaluates various technologies (wireless, hybrid and all-fibre) available to roll-out high speed first mile networks with speeds of 50 Mbit/s. It becomes clear that though wireless technology will be very important, it will not be the dominant technology to connect homes and businesses to broadband networks. Both in performance as in investment the wired technologies have the advantage. Wireless will be used to bridge the first meter, but not the first mile.

Hybrid copper-fibre networks (also known as Fibre to the Node/Curb) use the existing copper networks (cable, telephone and electric) to bridge the distance from the end-user to the fibre node, which is situated closer to the end-user than traditional exchanges. The speeds available for DSL connections are dependent on the distance between customers and the switch, with speeds deteriorating rapidly with distance so that high bandwidth, for example at 50 Mbit/s has a range limited to 450 meters which in most countries would cover only about a tenth of the population. Thus, in order to come within reach of customers high speed fibre networks are being brought to the curb or node (street cabinets). Cable networks, which are being upgraded in a number of OECD countries, may have an advantage because of having a higher maximum speed than DSL, but this is often outweighed by the shared nature of cable networks which means that the more users using the network at the same time, the less bandwidth is available per user. Although Broadband over Powerline technology is often cited as a potential competing technology to cable and DSL, there has been little large scale implementation to date of this technology and it is therefore hard to assess its potential in the market.

With fibre to the curb there is no need for main distribution frames which several incumbents have indicated that they will dismantle once they have completed fibre roll-out. However, at present in most OECD countries which have local loop unbundling, unbundling takes place at the main distribution frames. An important debate is therefore to determine the strategy for existing new entrants using unbundling. Sub-loop unbundling in competition with an incumbent does not seem to be a viable option on a large scale.

This leaves networks that are in competition with the incumbent with the option to either move ahead and invest in all-fibre networks or to be content with the role of service provider and use the network of the incumbent (or an available competing network) through wholesale broadband access.

Fibre to the home is perhaps the most future-proof technology in that it can handle most bandwidth intensive applications. There are different topologies for fibre networks and the way they are built influences the way they can be open to multiple service providers and local loop unbundling may not be effective under certain network configurations. This could mean that incumbents may regain market power or, at best, if cable is available a duopoly situation may emerge.

When looking at the business cases for a move to higher bandwidth networks, it becomes clear that for cable and ADSL2+ networks much of the investment to support the higher speeds has already been done. For VDSL2 and FTTH networks a significant investment still needs to be made. For incumbent telecommunications networks the investment in VDSL2 seems clearer than for new entrants and smaller competing networks. Incumbents can use savings in the operational expenditure of their network, together with other savings (*e.g.* sale of MDF locations) to support the roll-out of the network. Whether or not a new entrant will move up the ladder of investment and invest in new VDSL2 or FTTH networks is dependent upon local conditions.

The paper provides a financial model of a FTTH-network as an indication of what the costs of such a network might be and how these costs would be distributed between the various cost elements. Though the model is dependent upon a local situation in the Netherlands, it becomes clear that the costs are significant and that the monthly costs per subscriber are highly dependent upon penetration rates. The substantial costs involved raise questions as to the level of competition which will emerge in the market. Sharing of costs, especially the civil engineering costs and wiring of buildings, can have benefits and reduce investment risks.

The role of the government in the stimulation of the roll-out of these networks can be in three ways. The role of a stimulator is defined here as removing the barriers that may impede the investment and roll out in new networks. The role of producer is defined as actually investing in new networks and the role of regulator is limited to the government’s role as a telecommunications regulator trying to guarantee a competitive marketplace. Whether or not the government will have to perform any of these roles is dependent upon the local situation. A well-defined policy, which is discussed with industry and other stakeholders, with clearly stated goals and timelines, can help identify where bottlenecks are and which areas may be unprofitable. On the basis of such a policy the government can base its decisions to stimulate or to intervene.

Governments, especially municipal governments, can play an important role in facilitating the roll-out of fibre infrastructure. This role can be in providing or facilitating rights of way, and if necessary in joint public-private partnerships in infrastructure development.

INTRODUCTION

The aim of this paper is to provide an overview of developments in optical fibre communication technology and investment. It will provide a broad overview of the facets that are involved with the roll out of networks based on this technology. The paper does not aim to make normative statements on what kind of network is better or should be chosen by OECD countries. It will give an overview of the considerations that are involved in the development of investment in networks, aimed at facilitating more informed choice on such investments, and regulation of future networks.

At the moment many OECD countries are concerned about the future of telecommunication networks as convergence and investment in next generation networks (NGN) begins. One of the important questions in this context is what role optical fibre networks will play. Fibre technology has been used in the backbones of telecommunications networks since the late 1970s. Developments in recent years have seen optical fibre communication technology being used closer to the end-user. Optical fibre technology is now the standard way to connect medium to large enterprises to telecommunications networks and to connect the last mile (referred to as the first mile) of cable and PSTN based TV, telephony and broadband networks to their backbones. From the core to the sub-loop, telecommunication networks are now based on fibre which, in this paper, will be referred to as fibre based networks. The term 'fibre'-based is therefore not limited to networks that roll out fibre to the "last inch".

The paper is closely connected with ICCP papers on:

- Global opportunities for internet access developments (COM/DSTI/DCD(2007)3/FINAL), which goes into more detail on long haul, trans-oceanic networks.
- Public Rights of Way for Fibre Deployment to the Home (DSTI/ICCP/CISP(2007)5/FINAL) which goes much deeper into public rights of way.
- Convergence and Next Generation Networks (DSTI/ICCP/CISP(2007)2/FINAL).

TECHNOLOGICAL DEVELOPMENTS IN FIBRE[1]

This section examines the technology behind optical fibre based networks. It gives a brief overview of how optical fibre technology works and what various optical fibre based technologies exist. It also explores the various networks ranging from long haul to first mile. The section also gives an overview of the issues involved with building a fibre based network since, regardless of whether the customer whose house has been passed or connected is using the network, most of the costs of a network are in capital expenditure and most of that is in the physical engineering *e.g.* digging and providing ducts and a smaller part in the active component. The operational expenditure for operating the network adds only a small part to the overall cost.

What is fibre and how does it work?

Development on optical fibre started in the 1970s, but the first large-scale commercial use occurred in the late 1980s, and in the 1990s fibre networks revolutionised the telecommunication business. New developments came very quickly so that by the end of 2000 the technological developments were far ahead of actual demand. To give an idea of the speed of development: the first commercial fibre optic connection in April 1977 in Long Beach California was 6 Mbit/s requiring 2 fibres, one for each way of communication. These speeds have since then risen to 3.2 Terabit/s over single fibre, allowing for a million times increase in speed. After a relative lull in development at the start of the century new developments began again in 2006 again and the market looks optimistic for growth prospects of optical fibre communications.

Optical fibre uses light as a means to transmit data from one location to another. It consists of a light source (laser or LED), an optical glass fibre as the transmission medium and a detector. The laser generates a pulse of light of a specific frequency (called a colour or channel) which is detected on the other side by the detector and translated into an electrical pulse, which is then used by the device on the other side. It is possible to communicate both ways on the same fibre. A pulse of light normally indicates a 1 and the absence of light a 0. This can work at enormous speeds. Commercially available lasers currently reach speeds of up to 10 Gigabit/second and with the latest technology 40 Gbit/s and recent research in commercial networks has shown that it is possible to achieve 106 Gbit/s on a single colour.[2] Higher speeds are possible, but the challenges in reaching these speeds lie in the detector converting light back to electrical pulses. In addition to sending data faster over a single colour, it is also possible to combine several colours on a single fibre based on Wavelength Division Multiplexing (WDM).[3] At the moment there are systems commercially available that allow the usage of 160 colours on a single fibre, giving a total of 3.2 Terabit/s on a single fibre.[4] In laboratories speeds of up to 25 Tbit/s have been reached.

Optical fibre cables consist of multiple layers. From the inside to the outside there is first a glass core that allows the light to propagate. Glass cladding surrounds the core. This is surrounded with a plastic and /or Kevlar coating. Depending on the usage the fibre is surrounded with more protective layers.[5] Multiple fibres can be combined together to form one cable. Standard cables can carry up to 912 fibres in a cable. These cables are put in the ground in cable ducts or strung over poles in the air. When telecommunications companies lay fibre ducts on a route, they lay more empty ducts for later use. So companies might lay 12 or 30 ducts on a route and only fill 2 to 6 of those with fibre, leaving the rest for later. There are also cables available that combine copper twisted pair, coaxial cable, CAT5/6 and multiple fibres. These are used for connecting end-users.[6]

Benefits of fibre compared to other physical media

There are several benefits that give an advantage to networks built on fibre:

- Bandwidth on a fibre network is almost unlimited. Compared to satellite networks, there is a higher bandwidth and lower latency/round trip time for fibre networks.[7]

- Low attenuation and dispersion mean that no or few repeaters and signal regenerators are necessary.

- No influence from electromagnetic fields, corrosion etc., like in coaxial or twisted copper pair cables and no influence from rain, foliage, buildings, etc., as with wireless communications.

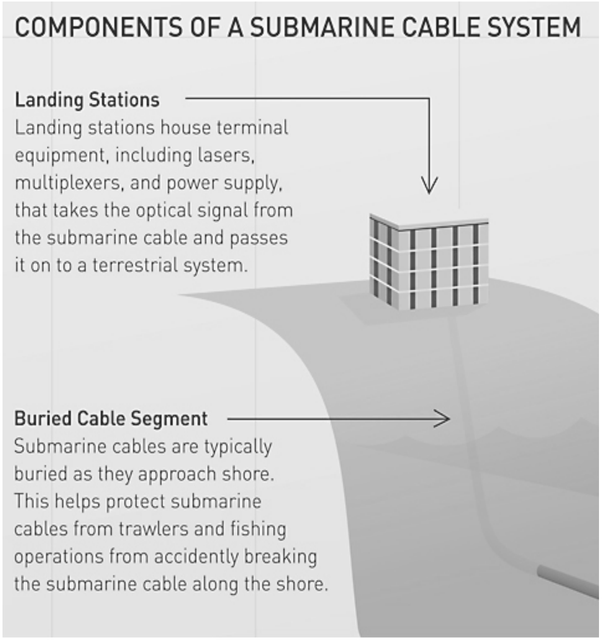
- Low weight and size: a thousand twisted pair telephony cables weigh 8 000 kilo/km, whereas 912 fibres weigh 495 kilo/km.[8] Metal cables also take more physical space than a similar amount of fibres.

- Costs: The costs of a fibre cable per kilometre are comparable to twisted pair and coaxial cables of similar lengths and similar number of strands. The capacity of fibre is, however, significantly higher.

Long haul networks

It is in the long-haul networks that optical fibre started to become the dominant transport medium for communications. Long-haul networks are used for carrying data across oceans and continents. Distances over 10 000 km will have to be traversed.[9] A long-haul network can therefore be seen as the leading edge of technical development. The higher bandwidth and longer reach without amplification, that could be achieved with fibre allowed for significant savings and made fibre the only choice for communications on long-haul routes. Technological developments that followed led to a boom in long-haul fibre networks in the late 1990s, both continental and submarine. Certainly the development of dense wave division multiplexing (DWDM) technology allowed for a significant increase in capacity. Where the networks first were constrained by one colour and the maximum speed that could be transferred over that colour, it became possible to implement multiple colours on a single fibre allowing for several multiple increases in the possible bandwidth. The networking technology on these rings is known as SONET/SDH. The demands on long-haul networks are the highest in the submarine trans-oceanic networks. Land-based networks offer some of the same challenges, but upgrading and servicing is easier. A typical network can consist of up to eight fibres. Because of the hazardous conditions at sea, the enormous depths (below 7 000m at some points) and the resulting strains put on fibres, they have to be protected by steel wires that help protect the system from pressure, sharks, anchors and fishermen. The cost allocations in such a network are 40% for the cable, 30% for the marine laying of the cable and 20% for the repeaters which need to be installed every 75-100km, while the rest of the cost is attributed to the end point equipment, project costs etc.[10] Not all capacity on the network is used right from the start of the network, so there is a difference between maximum design capacity and lit capacity. In order to light dark fibre capacity new investments are necessary in equipment at the end-points of the network,[11] but this is marginal compared to the initial investment.

Figure 1. Components of a submarine cable system



Source: Telegeography © Primetrica.

The upfront cost of such networks is of concern to investors. The Trans Pacific Express network between Asia and the United States cost USD 500 million[12] and will deliver a maximum of 5.12 Tbit/s with 1.28 Tbits initially lit. There are therefore two models used to finance these networks. The traditional way in the last decades has used a consortium of (national) incumbent telecommunication companies, as with the Trans Pacific Express network. There is little competition on some of these cables with rights of usage shared by the consortium members. This has led incumbents in some countries to abuse their position and charge high rents on submarine cables. On some undersea crossings competitive cables have been built and in certain cases with new sources of financing through large private equity parties. The submarine cable would first be financed by the private parties and costs recovered by capacity sold to telecommunications carriers as a carrier's carrier. The maximum capacity on a fibre is so high that the route is often overbuilt. In a competitive market with multiple providers providing similar cables, overbuild might result in competitors pricing on marginal costs only, which are close to zero. It is these enormous investments, technological developments, combined with an overbuild of capacity and strong competition, especially on the Atlantic routes, that led to the bankruptcy of several trans-oceanic networks in the recent past[13] and strong consolidation following that. Similar economic effects were seen in continental/backhaul networks and offer insight in the economics of fibre networks that are characterised by abundance and low marginal costs for expansion leading to difficulties in highly competitive markets. This will play a role in the discussion of investment aspects and business models.

Backhaul networks

The term backhaul networks is used loosely in this paper to refer to all networks that are not last/first mile networks and are not long-haul networks. Other terms for these networks are Metropolitan Area Networks, Wide Area Networks, Backbones, Regional networks etc. There is a huge variance in these sorts of networks, but they normally only reach up to 100-200 km in densely populated areas. These networks are used to carry traffic from the local and regional switching offices to the long-haul networks, or to distribute the traffic in metropolitan and regional areas between Points of Presence (POPs), ISPs, other networks, large corporate clients and Internet Exchange Points. As such they can be bottlenecks in a telecommunications network if the telecommunications company has sold more bandwidth downstream than it has available on the line (known as the contention ratio or oversubscription). This requires careful planning by the telecommunication company, but can technically be solved by using faster channels (more bits per seconds per colour), multiple colours or more fibres.

Networks at this level are designed by joining networks together in ring configurations. By choosing a ring configuration two nodes in the network are always connected by at least two paths. Combining several rings together leads to multiple redundant paths between any point in the network. The most used datalink layer protocols over fibre today are ATM, SONET/SDH and Ethernet. The protocols carry Internet-protocol (IP) packets and the data of traditional voice and mobile networks. Of these three protocols ATM is in the process of being discontinued on many networks and being replaced by networks based mostly on Gigabit and 10 Gigabit Ethernet[14] or Packet over SONET. SONET/SDH-networks will stay around for a while because of their use in long-haul networking. It used to be that for each and every access network there was a different backhaul network, but this is now changing and networks are moving to one common core network, based on Ethernet and IP, for the various access networks.[15]

It is in these networks that the growth in data traffic has been most pronounced. Traffic from end-users is aggregated at head-ends, such as DSL DSLAMs, cable head-ends and points of presence (PoP) for corporate customers. This traffic is sent onwards to central switching points in the network and from there exchanged with other regional, national and international networks. It is not well known how much traffic is exchanged between networks and how much traffic remains on the network of one telecommunications provider. The exchange can take place directly between networks, but in the Internet world it is also common to exchange traffic over an Internet Exchange Point. It is however a common misconception that all IP-traffic in a country is exchanged over Internet Exchange Points. In reality networks often exchange IP-traffic bilaterally without the IXP in between, to improve the reliability and to offload the link to the IXP. The link to the Internet exchange is in such cases used for interconnection with larger numbers of smaller networks and as an extra back-up route, should something happen to the main interconnections. Traffic between networks has grown between 50% and 100% each year.[16] Most of this traffic stays in the country or region where it originates.[17]

The switches that switch the traffic over the network of a provider and between networks of providers are built to not hinder the traffic as it is switched. Modern non-blocking architectures switch packets in less than one millisecond from one switch to another[18] and can switch over 1 Terabit per second. At one of the busiest IXPs, the AMS-IX in Amsterdam, traffic in April 2007 reached up to 260 Gbit/s and averaged 165 Gbit/s. In 2008 they expect to exceed 500 Gbit/s, with some customers needing multiple 10 Gbit/s ports to exchange traffic. It is this continuing growth in traffic that has made 10 Gbit/s networks more and more standard and called for the standardisation of 100 Gbit/s Ethernet, which is now ongoing.

In many OECD countries backhaul networks have seen an enormous overbuild of capacity in the late 1990s and the start of the 21st century. This overbuild was evident on the main routes, such as in the ‘golden triangle’ covering London, Paris, Frankfurt, Amsterdam. Between 10 and 20 networks have laid infrastructure on this route. In general companies would lay 12 ducts on these routes, filling 2 of these ducts and leaving 10 empty. On some routes there were thousands of available fibres. The customers that bought some fibres on these networks would often use WDM (wavelength division multiplexing) equipment to increase capacity on the lines and resell that capacity to their own customers in direct competition with the network that they had bought connectivity from in the first place. Similar situations occured on a smaller scale in metropolitan networks, also, leaving a number of larger cities in OECD countries with multiple networks and many empty ducts. In commercially less-attractive areas there may be only two or less networks with fibre connections in the first mile from a particular location, though even here there are often empty ducts available.

First Mile Networks – General principles and bandwidth

General principles

First mile networks, also known as the last mile, are defined here as all those networks connecting end-users and small and medium-sized enterprises with central switching locations and the backhaul networks. There are several technologies available to connect an end user to central switching locations and backhaul networks. These technologies can be either wired or wireless and make use of various wires or spectrum frequencies. There are general rules that dictate how well certain technologies are usable for various purposes and how many bits they can transport per second. These general rules are:

- When more electromagnetic spectrum is used, more bits can be sent. This means that the higher the spectrum frequency used for the transmission, the higher the achievable speeds, because spectrum is allocated in larger chunks in the higher part of the spectrum.
- Lower spectrum bands travel further (for a given amount of power) and (for wireless) more easily through and around obstacles. Higher bands travel shorter distances and less easily through and around obstacles.
- The more power is used, the more distance can be crossed.
- When one wants to send more bits per second, more electrical power is required.
- Communication over longer distances is affected by more distortion, interference and noise.
- The more metal lines in a bundle, the more distortion, interference and noise (this is not true for optical fibre, since two fibres in a normal cable will not interfere with each other).
- More noise, distortion and interference means less bits per second.
- More power means more distortion, noise and interference.
- The more simultaneous users on a shared network the less bandwidth there is on average.

These effects tend to be progressive and cumulative rather than linear. This means that if a connection is supposed to carry more bits per second, the trade-off lies in using more spectrum, more power and generating less noise and having better signal detection and shortening the distance and better shielding. If one wants to push more bits over a connection this is achieved by a combination of using more spectrum, reducing the amount of simultaneous users, shortening the distance, increasing the power of the line, etc. There is an absolute limit to the maximum amount of bits a channel can carry based on the spectral bandwidth used measured in hertz and the signal to noise ratio measured in decibels.

Bandwidth

Bandwidth is defined in megabits or gigabits per second. Bandwidth therefore consists of three elements: bits, time and the combination of time and bits *i.e.* sustained rate. The bandwidth in the first mile is the defining factor in the user experience. There are three elements to bandwidth:

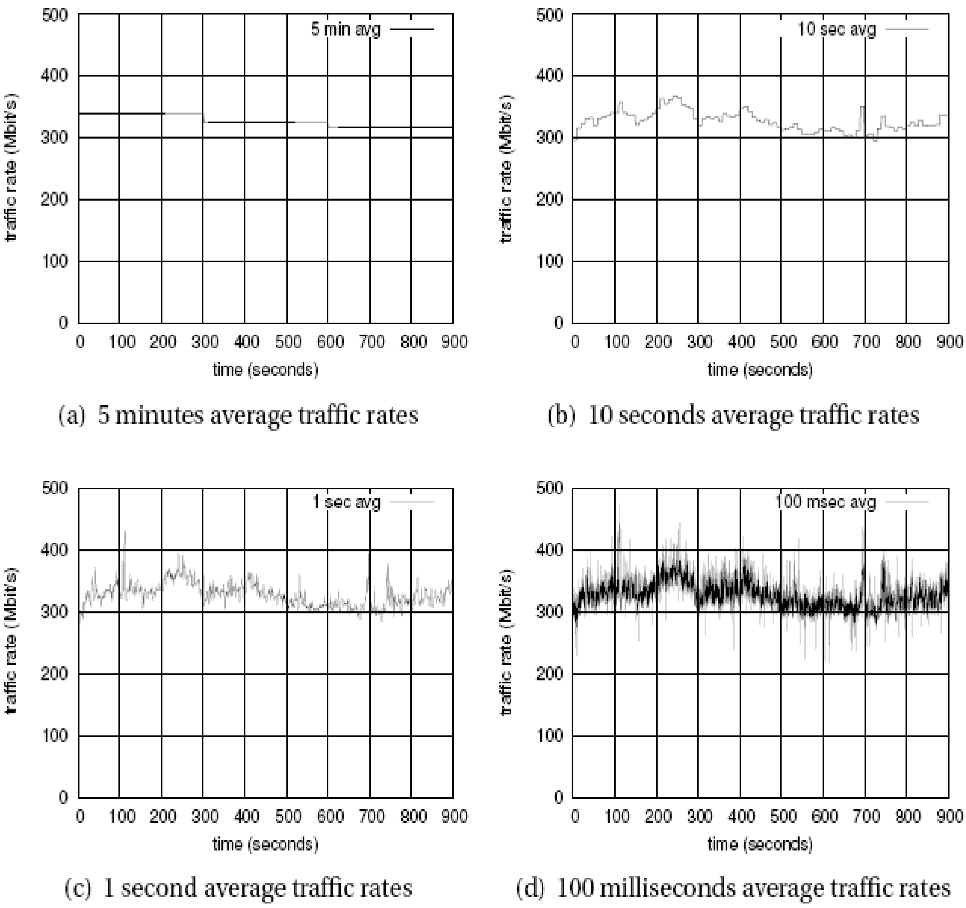
- Time: Time is one of the most important factors in the decision to make use of a particular service. Recent studies have shown that users are willing to wait on average four seconds for a web page to load. If it takes longer the amount of users waiting drops progressively.[19]
- Time (2): When users need to share bandwidth for instance because they access the same server or share the same access network, the number of simultaneous users will determine average download rates per user. The faster the network is, the higher the probability that the download of one user has already finished, before a second user starts. This results in both users not competing

for the same bandwidth and giving both a better user experience. A shared network might therefore be able to sustain a large number of short downloads with a very good user experience but might have trouble sustaining multiple sustained rate streams.

- Bits: The size of data sent and received will seriously influence the user experience. It is for this reason that new developments in better and more efficient encoding are continuously being investigated. Developments like the introduction of mp3, mpeg 2 and 4 encoding allow for smaller size music and video files, which in turn allows for the reduction of the amount of time that it takes to access this content. This development is strengthened with the introduction of networks that allow for more megabits per second to be downloaded.
- Sustained Rate: The combination of megabits and time leads to the amount of megabits per second that a connection can sustain. This characteristic is especially important for real time communications *e.g.* VoIP, video etc. With real time communication it is important that the connection does not peak so that packets will have to be queued and that delays remain well within a limit of 100 milliseconds. The sustained rate that a connection can offer will influence what kinds of application are possible and how many can be used in parallel. As Figure 1 shows these averages can fluctuate strongly (30%)[20], when viewed on a timescale of 100 milliseconds.

Figure 2. Average traffic rates over different time scales

The shorter the timescale the higher the fluctuation



(a) 5 minutes average traffic rates
(b) 10 seconds average traffic rates
(c) 1 second average traffic rates
(d) 100 milliseconds average traffic rates

Source: Van de Meent, 2006.

The maximum bandwidth that a connection can sustain over the physical link is dependent upon the physical characteristics of the link. The architecture of the network will determine how much of that bandwidth is actually available to the end-user. On some networks (wireless, cable and Passive Optical Networks) users have to share the same physical network. The more users contend for the same bandwidth the less bandwidth there is available on average per user. Contention can also be an issue in the backhaul part of the network, where there might be less bandwidth available towards the core of the network, than all the users individually can generate. For instance if there are 300 VDSL2 connections of 50 Mbit/s on a local DSLAM, than the backhaul part of the network would need to be able to support 15 Gbit/s towards the core of the network, if that part of the network should be uncontended. It is not very likely that all users will need the maximum bandwidth at the same time, allowing telecommunications companies to connect more people to the backhaul part, without noticeably hindering the usage of the network by individual users. This is especially the case when people use the network to read their e-mail or surf the web – this traffic has a bursty character. While one user is downloading a web page or e-mail, other users are reading and not utilising the available bandwidth. Watching videos and using peer to peer services lead to less bursty and more stable continuous usage of the bandwidth (a streaming video on demand may tax the network for the entire duration of the movie). The rate between the maximum amount of bandwidth needed if all users were to use the network at maximum speed and the actual bandwidth available is known as the contention rate. If the rate is 1:1 this means that the network is uncontended, when it is 1:10, this means the available bandwidth is shared with 10 other connections.[21] Telecommunications companies use statistical models on how many people use the network at the same time to estimate an ideal contention rate.

The question is how much bandwidth does an end-user need. The answer is not only dependent upon current use, but also on expected future use. Currently there is a lack of data in scientific literature on 'normal' usage of telecommunications networks. The only known scientific study on this topic was a study done in Japan. It shows that around 10% of the fibre users generate over 2.5 Gigabytes per day in traffic, but there is no clear separation between heavy users and normal users.[22] Furthermore there is little difference between upstream and downstream usage, which is contrary to current assumptions that upstream usage would be less than downstream usage.

Some idea of the amount of bandwidth an average household will consume in coming years is provided in a study by Arthur D. Little commissioned by Liberty Global (a cable company) which predicted that by 2011 the downstream requirements of households would peak at around 50 Mbits/s and the upstream requirements would peak at around 8 Mbit/s, under the assumption that an end-user will need less upstream than downstream bandwidth (Table 1). [23] The breakdown of the bandwidth usage they give for future usage is:

Table 1. Predictions on bandwidth consumption

Services	Downstream	Upstream
World Wide Web/E-mail	0.2-5 Mbit/s	2 Mbit/s
HDTV (per channel/device)	8-10 Mbit/s	0.5 Mbit/ss
Peer to Peer	0.2-5 Mbit/s	2 Mbit/s
VoIP	<1 Mbit/s	<1 Mbit/s
Interactive gaming	2 Mbit/s	3 Mbit/s
Instant Messaging	<1 Mbit/s	<1 Mbit/s
Audio, web radio, podcasts	<0.5 Mbit/s	<0.5 Mbit/s
Video conferences	2 Mbit/s	3 Mbit/s
Home security	2 Mbit/s	0.5 Mbit/s[24]
e-government	<5 Mbit/s	<0.5 Mbit/s
Average demand per household	**<50** Mbit/s	**<8** Mbit/s

Source: Arthur D. Little.[25]

2011 is not far off and experience in recent years shows that growth in bandwidth usage should also be considered for the period 2011-2020. Most networks capable of speeds around 50 Mbit/s will only be available by 2011-2015. The calculation does not take into account the growing use that P2P might have. Another complication is that the calculation is for an average household, not taking into account at what point the 70th, 80th and 90th percentile will lie. More research is required to determine at what bandwidth the introduction of new services will no longer be limited by bandwidth constraints. Clearly, as well, the consumption of bandwidth will depend on prices and whether consumers are willing to pay the prices which the market has set for bandwidth.

In general it can be expected that small and medium-sized enterprises will need more bandwidth than households. A 100 Mbit/s symmetrical connection is required for remote security cameras, remote backups, hosted applications etc. According to calculations a connection at this speed will also bring considerable savings for SMEs[26], because it becomes possible to outsource various elements of their IT-systems.

For the purpose of this report the focus will be on networks that can support around 50 Mbit/s downstream and above 10 Mbit/s upstream for an end-user. Such a network is capable of a range of simultaneous services. Networks that sustain lower speeds will probably limit the available uses for end-users and the possibilities for competition in services over the network, because bandwidth is scarcer. This study will focus on networks that will be generally available in the period 2010-2020 to end-users and have little bandwidth constraints.

First Mile Networks – Wireless

HSDPA and EV-DO

High Speed Download Packet Access and Evolution Data Optimized are competing 3G (or 3.5G) mobile wireless standards capable of delivering over 1 Mbit/s. These standards are currently being implemented by mobile carriers. The speeds these networks can achieve are up to 14 Mbit/s, however these versions have not yet been implemented. An HSDPA antenna currently needs to be closer than 250 meters to the user to achieve average speeds of around 1 Mbit/s for 20 users.[27] The limited capacities make these protocols a poor choice for providing end-users with high bandwidth in their homes, though it will be important in the mobile wireless handheld arena. Fibre is used extensively to connect the individual cells to the network, point to point wireless, E1/T1 lines and DSL-connections are also used.[28]

WiFi

The IEEE802.11x standard allows for speeds up to 54 Mbit/s for the 802.11g version and above for the upcoming 802.11n version. These speeds are shared among the users of the networks, so the more users there are, the less bandwidth is available to them when they use the network simultaneously. The maximum distance a normal access point reaches is 30 metres, though higher distances have been reported. This is, however, very much dependent upon such conditions as the quality of the antennae, the power used and the influence of objects in the area and whether the set-up is omni-directional or point-to-point. In first mile situations often a point-to-point setup is used to guarantee more consistent performance and to gain more distance. Here too the shared nature and short range of the signal will limit its use as a first mile technology. It will however be an important standard inside and around homes.

WiMAX/WiBro

The IEEE 802.16 standard (WiMAX) allows for speeds up to 40 Mbit/s over distances of up to 10 km. When users are using the network simultaneously, the bandwidth will have to be shared between them. The standard is relatively new and actual roll-outs are still limited. It is expected that in commercial situations the available bandwidth for an end-user will be less than the maximum theoretical limit and the range will be more limited than 10km, which is not dissimilar to the experience with other previously mentioned wireless technologies. Because of the high speeds possible, it becomes necessary to equip each cell with its own fibre or DSL connection, increasing the costs of roll-outs. Because of its range and relatively high speeds the standard is seen as an interesting possibility to bring data network coverage to rural areas. Korea has developed its own version of WiMAX called WiBro that allows for speeds up to 1 Mbit/s at a speed of 60 km/h. For a more in-depth analysis of WiMAX see DSTI/ICCP/TISP(2005)4/FINAL).

Wireless Networks – Conclusion

The current range of wireless networks is not capable of offering high bandwidth connectivity, comparable to wired networks. The extent to which future wireless networking technologies will be a competitive first mile technology is as yet uncertain, and is likely to vary depending on geography and population density. The shared nature inherent to wireless networks also places limitations on capacity availabilities.[29] Even when new spectrum is freed for broadband use, it is not likely that the offer will be competitive with existing wired networks. To offer end-users a competitive sustained rate, fibre and street cabinets would have to be brought closer than with VDSL or cable networks.[30] It is therefore most likely that future wireless networks will be built upon available fibre and hybrid networks and will not directly compete, but be part of a converged offer. Wireless networks, converged with wired networks, will however be an integral part of our lives, because they allow people to communicate when they are on the move and in and around work and home.

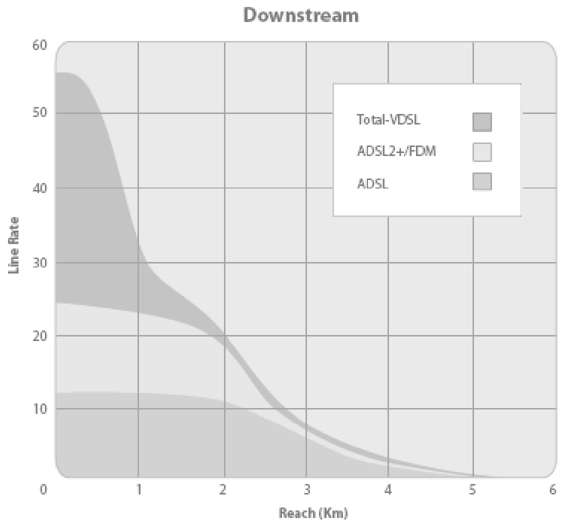
First Mile Networks – Hybrid

There are various forms of wired networks available that can deliver symmetrical speeds above 10 megabit/s. When these networks are based on existing infrastructure such as PSTN, cable and powerlines, they require fibre to be brought closer to the end-users premises to guarantee enough bandwidth, they are therefore known as hybrid fibre/coax/DSL networks.

xDSL

DSL standards are set by the ITU. DSL is an extension of the capabilities of the traditional PSTN network. The PSTN network was optimised for sending signals in the range between 300 Hz and 3 400 Hz. Signals above and below this range were filtered. This limits the speeds of the network to about 56 kbit/s. In order to allow for more data to travel over the line, the filters were removed to be able to send at higher frequencies. At the customer site and at the switching locations the two signals are split and sent either to the DSL equipment or the PSTN equipment.[31] Currently the standards allow for the use of spectrum up to 30 Mhz.

Figure 3. Relationship between download speeds and distance



There are various iterations of the standard, but most rely on an asymmetric transfer of data between the switch and the end-user, though there are some that can do symmetric transfer. Asymmetric transfer means that the switch also known as a DSLAM (Digital Subscriber Line Access Multiplexer) can send more bits/s downstream towards the user than the user can send upstream to the switch. Symmetric transfer means that upstream and downstream speeds are equal. Asymmetric transfer is chosen because there is normally more data flowing to the user than from the user (one click starts the download of a movie). The spectrum available on a PSTN connection is therefore divided into a large part for downstream data and a smaller part for upstream data. An ADSL2+ (ITU G.992.5 Annex M) connection can reach speeds of 24 Mbit/s downstream and 3.5 Mbit/s upstream. A VDSL2 (G.993.2) connection can reach speeds of up to 100 Mbit/s both upstream and downstream. VDSL2 does this by using a larger amount of spectrum, 30mhz vs 2.2mhz for ADSL.

The speeds advertised for DSL connections are however dependent upon the distance between the switch and the customer. Figure 3 shows how download speeds deteriorate with distance.[32] For VDSL2 this means that in order to deliver around 50 Mbit/s down and 30Mbit/s up, the switch has to be around 450 metres away from the customer.[33] The PSTN network is a point to point network and therefore the speed is dedicated to the use of that customer and does not have to be shared with other users. When the user wants to use IPTV over the connection this bandwidth will have to come from the 50Mbit/s allocation on the line. It is therefore not likely that the network will be able to sustain more than 3-5 concurrent HDTV streams, which are between 10 and 20 Mbit/s each.

The average local loop length to end users is, however, well above 1 km. In most countries less than 10% of the population lives close enough to an exchange to allow for speeds up to 50 Mbit/s.[34] So for companies that own the PSTN local loop to offer these kinds of speeds it is necessary that they build out to within reach of their customers. In order to come within reach of the customer the fibre network will need to be brought to the street cabinets. This kind of network is often known as fibre to the node or curb (FTTN). In the Netherlands KPN has estimated that it will need to go from 1 350 local exchanges to its 24-28 000 nodes so that it can come within 450 meters for 8 million of its customers. In the United States AT&T is currently rolling out its U-Verse network based on the same technology but longer average line distances. Similar initiatives are being undertaken by Deutsche Telekom, Swisscom and Belgacom. The cost of upgrading the network is estimated at USD 100-500 per customer.[35] In Japan and Korea VDSL2 is used to bridge the last 100 meters in large apartment buildings to the end-customer to bring speeds of 100 Mbit/s symmetrical bandwidth. This is described either as Fibre to the Building or Fibre to the Home.

For regulators the roll-out of VDSL2-networks adds a new twist to the existing discussion on sharing and unbundling of networks. With fibre rolled out to the node, there is less need for local exchanges in the network. The street cabinet functions as an exchange. These questions are currently heavily debated within the EU, with most of the debate occurring in the Netherlands and Germany. What has become clear is that the answer depends on the local situation. For alternative operators who used the unbundled local loop, the business case is often not positive[36] and they will either have to take the next step up the ladder of investment or will need to take a step back to offering wholesale broadband access. The business case for the incumbent is clearer. It can sell its MDF-locations, which might finance in part or in whole its VDSL roll-out. Furthermore it will benefit from lower yearly operational expenditure.

The main advantages of DSL-based networks are:

- Use of existing infrastructure allows for efficient implementation.
- Dedicated bandwidth towards and from the user, allowing for continuous streaming applications without interference from other users.

Disadvantages of DSL-based networks are:

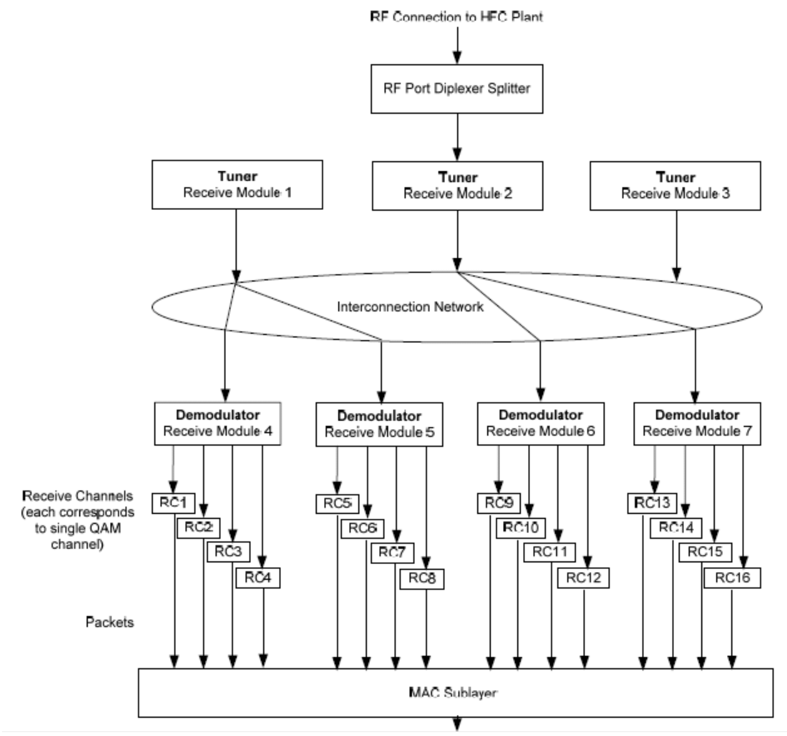
- Distance affects performance disproportionately making use over 5 kilometres hard and high bandwidth in the 50 Mbit/s range limited to +/- 450 meters.
- Little room left for improvement towards higher bandwidths.
- Streaming content (*e.g.* IPTV) may consume the downstream bandwidth of the line, thereby limiting downstream capacity for other services. More than 3-5 HDTV-streams will not be possible in most implementations.[37]

Cable

The design of cable networks started from a different premise since it was necessary to carry a large range of analogue TV channels over a long distance to a large number of people. In order to achieve this, the physical cable design was well shielded and optimised for transmitting a wide range of frequencies. The design of the coax cable allows it to use a much higher bandwidth of spectrum on the cable than other copper based networks such as power lines and PSTN. This in turn allows for a different use of the available spectrum for services. Traditionally cable networks in the United States used the frequencies from 54 Mhz up to 550 Mhz with a channel bandwidth of 6 Mhz for the transmission of television. In Europe the spectrum from 65 Mhz to 550 Mhz was used. The higher resolution of PAL and SECAM television required 6-8 Mhz wide channels. The coax cable however allows for the use of the frequencies from 5 Mhz up to 1 000 Mhz. Currently spectrum up to 850 Mhz is used for analogue and digital television.

Cable networks used to be one way (downstream), broadcast networks, where everybody would receive the same signal. The introduction of data services required the networks to allow for two-way communication and separate communication per customer. This was achieved by using the bandwidth from 5-42 Mhz for upstream transmission and the bandwidth of one or more television channels for downstream data, thereby achieving an asymmetrical system. This bandwidth of 6-8 Mhz (literally one TV-channel) allows for 40-50 Mbit/s of downstream capability per channel. The potential bandwidth however still has to be shared by multiple customers. Encryption is used to ensure that customers only receive what is meant for them. The new Docsis 3.0 standard which was ratified in 2006 and will become operational in the coming years allows for 160 Mbit/s downstream (and maybe more) and 120 Mbit/s up from end-users. This will have to be shared by those end-users. This is achieved by bonding a minimum of four channels together into one communications channel (see Figure 4). With current technology it might be possible to send up to 5 Gigabit/s (upstream and downstream combined) over an HFC network if no analogue or digital TV-channels were broadcast and all bandwidth was used for data networks.

Figure 4. An example of 4 times 4 bundled channels



Many cable networks in the OECD have in recent years made major investments to change their networks into hybrid fibre/cable networks (HFC) to be able to offer digital TV and Internet services to their customers. This required them to bring fibre closer to the end-users and to shorten the loop towards the end-user. The signal on the coax is recreated on the fibre to achieve the necessary distances from the central distribution points, where the cable modem termination system (CMTS) is located, to the local distribution points where the fibre-optic signal is converted to an electronic signal. The CMTS will multiplex the data into the channels and add encryption. Typically a local distribution point will be 10-20 kilometres away from the central distribution point, but this might be as far as 160 kilometres. Typically there are 500-1 000 subscribers on a single local distribution point.[38] It is possible however to use more than four channels to send data. The standard, referenced in Table 2, shows a possibility to use 4 times 4 bonded channels.[39] This could bring the amount of subscribers having to share 160 Mbit/s down to 250 on average. How this will work out in the future is currently not known, because the first products based on the standard will be available by the end of 2007. The cost of the new Docsis network are unknown, but likely to be lower than VDSL2 networks with fibre to the node, because cable companies have already invested in their HFC-networks to make previous versions of Docsis possible.

Advantages of Cable networks are:

- Possibility for 160 Mbit/s or more downstream bandwidth by combining 4 or more channels to a group of customers.

- Linear Television (scheduled TV programmes) is possible separate from the bandwidth of data-communication and therefore will not contend with other data services.

- Use of existing infrastructure allows for efficient implementation.

Disadvantages are:

- Shared nature of bandwidth, both up and down limits the bandwidth available to one user based on the use of the network by other users. The more users use the network at the same moment, the less bandwidth is available per user.[40]

- The availability of upstream bandwidth is more limited than downstream. This can hurt high capacity streaming applications that make extensive use of upstream bandwidth, such as security cameras.

- The network is best suited to broadcast type applications where a large group of users watch the same channels in a 'linear' fashion. Video-on-Demand at HDTV quality will be limited to a maximum amount of streams.

Powerline[41]

In some OECD countries powerline networks are also used as a first mile network technology. The idea behind Broadband over Powerline (BPL) is that electricity networks are probably the most pervasive wired networks available. Although the network was never designed to carry communication signals, it has the capability. Where it is used, speeds are currently up to 27 Mbit/s down and 18 Mbit/s up, shared between a group of subscribers. This does not leave room for IPTV. There are however several parameters to take into consideration when designing the networks. These are:

- The electric wires and the networks are designed to distribute energy and not data. For this reason BPL does not work past transformers. This means that every time there is a transformer in the electricity network the data has to be repeated past the transformer. Depending on the lay-out of the network this can require a significant amount of repeaters. This can increase the costs of rolling out a network.

- BPL may cause interference in a variety of wireless frequencies, because the cables are not shielded to protect them from this kind of interference and the way the technology works it is difficult to reduce this problem.

- It is still unclear what kind of distance BPL can traverse over the copper part of the network. It is to be expected that similar to DSL the possible bandwidth will decrease with distance and the distance that can be crossed is expected to be less than with DSL. In practice this means that fibre will need to be brought closer to the end-user increasing the costs of a roll-out compared to a DSL network.

It is too early to assess the future place of BPL in the market. There have been several trials, but little large-scale implementation as yet. This paper does not delve more deeply into the factors involved with BPL-networks and whether or not the technology will be a success.

First Mile Networks – Fibre

There are two basic kinds of first mile fibre networks with different characteristics and different strengths. They both dispense with the legacy networks and build only on the strengths of the fibre.

It is therefore possible to start with a clean slate design of the network, this way there is no need to compromise because of the limitations of legacy technologies. The limitations are therefore only based on the limitations of the chosen networking technology and network designs, which in turn might be limited by business model considerations and budgetary constraints. The main two competing systems, especially in the FTTH-market, are Ethernet Point-to-Point networks and Passive Optical Networks. Costs of a FTTH-network will be somewhere between USD 500 and USD 2 500 per household connection, depending upon various conditions. In some cases costs may be lower if, for example, ducts are widely available. For Paris, for example, the costs per household are estimated between USD 360 to 440 because of the extensive sewer infrastructure in the city and France Telecom has estimated costs of under USD 440 per household at the pre-commercial stage in large cities in France. Figure 5 shows estimates of total costs, including in-house wiring, of about USD 1 550.[42]

Building (Fibre) Networks

When building a fibre network investments have to be made into the following components:

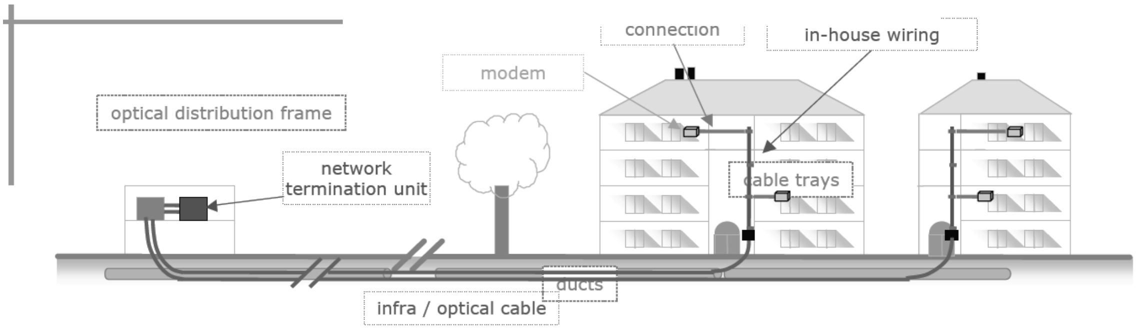
- Fibre and infrastructure to lay it in or to string it on. The investment in the aerial plants (fibre strung over poles), the trenches, the locations for Points of Presence and other physical infrastructure often account for 30-80% of investment costs and will last for at least 30 years, although they are often economically written off in 15 years.

- Active components in the network, these are all the optical and electric systems that make the network send and receive signals, such as switches, repeaters, etc. These need replacing every 5-7 years.

- Customer premises equipment: Equipment like modems and, if offered, decoders for IP-TV/digital TV.

- Personnel charges: management, network administration, billing, repair crews, customer support etc.

Figure 5. Fibre network layout and capital expenditure



CapEx per subscriber	
Infrastructure & buildings	€1,000
Optical cable	€50
In-house wiring	€350
Connection	€100
Active network components	€300
Active subscriber components	€200
total	€2,000

Source: ARCEP

The largest share of the investment is in capital expenditure in the engineering work required before the network is functional and operational. The design and roll-out of the network will take into account that customers will connect after the network is built by pre-installing hand holes, extra fibre etc. The total cost of the project will only rise marginally with extra people connecting.

The total amount of this investment is influenced by several factors that need to be taken into account:

- Size of the area that needs to be rolled out (without parks, lakes etc.).
- Distribution of houses in that area (x houses/hectare).
- Choice between trenches and aerial plant and the availability of existing infrastructure.
- Type of buildings: High rise buildings are cheaper than medium rise and suburban housing.
- Costs of rights of way and access to buildings.
- Municipal charges (*e.g.* cost of repaving, access to sewers, administrative charges, taxes etc).
- Type of area, soil etc. (mountainous vs. flat, rocks vs. sand etc).
- Need for special works to cross roads, highways, waterways etc.

These costs can seriously jeopardise a business model because they are sunk costs and are relatively fixed for an area regardless of the number of customers signing up.

The industry has come up with several good ideas to lower the costs of the passive infrastructure. There are now ways to:

- Use existing infrastructures, like existing telecommunications ducts, gas pipes and sewer networks to enter customer premises.

- Make use of extra capacity that other networks (gas, electricity) have built to cross rivers, streets etc. for future use.
- Rats and ferrets have been taught to pull fibre in situations where normal technologies do not work.
- Copper cables can be de-cored to make room for fibre without the need to build trenches.
- Some incumbents equipped PSTN cables with an extra empty tube for later insertion of fibre.

The way passive networks are rolled out is dependent upon local factors. It is sometimes said that the telecommunications industry would have liked to have given up some of the revolutionary advances in fibre technology for a similar dramatic step in civil engineering technology.

Point-to-Point

A point-to-point network, also known as a star network, is a network where a dedicated fibre (or fibres) is run to every end-user. This is the same design as is currently used for the PSTN and to connect large corporations with fibre to backhaul networks. The standard datalink protocol used here today is Ethernet. Ethernet has developed from an in-building networking technology to the new standard that networks use for building wide area networks and backbone networks, replacing ATM and SDH based networks. The main advantages of point-to-point networks compared to passive optical networks are:

- Every user has a dedicated connection. There is no influence from other users on download or upload speeds.
- An individual connection can be upgraded by changing the lasers at both ends. If an end-user has a 100 Mbit/s connection and wants to upgrade, it is possible to change the lasers on both ends to 1 Gbit/s or 10 Gbit/s. There is even a possibility for the inclusion of WDM technologies if so desired and to add different link layer protocols.
- Simple and cheap switches in the middle. There is no need for high-speed encryption in the switches to separate the traffic of different users.
- Ethernet is the same datalink layer protocol that is used for Local Area Networks, allowing for easy integration.

There are also some disadvantages to the use of point-to-point networks.

- They require central switches with a dedicated port per customer. This adds to the price for both switching locations and for switches.
- More fibre necessary for roll outs, compared to a ring topology, this adds to the price of the roll-out.
- No systems are available yet that allow for the integration of an analogue TV-channel on the same fibre. Some roll-outs therefore opt for a dedicated separate fibre to allow analogue TV on the same fibre.[43] This adds to the cost per subscriber. However this might change, depending on market demand.

Passive optical networks

Passive optical networks (PON) are fundamentally different from point-to-point networks in that PON does not use a fibre for every end node, but uses one fibre to connect multiple end-nodes. This is achieved by using a ring, bus or tree topology. Each topology has its own technical and financial benefits, but the differences are limited. The main characteristic of a PON-network is that the fibre in the network is shared by the various users. It is therefore a fibre-lean solution. For downstream communication it uses one laser sending the data and passive optical splitters to split the data towards the individual end users. The return path is the users sending their data back and the splitters integrating the data on the fibre. There are now also systems available that do coarse wavelength division multiplexing to allow for multiple colours to groups of end-users, so one group of end-users will communicate at one set of two colours and another group at a different set of two colours. Much like cable, the infrastructure is a shared medium, where the users need to share the available bandwidth, however PON-networks are shared between less people than a HFC-network. This so-called split ratio is generally 32-64 for PON networks whereas on an HFC-network available bandwidth is split between up to 1 000 users. The main advantages are:

- Fibre "lean", requiring less investment for the outlay of the network (a variant exists whereby an optical splitter is used at the central switching location to allow for PON using point to point fibre, this model is not lean on fibre, but does allow one optical port to be used to reach 16 to 64 customers).
- One optical port at the central office, allowing for cheaper transmission hardware and less maintenance.
- Smaller footprints for the central equipment than point-to-point networks.
- It is possible to split the fibre later on to add new subscribers.
- Long-distance transmissions for up to 60 km to reach up to 64 customers.

There are also some disadvantages to PON networks:

- Shared bandwidth, so usage from one user can influence other users. This is known as split-ratio.
- Hard to upgrade individual end-users to higher bandwidth. Users need to be upgraded all at once.
- Central switches require more logic and encryption to integrate and separate customer streams.

Many systems currently make use of a three colour system where two colours are used downstream, one for Internet data and one for broadcast television (analogue and digital) and one for upstream Internet data.

There are three competing standards at the moment for PON networks, these are:

- APON/BPON (ITU G.983): These were the first PON-standards, published in 1995 and updated in 2001, where BPON until recently was still deployed in networks. It allows for 622 Mbit/s downstream and 155 Mbit/s or 622 Mbit/s upstream with a 32-64 way split. It uses ATM as a link layer protocol.
- GPON (ITU G.984): This is the official successor for APON/BPON and was finalised in 2005 and is still under development. It allows for 2.5 Gbit/s downstream and typically 1.25 Gbit/s upstream, though 2.5 Gbit/s upstream is also possible. It allows for a 64-128 way split. It can use either ATM or Ethernet over GEM as link layer protocols. It can reach up to 60 km. Verizon for

instance uses GPON for its FiOS network, but European incumbents like BT and France Telecom have also indicated they want to make use of this technology.

- EPON (IEEE 802.3ah): This standard was finalised in 2004 by the IEEE. It differs from the previous two standards by using Ethernet only as the link layer protocol. It allows for symmetrical speeds of 1.25 Gbit/s and has a maximum reach of 20 km. Korea Telecom has recently decided to implement EPON. Currently work is underway in the IEEE on a successor that will allow 10 Gbit/s.[44]

There are heated debates between the proponents and opponents of GPON and EPON. Both variations are seeing extensive use in networks and are being actively implemented.

The way PON networks are built influences the way they can be open to multiple service providers. There are three basic ways to build a PON-network:

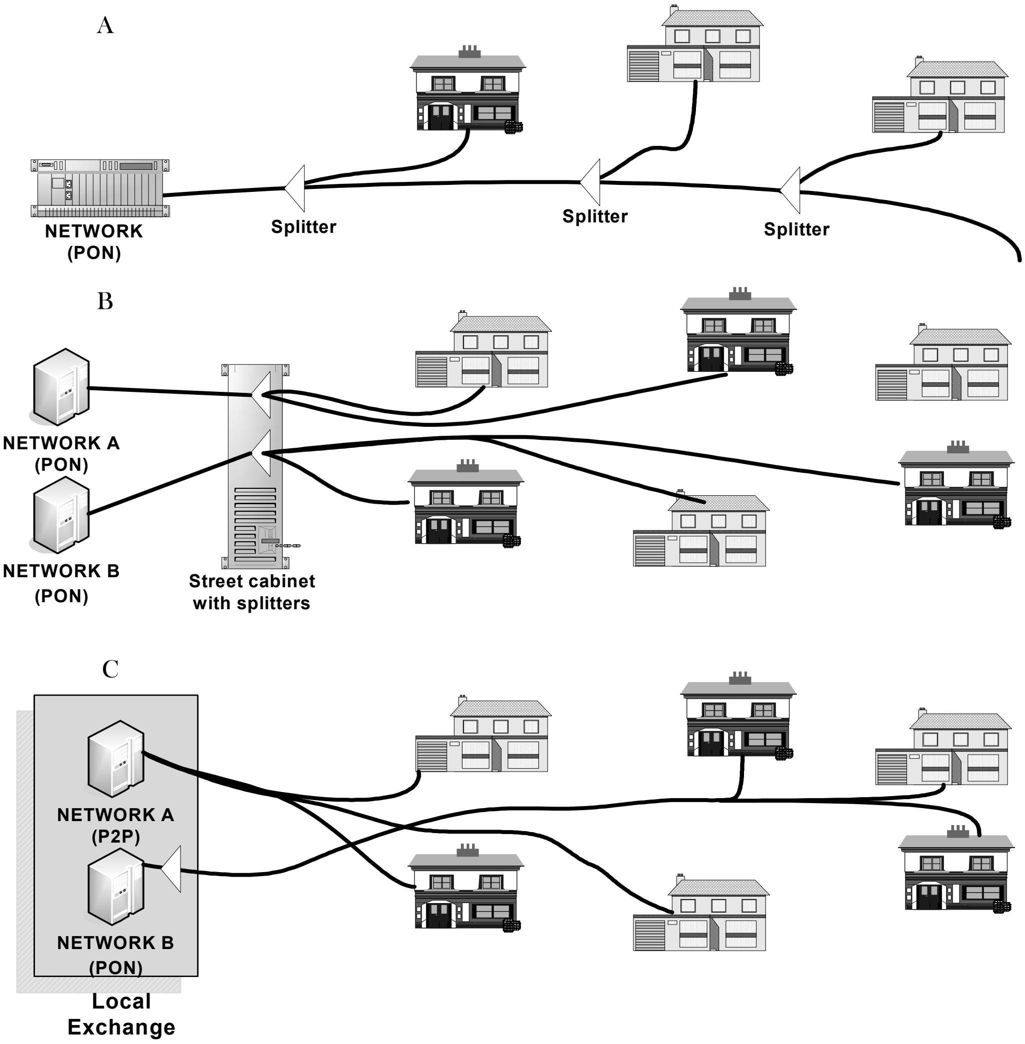
i) Fibre split close to the home of the user. One fibre is used to pass a group of homes. At each home a separate splitter is installed to divert the signal to and from the home. This is the most fibre lean solution, but makes it hard for other operators to share the infrastructure through local loop unbundling. If the network is shared this needs to be done through wholesale broadband access.

ii) Fibre split half way. A small bundle of fibres is brought to a street cabinet. In the street cabinet the optical signal is split and from the street cabinet the connection branches out using a point to point connection where every household has its own fibre. Switching providers is as easy as switching fibres from one provider's splitter to another's, although this does require a truck roll to the splitter, introducing costs for switching.

iii) Point-to-point with PON: The network is built as a point to point network, but can be used as both a PON and P2P-network with the splitter at the local exchange.

Figure 6 shows the three topologies.

Figure 6. Topologies for PON fibre networks



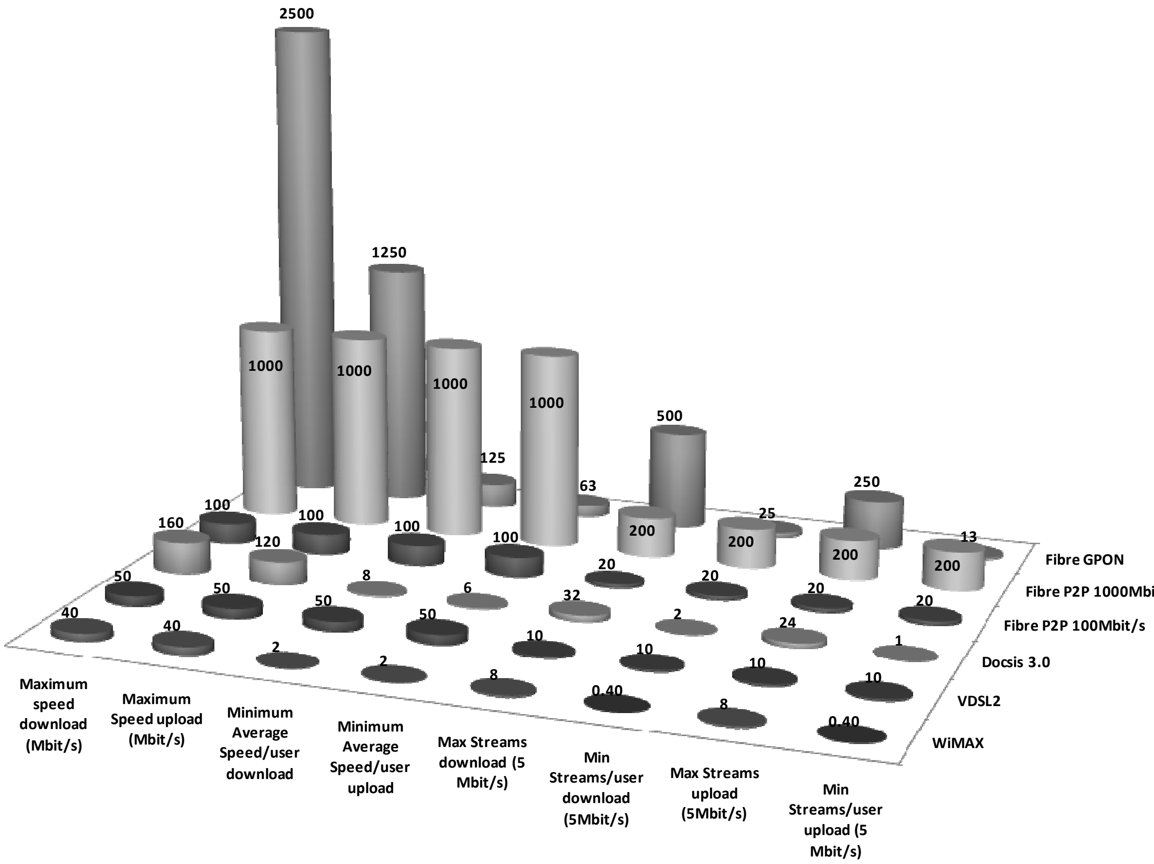
Comparison between networks

There is an ongoing debate on what solution is best to connect end-users to high bandwidth networks. The different solutions also have different regulatory implications in that existing regulatory tools, in particular local loop unbundling, may not be effective under certain network configurations. This means that incumbents may regain market power in local loops by investing in a specific configuration. Main demands that future users will have towards broadband networks will be seamless operation and user experience from one medium to the other, low cost and non-limiting towards future uses.

Wireless networks have some good characteristics with respect to cost for the last meters, mobility and flexibility. They are however not capable of sending large amounts of data over larger distances and to provide service to many users simultaneously. These limitations are for the most part inherent to wireless technologies. It is therefore expected that wireless networks will be mostly used in and around the end-users premises to bridge the last meter from the device to the physical network or for users who do not want or need access to high bandwidth. They will also be in use for mobile applications. As a first mile technology it cannot compete with hybrid networks on either bandwidth or cost. However, wireless may be the only viable choice for the "first mile" in certain geographical situations where population is extremely dispersed and remote and where spectrum scarcity and sharing does not pose problems.

Figure 7. Comparison of networking technologies

Difference between 1 user and 20 users. (See Appendix B)



Hybrid networks are a combination of existing technology and new technology allowing a lower capital expenditure compared to full fibre networks. Powerline communications will most likely remain a niche technology, because of the interference problems and the fact that the current technology is not competitive compared with DSL and cable networks. ADSL technology is limited in its downstream and upstream capabilities and will not be able to deliver bandwidth needs for the coming 15 years. With VDSL2 bandwidth is increased by moving the fibre close to the end-users. It allows end-users to sustain multiple high bandwidth streams. Cable networks are capable of even higher up and download speeds than VDSL. Cable is a broadcast network for shared use of both upstream and downstream bandwidth. Its capabilities in sustaining multiple on-demand streams is therefore limited by the amount of users and the bandwidth usage that they have. Both cable and VDSL seem to be able to sustain services that the average user uses in the coming years.

Fibre to the home networks provide the most bandwidth and the highest sustainable rates per end-user. Development of the technology is still ongoing. FTTH at present is the network that is most "future-proof", because it can handle the most new bandwidth-intensive applications. The choice between end-to-end and PON will be based on various preferences and both technologies might be used to reach a large amount of users and different kinds of users. Regulators will have to remain aware that the network topology chosen may have an impact upon the regulatory options.

Competition and regulation

In countries where policy is to develop competition through facilities-based competition without any sharing of networks then the different topologies chosen to develop fibre networks may not result in the need to make any changes in regulatory frameworks. The impact in those countries of the different network topologies may only be indirect in that different fibre topologies may have implications for the speeds which can be offered and the cost of providing service. In turn this may impact on the relative ability of a fibre network to compete with other technologies which may be close substitutes. In countries which have chosen to allow network sharing and unbundling as part of their policy framework to foster competition and reduce significant market power the topologies of the networks have implications from the competition and policy perspective.[45] This is because, as discussed earlier, different topologies have implications for the ease with which it is possible to let providers share the network, for instance to facilitate wholesale broadband access and for local loop unbundling. New entrants, in countries supporting network sharing, will also be able to compete more effectively if action is taken to reduce entry costs such as by setting wholesale prices for the incumbent's ducts or persuading municipalities to install large capacity ducts when undertaking road works. There are four levels at which this unbundling can happen:

i) Conduit and collocation facilities.

ii) Physical Layer Unbundling: Sub loop unbundling for DSL networks or dark fibre leasing in FTTH networks, or perhaps, Optical Layer unbundling (CWDM or DWDM in PON).

iii) Data Link Layer Unbundling: Dark fibre and link-layer electronics at each end. For example, Ethernet-based VLAN, or ATM-based virtual networks (in Europe also known as Wholesale Broadband Access).

iv) Network Layer Unbundling: Basic network service provided. For example, IP Layer 3 service over cable using policy-based routing to multiple ISP.[46]

In France Free has said that they will offer fibre-to-the-home and open it up to their competitors as well, their business model will either be an example of number *ii* or number *iii*. Stokab in Sweden is providing fibre under the second model.

LLU:

- The shared nature of both cable and PON networks makes it hard to implement local loop unbundling. In cable it is near impossible, because it would require giving every user their own connection instead of using a shared network connection. A point-to-point network is not often used for HFC-networks. In a PON-network it is only possible if LLU has been taken into account right from the start of the network and competing networks can access splitters in street-cabinets or local exchanges.

- LLU is possible with DSL and point-to-point fibre networks.

Wholesale broadband access:

Implementing wholesale broadband access is possible on all networks.

- On shared network infrastructures (cable and PON-networks) it is more difficult, since it is hard to guarantee all the service providers the same Quality of Service and maximise the usage of available bandwidth at the same moment.

- Downstream broadcast television on cable and PON-networks cannot be shared by different operators without limiting the amount of possible channels or by using a different colour on a PON-based network. Implementing wholesale broadband access will then require either the resale of the television signal or integrating IP-TV in the data-channel, leaving less bandwidth available for other data applications.

- IPTV will have to compete with the other data on a DSL-connection. In order to guarantee that there is enough bandwidth available for IPTV the ISP will have to reserve bandwidth for IPTV, this makes it more likely that the IPTV-provider and the ISP will need to work together and cannot operate independently.

- A point-to-point fibre solution without a separate channel for television will face the same situation as with DSL and IPTV, though the larger amount of bandwidth might allow the delivery of IPTV without the involvement of the ISP.

- When CATV is delivered over a separate fibre the point-to-point solution allows LLU on both the television as well as the data line and the consumer the choice of a provider and the way of delivering the signal (over IP or CATV).

The near future

In the near future there might also be a convergence of networks: A user will subscribe to one service provider and be able to access a variety of networks. The service provider will offer a bundle of networks *e.g.* FTTH combined with wireless technologies GSM, 3G, WiFi and WiMAX, DVB. The devices of the end-user will select whatever network is available and necessary. This development can be seen in:

- The offering of Unlicensed Mobile Access as offered by the Unik service of Orange and Vodafone offering broadband in combination with its mobile offerings.

- The development of FON *e.g.* its implementation by Neuf Cegetel in France. FON is a concept where users share their Wi-Fi-connection securely with other users of FON. In the implementation of Neuf, all Neuf customers share their connection with other Neuf users, creating 1.6 million hotspots accessible in France.[47]

- The implementation of software defined radio, which makes it possible to dynamically switch spectrum and protocols. This can (in theory) make a Wi-Fi-client or access point behave like a WiMAX antenna or access point or a 3G-picocell.

Technological choices determine the possibilities of the networks to support different applications and also determine both the business models and the regulatory options available. Wireless networks have several desirable capabilities, but are not able to offer the kind of bandwidth and performance that most families and businesses will desire for current and future applications. They will most likely be complementary to the wired networks. Cable and DSL-based HFC networks might offer households enough bandwidth for the coming years, but if the growth in traffic and bandwidth-intensive applications increases as in recent years neither are future proof. HFC networks will on average not appeal to businesses with over ten employees. Fibre-based networks offer all capabilities that are desired by households and businesses, where businesses will have a strong preference for point-to-point networks. For households there seems to be little difference between PON and point-to-point networks, each having its strengths. Both will see continued development, which will enable new possibilities. From a regulatory perspective a point-to-point network offers more possibilities for regulatory measures such as Local Loop Unbundling and Wholesale Broadband Access.

BUSINESS MODELS AND INVESTMENT DECISIONS

There are a variety of business models available to implement hybrid fibre and all-fibre networks. These business models are greatly dependent upon the investment decisions made by businesses and their investors. This section examines the factors that influence these investment decision and business models, such as the costs of an all-fibre network, the parameters for a business model, various kinds of business models, market parties and the risks involved.

Incumbents versus new entrants

When investing in new networks, hybrid or all-fibre, the incumbents have a different rationale from the new entrants. This will also influence their perception on what choices to make and what outcome is most desired. The government can also be an investor in new networks, this will be discussed in the next section.

An incumbent's choices are influenced by the current position it has in infrastructure and the interests of its shareholders, employees and management. The way most incumbents look at an investment in an all-fibre network is that they deem it to be too costly at the moment, compared to upgrading certain portions of their current infrastructure. For cable companies upgrading their HFC networks to carry more data services relies on installing new CMTS switches in the core and different customer premises equipment. This will allow them to move to Docsis 3.0 at a price that is almost solely related to the cost of equipment. Their current business model is such that it does not offer them large amounts of free cash flow, since revenue is mostly based on fixed fee monthly subscriptions. This leaves little basis to attract large amounts of investment either by issuing bonds or by floating new stock. It is therefore expected that these networks will move to Docsis 3.0 but will not move beyond this soon, by bringing the fibre even closer to end-users and decreasing the amount of users that share a connection. New entrants have a variety of reasons to invest in new networks. These may be to move up the ladder of investment, to create welfare benefits for the region, to gain first mover benefits etc.

For incumbents that operate a PSTN-network there are possibly three strategies to develop their networks. Each approach is favoured by some operators.

The first approach is to remain with the current ADSL2+ network and roll it out to areas that currently do not have broadband. This approach requires limited capital investment, but will also yield only limited connection speeds to the end-user. It might make the incumbent more vulnerable to new wireless and cable-based networks as well as losing customers through local loop unbundling. British Telecom has stated that it favours upgrading to ADSL2+.

- There are some incumbents that aim to upgrade their network to VDSL2, which will require them to bring fibre closer to the end-customer. Examples are KPN, AT&T, Belgacom and Deutsche Telekom. The major advantages in this approach lie in the higher speeds of the network, which allow for the introduction of new services and cost savings. The investments in the network can be significant, but are still much less than investments for an all-fibre network. Some incumbents believe that it is necessary to take an intermediate step before eventually shifting to an all-fibre network. Furthermore an investment into VDSL allows them to discourage competitors from entering the market with either an all-fibre or HFC network.[48] There are two points of criticism to this approach:

- Currently these companies still have a large cash flow from their voice-based services. However, voice revenue from fixed lines has steadily decreased in recent years and is set to decrease more in the coming years. The competition from VoIP providers, cable and ISPs might result in voice becoming just another service, equivalent to e-mail and Internet, with a similar pricing model. This could seriously affect the cash flow of the incumbents. If this is the case a larger proportion of the network might have to be financed by debt, increasing the costs of the network.

- There is little evidence that building a network to the curb now and to the home later will actually result in equal or less costs for an all-fibre network. It might end up costing more, because the way to build a DSL network efficiently might not be the same as building an all-fibre network efficiently, plus engineering costs have remained quite stable and might increase over time because of rising costs of labour, rights of way and inflation.

The upgrading of networks to VDSL seems to be in the best interest of the current shareholders and as such may be viewed as a short-term strategy. It allows the network owner freedom to invest and also to pay out dividends without increasing debts.

- There are some incumbents that have moved to all-fibre networks by bringing fibre to the building or house. Examples of this strategy are France Telecom, NTT, Korea Telecom and Verizon. The main reason for this move seems to be a competitive threat from either new entrants or cable incumbents. This strategy requires significant capital expenditure. The costs per household are estimated at between USD 500 and USD 2 500 per household, though Verizon is reporting their average is now around USD 850 per household.

There are market entrants that are rolling out hybrid-fibre[49] and all-fibre networks. In Japan and Korea new entrants like Softbank and Hanaro are entering the market aggressively and on a national scale. They benefit from the high density of housing in Japan and Korea which make their business case easier and less dependent upon capital expenditure for passive networks. In Europe examples of operators that have entered this market include Fastweb in Italy, Bredbandbolaget in Sweden, Free in France and Reggefiber in the Netherlands. Reasons for their initiatives include:

- Moving up the value chain, from an unbundled local loop operator to a facilities-based operator. The savings on leasing unbundled lines can be used to finance the network.

- A strong belief in the business case behind fibre and choosing conservatively the best areas to roll-out fibre.

- An incumbent who leaves enough room for other parties to enter the market, by not moving fast enough towards broadband development.

- A belief in a significant first mover advantage that might discourage competitors. In order to gain this first mover advantage high penetration rates are necessary. In some areas FTTH projects have been able to gain over a 70% market share in the first year, one might say making them the instant incumbent.

Whether new entrants and existing competitive telecommunications companies that make use of an unbundled local loop offer will be able to move up the value chain and build out their own network will be dependent upon local conditions, however research shows that in many cases there will not be a viable business case for new entrants presently using local loop unbundling to move to sub-loop unbundling to invest alongside incumbents.[50] New entrants are often disadvantaged compared to incumbents because they do not have access to existing civil works, like ducts and aerial plants and/or to rights of way. Furthermore they cannot use savings in capital and operational expenditure or sale of existing assets to finance the investment in the new network.

A special group of new entrants are the utility companies. In some countries *e.g.* Denmark and Canada, utilities have entered this market or have suggested that they would. The reasoning behind this is that they see investments in the passive network as an investment not unlike water, electricity, gas and sewers. They often have agreements and infrastructure that can be used to decrease the costs of a roll-out of passive infrastructure, for instance rights of way, access to buildings, ducts that cross under roads and waterways, aerial plants, etc. Their business models are geared to long-term investment with moderate but steady returns. Their existing position also decreases their risk profile when borrowing money and therefore the interest they pay. Often these networks are also owned by municipalities or have strong ties with the regions they are serving, so they are used as a tool for economic development by local governments.

Risks to a business model

With hybrid and all-fibre networks there are several risks that may influence an investor and a telecommunication network to go forward with the investment. The chosen technology presents a risk to the investor. With new and unproven technology it is unknown how the technology will perform commercially with real users. A major contributing factor is that it is unknown how users will want to use the technology and what applications will become available is unknown. It is also unknown how other technologies will develop and whether they will pose a threat. With respect to the networking technologies some of these uncertainties have been explored in the first chapter. The technology of fibre-based networks has matured in recent years so as not to be a factor of concern anymore.

Over investment in the local loop might lead to price competition that drives prices down to below the rate that allows investors to recuperate their investment. Investors have indicated that they are afraid that in the local loop the same situation of over-investment might arise as in the backhaul and trans-oceanic networks, where bankrupt competitors were pulled out of bankruptcy with clean balance sheets and competed with initial winners, leading to a second price war.

Regulatory risk is another form of risk that investors will factor in. Regulatory risk occurs when the regulator steps into the market in a manner unforeseen by the investors. This change might decrease the profitability of the organisation and its investors. The change can be the result of a regulatory requirement on the network, but also of a regulatory requirement on a competitor that will benefit that competitor. Whether regulatory risk is a potential problem depends upon the chosen business model, the vulnerability of the business model to regulatory changes, the stability of the legal framework and its interpretation, the clarity given by the regulator and the conduct of the company (and its competitors) in the market place. A business model that is based on, or can change to an open access model will suffer less from regulatory risk from structural separation, unbundling or wholesale requirements.

Cannibalisation happens when a company offers new products with a lower price and/or profit margin which substitute wholly or in part the existing products with a higher price and/or higher profit margin. This new product can threaten current revenues and profitability. In telecommunications this happens when people switch for instance from dial-up to broadband, because the fixed price of broadband allows them to save money. With hybrid fibre and all-fibre the chance of cannibalisation increases. The network moves from a situation of scarcity to a situation of abundance. With telecommunications companies in the OECD still dependent upon voice for up to 80%[51] of their revenues it becomes clear that cannibalisation by cheaper VoIP offers enabled by high bandwidth is a serious threat to existing business models.

Alternative business models

The business models employed to roll out hybrid fibre and all-fibre networks are diverse. When developing a business model there are several choices to be made on what the role of the owner of the network will be and how the costs of the network will be recovered. In order to finance the roll out of fibre-based networks several interesting business models have been developed, that will give insight into what choices there are next to a more traditional business model. These alternative models are:

- Welfare based networks.
- Customer owned networks.
- Service and advertisement financed networks.
- Open networks.

Some of the rationales behind these business models are examined below.

Welfare based networks

Telecommunications networks create large positive network externalities. It is hard for an owner of the network to internalise these externalities into the pricing of the network. There are some projects that try to internalise some of the positive externalities into the business case of rolling out a new network. For instance in Canada there is an idea to use broadband networks to achieve energy efficiency gains.[52] The benefits from the projected energy efficiency might be enough to finance the network. Similar ideas have been voiced by local governments and housing corporations when investing in new networks. The benefits from having the elderly live at home a year longer, or to be able to monitor remotely patients who would otherwise be hospitalised might be enough to finance the network. To develop these ideas in practice is often hard, because the benefits and savings often materialise over years, whereas the investment is up front. However, the ideas do show that networks are platforms on which new applications and services can be built that offer higher benefits than are visible from just looking at the business model of the network.

Customer owned networks

In a customer owned network the logic of the network is turned around. It is not the network operator or the ISP that comes to the customer and provides them with a network and a network service. In the case of a customer owned network the customers build out a network that will allow them to reach providers of services. The customers do this by bringing their network connections to a central marketplace (the central office switching location) where the service providers are present. The marketplace enables the customers individually and/or co-operatively to buy services. The development of these models is driven by the following market forces:

i) The availability of cheap fibre due to overinvestment.

ii) Less consumer lock-in through lower switching costs.

iii) More possibilities for end-users to choose the combinations of services of the combinations of service providers of their choice.

iv) Telecommunications providers having tiered charges for local connections (*e.g.* between two school locations). Sending more bits over a local link often costs more money even though the actual hardware used is exactly the same and would not incur a cost to the network provider.[53]

Whether these reasons will hold remains to be seen, since it is to be expected that telecommunications companies will adapt their business models in the face of competition. When this model is successful and reaches a critical mass it can be hard for for-profit networks to provide a competing network, since the customer-owned network can combine high-penetration rates with low costs and access to competing service providers.

Advertisement, content and service financed networks

Advertisements, content and services are often looked to as sources of revenue for network owners to pay for the networks. The benefits of having services pay for the network are that they might allow the costs of the network to be shared equitably amongst users according to the usage they make of the network, much in the same way as per minute charges paid the mobile and fixed line telephony networks. Advertisements have paid in part for the cable network and the growth of online advertising and the promise of targeted advertising have fuelled hopes that they might finance the network. Advertisements, content and services are often used in the same business model allowing users, if they wish, to pay more for content or services without advertising.

Whether or not this is a viable business model remains to be seen. Expenditures on both content and advertising are substantially less than for telecommunications networks and services and getting the pricing right for all content and services is difficult. Furthermore it makes the network owner dependent upon the service and content providers more than the other way around, which might lead to margins being squeezed by the service and content owners.[54] Disruptive technological developments might lead to a different balance in the usage patterns of services and content, which might negatively upset the finances of the network owner, similar to the introduction of VoIP. Such developments might lead to the blacklisting of new applications for fear of cannibalisation.

Open networks

There are some telecommunication firms that have indicated that they will open up their network for competitors right from the start.[55] This is similar to an unbundled offer or a wholesale offer. The business case for this model works by splitting the revenues for the different parts of the vertical stack of integrated telecommunications providers into a separated stack with passive network, active components and the services and content as separate layers. The business case for the passive network (and sometimes some of the active components) is seen as sunk capital expenditure that benefits most from a high penetration rate, which allows lower prices and/or higher margins. The network owner forgoes some of the profits that could have been made from offering connections, services and content directly to the end-user. This is compensated by guaranteed income over the fixed lines from all the operators that are offering services over the network.

Analysis by some investment firms[56] has indicated that there might be a premium for networks that focus solely on providing network access and are not involved in content or services. Margins on networks are consistently better than on content and services for telecommunications companies. Focusing on the network only would allow for lower operational expenditures and would increase operating and free cash flow.

Financial parameters for a business model

In Annex 1 some calculations have been made using a Dutch cost calculation model for FTTH-projects (summarised below as Table 2). This model has been commissioned by the Ministry of Economic Affairs in The Netherlands and validated by comparing it to Dutch FTTH projects and is used by the engineering consultancy firm Arcadis (http://ngn.arcadis.nl) to advise its clients.[57] The model calculates the price per household (connection) per month of triple play (television, broadband and telephone) offers. The model determines the average price per household connected based on the penetration rate (the amount of households that actually use the service as a percentage of the amount of houses passed/connected.) This model is included in this paper to give policy makers a view of the cost elements that are part of an all-fibre network.

Table 2. Price per household (Euros per month)

Penetration Rate	15%	25%	33%	50%	75%	100%	50% at 5% profit	50% at 7.5% profit
Triple Play	22	22	22	22	22	22	22	22
Monthly charge Passive	67,80	40,68	30,82	20,34	13,56	10,17	15,02	17,66
Monthly charge Active	19,44	17,94	17,43	16,91	16,42	16,28	14,83	15,85
VAT 19%	20,76	15,32	13,35	11,26	9,88	9,21	9,85	10,55
Total	130,00	95,94	83,60	70,50	61,86	57,66	61,70	66,06

From the model several conclusions can be drawn:

- The investment in passive and active infrastructure will be determined by the size of the area, the housing density, the type of houses, costs of repaving, the costs of the active equipment, etc. In the model, given the average housing density in the Netherlands, the cost of a passive network will range between EUR 500 and EUR 1 500, although it may be higher.

- The cost of active components is around EUR 750, but bulk purchases will result in discounts. This cost is for the largest part independent of actual take up of the service by consumers.

- Penetration rates greatly influence the monthly cost per customer. The higher the penetration rate, the lower the monthly cost.

- The monthly cost for an end-user also depends on the financing of the project. The more debt the network carries, the longer it will take for investors to recuperate their investment. At 40% debt financing and 10% per year dividend to shareholders it will take 4 years to repay the debt and for the network to start paying dividends. The kind of investors that are willing to invest in these networks are either long-term investors like pension funds or telecommunication companies who can use their existing cash flow.

- Governments can influence end-users monthly charge by influencing the costs of rolling out a network *e.g.* by the extent of the administrative charges and costs for repaving and in some countries by varying the applicable rate of the VAT-charge (many countries in the EU have two rates of VAT, a high rate at around 19% and a low rate at around 6%).

The model is limited to the Dutch situation, but it does show that there is not a lot of scope in the market place for multiple networks to roll out a new all-fibre infrastructure. If we assume a monopolist with a 100% market share (and no competition from hybrid-fibre networks), Table 2 shows the price per household in this model to be at EUR 57.66/month. When two networks roll out a network, without sharing costs, the average price for a subscription would have to be equal to the 50% marketshare subscription price of EUR 70.50/month. Adding more networks will decrease the average penetration rate and increase the average price per customer, if we assume all networks will make a profit. The increase in average price will also make it less likely people will subscribe and drive actual penetration rates down. Actual prices for a triple play offer over FTTH in the Netherlands currently range between EUR 45 and EUR 80.

Table 3. Cost of a passive network

Cost of passive network per household	250	500	750	1000	1250	1500	1750	2000	2250
Triple Play	22	22	22	22	22	22	22	22	22
Monthly charge Passive	6.17	11,87	17.56	23.26	28.95	34.64	40.34	46.03	51.72
Monthly charge Active	16.91	16.91	16.91	16.91	16.91	16.91	16.91	16.91	16.91
VAT 19%	8.57	9.65	10.73	11.81	12.89	13.97	15.06	16.14	17.22
Total	53.65	48.56	67.2	73.98	80.75	87.52	94.31	101.08	107.85

Given the parameters of the model it is also possible to enter various costs for the passive infrastructure. The investment in the active infrastructure (switches etc.) has been fixed at EUR 767. This way the monthly charges relative to the investment in passive infrastructure per household can be evaluated. This results in Table 3, which assumes a 50% penetration rate, so that at an average cost per household of EUR 2 000, the monthly charge would be at EUR 23/month. (There is an almost linear relationship between penetration rate and the monthly cost, so constructing a table similar to Table 3 and assuming a 100% penetration, the monthly charge for the passive network can be halved, therefore, at an average cost per household of EUR 2 000 it would be at EUR 23/month).

There are many factors that influence the choice for a business model. Penetration rate and capital expenditure are the main factors which influence the profitability of the model and the risk that an investor will need to face. The penetration rate influences the cost structure of a network owner and will in turn affect his pricing to such an extent that, depending on the market, it may be difficult for facilities-based competition to emerge and thrive. The impact of penetration rate on the monthly price for an all-fibre network is such that it is unlikely there will multiple networks to guarantee a competitive market. Even if we factor in existing cable and PSTN based networks, it is unlikely that there will be enough room in the market place for four or more physical infrastructures to every household. For regulators this will mean that there is a continuing possibility of (tacit) collusion in the market.

When examining the market from the point of view of investors, it becomes clear that the dynamic situation and the economics of an investment make it likely that many long-term investors will remain wary of investing in fibre to the home. The costs are substantial as is the risk posed by competing hybrid networks. Experiences with larger roll-out fibre projects in cities like Amsterdam, Paris, Verizon in the United States and in Japan, Korea and Singapore will show investors in OECD countries whether an investment in FTTH is a risk worth taking. If there is a clear first mover advantage and the competition of hybrid networks is not strong enough, long-term investors in other countries will be swayed to invest.

ROLE OF THE GOVERNMENT

The government could have a role when it comes to fibre-based networks: stimulator, producer and regulator. The role of a stimulator is defined here as removing the barriers that may impede the investment and roll out in new networks. The role of producer is defined as actually investing in new networks and the role of regulator is limited to the government's role as a telecommunications regulator trying to ensure a competitive marketplace.

New networks and the benefits that they may give societies demand a clear government vision as to what its role will be in order to balance the different demands by various stakeholders. Whether or not governments will need to play an active role and to what extent will depend on the local situation and will require a policy decision. A balanced framework for investment, such as that outlined in Figure 7, can be a helpful tool in ensuring a consistent implementation of government policy and certainty for commercial enterprises.

Some elements that should be incorporated into government policy are:

- An idea of the potential coverage of fibre based networks in terms of geography and population and the time-frame during which this may be available.
- What kind of involvement of governments is acceptable under what conditions?
- What regions are uneconomical from the point of view of a commercial operator and how can roll out in these areas be stimulated?

In general governments should remove barriers to entry and to investment, should facilitate a cost effective roll out, ensure that new services can develop, leave it to the market to the greatest extent possible to develop networks and markets, provide regulatory certainty and be vigilant in achieving a competitive marketplace for networks and services.

Stimulator

Governments on all levels, local and national, believe that the roll-out of high bandwidth fixed and wireless networks will benefit their economies and welfare. There are several areas where governments could, if necessary, help to facilitate roll-out of networks in a neutral manner without giving an advantage to either incumbents or new entrants.

In order to reduce the costs of rolling out and operating networks governments could facilitate:

- Establishing co-operation between the owners of multi-dwelling units and telecommunications companies. The goal would be to facilitate access by telecommunications companies to buildings and to decrease efforts by the owners of the buildings to facilitate multiple networks. In France, for new buildings, there is an attempt to persuade building companies by providing a certification which indicates the presence of a fibre cable accessible to all operators in the basement of the building. In Paris the local government decided to decrease the price of access to its sewers.

Local governments or government-owned utilities often own ducts which cross under roads, etc. Granting access to these facilities to operators might decrease costs for building new networks.

- Decreasing costs of repaving, administrative fees etc. leveraged by the local governments. The city of Deventer in the Netherlands agreed to charge a lower fee per meter for repaving on the condition that the network owners would arrange for the proper quality of repaving after the network had been rolled out.

- When building new neighbourhoods governments can incorporate the roll out of empty ducts throughout the site, together with other infrastructures, like sewers. This will allow easier access to customers for competing networks and might reduce the existing advantage of incumbent networks.

- Whenever governments open up roads and sidewalks for repair, providing new utility infrastructure, etc., they could allow network operators to add network infrastructure at minimal costs.

- When new networks are built governments can try to ensure greater co-ordination by operators to roll-out networks at the same time.

- In general governments should refrain from subsidising the roll-out of one network in a region unless there is clear evidence that no private investment is ready to invest in that region. There have been examples in the past where local governments paid for an ADSL-DSLAM (often to the incumbent) in the local exchange in order to get broadband access into the region. In some cases those subsidies took away whatever stimulus another operator had to enter into the region. If governments do subsidise one network to roll-out they should require that the network become accessible under equal conditions to other networks and service providers.

Governments can also stimulate the adoption of fibre based networks by end-users.

- Local governments can bundle their demands for new networks with the demands of companies to either procure a customer owned network or enter into an agreement with an existing network operator. It is important that the terms of these agreements enable competition on a services level and do not grant one operator a monopoly over those participating in the bundled demand.

- If governments are the initial customer helping to launch a new network, they should aim for this network to be open to other networks and service providers or make sure they do not pay a disproportionate amount as the initial customer.

Regulator

New fibre-based networks will pose new challenges for regulators. All networks have business models that are sensitive to roll-out costs, population density, penetration rates and therefore show significant first mover advantages and a bias toward existing networks on a local level. Various technological choices may influence regulators abilities to regulate after the networks have been built. It is therefore important for regulators to research how new technologies will influence the markets and how to best stimulate competition and balance consumers interests with the interests of network and service providers. Some points that will need to be taken into account:

- Wireless networks may not be a viable alternative for fixed networks in delivering high bandwidth to households. They will be important in many ways as a complement, and compete only for a limited range of services, or for light bandwidth users, and could play a role as a competitive constraint against hybrid and all-fibre networks. Government policies should reflect this.

- Integrated offers of wired and wireless networks (*e.g.* Quad Play) may become a competitive force. Regulators will have to be aware that network owners may want to leverage their position in one market to decrease competition in another market. For instance by denying existing and new wireless networks access to (new) wired networks.

- When there are multiple networks (cable, DSL, FTTH) regulators should identify if there are asymmetries in existing regulation and regulatory measures affecting those networks and remove the asymmetries to create a level playing field. In other words, examine what are the measures which can provide a incentive to facility-based competition.

- Regulators and governments should allow the roll-out of new networks regardless of whether there are existing networks in the area and regardless of whether these are government owned (*i.e.* they should not try to protect an existing investment in a network by a private or public/semi-public organisation). The competition between the networks will benefit the end-user.

- Business models for new networks are sensitive to roll-out costs, population density, penetration rates and therefore show significant first mover advantages and a bias toward existing networks on a local level. This may result in a different competitive situation in different regions. In one area an existing network may have such an advantage that no new players will emerge, whereas in others there will be multiple competing networks, who compete effectively. In some regions a new entrant may quickly reach a large market share, leaving little room for existing players and becoming the incumbent overnight. This will require regulators to balance national policies with local realities.

- Providing regulatory certainty for network operators when they roll out new networks should focus on the success of the networks and not on the success of the services provided over those networks. Regulators should keep the provision of services open and competitive and not grant a monopoly on services when providing regulatory certainty for the investment in networks.

Some governments have policies in place that facilitate local loop unbundling and wholesale broadband access. These policies should anticipate the technical specifics of new networks in order to facilitate local loop unbundling and wholesale access. Some specifics that need to be taken into account are:

- The space that street cabinets of new VDSL networks require is substantial. This may result in local governments and citizens objecting to the placement of multiple street cabinets in the same location for esthetical reasons. National policies should take these local problems into account and allow for the possibility of local solutions. Such solutions could include: collocation in street cabinets, requiring the construction of less obtrusive street cabinets (indoors, underground, etc.), or overruling local objections and requiring local governments to allow multiple street cabinets.

- A problem of stranded investment is raised by the closing of existing MDF-locations if these are currently used by alternative operators.

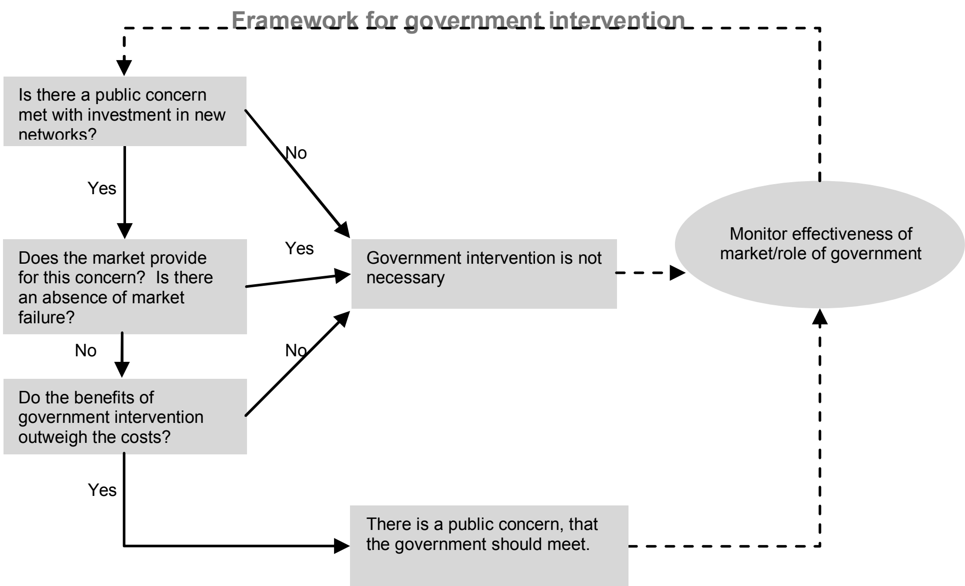
- As shown there are different ways to facilitate unbundling of PON-networks. If unbundling is a regulatory tool, then the question of whether unbundling should be incorporated in network design from the start needs to be considered and balanced against the need to allow investors to take their own technological decisions.

- Policies should enable local traffic to be exchanged locally by allowing local interconnections between regulated and unregulated networks. When IP-traffic from one ISP's customer to another ISP's customer (*e.g.* P2P traffic or security camera) is within a region, policies should enable the traffic to stay local and not to have to be transported over backhaul networks across the country to be exchanged between two ISPs. This will decrease pressure on the backhaul links and enable better competition between ISPs, lower costs and higher quality of service for end-users. To facilitate this it may be necessary to either require the incumbent to allow local interconnection or to have a neutral and open interconnection point, where customers, network providers and service providers can connect to the network.

Investor

In many OECD countries there is a debate whether the government (local governments) should do more than stimulate and regulate the roll out of fibre based networks and actively invest in new networks. It is not within the scope of this paper to fully examine the benefits and costs of such interventions in the market place. As a general rule government intervention in the market should be as minimal as possible. If governments do invest in new networks, they should determine to what extent this is necessary because of market failure and only invest to correct this failure. Figure 8 provides a general framework that can be used to determine whether government intervention is warranted.

Figure 8. Framework for government intervention



There are three questions that governments need to answer before they decide to invest in new networks.

i) Is public welfare enhanced with investment in new networks?

The new generation of telecommunications networks do provide significant advantages over the current generation of networks. They provide more bandwidth at lower cost, allowing for new services stimulating the economy and efficiency. Positive externalities can also be anticipated. New networks can be viewed as enhancing public welfare.

ii) Is there market failure?

Governments should clearly identify whether the market already provides the networks that are required and if there is market failure. If the networks are already provided and there is market failure, government intervention should be limited to removing entry barriers to new entrants and if necessary regulating existing networks to compensate for market failure. If the required networks are not available and no market investment is to be expected in a foreseeable period and this is due to market failure, then governments can consider investing themselves.

iii) Do the benefits of government intervention outweigh the costs?

Calculating the benefits of new networks is not easy. New networks provide a combination of tangible and intangible benefits. Benefits follow from enabling new services, lowering transaction costs, realising efficiencies, thereby contributing to economic growth and public welfare. Investment in new networks often will not result directly in creating a substantial number of new jobs, drawing new industries to a region or significant changes to the economic structure of a region. Economic growth and public welfare are the result of a combination of factors of which the availability of telecommunications infrastructure is one. It can be said that if adequate telecommunications infrastructure is not present, it will be harder for regions to increase economic growth and public welfare.

When governments do make the political decision to intervene in advanced telecommunications networks they will have to determine how they intervene. The intervention should foster competition and result in an open network that supports a competitive environment. Some elements to be considered for intervention and investments are:

- Regulatory interventions should be limited to the extent that they compensate for the market failure.

- When governments subsidise new networks or participate in public-private partnerships these should result in open networks that foster competition. It may be the case that a monopoly in the fixed infrastructure is unavoidable, but this should not lead to a monopoly either in wireless infrastructures built on top of this fixed infrastructure or in the provision of services over this infrastructure.

- Government's role in investing in physical infrastructures and provisioning services should be on a gradual scale with roughly the following steps:

i) Digging trenches and laying ducts, removing a significant part of the costs of rolling out a network.

ii) Providing passive network infrastructure to which network providers can connect their active infrastructure.

iii) Providing an active network over which others can provide their services.

iv) Providing services over the network to end-users.

- If governments are investing in networks and services, they should periodically evaluate whether there is still a necessity to do so and preferably state a fixed term at the start of the investment when the decision will be evaluated.

- The business model of the network should not be made dependent upon the provision of services and network connections should be available separate to services.

- A neutral and open network also requires a neutral and open interconnection point, where customers, network providers and service providers can connect to the network.

- The network topology chosen for the network should be designed with competition in mind. A point to point network is therefore desirable over a PON-network.

- Governments should differentiate as little as possible between service providers and users of the network. Differentiation between users and service providers should reflect costs, efforts and service levels, allowing users to become service providers without an additional barrier.

CONCLUSION

The technology for telecommunications networks has quickly developed in the last decades. In the core of the network copper and wireless links have been replaced by fibre. Technological advances in fibre and laser technology have resulted in an abundance of available bandwidth in the core and backhaul networks and a subsequent drop in prices for bandwidth. This has enabled businesses and consumers to access the services of their choice on a global scale. In order to be able to deliver new services over the network, more bandwidth is necessary for the end-user and this has prompted telecommunications providers to evaluate various ways of delivering more bandwidth to end-users.

Growth of bandwidth usage has been between 50% to 100% per year globally. Every new advance in bandwidth has enabled new services over the available bandwidth. Unfortunately bandwidth and service usage by end-users is not sufficiently documented. This makes it hard for policy makers to know what is enough bandwidth and to make international comparisons. Average demand of a household for bandwidth is expected to be around 50 Mbit/s downstream and 10-50 Mbit/s upstream for the period 2010-2020. The more bandwidth that becomes available to end-users, the easier it becomes to develop new services and technologies and for end-users to buy services from competing service providers.

The development of fibre networks for long haul and back haul has shown that telecommunications networks may be over provisioned with capacity from the start, which might lead to intense competition on marginal costs. This has made investors wary of investing in new networks such as Fibre to the Home. The technology used in long haul and back haul networks is now migrating to the edges, ensuring that there will be enough capacity for future use.

Evaluation of the various technological options has shown that wireless networking technologies have excellent characteristics of mobility and flexibility. However the bandwidth they can deliver is limited compared to wired technologies. The reality of wireless is such that in many urban areas, because of its shared nature and electromagnetic properties, it may be neither a technical nor an economically viable choice as a first mile technology. It will however be important in and around houses and businesses and for mobile use.

Hybrid fibre-copper wired networks have significant advantages over all-fibre networks from a financial point of view. They require less investment in the local loop by reusing the existing infrastructure. Broadband over Powerline is viewed as a potential “third wire” to compete agains DSL and cable but it is too early to assess the performance of this technology. Cable and DSL-based networks are already deployed worldwide and it is likely that Docsis 3.0 and VDSL2 respectively will be the upgrade technologies chosen by most telecommunications companies. Both, however, have limits to the amount of bandwidth they can provide to end-users and no clear upgrade paths should bandwidth become constraint.

All-fibre networks have no foreseeable bandwidth problems. Both PON and Point-to-Point Ethernet networks are capable of delivering a wide range of existing and new services and have clear upgrade paths should available bandwidth become a constraint. The choice of network topology will determine the ways a regulator can regulate an all-fibre network.

The business models for fibre-based networks depend on high upfront investments in infrastructure. Penetration rate and capital expenditure are the main factors, which influence the profitability of the model and the risk that an investor will need to face. The penetration rate influences the cost structure of a network owner and will in turn affect pricing to a large extent so as to raise questions as to whether, in a given market, facilities-based competition will emerge. The impact of penetration rates on the monthly price for an all-fibre network is such that it is unlikely there will multiple networks to guarantee a competitive market. Even if we factor in existing cable and PSTN-based networks, it is unlikely that there will be enough room in the market place for four or more physical infrastructures to every household. For regulators this will mean that there is a continuing possibility of (tacit) collusion in the market.

When examining the market from the point of view of investors, it becomes clear that the dynamic situation and the economics of an investment make it likely that many long-term investors will remain wary of investing in fibre to the home. The costs are substantial and the risk posed by competing hybrid networks can be substantial. Experiences with larger roll-out fibre projects in cities will be important in helping evaluate whether investment in FTTH is a risk worth taking. If there is a substantial first mover advantage and the competition of hybrid networks is not strong enough, long-term investors might be swayed to invest. For the moment market dynamics are more favourable to short-term investors and hybrid fibre networks and in some locations to local and regional FTTH networks.

Governments and municipal governments could, under certain circumstances, play a positive role in stimulating the roll-out of fibre-based networks by removing barriers to entry and stimulating the usage of these networks. Working together with telecommunications companies to decrease the investment through the sharing of costs and co-operation with building owners can be beneficial. Governments should be aware that their initiatives can have a distorting effect on the market and carefully balance their actions. When governments act as an investor they should be even more aware of their effect on the market place and choose a role that influences the functioning of the market as little as possible.

For regulators the introduction of new networks will bring new questions on how to regulate new networks and will put a different perspective on existing questions. Regulators will have to take into account questions of topology of networks, regional differences, the position of competitive networks in the face of investments by parties with significant market power and asymmetric regulation of different network infrastructures.

APPENDIX A. COSTS OF AN ALL-FIBRE NETWORK

In the first section the factors that are involved with rolling out a fibre based network were examined. For many policy makers it is hard to obtain an overview on how the various parameters in building out a network are influencing the total cost of connecting an end-user. To obtain a better understanding of these parameters and the costs, the Ministry of Economic Affairs in the Netherlands commissioned a study by Arcadis (see http://ngn.arcadis.nl/) an engineering consultancy to build a cost-model of an all-fibre network. The cost-model has been validated by the costs of several Fibre to the Home projects in the Netherlands. The model is geared towards the Dutch situation and can therefore not be easily copied by other nations, but it does give policy makers a feel for the costs that are involved and how costs for active and passive networks influence the monthly costs for the end-users.

The model makes the following assumptions:

- The network is a 100 Mbit/s Ethernet-based end-to-end network and not a PON-based network.
- The infrastructure is buried underground and there is no usage of aerial infrastructures.
- The costs of triple play services are: television EUR 10/month, telephony EUR 3.50/month and Internet access EUR 8.50/month.
- The costs for the depreciation of the pavement to the local government are EUR 4.50. In the Netherlands this can be as high as EUR 22, but for instance the municipality of Deventer has decided to lower this charge to EUR 2. This difference saves on average EUR 200 per household in passive infrastructure.
- A separate fibre for analogue CATV is used.
- Net housing density is used, with the size of parks deducted from the area size.
- Interest on loans is 7%.
- Economic write off period for the network at 25 years.
- The areas are based on Dutch neighbourhoods.[58] The total make up of the city most likely does not represent an average town in the Netherlands, but for the interest of this study this is less relevant.
  - De Baarsjes, Amsterdam: A high density, medium rise multi-dwelling area
    - 8 543 medium rise apartments
    - 55.76 hectares
  - Minervalaan, Amsterdam: A medium density, medium rise multi-dwelling area
    - 2 846 medium rise apartments
    - 51.1 hectares
  - Bateau-Noord, Nieuwegein: (mixed area suburban area)
    - 2 283 low rise one family houses
    - 1 074 medium rise apartments
    - 103 hectares

- Doorslag, Nieuwegein (medium density suburban area)
  - 2 134 low rise one family houses
  - 534 medium rise apartments
  - 106 hectares
- Zuilesteijn, Nieuwegein (low density suburban area)
  - 2 313 low rise family houses
  - 474 medium rise apartments
  - 163 hectares
- High rise area, not based on real neighbourhood
  - 600 apartments
  - 6 hectares

Based on these numbers the model returns the following results:

- The average price per house connected is calculated at EUR 872 for the passive infrastructure and EUR 767 for the active infrastructure. For a total average price of EUR 1 639 per household.
- Passive infrastructure costs between EUR 549 and EUR 1 189.
- Active infrastructure has a relatively fixed price of EUR 767 on average. This is because the price is dependent upon the per-port cost of central switches and customer premises equipment.
- The cost of passive infrastructure is 53% of the capital expenditure.

Area	Size area	Low rise	Medium rise	High rise	Total	Per house, passive	Total passive	Per house, active	Total active
High density medium rise	56 ha.	0	8.543	0	8.543	€ 736	€ 6.286.238	€ 764	€ 6.524.164
Medium density medium rise	51 ha.	0	2.846	0	2.846	€ 795	€ 2.263.496	€ 767	€ 2.184.148
Mixed area suburban	103 ha.	2.283	1.071	0	3.354	€ 960	€ 3.218.259	€ 766	€ 2.570.561
Medium density area suburban	106 ha.	2.134	534	0	2.668	€ 1.021	€ 2.724.278	€ 771	€ 2.058.335
Low Density Suburban Area	163 ha.	2.313	474	0	2.787	€ 1.189	€ 3.313.453	€ 770	€ 2.145.046
High Rise Area	6 ha.	0	0	600	600	€ 549	€ 329.469	€ 792	€ 475.440
TOTAL	485 ha.	6.730	13.468	600	20.798	€ 872	€ 18.135.193	€ 767	€ 15.957.694

Based on these numbers, the impact of various penetration rates have on the average price per household per month can be determined. The numbers below are based on 60% private financing and 40% debt financing at 7% interest. The desired profit margin is 10%. Taxes are included in the model. The active equipment is replaced every seven years at the same cost as at the start. The model might not be fully accurate, since it has taken in only limited financing for staff of EUR 120.000, but since the cost of staff can be calculated on a monthly basis this can be added in later. However in the cost of the Triple Play offer a part of staff costs has been included. The triple play offer[59] is priced at EUR 22 per month, which is consistent with prices both in France and in The Netherlands for triple play offers on DSL and FTTH networks and does include staff costs in these countries. The other charges are for the network, regardless of whether services are being used or not. There is no extra income in the model from service providers offering services and differentiation in speeds.[60] The numbers in the last 4 columns show the effects of a different profit margin and of a 40% - 60% - 80% growth over 3 years.

Penetration Rate	15%	25%	33%	50%	75%	100%	40/60/80	50% at 5% profit	50% at 7.5%	40/60/80 at 7.5%
Triple Play	22	22	22	22	22	22	22	22	22	22
Monthly charge Passive	67,80	40,68	30,82	20,34	13,56	10,17	13,09	15,02	17,66	11,37
Monthly charge Active	19,44	17,94	17,43	16,91	16,42	16,28	16,16	14,83	15,85	15,13
VAT 19%	20,76	15,32	13,35	11,26	9,88	9,21	9,74	9,85	10,55	9,21
Total	130,00	95,94	83,60	70,50	61,86	57,66	60,98	61,70	66,06	57,71

What can be seen from this table is that the cost of active equipment is a high burden on the monthly costs, up to as much as 28% of the costs. It also remains relatively unchanged throughout the model, regardless of penetration rates and profit margins on capital. This is due to the recurring charges every seven years. The model does keep prices at a fixed level for the 25 year life of the network and incurring these charges 3 times. Whether or not this is realistic is hard to say. On the one hand it could be argued that prices for active components are decreasing year-on-year and the growth of the market because of fibre to the home projects, would allow for a significant decrease in costs over 25 years, both for customer premises equipment and for the core switches. On the other hand it could be argued that through the years more functionalities will be added to the network and that for this given price the end-user will get more and more features. Another important aspect of the model is that even though some prices will go up through the years for the most part the model is not affected by inflation. This means that the price for the network each year will be a smaller part of a household's budget, leaving more room for services.

Modelling Sun City

Sun City in Arizona, United States is a retirement community for active seniors aged 55 and over. In this sense it is a good model of a relatively affluent suburban community in the United States. If the network were built there on the same model this would result in the following investment:

Calculation of investment in Sun City

Area	Size Area	Low Rise	Medium Rise	High Rise	Total	Per house passive	Total Passive	Per house Active	Total Active
Sun City 1	945 ha.	6.933	0	0	6.933	€ 2.151	€ 14.909.722	€ 764	€ 5.299.929
Sun City 2	945 ha.	6.933	0	0	6.933	€ 2.151	€ 14.909.722	€ 764	€ 5.299.929
Sun City 3	945 ha.	6.933	0	0	6.933	€ 2.151	€ 14.909.722	€ 764	€ 5.299.929
Sun City 4	945 ha.	6.933	0	0	6.933	€ 2.151	€ 14.909.722	€ 764	€ 5.299.929
TOTAL	3.780,0000 ha.	27.732	0	0	27.732	€ 2.151	€ 59.638.888	€ 764	€ 21.199.716

The model cannot deal with an area size of more than 1 000 hectares, so the area is split up in 4 areas of equal size. The price per passive connection goes up to EUR 2 151 per household. At 50% market penetration over 25 years this means that the charge for the passive connection will rise to EUR 49.35. Passive will be EUR 16,50 and VAT will be EUR 16.69, for a total charge of EUR 104.54/month. However these numbers are no guarantee of the actual costs, since there are huge differences between the United States and the Netherlands and the model is not designed for the US situation. It is therefore only given to give readers an idea of how this model might work out in a different country with different population densities.

APPENDIX B. COMPARISON BETWEEN NETWORKING TECHNOLOGIES

Technology	Users	Maximum speed download (Mbit/s)	Maximum Speed upload	Minimum Average Speed/user download	Minimum Average Speed/user upload	Max Streams download (5 Mbit/s)	Min Streams/ user download	Max Streams upload	Min Streams/ user upload	Min Time to Download 1 Gigabyte in (hr:min:sec)	Max. Time to download 1 Gigabyte (hr:min:sec)	Min. Time to upload 1 Gigabyte (hr:min:sec)	Max. Time to upload 1 Gigabyte (hr:min:sec)
HSDPA/HSUPA	1	14	6	14	6	3	3	1	1	0:09:31	0:23:09	0:09:31	0:23:09
HSDPA/HSUPA	20	14	6	1	0,3	3	0,14	1	0,06	0:09:31	0:23:09	3:10:29	7:42:58
Wifi 802.11g	1	54	54	54	54	11	11	11	11	0:02:28	0:02:28	0:02:28	0:02:28
Wifi 802.11g	20	54	54	3	3	11	1	11	1	0:02:28	0:02:28	0:49:23	0:49:23
Wifi 802.11n	1	248	248	248	248	50	50	50	50	0:00:32	0:00:32	0:00:32	0:00:32
Wifi 802.11n	20	248	248	12	12	50	2	50	2	0:00:32	0:00:32	0:10:45	0:10:45
WiMAX	1	40	40	40	40	8	8	8	8	0:03:20	0:03:20	0:03:20	0:03:20
WiMAX	20	40	40	2	2	8	0,40	8	0,40	0:03:20	0:03:20	1:06:40	1:06:40
WiMAX	250	40	40	0,16	0,16	8	0,03	8	0,03	0:03:20	0:03:20	13:53:20	13:53:20
ADSL	1	24	4	24	4	5	5	1	5	0:05:33	0:38:06	0:05:33	0:38:06
ADSL	20	24	4	24	4	5	5	1	5	0:05:33	0:38:06	0:05:33	0:38:06
ADSL	250	24	4	24	4	5	5	1	5	0:05:33	0:38:06	0:05:33	0:38:06
VDSL2	1	50	50	50	50	10	10	10	10	0:02:40	0:02:40	0:02:40	0:02:40
VDSL2	20	50	50	50	50	10	10	10	10	0:02:40	0:02:40	0:02:40	0:02:40
VDSL2	250	50	50	50	50	10	10	10	10	0:02:40	0:02:40	0:02:40	0:02:40
Docsis 2.0	1	38	27	38	27	8	8	5	5	0:03:31	0:04:56	0:03:31	0:04:56
Docsis 2.0	20	38	27	2	1	8	0,38	5	0,27	0:03:31	0:04:56	1:10:11	1:38:46
Docsis 2.0	250	38	27	0,15	0,11	8	0,03	5	0,02	0:03:31	0:04:56	14:37:12	20:34:34
Docsis 3.0	1	160	120	160	120	32	32	24	24	0:00:50	0:01:07	0:00:50	0:01:07

Technology	Users	Maximum speed download (Mbit/s)	Maximum Speed upload	Minimum Average Speed/user download	Minimum Average Speed/user upload	Max Streams download (5 Mbit/s)	Min Streams/ user download	Max Streams upload	Min Streams/ user upload	Min Time to Download 1 Gigabyte in (hr:min:sec)	Max. Time to download 1 Gigabyte (hr:min:sec)	Min. Time to upload 1 Gigabyte (hr:min:sec)	Max. Time to upload 1 Gigabyte (hr:min:sec)
Docsis 3.0	20	160	120	8	6	32	2	24	1	0:00:50	0:01:07	0:16:40	0:22:13
Docsis 3.0	250	160	120	1	0,48	32	0,13	24	0,10	0:00:50	0:01:07	3:28:20	4:37:47
Powerline	1	27	18	27	18	5	5	4	4	0:04:56	0:07:24	0:04:56	0:07:24
Powerline	20	27	18	1	1	5	0,27	4	0,18	0:04:56	0:07:24	1:38:46	2:28:09
Powerline	250	27	18	0,11	0,07	5	0,02	4	0,01	0:04:56	0:07:24	20:34:34	6:51:51
Fibre P2P 100Mbit/s	1	100	100	100	100	20	20	20	20	0:01:20	0:01:20	0:01:20	0:01:20
Fibre P2P 100Mbit/s	20	100	100	100	100	20	20	20	20	0:01:20	0:01:20	0:01:20	0:01:20
Fibre P2P 100Mbit/s	250	100	100	100	100	20	20	20	20	0:01:20	0:01:20	0:01:20	0:01:20
Fibre P2P 1000Mbit/s	1	1000	1000	1000	1000	200	200	200	200	0:00:08	0:00:08	0:00:08	0:00:08
Fibre P2P 1000Mbit/s	20	1000	1000	1000	1000	200	200	200	200	0:00:08	0:00:08	0:00:08	0:00:08
Fibre P2P 1000Mbit/s	250	1000	1000	1000	1000	200	200	200	200	0:00:08	0:00:08	0:00:08	0:00:08
Fibre BPON	1	622	155	622	155	124	124	31	31	0:00:13	0:00:52	0:00:13	0:00:52
Fibre BPON	20	622	155	31	8	124	6	31	2	0:00:13	0:00:52	0:04:17	0:17:12
Fibre BPON	32	622	155	19	5	124	4	31	1	0:00:13	0:00:52	0:06:52	0:27:32
Fibre GPON	1	2500	1250	2500	1250	500	500	250	250	0:00:03	0:00:06	0:00:03	0:00:06
Fibre GPON	20	2500	1250	125	63	500	25	250	13	0:00:03	0:00:06	0:01:04	0:02:08
Fibre GPON	32	2500	1250	78	39	500	16	250	8	0:00:03	0:00:06	0:01:42	0:03:25
Fibre GPON	64	2500	1250	39	20	500	8	250	4	0:00:03	0:00:06	0:03:25	0:06:50
Fibre GPON	128	2500	1250	20	10	500	4	250	2	0:00:03	0:00:06	0:06:50	0:13:39
Fibre EPON	1	1250	1250	1250	1250	250	250	250	250	0:00:06	0:00:06	0:00:06	0:00:06
Fibre EPON	20	1250	1250	63	63	250	13	250	13	0:00:06	0:00:06	0:02:08	0:02:08
Fibre EPON	32	1250	1250	39	39	250	8	250	8	0:00:06	0:00:06	0:03:25	0:03:25

NOTES

1 Based on Computer Netwerken 4e editie, A. Tannenbaum, Pearson Prentice Hall, 2003.

2 Press Release Siemens New record – Siemens researchers achieve transmission rates of 107 Gbits per second over a single fibre channel using purely electric processing in transmitter and receiver http://www.siemens.com/index.jsp?sdc_p=fmls5uo1426061ni1079175pcz3&sdc_bcpath=1327899.s_5.

3 There are two kinds of Wavelength Division Multiplexing: *i)* Dense Wavelength Division Multiplexing (DWDM), where channels are close together with little frequency space in between, allowing for use of the entire spectrum and many channels and *ii)* Coarse Wavelength Division Multiplexing (CWDM) where there is much more difference between the channels allowing for less channels, but much cheaper equipment. In layman's terms CWDM uses a distinctive colour for every channel and DWDM uses a slightly different colour for every channel.

4 Datasheet NEC Spectralwave 160, http://www.necam.com/onsd/collateral/SW160_datash.pdf.

5 Cables are for instance rodent protected. Squirrels, rats and other rodents have been known to bite on the cables. Undersea cables are protected by steel against sharks, fishermen's nets etc. http://www.nyquistcapital.com/2006/11/27/squirrels-ate-my-fios/.

6 This type of cable is used by Lijbrandt Telecom in Hillegom, The Netherlands. They run fibre close to the end-users location, where active equipment changes the signal into an electrical signal over the twisted pair for telephony, the CAT5/6 for data and coaxial cable for analogue TV. They currently do not use the fibre part of the cable to deliver data to the house, though it has been connected to their backhaul networks. Currently the CATV, data and PSTN line are connected. Source: Fred Terwijn, Marketing Department, Lijbrandt Telecom.

7 Geo stationary satellites are located at a distance of 35 800 kilometers from the surface of the earth. A roundtrip to and from the satellite will therefore be 71 600 kilometers or around 0.54 seconds (almost twice the circumference of the earth) and much longer than the longest fibre routes on earth. (See footnote 8.)

8 Twentsche Kabel Fabriek, datasheet broadband fibre optic cables http://www.tkf.nl/documentatie/pdfEN/TKF-T-5-EJ06M02c.pdf.

9 At these distances the speed of light in fibre becomes an issue for the time it takes between two points for communications to make a round trip. The speed of light is about 2/3 of the speed of light in vacuum. The commonly used route through the Mediterranean, past Suez, India and Singapore between the United Kingdom and Japan has an approximate length of 27 000km. Round trip time for communications is over 0.2 seconds, which is the threshold for real-time communications. Prof. Murai at the OECD "Future of Internet" conference in April 2006 suggested we needed straighter fibre-optic routes to overcome this potential problem, because in a straight line, the distance London-Tokyo is only 9 600 km. However this route goes via Norway and Siberia with obvious problems for building the line. There are some fibre optic networks in use that take the trans-Russia/Siberia route past oil-pipelines.

10 http://www.subtelforum.com/Issue%2018.pdf, Marc Fullenbaum, "Secrets and lies in regional systems", *Submarine Telecomforum*, Issue 18, January 2005.

11 The latest network long-haul submarine network to go live is FALCON. Quote: "Deployment of FALCON is underway, with some segments already live or nearing full service launch. Self healing Gulf loop, providing maximum design capacity of 1.28 Tbps. Initial launch capacity 50 Gbps. Four fibre pair route

linking the Gulf to Egypt and India. Design capacity of 2.56 Tbps, with initial launch at 90 Gbps. Approx. length 10,300km." http://www.flagtelecom.com/index.cfm?page=4023.

12 "Verizon to Build Trans-Pacific Express": http://www.officeroutlook.com/news/Services/1522.htm.

13 "A View of the Submarine Systems Supply industry", Georges Krebs, *Submarine Telecoms Forum*, May 2006, http://www.subtelforum.com/Issue%2026.pdf.

14 "ATM's Not Dead!", 14 December 2006 http://www.lightreading.com/document.asp?doc_id=112852.

15 Networks based on a common core are BT's 21CN network, KPN's ALL-IP network and Telstra's proposed Common Core network.

16 "Internet traffic growth: Sources and implications", Andrew M. Odlyzko, University of Minnesota, http://www.dtc.umn.edu/~odlyzko/doc/itcom.internet.growth.pdf.

17 "The Impact and Implications of the Growth in Residential User-to-User Traffic", Cho *et. al.* Sigcom'06. http://www.sigcomm.org/sigcomm2006/discussion/showpaper.php?paper_id=21. This paper shows that for Japan only 30% of traffic is international traffic.

18 http://www.ams-ix.net/ttm/stats.php?sender=matrix&receiver=matrix&size=small&type=delay&time=now-24h&submit=submit.

19` http://www.akamai.com/html/about/press/releases/2006/press_110606.html.

20 Van de Meent cites cases where 100 milliseconds peak traffic was multiple times higher than the 5 minute average. "Network link dimensioning: a measurement and modeling based approach", R. van de Meent, 2006, CTIT Ph.D.-thesis series number 06-79, http://wwwhome.cs.utwente.nl/~meentr/research/dl.php?thesis-rvdmeent-network-link-dimensioning.pdf.

21 http://www.xs4all.nl/uk/allediensten/toegang/bdsl/specificatiessdsl.php.

22 "The Impact and Implications of the Growth in Residential User-to-User Traffic", Cho *et. al., op.cit.*

23 A similar calculation is given by Joel Goergen (Force10 Networks) and Mark Nowell (Cisco) when presenting the need for 100Gbps Ethernet: http://grouper.ieee.org/groups/802/3/hssg/public/mar07/goergen_01_0307.pdf.

24 New digital, Internet-enabled, security cameras have higher resolutions than analogue cameras and will have rates of around 2-7mbit/s per camera. A small size company might need up to six of these to cover all angles: http://www.axis.com/products/video/design_tool/calculator.nl.htm Axis 210 camera, 30 frames/s, 704*576 resolution.

25 *Nieuwe generatie netwerken in Europa, Breedband in 2011 en daarna*. Arthur D. Little for Liberty Global, 2006, http://www.vecai.nl/downloads/docs/ADL_Report.pdf.

26 Information provided by Clearmind Consultancy shows estimated savings of between EUR 10 000 and EUR 30 000 per year on ICT-expenditure for an SME when moving from the current telecommunications to a broadband connection of 100 Mbit/s.

27 HSDPA and beyond, Whitepaper, Nortel: http://www.nortel.com/solutions/wireless/collateral/nn_110820.01-28-05.pdf

28 "Backhaul Packs 'em in", 13 December 2006, http://www.lightreading.com/document.asp?doc_id=112773.

29 Wireless Last Mile, Final Report SES-2006-9, Steve Methley, Plextek, report for Ofcom, 20 November 2006: http://www.ofcom.org.uk/research/technology/overview/ese/lastmile/

30 The 500 Mhz-2.5 Ghz range has the best properties for broadband wireless networks. Even if that full 2000Mhz were freed for broadband access it would deliver a maximum of 6000-8000 Mbps (at 3-4 bits per

Hz). If shared among 100 users there would be 30mbps upstream and 30mbps downstream available per user. It is highly unlikely that this amount of spectrum will be available in the coming decades in these bands. This leaves only the higher bands available for broadband and these suffer from poor performance when it rains, over large distances and when there is no line of sight.

31 Tannenbaum, 131.

32 Source: http://en.wikipedia.org/wiki/Image:ADSL_Line_Rate_Reach.gif, Similar graphs available from *e.g.*: Tanenbaum, Alcatel Lucent etc.

33 The exact distances will vary based upon various factors, like age and quality of the line, shielding, amount of lines in a bundle and other things that can influence the quality of the line.

34 UK's Broadband Local Loop Lengths: http://www.ispreview.co.uk/cgi-bin/news/viewnews.cgi?id=EEFplFyZEkrNkluWdw and Loop Lengths and Architecture presentation at IEEE EFM, Raleigh, NC, Jan 14-16th 2002: www.ieee802.org/3/efm/public/jan02/mickelsson_1_0102.pdf.

35 "Optical Access Networks: Is economics still the sticking point?", Presentation by Roy Rubinstein at Optical Network Europe 2006: http://fibers.org/dl/one/presentations/07.RoyRubenstein.ppt.

36 "The business case for sub-loop unbundling in The Netherlands", Anaylys, 2006, report written for OPTA. http://www.opta.nl/download/Analysys+Final+Report%2Epdf.

37 An average household (two parents, two children) will often have 2-3 televisions, 1-2 personal computers and 1 or more recording devices. In some OECD countries larger households are also common. Combined usage of televisions etc. might lead to a higher demand in HDTV-streams than the 3-5 possible.

38 Netwerkstructuur Hoofdnet, picture of the Essent @ Home network: http://www.corp.home.nl/NR/rdonlyres/CD94491F-9967-411A-81DF-717747D4F116/0/hoofdnetekc.gif.

39 "Data Over Cable Service Interface Specifications, Docsis 3.0", Cable Television Laboratories Inc. http://www.cablemodem.com/downloads/specs/CM-SP-PHYv3.0-I02-061222.pdf.

40 "Cable Confronts Bandwidth Crunch", 24 January 2007, http://www.lightreading.com/document.asp?doc_id=115344&site=cdn.

41 "The Technology of Broadband", Peter Darling, page 14, *Telecommunications Journal of Australia*, Volume 56 No/3/4, and http://tprc.org/papers/2003/246/Tongia-PLC.pdf.

42 In terms of the exchange rate between the Euro and Dollar in early 2007.

43 Analogue TV is a cheap way of distributing TV-channels in a house. With digital TV every TV in the house needs a dedicated decoder, which adds to the cost of the roll-out.

44 http://www.ieee802.org/3/av/ and in an e-mail with Glen Kramer the chair of the IEEE 802.3av working group.

45 Presently 28 of the 30 OECD countries use local loop unbundling as part of their regulatory policy. Mexico is discussing the possibility of requiring unbundling.

46 Based on a presentation by Professor Sirbu at OECD.

47 More ISPs are looking into using FON or FON-like technology *e.g.* Time Warner in the United States.

48 http://www.friedlnet.com/product_info.php?cPath=43_47&products_id=4075.

49 The hybrid part is in the last 100 meters to the end customer to allow for the use of existing wiring in buildings or to make use of cheaper active equipment.

50 "The business case for sub-loop unbundling in The Netherlands", Anaylys, 2006, report written for OPTA. http://www.opta.nl/download/Analysys+Final+Report%2Epdf.

51 A significant part of that may be in mobile voice tariffs. In fixed-line networks this ratio is often lower. However the convergence of networks enabled by new high bandwidth networks and competition will also be felt in the mobile networks.

52 "An alternate strategy for FTTH", presentation by Bill St. Arnaud (CANARIE) http://www.sandelman.ca/tmp/Green-Broadband.pdf.

53 It has been the author's experience that a fibre connection between two locations would double in price going from 34 Mbit/s to 155 Mbit/s and double again when going to 655 Mbit/s or 1 Gbit/s, even though neither the active components (switches etc.) nor the fibre itself would need to be changed.

54 Examples of such a squeeze are the negotiations between the NFL in the United States and the cable companies and of music companies with iTunes.

55 Networks that have indicated they will follow this business model are Free in France and KPN in the Netherlands.

56 "'Wholesale Salvation', Retail-Wholesale split offers upside", December 2006, Bear Stearns available at: http://www.ccc.asn.au/files/pressrelease/paper_17.pdf and "The Dumb Pipe Paradox", Bernstein Research, 27 February 2006

57 The total costs seem to be in line with costs elsewhere. Chungwha Telecom reserves around USD 1000 per household for an investment in FTTH: http://www.lightreading.com/document.asp?doc_id=113797.

58 Sun City, Arizona, United States has a housing density of seven houses per hectare. The Netherlands averages between 15 and 40 houses per hectare.

59 Whether or not this telephony charge is a fixed rate fee for calling nationally and internationally is greatly dependent upon national circumstances. In France it often is. In the Netherlands it often is not.

60 There is also no technical reason to offer people less bandwidth on the local network, as the limits on the local network are set by the speeds of the lasers in the network equipment and there is no cost associated with offering higher or lower speeds on the local networks. It is more expensive to offer people less speed on the local network, because that requires administration. Speeds to the Internet can be managed, for instance, by setting bandwidth caps, by limiting bandwidth to the Internet or by setting different contention rates.