Tijdschrift van het NERG

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DE VERENIGING NERG

Het NERG is een wetenschappelijke vereniging die zich ten doel stelt de kennis en het wetenschappelijk onderzoek op het gebied van de elektronica, signaalbewerking, communicatie- en informatietechnologie te bevorderen en de verbreiding en toepassing van die kennis te stimuleren.

BESTUUR

LIDMAATSCHAP

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HET TIJDSCHRIFT

Het tijdschrift verschijnt vijf maal per jaar. Opgenomen worden artikelen op het gebied van de elektronica, signaalbewerking, communicatie- en informatietechnologie. Auteurs, die publicatie van hun onderzoek in het tijdschrift overwegen, wordt verzocht vroegtijdig contact op te nemen met de hoofdredacteur of een lid van de Tijdschriftcommissie.

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Het is laat – ik weet het – maar hier is dan eindelijk het gecombineerde nummer 3 / 4, 2004 van het Tijdschrift. Dit is tevens het laatste nummer onder mijn hoofdredacteurschap. Ik heb deze functie met veel plezier uitgeoefend de laatste jaren, maar hoofdredacteur zijn van het Tijdschrift van het NERG is in de loop van de tijd een steeds zwaardere en tijdrovende taak geworden, die ik – helaas - steeds moeilijker weet te combineren met werk, gezondheid en gezinsleven.
Gelukkig staat er een enthousiaste en nauwgezette opvolger klaar, waarvan ik weet dat hij het hoofdredacteurschap op een meer dan professionele wijze zal overnemen. Zijn naam is Michel Arts en hij is al geruime tijd een bijzonder gewaardeerd lid van de redactiecommissie. Met Michel aan het roer durf ik dan ook met een gerust hart een stapje terug te doen, want ik blijf wel lid van de redactiecommissie. Tevens heb ik het voornemen om mij verkiesbaar te stellen als voorzitter van de Tijdschriftcommissie op de eerstvolgende Algemene Leden Vergadering, gezien de huidige voorzitter Bart Smolders statutair moet aftreden.
Dit lijkt mij dan ook een mooie gelegenheid om Bart te bedanken voor zijn grote inzet voor het Tijdschrift. Hij kan terugblikken op een vruchtbare periode waarin hij erin geslaagd is het vernieuwingsproces van het Tijdschrift in te zetten en met een mooi resultaat af te sluiten. Bart, bedankt!

Na deze afscheids, introductie- en dankwoorden over tot de orde van de dag: In dit laatste, gecombineerde nummer van het jaar treft u traditiegetrouw een overzicht aan van de dit jaar uitgebrachte voor ons relevante proefschriften voor zover wij die hebben kunnen achterhalen.

Naast het proefschriftenoverzicht treft u in dit nummer tevens een aantal Nederlandse bijdragen aan ISSLS-2004 aan. ISSLS is het International Symposium on Services and Local accesS. ISSLS werd in 2004 in Edinburh, Scotland gehouden en kende een bijzonder goede vertegenwoordiging uit Nederland, waarvan u door middel van dit nummer van het Tijdschrift kennis kunt nemen. Dit is met name mogelijk geworden door Frans Speelman die met veel enthousiasme en inzet in een bijzonder korte tijd alle bijdragen bij elkaar had.

Proefschriften

Hieronder treft u, traditiegetrouw het overzicht aan van de proefschriften behorende bij de promoties in 2003 en 2004 aan de de Technische Universiteit Eindhoven en de Universiteit Twente. Van de Technische Universiteit Delft is geen overzicht ontvangen. Voor detailinformatie verwijzen wij u graag door naar de bibliotheek van de universiteit waar de promotie heft plaatsgevonden. Onderstaand vindt u de adressen:

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Tackling the complexity of residential gateways in an unbundling value chain

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Keywords: residential gateways, home networking, digital rights management, service architectures, user interfaces

Abstract

Various crucial multi-disciplinary issues have been investigated concerning residential gateway (RG) technology applicable in an unbundled telecommunications value chain. We find that the Calculating-with-Concepts method can be used to construct an unambiguous frame of reference for digital rights management and end-to-end security architectures. We also conclude that some types of RGs can perfectly act as explicitly configured or transparent proxy-caches at the lowest level of a caching hierarchy. Furthermore, we discovered that the Lightweight Directory Access Protocol seems attractive for remote RG configuration management. Finally, linking devices, services, and RG functionality via a user interface with intuitive object based metaphors can enhance the user experience significantly.

Introduction

In the coming years more and more households will be connected to various service providers via broadband connections [9]. It is obvious that commercial viability of broadband services is greatly dependent on the user friendliness of the delivery to the households as well as on the distribution to the end-user equipment. For that purpose an intelligent telecommunication infrastructure in the home will be required, next to new end-user equipment such as wireless web tablets. Furthermore, the consumer demands the ability to choose from a broad selection of vendors, service providers, access network providers, etc. A technological decoupling of the telecommunication systems architectures, combined with an unbundling of the total telecommunication value chain, is therefore foreseen. Originally, the telecommunications market was a vertically organized market, which means that services and network connectivity are strongly linked. A trend can be observed where this strong coupling is released and services from the same provider become available via several networks, and services from different providers are offered via one network. This means that the players in the market do not offer full end-to-end solutions to the customer, but only components that can be combined to make up full services [12].
These trends will have significant consequences for future service and network architectures, in which the Residential Gateway (RG) will play a crucial role. The required functionality and thus the complexity of the RG increases exponentially with the diversity of the services delivered and with the bandwidth offered by the access network. However, any detailed vision on this increase in RG complexity and consequent technological development is still lacking. In the development of RG architectures, there is a clear separation between companies developing home networking solutions (Consumer Electronics and IT-industry) and companies delivering access networks (telecom- or cable operators and vendors). This can be easily seen by looking at which companies participate in the more CE- and IT oriented industrial consortia such as the Digital Home Working Group (DHWG) and the Universal Plug and Play (UPnP) Forum versus the more operator oriented consortia such as the Digital Subscriber Line (DSL) Forum and the Full-Service Very high speed DSL (FS-VDSL) Committee, now Study Group 16 of ITU-T [17]. Some of the issues that these groups discuss are rather similar, but are tackled from different perspectives. As a result, there is no common view on questions such as what security requirements an RG should have, and where broadband content is stored best. This makes achieving a really seamless connection of home networks with the outside world fairly unlikely in the near future.

The Residential Gateway Environment project (RGE) is a collaborative R&D effort of KPN, Philips, TNO Telecom and the technical universities of Eindhoven and Delft [19]. The project focuses on a number of key issues that play a role in enabling the seamless connection of future access and home networks in an unbundled telecommunication value chain:

- Medium term migration scenarios towards an open (for service providers), user-friendly (for consumers), and cost-effective (for all parties involved) RG architecture.
- The role of the RG in a comprehensive network-, service-, and management architecture, and especially the consequences for security, privacy, local storage and protection of content.
- Management and control of multiple services, home networks, and the RG, with specific attention to the role of the consumer and the commercial parties, and the consequences for the design of user interfaces.

RGE is part of the B4 initiative, a joint R&D effort of Dutch industry and academia focusing on broadband access and home networking technology [19]. Many results of the project have been visualized in a demonstrator at the TNO Telecom premises, and will be disseminated for commercialization by the Dutch ICT industry.

This paper summarizes the main results of RGE achieved to date. In the following section we compare the functionality of the different broadband RG solutions currently on the market within in the framework of a new RG classification model. We then match the roadmaps of the various companies and consortia with the user requirements for future RGs and draw some evolutionary paths for the mid-long term. The advantages and disadvantages of storage of multimedia content at home or in the public network and the role RGs can take in content delivery networking are investigated in section 3. Then we show that some of the digital rights management and security issues concerning RGs can be successfully dealt with if all parties involved use a common, unambiguous (and consistent) frame of reference in which they can agree on assumptions and solutions. In section 5 we discuss some of the complexity involved with RG management and control in an unbundled value chain. Finally, we describe how RGs can be used for the development of novel applications such as integrated atmosphere control and for hiding system complexity from the user.

Convergence of RG technology

The term Residential Gateway is not strictly defined. It is widely used for many different devices that are sold under as many different proprietary names. A general consensus can be observed if an all-encompassing definition is used, such as "A Residential Gateway is one or more devices that connects one or more access networks to one or more home networks and delivers services to the home environment" [4]. A great variety of devices are possible within the framework of this definition. These include DSL modems with Dynamic Host Configuration Protocol (DHCP)-server and Internet Protocol (IP)-routing, set-top boxes, home telephony switches, cable modems with a separate router, and remote metering equipment. Industry generally agrees that some convergence will take place in the not-too-far future [10]. For broadband network operators, a detailed vision on RG evolution is crucial to anticipate new tasks to be fulfilled in the future, such as service packaging, remote management, network storage provision, etc. [7]. We derived some evolutionary paths for RGs by first stating a set of user requirements to which future gateways should comply, and then assessing a number of current solutions and their roadmaps, as far as could be derived from the literature. The solutions we investigated are chosen from the realm of broadband communications and are currently named set-top boxes, game consoles, desktop PCs, and broadband modems, the latter including DSL modems, cable modems, Integrated Access Devices (IAD) and Media Terminal Adapters (MTA). Special attention is given to the question of whether or not RGs are going to support concurrent multiple access network connections. This issue is of particular interest to service providers who want to be able to deliver services based on the characteristics of different networks.

To avoid the necessity of analyzing every single RG solution and to enable the determination of more general trends, we devised a new, OSI-based ontology that can be used for the classification of RGs. It is shown in Figure 1, and described in more detail in reference [4]. The RG is represented as an entity connecting the access network (AN) physical media with the home network (HN) physical media, and comprising a number of protocol pro-

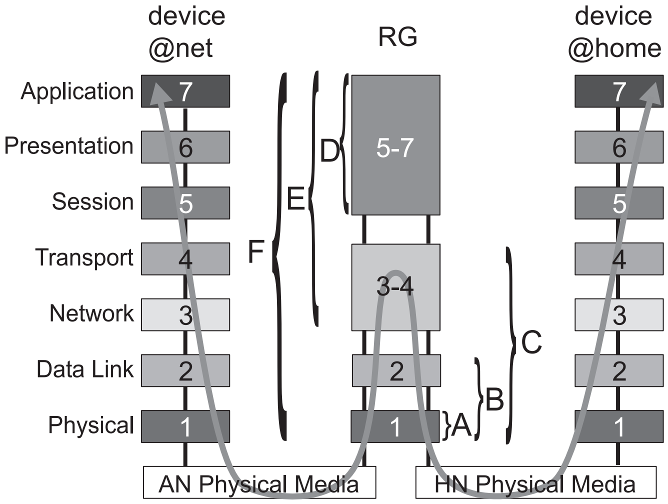


Figure 1: RG classification model based on OSI

cessing units that deliver services to the home environment. The units are connected with solid lines to show that an RG can be a single integrated device, have a modular architecture, or consist of a number of separated systems distributed in the network (mostly the home network). Any end-user device in the home network is named "device@ home" in our model, and is represented by separately connected single-layer units to symbolize that the device can be a single device or some sort of sub-network. The same counts for the stack called "device@net", which can be a server directly connected to the access network or any set of collaborating devices in the Internet. The double-headed, W-shaped arrow represents the data flow and the processing activity for a communication session between a "device@net" and a "device@home" through an RG that connects the access network with the home network and delivers only bridging and routing functions to the home network.

Six types of RGs are distinguished, hereafter called Type A to Type F (see braces in Figure 1). RGs of *Type A* are just physical layer converters and are transparent on layer 2. Current examples of such RGs are Integrated Services Digital Network (ISDN) network terminations and Ethernet Optical/Electrical (O/E) converters. RGs of *Type B* also terminate layer 2 of the access network and are transparent on layer 3. Current examples are DSL- or cable modems with a Universal Serial Bus (USB) interface and home telephony switches. Also Voice-over-Broadband hardware falls in this category. RGs of *Type C* have integrated router functions and deliver L3-services (mostly IP) to the home environment. Commonly used examples are broadband modems with an integrated or a separate IP router and DHCP server. RGs of *Type D* are often desktop PCs or dedicated consumer electronic devices that act as service platforms to other devices in the home. Examples are Personal Video Recorders (PVR), many set-top boxes, game consoles, and home- or media servers. RGs of *Type E* are like Type D, but also deliver L3-services to the home environment. The best examples here are the PCs running Linux and router software, used by many early adopters of broadband access to act as a firewall (amongst other services) between the broadband modem and the home network. Also, many Open Service Gateway initiative (OSGi)-enabled services gateways with Ethernet WAN interface belong to this category [14]. Finally, RGs of *Type F* include all OSI layers, such as any RG of Type C with integrated firewall and web-based management services.

The publicly available information we investigated includes RG solutions and roadmaps of companies such as Pace Micro Technology, Microsoft Corporation, Sony Corporation, Nintendo, SEGA Corporation, NEC Corporation, Hewlett-Packard Company, Samsung, Koninklijke Philips Electronics N.V., Compagnie Financière Alcatel, and Siemens AG. We also studied the efforts carried out by industrial consortia and standardization committees such as CableLabs, OSGi, HomeGate [16], FS-VDSL, and DSL Forum. For future Type F RGs, the user requires that they should (1) be always switched "on" and operational, (2) be fairly reliable, (3) be manageable, preferably remotely, (4) have a depreciation time longer than three years, (5) be priced affordably and/or deployable by means of subsidized business models, (6) serve multiple peripherals (devices@home), most likely on multiple home networks, and (7) support various services. This list does not pretend to be complete, but merely summarizes the criteria used to draw evolutionary paths.

Our analysis led to likely evolutionary paths for four current broadband RG solutions. These results are sketched in Figure 2. It can be concluded that, on the time scale between now and 3-5 years, especially set-top boxes and broadband modems, in contrast to game consoles and PCs, have a strong potential to evolve towards gateways that deliver network services to the home on all OSI layers, though they will probably not converge. It can also be expected that Game Consoles and STBs con-

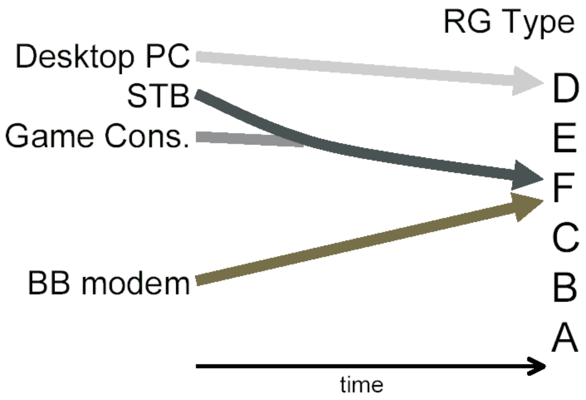


Figure 2: RG evolutionary paths in the mid-long term

verge to Type F RGs that are almost technologically indistinguishable. Broadband modems will, however, remain technologically different. Further convergence is only expected on the long term with the deployment of fiber access. Only dedicated and reliable embedded PCs will evolve to Type F RGs. The standard desktop PC will remain a Type D device that, together with a Type C broadband modem, will form a Type F RG. The main advantage of the separation of modem/router functions and processing on the application level in two different L2/3 interconnected devices, or by means of a modular RG architecture, is that the different modules then can be provided, managed, and possibly subsidized by different providers in a horizontally organized market, such as network connectivity providers and service providers. A well-defined and open interface between the modules then becomes a necessity.

In the context of our model, we have not found any compelling reasons for the RG industry to support concurrent multiple broadband access network connections on a single RG in the near future. The arguments against such an evolution in the coming 5-10 years are:

- Most RG defining consortia focus on just one access technology per device.
- Most households are expected to subscribe to not more than one broadband connection simultaneously in the near future.
- In the mid-long term, many RGs will be sold to the consumers by access network providers or strongly related service providers within a subsidized business model. The provider will therefore not be interested in stimulating RGs with access technologies other than the ones that enable the consumer to connect to preferred parties. On the long term this may change, when value chains unbundle and business models become more horizontal.
- Most current and future services mentioned in the literature can be enabled perfectly well by a single broadband access network connection of any technology. The main exception is probably broadband access via satellite, using DSL or narrowband technology for the upstream traffic.

Local or network storage?

The discussion on where content could be stored best, at home on a Type D-F RG or in the public network, is complicated and confusing. Many business and regulation related issues play a role, such as production costs, initial investment costs, applicable business models, privacy, and responsibility. But also more technical constraints come into play, such as content protection, scalability, available bandwidth, Quality-of-Service (QoS), parallel recording ability, and the availability of Content Delivery Networks (CDN) techniques. We investigated advantages and disadvantages of storage of multimedia content at home or in the public network in various ways. Here we present two examples. First, we look at a specific case of a service where local or network storage might be considered: personal video recording (PVR). Then the use of CDN techniques by RGs, in particular proxy caching, will be discussed.

A PVR is an interactive recording device or function for television programs. Unlike the traditional videocassette recorder, it records the programs in a digital format (MPEG-1 or MPEG-2) on a hard disk. Currently, most PVR functionality is implemented locally in the home in a high-end set-top-box or Type D RG, equipped with a hard disk of sufficient capacity and digital recording hardware and software. In addition a consumer normally subscribes to a service that provides an Electronic Program Guide (EPG) via a telephone or Internet connection. Here we will call this implementation a “Home PVR (HPVR)”. The PVR function can also be realized as a “network service”, where the content is stored on disk drives located in the public network. A consumer may have personal disk space on a network server that can be used for own recordings, or may have access to TV-programs that are kept in storage by a service provider. We will call this implementation a “Network PVR

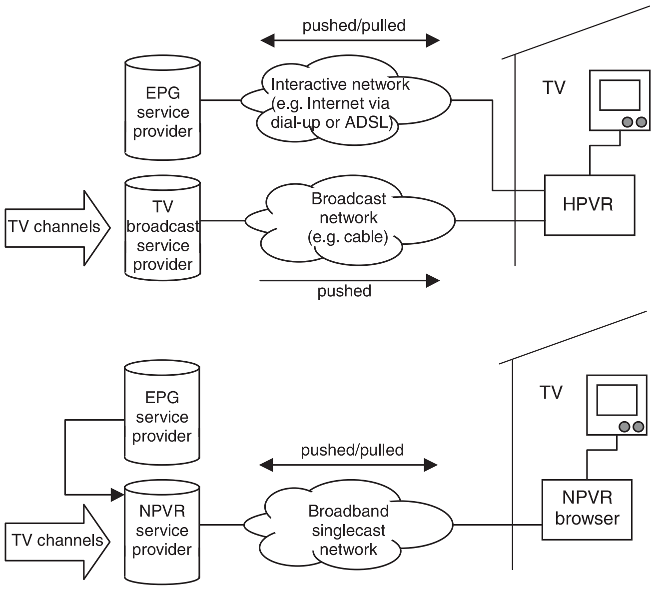


Figure 3: Schematic overview of HPVR and NPVR setups

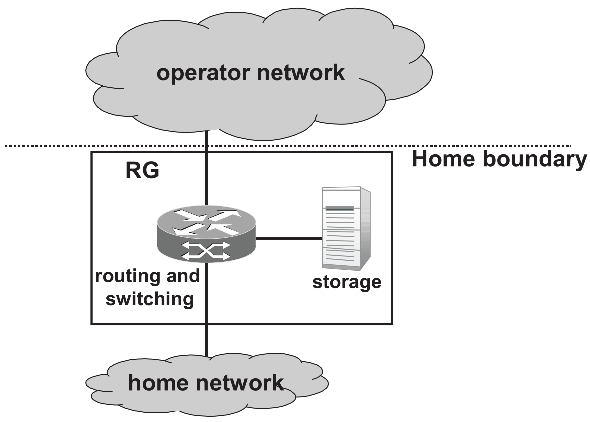
(NPVR)". In Figure 3 both implementations of HPVR and NPVR are schematically drawn.

The characteristics of HPVR and NPVR that are compared include the access network requirements, the consumer premises equipment requirements, the parallel recording capabilities, the integrity of EPG meta data, the storage capacity, and the peer-to-peer networking functions. Here we give a summary of that comparison. An important difference between HPVR and NPVR is the type of connection to the home. An HPVR relies on the programs being offered on a broadcast medium (e.g. cable) combined with a narrowband interactive connection for the EPG. The NPVR, in contrast, needs a dedicated interactive broadband singlecast connection between the NPVR-server and the home. The penetration of broadband singlecast media is still limited, but growing rapidly. The HPVR is a set-top-box or PC plug-in with one or two tuners and a hard disk drive of >100 GB that can sustain a limited number of simultaneous data streams to and from the disk. It also contains processing hardware for video coding and decoding and for the EPG control. The home equipment for the NPVR is a box or PC plug-in with a modem and processing hardware for video decoding only. The parallel recording capabilities for the NPVR have hardly any limitations, because resources are shared over a large number of subscribers, which keeps the relative costs low for providing extra channels. Integrity of metadata for the EPG is not guaranteed in the HPVR between successive daily downloads. For the NPVR the integrity of the meta-data is better guaranteed, because they reside in the server that has almost instantaneous access to these program data. The amount of storage sets a hard limit for HPVRs that will shift upwards with new generations of hard disk drives for new releases of boxes. In principle there is no storage capacity limitation for an NPVR. PVR users may want to share their content with others. For an HPVR this means that the content has to be physically transferred from one box to another. In the case of personal storage space being available on an NPVR; only the "pointer" to the content has to be exchanged.

Network- and server overload are serious threats to the success of broadband services like PVR. It might therefore be useful for RGs to support CDN techniques such as caching or IP Multicast, since RGs are part of the service delivery chain. An RG with caching functionality will be of Type E or F. It will perform as a cache at the lowest level of a caching hierarchy. Two different basic concepts of caching architectures can be identified: explicitly configured proxy-caches and transparent proxy-caching with request interception and redirection. To understand how both mechanisms can be implemented in an RG, it is necessary to make a clear distinction between two separate functions that can reside in the RG: the switching and routing function on the one hand, and the storage or caching function on the other hand. The RG can therefore not be seen as a stand-alone cache, but more as an advanced switch/router, combined with a cache, in one single physical device. This is depicted in Figure 4 [11].

To store content on the RG, content requests must be directed to its cache. Explicit configuration of the RG as the proxy-cache for use by the end-user devices would cause content requests to be routed

Figure 4: Routing/switching and storage function of the RG



by the RG towards its own storage function in a very straightforward manner. The RG then will act as a normal cache by serving the requested content to the end-user device, or by fetching the requested content from another cache or server first and then serving it to the end-user device. The cache can also be implemented in a way more transparent to the user. Of course, content requests should still be directed to the storage function of the RG so it can act as a forward proxy-cache. In this case, however, transparent interception and (re)direction of content requests is performed by the routing and switching functions of the RG.

Digital Rights Management and security architectures concerning RGs

Issues on Digital Rights Management (DRM) have not been settled for either version of the PVR function. DRM is in fact one of the greatest challenges in this digital age. The traditional rights management schemes are not adequate to cope with the technological advances, especially in the IT domain, and some distributed systems have made it easy to acquire, copy or share digital content illegally. The companies that produce or distribute digital works need a system that allows them to control this distribution in such a manner that their rights will be respected. Unfortunately, DRM is an ambiguous term, i.e. different parties assign different meanings to this term. For example, one party includes business processes in the scope of DRM, whereas others limit themselves to the (secure) delivery of a piece of content. Consequently, much of the discussion on DRM is quite meaningless, and easily leads to misunderstandings. Furthermore, the number of different DRM technologies is rather large, as are the number of relevant standards and standardization organizations. In reference [13], ten of these standardization activities have been discussed. Also, each of the presented technologies is solving only a part of the complete problem and they usually lack any form of interoperability.

In relation to RG technology, it should be realized that DRM and information security are end-to-end issues, and concern all parties involved, their organizations, processes and systems. Any lack of coherence and consistency in the way various organizations think about DRM and security, implement their processes, and use their systems in the roles assigned to them, makes architectures unnecessarily complex, interconnected, and prone to changes. This influences RG security negatively, as hackers usually only require a single exploitable weakness to inflict damage. Hence, these parties need to agree on all the assumptions and solutions, each from their own point of view. This requires a common, unambiguous (and consistent) frame of reference between such parties.

To construct such a frame of reference, we first need to find a method to deal with the added complexity induced by unbundling. Complexity refers to the human property of not being able to handle more than about seven concepts and their mutual relations at one particular time. Furthermore, a given concept may have a different meaning (semantics) depending on the context in which it is used, leading to ambiguity of words. This is particularly relevant to network- and service architectures involving RGs (called “RG environments” in this paper) as there are many relevant concepts, such as “networks”, a “residential gateway”, “applications” running on a Type D-F RG, on some device@home, or some device@net, “servers” running applications, or running “services” that themselves act as “users” for other services (e.g. proxies), and so on. In this paper we present a method that is capable of finding and resolving ambiguities in the process of specifying requirements. It makes use of several small and distinct models that consist of a well-scoped topic, containing concepts and their mutual relations, complemented by specification rules that restrict the semantics and govern implementation. All models are formally related to one another.

In our effort to describe and combine the models, we have found the Calculating-with-Concepts (CC) method a valuable tool to achieve these goals [3]. This is the first time that CC has been applied in telecommunications. The CC-method specifies the concepts involved, and their mutual relations. The concepts and relations are just syntax, and provide the vocabulary in which to express concerns, or rules that must apply. The semantics is defined in terms of restrictions, i.e. rules about the relations that must be valid. Each rule coincides with one specification, and thus the creation of a topic description implies that the specifications for that topic are created. One of the unique features of a CC model is that it has two representations, one using natural language (e.g. English or Dutch), and the other using mathematical expressions (i.e. formal language). The former is useful to quickly convey the concepts, their relations, and accompanying specifications between people that are not required to know that much about the underlying method. They will perceive it as a 'specification as usual', albeit without inconsistencies or ambiguities. The latter ensures that ambiguities can be detected and resolved, and consistency can be properly checked.

In reference [8] we attempted to visualize how a typical security and DRM framework might look like for an RG environment, using CC. It consists of a description of frames of reference with respect to basic concepts such as systems, security, content and data. These descriptions provide 'rules' that must be taken into account when used by specification models. We then defined some of the core concepts, relations, and specification rules that apply for a security architecture for RG environments. More specifically, we looked at applications, services, service properties, the service provider and the service packager role. Each of the specified models can be integrated with the more generic reference models concerning systems, security, content and data.

We also looked at authorized domains as a means for providing content to a household. An Authorized Domain (AD) is a DRM system, in which the rights to access some content are linked to a virtual network of devices [5,13]. This is in contrast to many currently available DRM systems, where the rights are primarily linked to a single device. The main advantage for the AD approach is the fact that in such a system the content can easily be shared within the set of devices that belong to the same domain and can thus guarantee interconnectivity in the home network. To make this approach work, the devices first have to be registered to the AD. The registration model, constructed with the CC method, will be shown here as a typical example of the many models that act as primary building blocks for the security and DRM specifications of RG environments as can be found in reference [8].

Abbr.	**Concept**	**Description**
AD	Authorized Domain	An Authorized Domain is a set of AD devices
CDEV	Common Device	e.g. a PC, a personal video recorder, a TV set, and so on, that are *not* part of an AD
ADDEV	AD Device	Like a common device, but now it belongs to a specific AD
ADM	AD Manager	The ADM is a device, that has started the AD and manages the joining and leaving of other devices.
Adcr	AD Credential	Some token (data), with which an AD device can prove that it has joined a specific AD.

Abbr.	**Relation**
Bt	AD device *add* belongs to authorized domain *ad*.
Nbt	Common device *cd* does not belong to authorized domain *ad*.
St	AD manager *adm* started the authorized domain *ad*.
Man	AD manager *adm* manages the authorized domain *ad,* i.e. it controls who belongs to the authorized domain and therefore controls the size of the domain.
Join	Common device *cd* joins the authorized domain *ad*
Leave	AD device *add* leaves the authorized domain *ad*
At1	Common device *cd* authenticates the ADM *adm*
At2	ADM *adm* authenticates the common device *cd*
Az	ADM *adm* authorizes the common device *cd*
Gen	ADM *adm* generates the AD credential *adcr*
Rx	Common device *cd* receives the AD credential *adcr*
Tx	ADM *adm* transmits the AD credential *adcr*
Own	AD device *add* owns the AD credential *adcr*
Del	AD device *add* deletes the AD credential *adcr*
bc1	Common device *cd* becomes/transforms into AD device *add*.
bc2	AD device *add* becomes/transforms into common device *cd*.

Rule	
1.	An authorized domain *ad* has been started by one and only one ADM.
2.	An authorized domain *ad* is managed by one and only one ADM.
3.	An ADcr is generated by one and only one ADM
4.	An AD Device *add* owns one and only one ADcr.
5.	A common device *cd* receives one and only one Adcr.
6.	An AD Device *add* belongs to one and only one authorized domain *ad*.
7.	If an authorized domain *ad* is managed by ADM *adm*, then *ad* has been started by *adm*.
8.	If a common device *cd* has joined an authorized domain *ad,* then *cd* has been authorized by ADM *adm,* which manages *ad.*
9.	If ADM *adm* has authenticated a common device *cd*, then *cd* has authenticated *adm*.
10.	If ADM *adm* has authorized a common device *cd*, then *cd* has been authenticated by *adm*.
11.	If a common device *cd* has joined an authorized domain *ad,* then *cd* has received AD credential *adcr*, which has been generated by ADM *adm*, which manages authorized domain *ad*.
12.	If an AD credential *adcr* has been transmitted by ADM *adm*, then *adm* has generated *adcr*
13.	If a common device *cd* has become AD Device *add*, then *cd* has joined authorized domain *ad*, to which *add* belongs.
14.	If a common device *cd* has joined the authorized domain *ad*, then *cd* did not belong to *ad*.
15.	If an AD Device *add* has belonged to authorized domain *ad*, then *add* has owned AD credential *adcr*, which has been generated by ADM *adm*, which manages *ad*.
16.	If an AD Device add has become a common device *cd*, then *add* has left authorized domain *ad*, which *cd* has joined
17.	If an AD Device *add* has left an authorized domain *ad*, then *add* must have belonged to *ad*
18.	If an AD Device *add* has left an authorized domain *ad*, then *add* has deleted AD credential *adcr*, which has been generated by ADM *adm*, which has managed *ad*
19.	If AD device *add* has deleted AD credential *adcr*, *add* has owned the *adcr*.

Table 1: Definition of the concepts, relations, and rules of the RGE Authorized Domain Management model of Figure 3, constructed by means of the CC method.

The investigated system consists of a (home) network of devices. Devices do something with content (music or movies), for instance storing or accessing. Examples are CD players, DVD players, TVs, PVRs, PCs, and any Type D-F RG. One can distinguish the so-called AD devices, which are part of an authorized domain, and the so-called common devices that are not part of such a domain. An Authorized Domain is the aggregation of a set of AD devices that have been authorized to be part of that domain and therefore are trusted to handle the content and the rights in a correct manner. Only common devices can join an AD (they do *not belong to* a domain yet) and only AD devices can leave an AD (they *belong to* exactly one domain). In our model *join* is synonymous to *register* and *leave* is synonymous to *de-register*. To control and manage the authorized domain, there is the ADM (AD

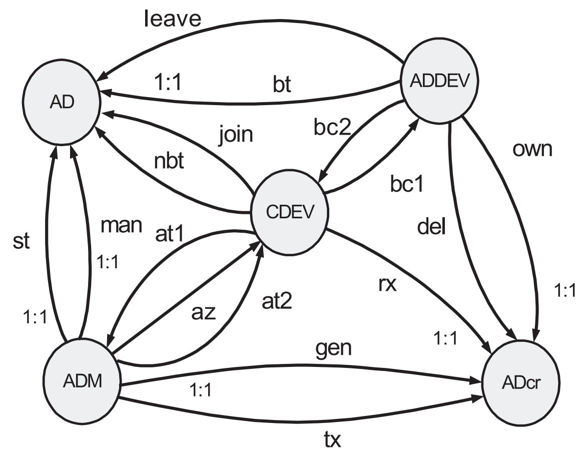


Figure 5: RGE Authorized Domain Management model

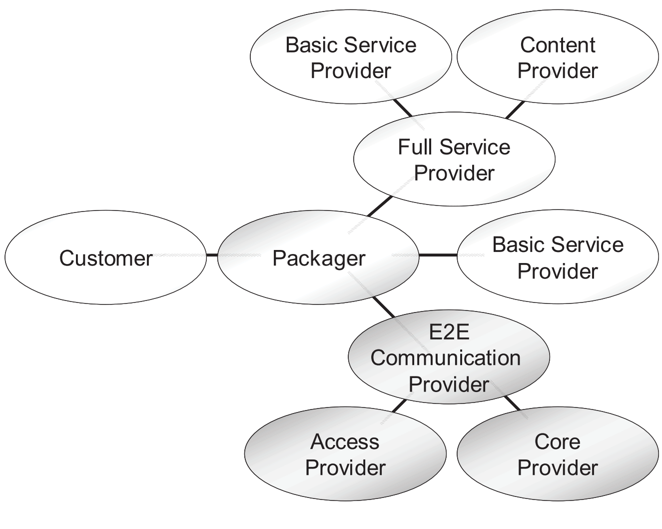
manager), which has started the domain in the first place. The ADM controls which common devices can join the domain and which not. The *authentication* of the common device is part of the *join* protocol. In this protocol the common device is *authorized* to become a member of the domain. Before this authorization is given, the common device and the ADM authenticate each other in a two-way *authentication* protocol. After the authorization is given, the ADM will generate and send the relevant credentials to the common device. The credentials are essential for the AD devices to prove to other devices of the same domain that they are indeed belonging to that AD. When the AD device is leaving the domain it will delete its credential and becomes a common device again. This Authorized Domain Management model can be described as shown in Figure 5 and Table 1. Figure 5 shows the five different concepts involved and their relations to each other. Table 1 shows the definition of the concepts, their mutual relations and the restrictions or rules in natural language. The formal representation of this model falls out of the scope of this paper. In reference [8] we also constructed models for content rights provisioning and processing, and show how these models and the domain management model can be linked together into one consistent and unambiguous authorized domain specification.

RG management and control

In this section, we show how we determined what is required in terms of generic control and management of an RG to make service and content delivery in an unbundled value chain possible. The requirement analysis was performed by developing three scenarios for the delivery of one or more services via an RG and home network to consumers. The first scenario is taken from the HomeNet2Run project [18]: a family with two adults and two children uses an integrated home entertainment environment. In the second scenario a consumer enjoys the service Personal TV (PTV), which consists of the following components that are integrated by the PTV service provider: broadcasting TV via cable or Internet, real video-on-demand, Internet (Internet access, email, homepage, ..), interactive TV/ gaming, EPG, multi-media content searching, and management by mobile users. A PVR is one of the key devices enabling this service. The third scenario is a monitoring and control scenario, containing the services videoconferencing, video monitoring, and home monitoring and control. From these scenarios we have extracted a superset of requirements that should be put on an RG. More detailed results can be found in reference [6].

For the assignment of management and control tasks to parties, it is not practical to consider every possible service delivery value chain separately, because of the large diversity of services that can be offered by means of an RG and of players that could be involved. Instead, it is more efficient to identify generic roles with a clear function and responsibility in the service delivery process. In concrete cases, the same company can fulfill more than one role, or sometimes specific roles are absent. Because of the unbundling of the telecom value chain, we needed to introduce a new role when evaluating the given scenarios along a role-based

Figure 6: Overview of the role-based model for service delivery via an RG. Next to Customer and Packager, three types of Network Providers (Access, Core, and E2E Communication Provider) and three types of Service Providers (Basic Service, Full Service, and Content Provider) are distinguished [6].



business model containing the well-known roles of Service Providers, Communication Providers and Customer: a party that combines services offered by Service Providers and networks offered by (Access) Communication Providers into useful packages for the consumer. We will call this new role the Packager. Figure 6 depicts our generic, role-based business model for the delivery of end-user services via an RG, including the Packager. Note that the model is concerned with business relations and not with a physical network configuration. Therefore, the lines in the picture indicate relations between the different roles and not necessarily the route information or content will take.

The role of Packager can be characterized as follows. The Packager:

- combines one or more end-user services and connectivity services and offers this as a package to the Customer.
- is the single point of contact for the Customer.
- is responsible to the Customer for the delivery of the services with the quality as agreed upon when the Customer subscribed to a service.
- has contracts with one or more E2E Communication Providers (E2E-CPs) and one or more Full Service Providers (FSPs) to obtain end-user services and connectivity. The E2E-CP offers end-to-end connections from Customers to FSPs.

The role-based model was used for selecting a subset from the superset of management and control functions for every scenario, and assigning them to the roles involved. It then became clear that the Packager is most logically responsible for the RG, but other roles must be able to access and operate (parts of) the RG functionality as well. The Packager plays an important role during the selection, installation and pre-configuration phase of requested services. It also plays a role in managing incident and error reports. Many of these tasks can be fulfilled directly by the RG. The service platform on the RG plays an important role in fulfilling these requirements. In the future, it is not realistic to expect the consumer to fulfill the full Packager role, as he is often doing now.

Next, we investigated what protocol could be used for the remote configuration of RGs by the Packager. Three important aspects should then be taken into consideration: centrally vs. distributed based management, pull vs. push model, and in-band vs. out-of-band management. In a centrally based management model, one party has full management control over the RG. In a distributed management model, each party involved with the service delivery will be responsible for the management of his own part of the service it delivers. Service Providers are not dependent on the Packager when they want to do a service update on the RG, and a Packager does not need to have specific knowledge of all services that are installed on the RG. Such a model has many advantages especially in the case of open business models in unbundled value chains.

In a push model, the initiative to configure or update parameters in the RG is taken by the Providers and the Packagers. This causes them also to be responsible for the correctness of the configuration information stored in the RG. With a pull model, the owner of the RG decides when a configuration update should be carried out. This avoids conflicts about who may perform a certain software or configuration update on the RG. Providers are only responsible for the availability of the correct configuration information. The Customer is responsible for the information on the RG, which is in line with his ownership of the box. However, a push model might still be preferred in isolated cases, for example if the RG is not owned by the Customer, or if any influence of the Customer on the RG configuration is undesirable.

With in-band configuration management, the network connection used for the configuration of a certain application or service is also used to transfer configuration information from a management system to the RG. With out-of-band management, a separate physical or logical connection is used for the complete configuration of all services running on the RG. This reduces the number of protocols required for automatic configuration. Furthermore, the communication with the RG remains possible when something goes wrong during the configuration of a service.

Concluding, a distributed management model, based on out-of-band management and a pull model, is preferred in future unbundled telecommunication value chains.

The Lightweight Directory Access Protocol (LDAP) seems an attractive protocol for remote configuration management of RGs, because it supports all the above requirements. It is a communication protocol between an LDAP client and an LDAP server, which enables clients to retrieve information from or modify information on a tree-like database. If the RG contains an LDAP client and the configuration data is stored in LDAP servers, then a typical pull configuration model is created. Furthermore, LDAPv3 makes it possible to perform remote configuration management in a distributed way. As far as we know, this is the first time that LDAP is considered for RG management.

The "Intelligent Home Stage"

The potential complexity of an RG environment as described in this paper is overwhelming. It is therefore crucial to hide system complexity from the user, by integrating the communication, entertainment, information and home automation functionality of the RG via an intelligent user interface. For that purpose, we based an abstraction of the RG and network functionality on the notion of a stage with RG functionality represented as objects on the stage. The stage is referred to herein as an Intelligent Home Stage (IHS) [15]. The goal of the IHS is to enable the user to combine or link RG functionality via intuitive object based metaphors. As a first example we implemented an atmosphere selection application based on combinations of music, video and light. The system is accessed via a multi-platform user interface that includes the use of tangible tokens, a pen tablet, and a speech interface. Personalization is supported by enabling the user to program and invoke new atmosphere settings via the tangible tokens and by changing object settings in the stage metaphor.

To create appealing and realistic atmosphere settings, we first needed to have an idea of how people experience their living room today. We therefore visited six couples, and investigated what are for them the important elements of user experience in the living room in different contexts. The method is described in more detail in reference [1]. It included several interviews and the creation of mind maps and collages. To validate our atmosphere controller, we invited the same couples for lab tests. We conclude from these experiments that the linking of products and RG functionality via an intelligent user interface adds value as it can enhance the experience people have in the living room.

Conclusions and future work

RGs including a switching/routing function and a storage or caching function can perform as an explicitly configured proxy-cache or a transparent proxy-cache with request interception and redirection at the lowest level of a caching hierarchy. This can be useful for end-to-end QoS and should therefore be taken into account in future network architectures.

Both HomePVRs and NetworkPVRs have advantages and disadvantages, and will most probably coexist in the market. Service architectures incorporating both solutions might offer added value to the consumer.

Current DRM solutions can not be applied in future open RG architectures. The CC method can be used to construct an unambiguous frame of reference for designing the DRM and security architectures needed. Such a frame of reference is essential for an environment in which many different parties are involved and responsibilities are spread.

A party fulfilling the Packager role is most logically responsible for the RG. The Packager has an important task during the selection, installation and pre-configuration phase of requested services. It also manages incident and error reports. It is not realistic to expect the consumer to fulfill the Packager role in the future. Commercial parties should therefore take this up.

An out-of-band, distributed based management model is preferred for remote configuration management of RGs by the Packager. Furthermore, a pull model has clear advantages over a push model in most cases. LDAP fulfills these requirements and therefore seems an attractive protocol for remote configuration management of regulations.

IHS is a useful interaction metaphor for studying the RG's opportunities for offering user-friendly interfacing to the services. Linking of products and RG functionality via such a user interface can enhance the experience people have in the living room

In the near future, these results will be extended with:

- Migration scenarios of access networks in the Netherlands and their network terminations.

- An example of an end-to-end security architecture incorporating RGs, designed using CC.
- Privacy issues involving RGs.
- Model calculations that quantify the benefit of using Content Delivery Networks techniques (caching and multicast) in the RG and at several hierarchical levels in the public network for simultaneous best-effort and high-priority-class traffic.
- Remote control of RGs with OSGi-based services using LDAP or other protocols such as TR-087, currently under development by the DSL Forum [17].
- Specific service architectures incorporating remotely managed services with end-to-end security.
- Interworking requirements between the main wired and wireless home networking technologies and service- and device discovery protocols, and of the role the RG could play in achieving this interworking.
- The influence of building traditions and legacy of family houses in the Netherlands on the physical installation and topologies of home networks and RGs.
- A basic understanding of the relation between atmosphere and user needs.
- An extension of the demonstrator with advanced communication services, the basic atmosphere controller, home automation, multimedia content search- and find algorithms, and basic content protection using LicenseScript [2].

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Fibre-to-the-home in a broad perspective: multi-dimensional modelling of the first mile

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Keywords: Broadband, First Mile, FttH, Business Model, Value Web.

Abstract

This paper describes the approach for the development of a generic business model for the deployment of FttH in the Netherlands. It is based on a graduation research performed by Christian Berghout. It uses Baken's Infrastructure Cube to deconstruct the FttH market into a value web of functions. The Function Model provides a framework for describing, analysing, comparing and visualising FttH business models. Based on viability considerations, six possible business model configurations for the network functions appear.

Introduction

In Europe, the political leaders advocate the introduction of broadband as one of the crucial spear points to bring it in the lead on a global scale [11]. The Dutch Central Government considers ICT in general and broadband in particular to be of great national interest. It underlined its ambition to accelerate the rollout of broadband infrastructures by stimulating the preparation of pilot project in several cities [15]. The *Broadband Expert Group* and the *Andriessen Committee*[1] stated that FttH is the best technical and most future proof broadband network and the inevitable successor of the conventional access networks [10].

However, at present market parties are reluctant to invest in FttH on their own due to the high initial investments and the high risks involved. This leads to a situation where many actors await the coming developments, stagnating FttH deployment. A way to overcome this stalemate position is the cooperation among both private and public actors. This means a radical change in the market structure and as a consequence, actors' current positions in the market have to change.

A multi-actor business model is required to shape the new FttH market and to divide responsibilities between actors. The formation of a broadband value web will only succeed if the actors individually and as a whole are able to make a profitable business case.

The development of a viable business model requires a multi-dimensional approach. Baken's Portfolio Model [6] describes seven dimensions: the commercial, technical, operational, financial, managerial, legal and human resource portfolio [3]. Degrees of freedom exist for each dimension. For instance different FttH configurations (Optical Ethernet, APON, EPON) exist in the technical dimension. These are still being refined and developed. The degrees of freedom in the managerial/organisational dimension are dominant in the development of a business model. The other dimensions pose the boundary conditions.

Aim

The aim of the main research was the development of a generic business model for the deployment of FttH in the Netherlands in its technological, economical and legal context. It focuses on the derivation of viable business model configurations for the network functions, with a focus on multiple participants cooperating to bring FttH to deployment. This paper describes the main findings of the research.

Business model and value web

A business model can be seen as a blueprint for how a network of organisations cooperates in creating and capturing value from technological inno-

1 Andriessen, a former Dutch Minister of Economic Affairs, chairs committees dealing with FttH rollout in the cities of Amsterdam, Rotterdam and the Hague. Professor Baken is a member of both the Andriessen Committee and the Broadband Expert Group.

vation [7]. It comprises the following elements (based on [12]): an architecture for the product, service and information flows, including a description of the various business actors and their roles, the potential benefits for the various business actors, the sources of revenues, the contribution or value added by each actor ('value proposition'). One of the main elements in the definition is the architecture for the product, service and information flows, including a description of the various business actors and their roles. A value web describes such architecture. A value web may be viewed as consisting of a series of inter-twined value chains with multiple entry and exit points [9].

A generic business model for FttH should be generally applicable to the FttH market. It therefore only takes into account those aspects that are generally valid and relevant for FttH business models. These aspects influence the entire market and are not dependent on a specific situation. A generic business model should also be flexible, so as to ensure that it may be used as a basis for a specific business model for a specific case.

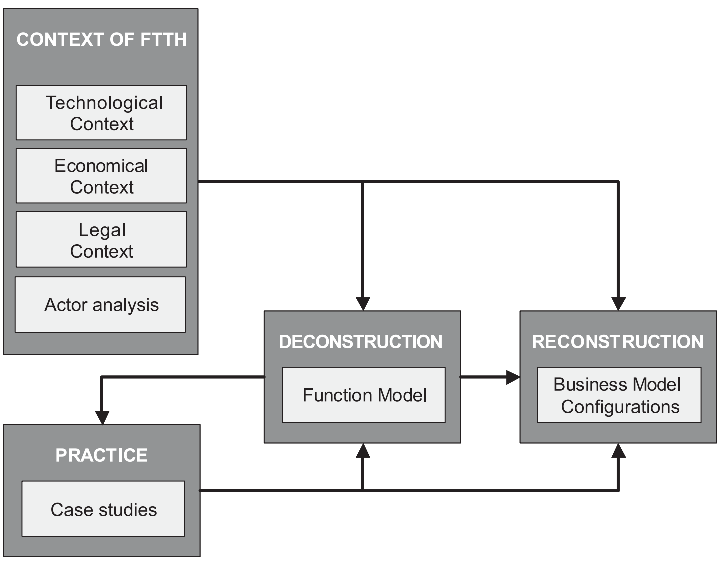
Method & Approach

The main research analyzes the technological, economical and legal context of FttH. In addition it analyzes the aims, interests and means of actors that could be potentially involved in FttH deployment. This is important for the position that these actors might want to occupy in the FttH value web. This paper does not describe these aspects, but focuses itself only on the deconstruction and reconstruction of the FttH market.

The method used to develop a business model is to deconstruct the process of service provisioning in the FttH market into principle activities and to reconstruct it into business models (see Figure 1). Timmers [12] applied this approach to identify architectures for business models for electronic markets while Baken used it for the ICT sector [2]. The principle activities that are the result of the deconstruction are referred to as *functions*[2]: *A function is constrained by the smallest scale of business activity that could exist independently in the market. It controls assets, processes and information and masks the internal processes or operations from the 'outside world'*.

Baken's Infrastructure Cube [1] is used to deconstruct the FttH market into functions. This cube is a tool for the modelling of infrastructure economies. It describes three generic dimensions and illustrates them using a cube, see figure 2. The first dimension (*geographic dimension*) describes the geographic architecture of the infrastructure (home, street, neighbourhood, town, region, country, continent, globe). The second dimension (*functional dimension)* describes the main functions that have to be performed in the value web in order to operate and exploit the infrastructure. For the ICT-infrastructure the OSI-model provides a commonly used division in functions [17]. The Broadband Expert Group [10] extended and simplified

Figure 1: Research Approach. This paper focuses itself on the deconstruction and reconstruction part.



2 The definition of a function is based on the definition of a 'role' in Ballon & Arbanowski [5].

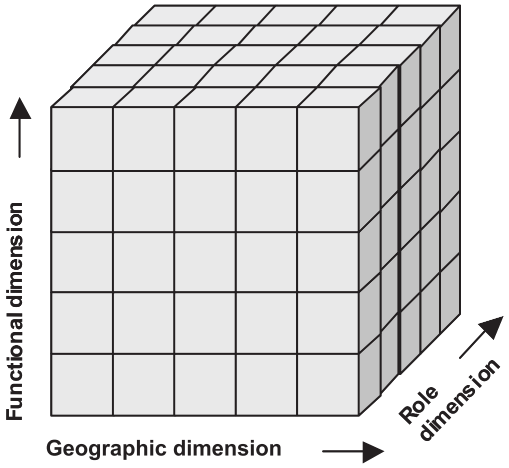


Figure 2: Baken's Infrastructure Cube

the 7-layer OSI-model to a four-layer model for FttH with the following functions: 'content and applications', 'service provisioning', 'active infrastructure and switching' and 'passive infrastructure'. Finally, the third dimension (*role dimension*) describes the different generic roles that the functions have to play. Examples of roles are design, finance, construction, maintenance and exploitation. In a way each function has its own value chain.

In the main research, each function is consequently described in detail using Baken's Portfolio Model [6]. Each portfolio describes some aspect of the functions main activity. The main portfolios are the commercial, technical and operational portfolios. They describe the function's value proposition, technical infrastructure and main processes, respectively.

The resulting set of functions is defined as the *Function Model*. *A function model represents the collection of all functions in a market that are performed to design, produce, market, deliver and support a service regardless of the actor that performs them*. In other words, the Function Model describes the set of relevant functions behind a service offering. Note that the Function Model does not describe the principle activities within a single organisation such as in the case of a value chain. It describes the total set of essential functions that are necessary in the provision of a service. These functions, and not the actors performing them, are the primary elements in the Function Model. The actors come in to play during the reconstruction phase.

The Function Model and the description of the portfolios for each function together constitute the generic business model. The Function Model was used to analyze the business models of thirteen case studies of Dutch, foreign and company FttH initiatives. By mapping the actors on the Function Model, and including the relations between actors and the revenue flows, a number of FttH business model examples was obtained.

As mentioned before, Baken visualises the three dimensions in a cube as shown in figure 2. The cube is divided into cells. Each cell corresponds with a certain role of a certain function on a certain geographical scale. The reconstruction of the FttH market into business models is the process of assigning actors to cells. In order to create a realistic value web, related functions and roles should be grouped to form clusters. These clusters should work together in order to provide services to the customers. For the purpose of this paper the cube is restricted to a two-dimensional model for the functional and role dimension.

Reconstructing the FttH market is therefore seen as the clustering of functions, and allocating (types of) actors to the clusters. The meaning of clustering is the merger of one or more functions. Hence a cluster is responsible for all the principle activities of those functions. The meaning of occupying a cluster is as follows: a party or a consortium of parties takes responsibility for performing the necessary activities to deliver the service associated with the cluster. This does not mean that the party performs all the roles associated with this cluster; it can outsource one or more of these roles to other parties. However it still bears the responsibility for the performing of a cluster as a whole and the (commercial) risk of failure. An occupant of a cluster is considered to be a separate economic entity with a separate profit and loss responsibility.

Results

A brief description of all the functions in the FttH market, together with typical examples of the product or service they provide is given below. A value web representation of the functions is shown in Figure 3. It shows a further deconstruction of the model of the Broadband Expert Group and introduces two new intermediary functions: the Packager and the Broker. These functions are not essential for the FttH value web to function, but are likely to make it work better.

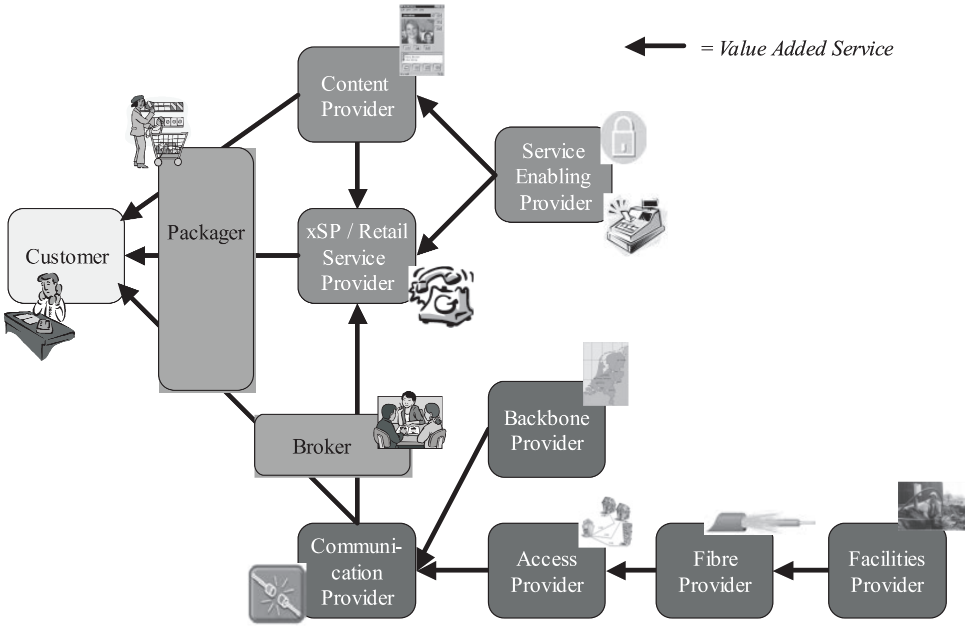


Figure 3: FttH Value Web

Customer - An active customer of services (residential or business customer). The main difference between the Customer and other functions is that it consumes the services instead of trying to make money out of them.

Packager - Provider of a package of services consisting of services from one or more other functions (e.g. xSP, Content Provider, Communication Provider). An example of a service package is: active connection + local intranet + Internet access + television + pay-TV channel. The added value of the Packager function is the reduction of complexity between the Customer and the other functions. The function is comparable with the supermarket in the consumer goods market. It also provides a marketing and sales channel to the other functions, which can ease rapid service deployment and can make their sole existence possible.

Content Provider - Provider of content (e.g. websites, music, video) and applications (e.g. e-mail, voicemail). Parties in this function can serve an entire continent or even the world, but also just a single town or neighbourhood (e.g. a provider of municipal services).

xSP/ Retail Service Provider - Provider of communication services such as telephony, Internet access, television and an intranet. In order to provide these services to Customers they have to buy connectivity directly from the Communication Provider or indirectly from the Broker. The xSP interconnects at the Service Node[3] in the access network in order to provide its services.

Service Enabling Provider - Provider of wholesale services to other providers (e.g. xSPs) in which the latter are supported in the service provisioning to Customers. Examples of services are middleware/ IT-building blocks (e.g. billing, security). The added value of this function is that it may be too expensive for many (small) xSPs and Content Providers to develop their services from scratch and to perform all necessary tasks themselves. The Service Enabling Provider could provide them with enabling services in order to develop the end-user services. It may even make their existence possible. The Service Enabling Provider may also provide enabling services to other functions such as the Communication Provider and the Packager (the relationship is not depicted in figure 3).

Broker - Intermediary between the Communication Provider function and the xSP function. The Broker purchases distribution rights on many local access networks, joins them and resells them to xSPs. The idea behind the function is that once there are many local FttH initiatives, each of them served by a different party in the Communication Provider function, the market place between these

3 The Service Node is the regional access point, often referred to as the Central Office.

parties and parties in the xSP function becomes very complex. Many negotiations would have to take place. The Broker bundles the access rights to many local FttH networks and provides a single access point to both Communication Providers and xSPs. Note that the Broker function can have many forms such as a middleman, an arbitrator or a coordinating body.

Communication Provider - Provider of an end-to-end connection with a certain QoS that is required to deliver services of xSPs to the Customer. Tasks to be performed are the conversion of signals from the backbone to the access network and vice versa.
The technical means of the Communication Provider is equipment (mainly routers and management systems) to route traffic to the right destination and to provide the conversion between different technologies and protocols. This equipment is located in the Service Node. Therefore the Communication Provider can be associated with OSI-layer 3 functionality. The investments (Capital Expenditure, CAPEX) for the equipment are not very scalable due to the high number of customers served by one piece of equipment. Therefore economies of scale are very important.

Access Provider - Provider of an active point-to-point connection (with a certain QoS) between the Customers' Premises and the Service Node in the access network. The Access Provider installs the basic transmission equipment in the Customers' Premises, the Service Node and possibly the Remote Node[4]. The investments are scalable to a large extent due to the fact that the components (lasers, switches, etc.) serve individual or small groups of customers.

Fibre Provider - Provider of passive fibre connections (including connectors and mini-ducts) between the Customers and the Service Node. Hence, this function provides the transmission medium or the dark fibre connection. Often the fibres are one-on-one contained in mini-ducts to be blown through the duct network of the Facilities Provider. The investments are scalable to a large extent as fibres (and mini-ducts) can be blown when the Customer actually wants to subscribe himself. Note that in practice, a trade-off exists between the cost savings of blowing fibres only when the Customer wants a connection and extra labour costs. The payback period is very long (e.g. 10-15 years) and the returns are low.

Facilities Provider - Provider of civil technical infrastructure consisting of (main) ducts and other facilities (e.g. buildings)[5]. The Fibre Provider uses the duct network. The other functions can install equipment in the buildings (these relationships are not depicted in figure 3). Note that the main part of the investments in a FttH network is to be performed by parties in this function. The investments are limited scalability due to the necessary upfront investments (although investments for the drop loop can be postponed until a customer actually wants a connection). The payback period is long (e.g. 15-20 years) and the returns are low.

Backbone Provider - Provider of connectivity outside the access network to the Communication Provider (city-rings, regional/ national/ international transport networks). Note that this function falls outside the scope of this article.

Figure 4 gives a simple illustration of the division of technical responsibilities between the network functions (Facilities Provider, Fibre Provider, Access Provider and Communication Provider) in the geographic versus functional dimension of the Infrastructure Cube. These network functions are clustered to basic business model configurations later in this paper. The three lower functions in the figure are technically directly related to FttH, while the Communication Provider function is not. In addition these functions are primarily local, while the activities of the Communication Provider are more regional.

Function Model

The Function Model is depicted in figure 5. It can be used to visualise business models. Actors can be mapped according to their responsibilities as well as the main cash flows. Hence it can be used to design or to analyze existing business models. The Broadband Expert Group model is depicted in the left column in order to clarify its relation with the

4 The Remote Node is the local access point. In the case of Optical Ethernet, the Remote Node (often referred to as the Remote Office) contains active equipment. The Remote Node in a Passive Optical Network (PON).contains a splitter/ combiner.

5 Note that it is also possible to hang the fibre cables in poles, but this paper assumes that fibre cables are buried underground such as is the case in the Netherlands.

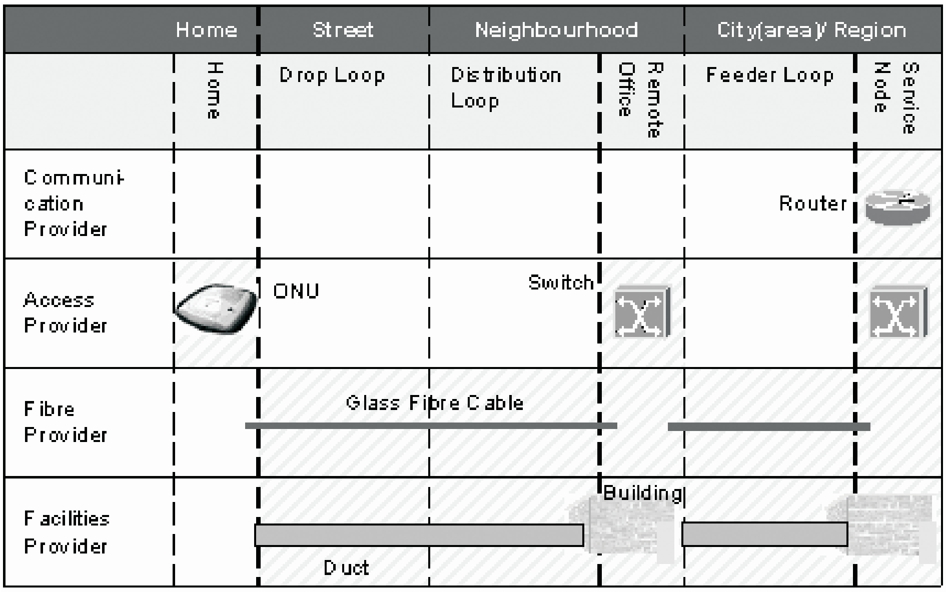
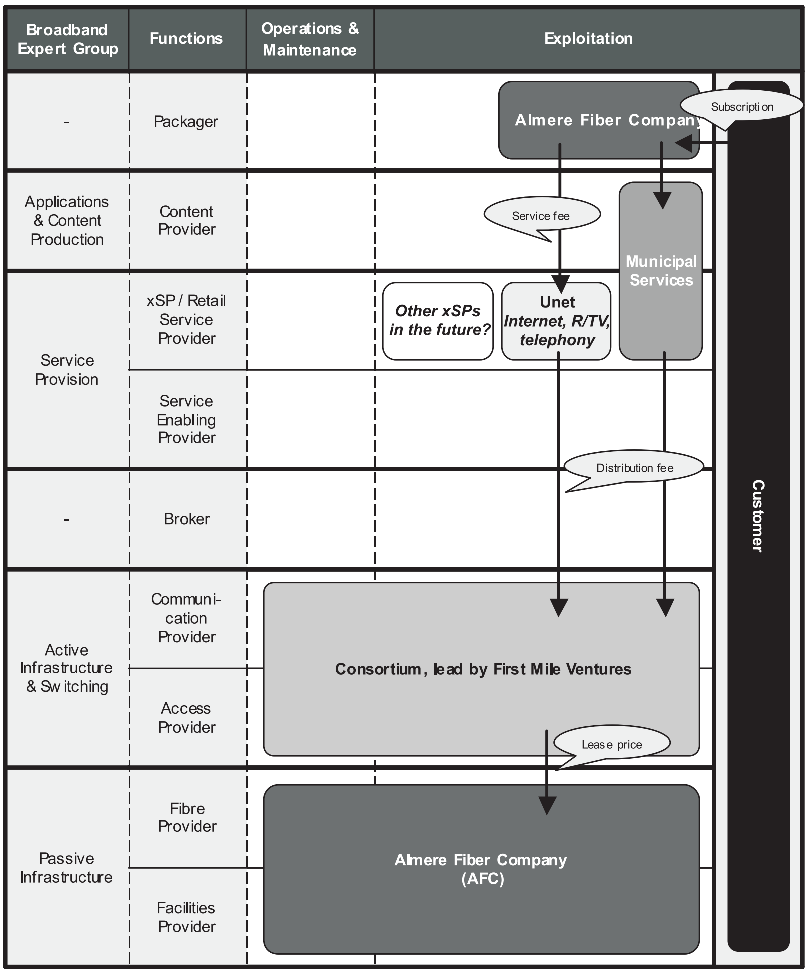


Figure 4: Division of technical responsibilities between network functions (for Optical Ethernet)

functions, which have been derived from it. The horizontal layers in the Function Model represent the functions. Two roles of the role dimension (Baken's Infrastructure Cube) are depicted on the vertical axis: 'Exploitation' and 'Operations & Maintenance'. These roles generate the revenues and are responsible for most of the Operating Expenditure (OPEX).

Figure 5: Function Model with the mapping of the Almere business model.



A party is responsible for one or more functions. This can be visualised by mapping the party on the specific cells. Arrows illustrate cash flows between actors. These run from the party that provides the cash flow to the party that receives it. Hence all incoming arrows constitute the revenue of a party. Arrows may also be used to illustrate service and or information flows. In most cases the delivery of a service is directly opposite to the way the cash flow runs. As an example the mapping of the business model of one of the studied cases is shown in Figure 5 and elaborated in the next section.

Mapping of specific business models on the generic Function Model allows an easy comparison between specific business models. This mapping also makes easy communication about these models possible. All thirteen cases from the main research fit into this generic framework [5].

Brief Case Study Example: Almere Fiber Net

Almere is a new city (created in 1975) about 35 km east of Amsterdam. It is growing rapidly, to about 180.000 inhabitants in 2005. The city is deploying an FttH pilot [15] in an area with 1700 homes and 450 companies. The aim of the pilot is to find the necessary conditions for the development of a broadband infrastructure and services. The city investigates how it may support the organisation behind the realisation and exploitation of FttH and which services are leading to a greater demand for broadband.

Almere uses the following business model: *Almere Fiber Company* (AFC) deploys the passive infrastructure (Facilities Provider and Fibre Provider functions). The local authority owns this organisation. AFC leases out an exclusive concession for the Active Infrastructure (Access Provider and Communication Provider function) by holding a beauty contest. A consortium, formed by *First Mile Ventures*, won this contest and can deploy the active infrastructure exclusively for the first five years. After this period, it may be decided that other parties are allowed to make use of the passive network. AFC also acts as Packager. Customers pay to AFC for their service package, containing services like fast Internet, digital R/TV and VoIP. These services are provided by Unet. The aim of the local authority to participate in the pilot is to ensure the open character of the network and to ensure the availability of services and their quality.

Reconstruction

As mentioned before, the main bottleneck towards FttH deployment lies in the occupation of the network functions, as they are essential in the value web. The following functions are referred to as network functions: Facilities Provider, Fibre Provider, Access Provider, and Communication Provider. Note that the Backbone Provider is a network function as well, but that it falls outside the scope of this research. The provision of services is dependent on the availability of the network, as they cannot be delivered without one. It is assumed that the service functions will evolve once the network is there[6]. Therefore the reconstruction is mainly focused on the reconstruction of the network functions into basic business model configurations. Also note that a basic principle for FttH networks is often an open model, i.e. open access for service providers. This provides for a natural division between network and service functions.

Types of Actors

Actors can occupy the clusters in the basic business model configurations. They can be divided into three groups according to their common interests in FttH network deployment: parties with no profit motive, parties with an indirect profit motive, parties with a direct profit motive.

Parties with no profit motive

Public parties

Public parties generally have other aims than making profit. Examples are local authorities, hospitals, schools and universities. Their common interest in FttH deployment is to promote the interests of inhabitants by ensuring that FttH becomes available (for all inhabitants) at reasonable consumer prices. These interests can be economical and social. In addition public parties can be consumers of broadband services themselves that want to lower their telecommunication costs. Public parties that are willing to invest in FttH often operate locally or regionally. Note that market activities by public parties are often restricted.

6 The availability does not guarantee the demand for and the use of broadband services (see for instance [8]). Nor may the availability of the network be the only resource necessary for inducing service providers to develop and provide services. Possibly, the Service Enabling Provider function has to be established first to provide for basic enabling services like billing, accounting and invoicing.

Non-profit parties
Non-profit parties are parties that have other aims then making profit, such as promoting the interest of inhabitants. They generally accept a lower Return on Investment and a longer payback period than most (other) private parties. An example is an association of house owners or tenants (as representative of inhabitants). Just like public parties, it benefits from the availability of FttH. Non-profit parties often operate locally or regionally.

Parties with an indirect profit motive
This group of actors contains private parties that aim at generating profits from occupying service functions, or from activities that otherwise benefit from FttH deployment. Examples are real estate developers, housing corporations, service providers, content providers, building corporations and maintenance firms.
Parties with an indirect profit motive benefit from the deployment of FttH, as this means that they are able to yield more profit with their core activities. They are not specialised in the occupation of network functions but may be willing to play a role in the network functions in order to 'help' realise FttH. It is even possible that these parties do not necessarily have to make (much) profit in the network functions, as long as they are able to make profits in their other activities. Therefore it is likely that in such a situation (when applicable) in return for their support, they want to have guarantees for the provision of their 'main' services (e.g. building the network, being the first party that is allowed to provide certain services). Housing corporations or real estate developers may support FttH deployment because it increases the value of their houses or real estate.

Parties with a direct profit motive
This group contains parties that aim at yielding profits directly from the occupation of the network functions in the FttH value web. These are (mainly) network operators such as the current incumbent operators (telephony and CATV operators), (new) ADSL operators and (other) new entrants. New entrants can be for instance foreign operators and system integrators, but also parties that were not involved in telecommunications before such as utility companies.

Competition
Three types of competition in the network functions can be distinguished: *no* competition in a function (*monopoly*), competition *in* a function and competition *for* a function.

No competition in a function (monopoly)
No competition in a function implies a monopoly. This means that a single party exploits the function. The advantage is that network costs are minimised (due to the absence of the required facilities to enable competition). In addition revenues do not have to be shared, making the exploitation of the function more feasible. The main disadvantage is that the specific party holds a power position, which may be abused. Note that whether a power position will actually be abused will mainly depend on the type of party that exploits the function. Parties with a profit motive are more likely to abuse a power position than parties with no profit motive.

Competition in a function
Competition in the network functions implies that more than one party exploits a function within a specific area. Central Governments often desire competition in the access network. Their aim of competition is basically the interest of the consumer: more freedom of choice, lower customer prices, more drive to innovation and more diversity in services. However, competition does not automatically lower customer prices due to the costs of competition. Costs of competition are higher total network costs due to the fact that competition exists. These higher costs are caused by the duplication of equipment and extra facilities required to enable competition. As a consequence of the costs of competition the costs per customers may rise. Note that, in general, the 'higher' the network function in which competition is introduced, the lower the costs of competition. In addition the services provided in the network functions are more or less similar.

Competition for a function
Competition *for* the network implies that there is competition *for* the exploitation of a (set of) function(s). Different parties can exploit the (set of) function(s) consecutively in time and in different geographic areas, e.g. via a concession. This form of competition is an alternative to full competition and a monopoly. This prevents a power position that comes with a monopoly, without having all the costs of extra facilities and shared revenues that come with full competition.

Design Guidelines

There are many possible ways to cluster the network functions. However, not all possible configurations of clusters are viable. Based on the theory and practice analyzed in this research, a number of guidelines may be formulated for the reconstruction of a viable value web. Note that these are guidelines rather than strict rules.

Guideline 1: Each cluster has to get benefits

The first guideline is that each cluster has to get benefits, or in other words: it has to be economically viable. Parties will not occupy a cluster of functions that is unable to get benefits. Such benefits are often direct profits but can also be less tangible such as brand building, involvement in the shaping of the market, sustaining a future market position ('competing for the future'), increased attractiveness of homes with FttH connection, or just 'to take part in the game'. The different types of actors may aim at different benefits. The above shows that functions that are not profitable on their own cannot exist by themselves and should be clustered with at least one other function to create a profitable cluster. Note that a value web as a whole will only function properly when all parties benefit from their participation. This does not mean that individual benefits are optimised.

Guideline 2: A cluster can only contain network functions that are adjacent to each other

An adjacent function is one that precedes or follows a function in the value web. This guideline is rather straightforward, because the network functions are technically complementary. It is not likely that non-adjacent functions are clustered (without the functions in between), such as for instance the Communication Provider and the Facilities Provider functions. The clustering of non-adjacent functions will incur extra costs, as more facilities are required to provide for open interconnection with other functions and it would not be possible to integrate equipment (for instance the equipment of the Access Provider and the Communication Provider functions). Another reason is that when two non-adjacent functions are clustered, a party that occupies such a cluster might have a power position that can be abused. This because another party could get squeezed when it buys as well as sells its product to the same player. The result can be a poor negotiating position.

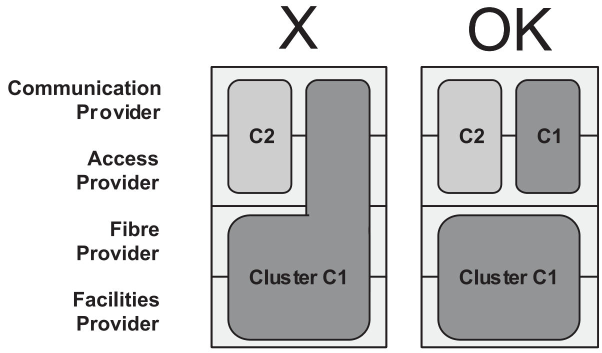


Figure 6: Visualisation of guideline 3 about competition.

Guideline 3: All functions in a cluster have the same form of competition; when two functions have different forms of competition, they should be part of different clusters.

Competition in FttH is often a desired situation by the government. Different forms of competition can exist in different clusters. However, all functions within a cluster have to have the same form of competition as their activities are merged. A split between clusters indicates that the activities contained in both clusters are separated[7]. Generally different parties are responsible for them. When two functions have different forms of competition, they cannot be clustered. Clustering would imply vertical integration between the functions and thus hinders competition. For instance, a cluster cannot contain both a monopoly and a competitive function. Otherwise a monopolist in a cluster can favour itself in another cluster with a competition function. Note that it is still possible that a party is active in both clusters. This does not matter as long as there is a financial and economic transparency between the two (by, for instance, separate business units within one company).

Guideline 4: The Facilities Provider function is a monopoly

The Facilities Provider function can be seen as a natural monopoly because costs are minimised when there is a single 'supplier'. In practice there often is a lack of space underground and this scarcity also limits the possible number of networks [13]. Therefore it is assumed in this paper that it is not likely that more than one facilities network exists to individual homes and that a monopoly in the Facilities Provider function is the best and most likely solution. Practice however may show otherwise. Note that as a consequence of guideline 3,

7 In the network, the lower cluster has to provide a open (technical) interface to the cluster above.

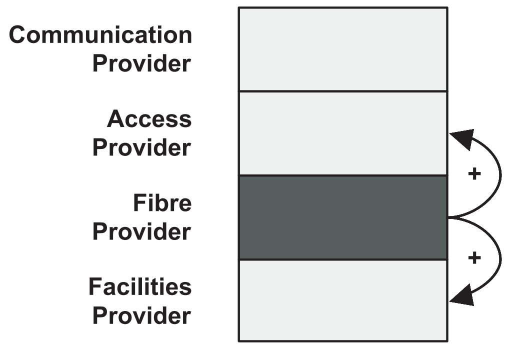


Figure 7: The Fibre Provider function has to be clustered with the Facilities Provider and/ or the Access Provider function (guideline 5).

functions that are clustered with this function have to be a monopoly as well. Competition is possible in the other functions that are not clustered with the Facilities Provider.

Guideline 5: The Fibre Provider function cannot exist on its own

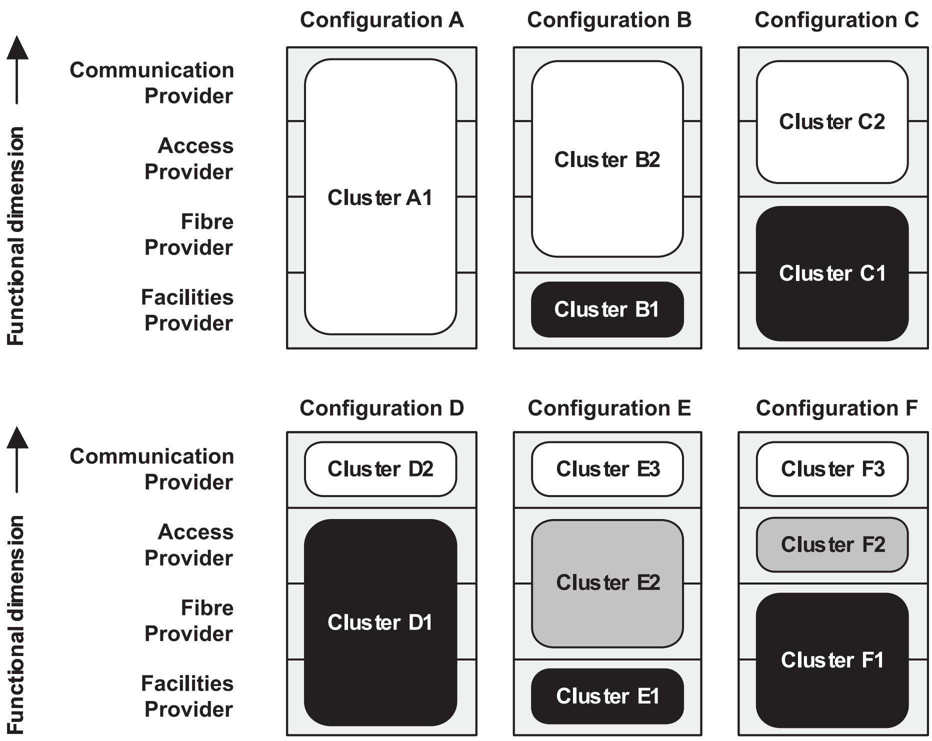
The Fibre Provider function is assumed to be unable to exist on its own. It is not likely that a party wants to exploit only the passive fibre connection. In addition there should not be too many actors in a starting market as it makes the value web far too complex. This would lead to difficulties in the making of agreements, slow down the value web, and make it more expensive. It would also become more difficult or even impossible for actors to make a profit in a single function[8]. It is more likely that the Fibre Provider function is clustered with either the Facilities Provider or the Access Provider function (this also follows from guideline 3).

Applying the guidelines results in six possible basic business model configurations. Figure 8 illustrates them. Each configuration clusters the functions in a different way. Some general remarks can be made. The lowest cluster is always a monopoly as this cluster contains the Facilities Provider function.

The splits between clusters means that this is the place where interconnection takes place and thus interconnection facilities have to be present. When competition exists, the interconnection facilities have to accommodate it.

The first four basic business model configurations can be found in practice. In addition all business models in the case studies in the original research match one of the first four configurations. This says something about the likeliness of the models.

Figure 8: Basic Business Model Configurations.



8 The only way to proof that particular functions cannot exist on their own is by making a business case per function. This can only be done per specific situation.

Configuration	Pros	Cons
A	■ Simple due to vertical integration. ■ No interconnection facilities required.	■ All investments are borne by a single entity. ■ No competition in the network functions.
B	■ The main financial bottleneck is separated from the actual network itself. ■ Legally seen to cause the least difficulties when the government wants to exploit part of the network (B1) by itself. ■ Not much telecom specific knowledge is required for B1.	■ Difficult (and expensive) to make competition in/ for B2 possible. ■ Combined installation and operation of the ducts and fibre cables might be cheaper.
C	■ Comparable to the ADSL situation. ■ The functions in both C1 and C2 have similar technical characteristics (integrated components can be used). ■ Proven in practice (Stockholm, Milan). ■ Depreciation period of equipment in C2 equals a reasonable concession period (5-7 years) in case of competition for the exploitation of C2.	■ Competition in C2 is not possible in PONs. ■ High switching costs when the party in C2 changes because much equipment has to be replaced (lock-in effect for customers).
D	■ D1 contains all functions of a local nature and all FttH specific functions. In fact the technology used in D1 is not necessarily FttH. D2 is of a more regional nature and not FttH specific. ■ Low switching costs when the party in D2 changes.	■ A party in D1 has to have knowledge about the Access Provider function. ■ No competition possible in three lower functions (power position for the occupant). ■ The equipment of the Communication Provider and Access Provider cannot be integrated, possibly resulting in higher overall costs.
E	■ The main financial bottleneck is separated from the actual network itself. ■ Legally seen to cause the least difficulties when the government wants to exploit part of the network (E1) by itself. ■ Not much telecom specific knowledge is required for E1. ■ Cluster E3 is independent of FttH. ■ Low switching costs when the party in E2 changes.	■ Complex (high number of clusters). ■ The equipment of the Communication Provider and Access Provider cannot be integrated, possibly resulting in higher overall costs. ■ Difficult (and expensive) to make competition in/ for E2 possible.
F	■ F3 is not dependent on FttH. ■ Simpler Operations & Maintenance for F1 through combination in installation and maintenance. ■ Low switching costs when the party in F2 changes.	■ Complex (high number of clusters). ■ The equipment of the Communication and Access Providers cannot be integrated, possibly resulting in higher overall costs. ■ Competition in F2 is not possible in PONs

Table 1: Most important pros and cons of the basic business model configurations.

However, no definite conclusions can be drawn from the case studies with respect to the viability of the business model configurations. This is because their success or failure cannot be evaluated yet; it has to show itself in the coming years. In addition the sample size of the analyzed case studies is too small. Interviews also showed that most existing Dutch business models are based on the Broadband Expert Group model (configuration C).

The fact that the last two configurations are not found in practice is probably because they are more complex (three clusters rather than two) and therefore not very likely to occur in a starting market. They may evolve in the future.

Table 1 shows the most important *pros* and *cons* for each of the six configurations. Note that the pros and cons in the table are not meant to be exhaustive.

Discussion and conclusions

Discussion

This article focuses on business models for FttH deployment as a way to provide for broadband services. This does not mean that FttH is the only possible broadband infrastructure or that FttH is the best for all situations. TNO investigated which infrastructures can be used to realise broadband connections in an urban environment [14]. It was concluded that depending on the requirements of four typical service packages full copper, hybrid fibre and full fibre technologies can be used as broadband access network, with only the full fibre technologies supporting all service packages.

Note that the assumptions made and the context used are specific for the Dutch situation. In situations where the dominant factors differ from the Dutch situation, the choices in a business model can be different.

Conclusions

The development of a viable business model requires a multi-dimensional approach. The managerial/ organisational dimension is dominant; the other dimensions pose the boundary conditions.

The Function Model and the descriptions of the functions (see main research) constitute the generic business model. The Function Model provides a framework for describing, analysing, comparing and visualising FttH business models.

Based on viability considerations, six basic business model configurations for the network functions appear. Three of these configurations can be found in practice and one in theory. Recent experiences indicate that configurations A and C are favoured.

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Policy and role of public organisations and their requirements on new broadband access infrastructures

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Keywords: broadband access, broadband services, policy, requirements, government.

Abstract
This paper is based on actual experiences of our institute in supporting city councils and public organisations aiming to stimulate the broadband access evolution. It highlights the current situation in the Netherlands and stimulates the discussion of the possible roles of government in modern countries. It gives a new and comprehensive overview of the relation and interdependency between broadband access infrastructure, broadband services and requirements of public organisations.

1 Introduction
The Netherlands holds a rather unique position, having amongst the highest cable penetrations in the world (96%) and a total broadband penetration amongst households (16%), being already the highest in Europe [1]. Many city councils and public corporations in health, education, housing and utilities are playing an active and stimulating role in the ongoing broadband evolution. These public organisations write broadband policies, start project teams, make contacts with network and service providers, investigate the local need for broadband services, organise symposia on the broadband theme, attract public and private finance and even in some cases start implementing their own broadband pilot projects. This paper deals with the question: why are these public organisations starting all these stimulating activities, what roles can they play and what are their concerns in imposing requirements on the broadband access infrastructures they will get in their cities. It also elucidates the role of national government in supporting these local public organisations. Furthermore, it assesses the various broadband options a project or municipality can choose from and relates these options to the services that the infrastructure needs to support. Then, for the urban case, the various options are validated. This paper has been based on a study done on behalf of the city council of the Hague, and sponsored by the ministry of Economic Affairs [2].

2 Policies of city councils and public organisations

2.1 National Broadband Policy
In the Netherlands, a National Broadband Expert Group has made a broad range of recommendations to the cabinet for achieving a national lead in the field of broadband infrastructures and applications [3]. These recommendations were only partly accepted by the Dutch Cabinet; the role of market and local initiatives was more strongly emphasized instead of intervention by the central government. City councils, public organisations and some private companies in the Netherlands have now taken the lead in the development of broadband infrastructures. A number of cities have started pilot projects, financed and stimulated by the ministry of Economical Affairs [4]. Other cities have used their own financial resources to start broadband projects.

In this paper we will follow the Expert Group with the interpretation of the term "broadband" as follows: a connection that is symmetric and 'always on' and with a sustained rate of 10 Mbps and higher. This definition is different from that used by some other authors [1]. Rates between 128 Kbps and 10 Mbps are called "midband" and rates below 128 Kbps are called "narrow band". In the chapter 2.3 we will give an overview of policies related to the broadband theme, with the relation to different roles as given in chapter 2.2.

2.2 Possible roles

Depending on their policy and ambition, city councils and public organisations can take different roles in ICT infrastructure related projects. We might see the following roles to materialise, displayed in ascending order of level of involvement:

- *Supervisor*; giving permission to private parties for digging and installing and with a policy to co-ordinate digging and installing of ducts and cables for various utilities like electricity, water and telecommunications.
- *Facilitator*; advising how to conform to certain rules, streamlining the formal and legal paperwork, organising events.
- *Stimulator*; supporting private parties by (partly) subsidising an event, research or broadband pilot.
- *Demand aggregator*; getting enough critical mass by combining the demand of public and private parties in the market.
- *Launching customer*; finding the government organisations, which will be the first customers.
- *Investor*; providing funds for direct investment or supplying a government-backed loan. When an investment is made in a new venture together with private companies, a Public Private Partnership is formed.

2.3 Different ICT policies and related roles

In the Netherlands we see public and private organisations being active in the stimulation of ICT use. We have observed 7 examples of policies in which municipalities are active recently. These policies are often related to a policy of the central government and tend to be a mixture of municipal and central government's policies.

- To stimulate development of novel technologies and applications, the government initiated a nationwide *R&D programme* named Freeband. In the programme, companies, universities and research institutes collaborate in order to develop new broadband applications and build demonstrators for them [9].
- To bridge the *digital divide*, the Ministry of the Interior and Kingdom Relations started the project "Digitaal Trapveld" (digital playground) in April 2000 to give access for underdeveloped groups to computers and the Internet. Target groups were children, seniors, job-less people and members of an ethnic minority. This policy has been successful in at least 440 local projects in the greater cities in the Netherlands [5]. It didn't necessarily always bring broadband access, because these local projects work with available access infrastructure.
- Fast *flat fee Internet* for all. One of the advantages of ADSL and Cable Internet is its flat fee billing aspect. In 2003 ADSL providers have a reach of only 85% of the households in the Netherlands. Cable providers in 2003 have made 70% of their consumers ready for connection on 2-way communication services. Thus about 15% of the households in the Netherlands do not have access to current flat fee Internet infrastructures. These households are part in most cases of sparsely populated rural areas. Local initiatives, with the strong support of the municipality, have materialised in these areas. The incumbent operator KPN is willing to make the necessary investments in the local exchange if these groups were able to get the signatures of at least 325 households willing to pay for an ADSL connection. The result is that KPN expects to increase the reach of ADSL to 97% in 2004.
- Policies to stimulate *e-governement*. With these policies the city council is offering the citizen an extra outlet for the existing services they get in the town hall and new services to improve the services to the community and the interaction with citizens [6]. In 2003 100% of the municipalities in the Netherlands have a web-site, with a high variety of e-government services offered. On the short term this doesn't bring broadband, but on the longer-term e-government services may be extended to broadband services like live video connections to the meeting of the local city council.
- Policies to realise a metro network often called a *city-ring*, to give a broadband connection to business and office areas in the city. If the offices of public organisations are connected to the city-ring and the city council plays an active role to connect these organisations, the council is playing the role of launching customer. The GigaPort project has stimulated and organised the building of dark fibre rings to connect municipal and non-profit organisations in cities like Arnhem, Leeuwarden and Nijmegen [7].
- The development of a *new housing estate* gives rise to the occasion of realising a future-proof ICT infrastructure. It is an attractive service of

the housing corporation to have the possibility of offering a broadband connection, preferably optical fibre, to the home. This policy has been followed in recent years in new housing estates in many Dutch cities like Amersfoort-Vathorst and Enschede-Roombeek [3]. In other new housing estates a consortium under the name Trilink has prepared the area for broadband by installing empty mini-ducts in a duct-system, containing also conventional copper pair cables.

- The ministry of Economical Affairs, as part of the "Breedbandproeven" arrangement, stimulated and financed eight projects for the development of *broadband pilots* [4] in 2002-2003. In most cases these pilots were related to broadband infrastructure projects in existing residential areas. The subsidy was given for the development of the pilot plans. In some cases these plans were developed with a masterplan towards a complete roll out of passive optical fibre networks in the city [8], with the municipal bodies having a minor share in the Public Private Partnership.

The relation between the above policies and the possible roles of paragraph 2.2. is given in Table 1. The last 3 policies in this table are related to broadband access nowadays. The information services demanded in the first 4 policies will however require more and more a broadband infrastructure in the near future.

The requirements of a public organisation towards the technological options for broadband access infrastructures are discussed in the next chapter.

Table 1: Policy-profiles and the most likely associated roles of public organisations.

	Supervisor	Facilitator	Stimulator	Demand aggregator	Launching customer	Investor
National R&D progr.			X			
Digital divide			X			
Flat Fee Internet for all			X	X		
E-government					X	
City-ring	X	X		X	X	
New housing estate	X	X	X			X
Broadband pilot	X	X	X	X	X	X

3 Requirements on infrastructures and technology options

3.1 General requirements on broadband access infrastructures

Depending of the role a public organisation takes, a lower or higher degree of influence on the choice of the technology for the infrastructure is needed. Roles as "launching customer" and "investor" will almost certainly imply the involvement of the public organisation in setting the requirements. At first the public organisation has to consider the general aspects, which we will discuss in this chapter. These general aspects can be made more specific by the public organisation when more details about their priorities and circumstances surrounding the broadband ambition become clear. In this paper this has been done for an urban municipality 'case'. If the policy is related to a profile of broadband services, the relation between the service and the network requirements should be made as well, leading to specific service requirements as discussed in chapter 4. The aspects on which a general requirement should be formulated are:

Reach and Penetration factor

Reach deals with the total geographical area, which can potentially be served (e.g. maximum coverage area of a wireless technology or maximum distance for DSL-technologies). The maximum number of subscribers that actually can be connected (sometimes restricted by technical aspects) within a certain coverage area is usually defined in the form of a penetration factor

In case of "broadband to all" policies, the penetration should be as high as possible, and the reach/distance should be enough to economically cover the needed distance between user and the first aggregation point in the access network.

In the case of a city-ring, it is sufficient that the access network reaches all the targeted offices and businesses.

Restrictions in reach may be related to the distance to the central office (telephony exchange) in case of DSL, or more general the service node or remote node (hub) with most of the other technologies. In most cities a maximum distance of 5 km is sufficient. If the technology used in "the last mile" is not able to bridge the distance, it is possible to use a broadband feeder network (resulting in a hybrid access-infrastructure).

Regarding level of penetration some optical and wireless technologies require line-of-sight between the client and the (radio, optical) antenna mast. In rural areas this is less restrictive than in urban areas. Using full copper technologies, the number of active DSL subscribers connected within the same feeder cable has its limitations.

Future proofness

The infrastructure should be scalable regarding the number of active clients and able to support future growth in use per client. It should be possible to support future services.

It is desired that the upgrade of the infrastructure by just changing the active components and by keeping the passive cable infrastructure in place is possible. The use of the radio spectrum should be protected by a government license, to protect investments made in transmitter/receiver equipment specific for a certain frequency band from interference by other radio sources.

Maturity

A mature technology ideally has better operational qualifications and has a certain product interoperability (guaranteed by standardisation) and commercial availability. If a mature technology meets the specific requirements, this is often preferred. The maturity of an infrastructure depends on degree of standardisation and the acceptance of the standard by the users and other operators. Many of the access technologies used are already standardised within ITU, IEEE or ETSI.

The risk of taking a technology, which has its standardisation not finished, is that systems should be replaced on a shorter term by standardised and improved versions. Maturity also tends to relate to the number of industries offering the solution, in turn relating to price levels

Openness

Openness deals with the possibility of different operators using the same network at the same time. There is the European regulation framework in place, which requires this openness for several services [11]. A public organisation or city council should always pursue the goal of openness and the possibility of free competition.

Interconnection between networks may be possible on the service layer, the networking layer and even on the physical layer.

On the physical layer the term unbundling of the local loop is used. Unbundling of the local loop is realised in the Netherlands with regard to copper pair infrastructures. Cable operators recently are making steps in opening up their infrastructures. With regard to fibre infrastructures, unbundling is of special interest because the investment of a fibre infrastructure is expensive and fibre infrastructures have the possibility of carrying all basic services; TV, telephony and data. Fibre infrastructures that are partly financed by government should be open to more than one operator for each of these basic services. Discussion and research are going on how this role of network operator on an unbundled passive fibre network may be fulfilled with an acceptable economic return.

Price

The price citizens have to pay for their broadband connection should be affordable. This means that city councils should strive to let the free market mechanisms work in order to let the consumer makes his choice for an offering with an acceptable price / quality.

To stimulate the use of new broadband infrastructures a temporary subsidy may be used. In some cases the government subsidises the connection charge for a restricted period. This has been done in The Dutch Smart Community pilot in the Eindhoven region, called "Kenniswijk" [10]. According to EC regulation [11] this was only possible in the case of no preference for the technology to be used.

3.2 Technology options

Below, a vast range of options for an access infrastructure will be discussed. They will be covered in the following clusters:

- Fixed Wireless technologies (§ 3.2.1)
- Full copper technologies (§ 3.2.2)
- Hybrid fibre technologies (§ 3.2.3)
- Full fibre technologies (§ 3.2.4)

3.2.1 Fixed Wireless Technologies

Local Multipoint Distribution System (LMDS) and Multichannel Multipoint Distribution System (MMDS).

LMDS and MMDS are systems that are based on the same technology as radio relay systems (often used for leased lines). Usually the regulator allocates a frequency space. In contrast to the traditional (point-to-point) radio relay systems, LMDS/MMDS systems can share a channel data rate between multiple users (point-to-multipoint). Although use of frequency bands differs internationally, in the Netherlands for LMDS these are channels in the 26 GHz band and for MMDS in the 2,6 GHz and 3,5 GHz band. Typical data rates are

2-26 Mbit/s for MMDS and 34-84 Mbit/s per channel[1] for LMDS. Although the channel data rate of MMDS is lower than LMDS its reach is higher (in the order of 15-20 km); a typical LMDS base station coverage is 4-7 km. The sharing bandwidth functionality makes this technology potentially interesting for use as a residential broadband access technology.
Due to the use of a high frequency-band LMDS and MMDS often need a '*Line of Sight*' (LoS) connection i.e. between base station and customer transceiver there should be no obstructions by buildings or trees. New technologies do permit MMDS to work as a 'near LoS' technology that does allow for some objects standing in its path. Consequently this technology is often seen in rural areas where building density is low and where the access to fixed (telephony, cable) broadband access infrastructure is limited.
The *maturity* of LMDS and MMDS systems regarding availability of products is at a good level. The IEEE 802.16 is active in standardising the way the frequency band is used (2-11Ghz and 10-66 GHz), with the WiMax Forum conducting interoperability testing of equipment. The *cost* of LMDS and MMDS equipment differs that MMDS equipment is usually cheaper than LMDS equipment because it is more positioned for the consumer market while LMDS is still mainly used for the traditional leased line business segment.

Free Space Optics (FSO)

FSO is a 'laser through the air' technology, which is often used to interconnect the LANs between buildings of the same company (or on campus between university buildings). Most products offer data rates between 100 Mbit/s and 622 Mbit/s, and bridge distances of 1 to 4 km, some vendors claim data rates of 10 Gbit/s, however this is usually over a shorter distance. FSO is a point-to-point technology requiring subscribers to have their own transmitter/receiver pair.
Typical *prices* of this technology are orders of magnitude higher than for e.g. Wireless LAN or ADSL equipment. Furthermore none of these investments can be shared with multiple subscribers, as is the case with LMDS and MMDS.
Regarding *spectrum use* the advantage of FSO is that there is no requirement to obtain a licence for a certain 'wavelength band' (as usually is the fact with LMDS and MMDS), since capacity is not a problem in this part of the spectrum.
Similar to LMDS (and MMDS), FSO also needs a clear *Line of Sight* path between receiver and transmitter. FSO transmitters therefore are usually installed on the roof of buildings.

Wireless LAN (WLAN)

Wireless LAN is a well known technology that has seen a widespread adoption for realising Internet or LAN access within the home domain and also in the surroundings of public places, in the form of 'hotspots' (like hotels, airports, corporate buildings and university campuses). Part of the popularity of this technology is that the user is not required to obtain a license for the use of the frequency band.
This is because it uses the license-free 'Industrial, Scientific and Medical' (ISM) frequency bands. The use of the ISM bands implies that in certain areas the frequency band can become 'crowded' resulting in a drop of the effective data rate, or no connection at all. As a consequence both coverage and end user data rates cannot be guaranteed, making the WLAN technology a less *future proof* access network investment compared to a licensed LMDS or MMDS infrastructure.
Typical effective data rates for the most common WLAN-standard (IEEE 802.11b using the 2.4 GHz band) are between 1-7 Mbit/s although usually 11 Mbit/s is advertised as the maximum (theoretical) data rate. A newer WLAN-standard, which is backwards compatible with the IEEE 802.11b, is capable to realise higher data rates, advertising a maximum (theoretical) data rate of 54 Mbit/s. In pratice the effective datarate is lower, at around 37 Mbit/s. This same data rate can also be obtained by the IEEE 802.11a standard, using a higher ISM frequency band (5 GHz).
Because of regulatory restrictions regarding the transmit power in the ISM-band the reach of WLAN is between 30-300 meters. The maturity of WLAN is at a good level due to the IEEE 802.11 standardisation and interoperability testing by the WiFi Alliance.
Since the adoption of the WLAN for indoor and outdoor use has been high, the *price* of standard WLAN equipment has dropped significantly.

1 These figures are calculated taking for MMDS a reference bandwidth of 28 MHz resulting in 84 Mbit/s and for LMDS a reference bandwidth for MMDS of 34 MHz resulting in 26 Mbit/s. Since this is a shared medium end-user capacity will be lower. Actual data rates might vary depending on vendor product implementation and use of frequency band.

Satellite Communications (SatCom)

Internet access via satellite is available in many countries and most popular in communities where there is already a satellite dish installed for the reception of regular television broadcasts and fixed broadband options are unavailable (e.g. DSL or Cable Internet). If the TV-satellite dish is used, then only downstream data can be delivered via the Satcom channel and the upstream needs to be sent via a regular telephone modem.

For bi-directional 'Internet via Satcom' a new dish and transmitter need to be installed. With such a set-up (depending on the capacity that an Satcom ISP has leased on a satellite) a maximum of 38 Mbit/s downstream and 2 Mbit/s upstream can be achieved (when the Digital Video Broadcasting-standard is used). This capacity is shared among multiple users. Although the reach of the Satcom technology itself poses no problems -a country can be covered by one spot beam of a satellite- there should be an unobstructed '*Line of Sight*' between the dish and satellite. This does pose some problems for apartment complexes where residents do not have rooftop access. This can be solved by installing a shared Satcom dish but often requires the approval of all residents.

The *costs* per month for Satcom access is quite competitive although still a bit higher than DSL or cable access, however the installation cost of a new bi-directional Satcom dish is quite prohibitive usually in order of 1500-4000 Euro.

3.2.2 Full Copper Technologies

Digital Subscriber Line (DSL) technologies use the copper telephony access-network to transmit data. Depending on the type of technology this could be done over the same wire pair as used for telephony or by using an extra wire pair dedicated for DSL-transmission.

Although ADSL is probably the best known DSL-technology, other new DSL varieties exist; each designed for realising symmetrical or asymmetrical bit rates at a certain distance. An overview is given in figure 1.

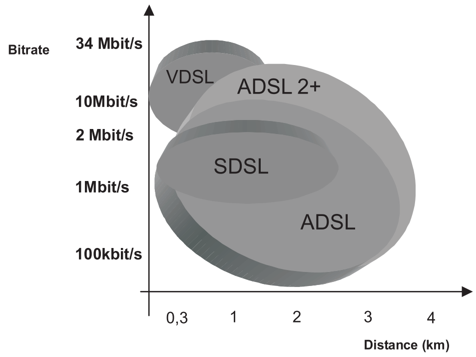

Figure 1: Overview of DSL-standards

High speed DSL, Asymmetric DSL and Symmetric DSL (HDSL, ADSL and SDSL)

The first DSL-technologies have been High speed DSL (HDSL), Asynchronous DSL and Synchronous DSL (SDSL). High speed DSL (HDSL) has been around for many years, but needed its own dedicated telephone copper pair(s) and is mainly used for the business segment (e.g. for providing leased lines of 2 Mbit/s). ADSL is the first DSL-technology providing broadband Internet access to the consumer segment, using the same copper wire pair as used for telephony service. The theoretical data rate for ADSL is 8 Mbit/s downstream and 640 kbit/s upstream

Recently SDSL was introduced in the Netherlands but -like HDSL- it was designed for transmission over a dedicated wire pair. The advantage of SDSL is that it has a higher upstream capability then ADSL, resulting in to a symmetrical data rate of 2.3 Mbit/s. An important aspect of DSL-technologies is that the effective data rate depends on the actual distance between the subscriber modem and the telephony exchange building. The typical threshold distance for ADSL service (used by operators in the Netherlands) for granting a connection is between 3-4 km, which translates to 75% - 90 % of the households.

The crosstalk in a bundle of copper wires increases with the total number of active DSL-connections. This spectral pollution will influence the effective data rate of all subscribers (in the same bundle of wires). Currently it is unknown how many active DSL-connection can in practice be accommodated; when the comings years more DSL-connections will be realised these limits will become clearer.

Even though there are still some interoperability issues between DSLAM and modems vendors the main issues are resolved, resulting in a market where the subscriber can choose his own ADSL-modem while choosing his provider. Therefore this market has *matured* to standardised, *price*-competitive market.

Regarding the *openness*, it can be mentioned that 'local loop unbundling' is like in many other countries a regulatory requirement in the Netherlands that enables DSL-providers to get direct access to the copper wire pairs from a co-location space inside the telephone exchange.

ADSL2(+)

With the growing demand for higher data rates also new DSL-technologies have been developed. ADSL2 uses better modulation methods and has less overhead than ADSL, resulting in a higher data rate (at a certain distance) or a larger distance (at the same data rate). The maximum data rates ADSL2 can realise are 10 Mbit/s downstream and 1,4 - 3,5 Mbit/s upstream. By using a higher spectral bandwidth (up to 2.2 MHz instead of the 1.1 MHz used by ADSL) ADSL2+ can realise maximum data rates up to 24 Mbit/s. The high end of these data rates can only be realised on shorter distances.

ADSL2(+) products are just recently on the market and standardisation recently finalised, however it has not yet reached its full maturity regarding interoperability between equipment vendors.

When the goal is to provide the majority of household with this type of (improved) DSL-connection, the limit in reach will become a bottleneck. This can be solved by introducing fibre in to the access network and shifting the location of the DSL-Access Multiplexer towards the subscriber; this is explained in the next paragraph.

3.2.3 Hybrid Fibre Technologies

Hybrid Fibre VDSL

Although ADSL2(+) can still maintain a distance of several km at lower data rates the VDSL-technology has been designed to only realise high data rates at relatively small distance. VDSL could be rolled out just from telephony exchange location, and only offered to a select number of subscribers (who live within the reach). But when the ambition is to reach a large number of subscribers (high penetration factor) the use of a broadband network is needed feeding the VDSL DSLAM, with the DSLAM on street cabinet location. This hybrid access network, using 'Fiber to the Curb' (FttC) to feed the VDSL copper drop loop is shown in figure 2.

VDSL can realise symmetrical as well as asymmetrical data rates. Typical symmetrical data rates are between 6.4 Mbit/s and 28 Mbit/s. The typical distance of VDSL will be 1-2 km for lower data rates and only hundreds of meters for 10 Mbit/s and higher. In the Europe VDSL has yet to breakthrough, a limited rollout or trial can found in Norway (TeleNor), Italy (Telecom Italia) and Belgium (Belgacom).

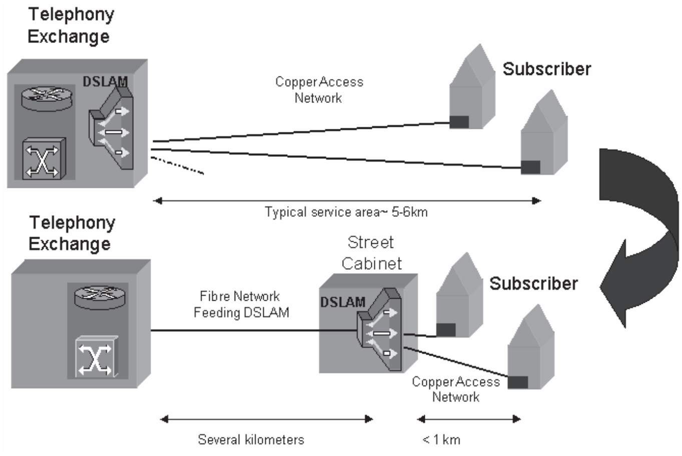

Figure 2: Migration towards Hybrid Fiber access network

Making the access infrastructures open for competitors to implement VDSL will mean that access to the street cabinet should be possible. Although there are some discussions and unilateral offers regarding 'sub-loop unbundling', it is not yet fully legislated; also some operational issues remain unclear.

Hybrid Fibre Coax (HFC)

The cable operators in the Netherlands have undertaken an upgrade of most of their cable network to support 2-way communications and together they can potentially connect 70% of all cable TV households to the Internet service. Most of the cable networks already consist of a fibre-feeding network between the city and district centre, in effect already using both fibre and coaxial cable in the access part of the network.

Although there are still old proprietary internet cable modem systems operational, the most dominant systems will soon be the ones following the EuroDocsis standard (Data Over Cable Interface Specification). This standard, based on the U.S. Docsis standard is a mature and well-defined standard. Before a new modem following the EuroDocsis standard is released by a vendor it is tested and certified by the EuroDocsis Certifcation Board (TComLabs) to ensure product compliance to the standard and interoperability.

Using this EuroDocsis standard a maximum downstream channel data rate of 38-52 Mbit/s can be reached. Upstream 10 Mbit/s is possible, or even 30 Mbit/s if a newer version of the EuroDocsis standard (2.0) is used.

An important aspect with a HFC network is that this channel capacity needs to be shared between users. Depending on the specific operator dimensioning currently around 2500 users might share a downstream channel and 160 the upstream capacity. It should be mentioned that depending on the environment (urban or rural) and country these number differ greatly.

In order to evaluate in this paper the potential of the HFC technology in an urban environment (with a high penetration factor) we defined two HFC-cases. These cases might not yet been implemented in the Netherlands but could be implemented in the near future.

In defining these cases we use the fact that there is already fibre in the access portion of the network. This means a cable operator can steadily introduce more capacity in this network, by terminating the different coaxial segments onto separate fibres or wavelengths.

A realistic near future HFC-scenario is that using ten data channels of 38 Mbit/s downstream and five 5 Mbit/s upstream (by using EuroDocsis 1.1) a total number of 800 subscribers are connected.

A more futuristic HFC+ scenario is that the coaxial cable can be terminated onto the fibre on an even deeper level of the HFC-infrastructure: the lower district or area centre. At this level usually around 120 users are connected per centre. The bit rate per channel is 52 Mbit/s downstream and 30 Mbit/s upstream (using EuroDocsis 2.0) (again using 10 channels down and 5 up). Assumed in this HFC+ case is that the cable network is made out of rather new coaxial cables and network elements optimised for less susceptibly to interference.

An interesting aspect of HFC-networks is that they have the capability to transmit Video content via their normal analogue or digital (DVB) 'broadcast' part of the cable network, while only using their bi-directional capacity of the network for e.g. Internet access and Telephony. A HFC network is able to offer a 'triple play' of service via one network (video, telephony and Internet service).

Power line Communication (PLC)

There are several types of PLC systems currently on the market:

- The 'indoor PLC' systems; these perform several home-automation and basic personal data-transmission (e.g. between PC and printer) functions.
- The 'outdoor PLC' systems; connecting several PLC-modems to a central hub location (usually a power utility cabinet or small power transformation building).

The 'outdoor PLC' systems have a potential to function as an access-network technology. However the reach of this type of PLC systems are between 200-300 meters, requiring an other broadband access network technology to 'feed' the PLC system outside the house. This is why PLC can also be called a Hybrid technology, using both e.g. fibre and the power network cables in the access part of the network.

The data rates that are supported are rather low when compared to the other access-technologies; typical 1,5 Mbit/s can be realised per channel, with a limited number of channels available in the PLC-spectrum (around three). These three PLC channels can be combined to achieve a total of 4,5 Mbit/s.

Specific national norms for the use of the spectrum by PLC vary from country to country (or sometimes are not present), therefore a uniform PLC implementation is not yet defined or standardised.

Currently pilots are done with this technology in several countries. In the Netherlands the PLC-trial by energy company Nuon was terminated and no follow up has been planned.

3.2.4 Full Fibre Technologies

Optical Ethernet (OE)

Optical Ethernet makes use of Ethernet protocol that is widely used in Local Area Networks. Depending on the optical fibre used (single mode fibre can support higher data rates at larger distances than multimode fibre), typical distances between 550m and 10 km can be realised, together with data rates of 100 Mbit/s to 10 Gbit/s (symmetrical).

For some years, Optical Ethernet has seen its application as a way to interconnect LANs (effectively realising a 'Wide Area Network') or as a metropolitan 'leased line' alternative ('Metropolitain Area Network'). Recently it is also used in 'Fibre to the Home' (FttH) trials. When realising an Optical Ethernet infrastructure, usually a new fibre network needs to be realised. Although the fibre itself is in the same price range as twisted pair copper, the labour involved in digging and building new cabinets can be very *costly*.

If a single mode fibre is chosen, an initial FttH rollout dimensioned at 100 Mbit/s speed can be easily

upgraded to 1 Gbit/s (or even 10 Gbit/s if required), making this part of the passive infrastructure more *future proof.* Also the use of special ducts where fibre can be added or removed after the ducts have been buried is an interesting technique that can be used to keep the infrastructure *upgradable*.
Optical Ethernet products are readily available and already used in the LAN/WAN/MAN market with standardisation driven by the IEEE 802.2 group, making it a *mature technology*. Also vendors are addressing functionality like per subscriber Quality of Service (QoS) when OE is used as an access network technology.

ATM and Ethernet Passive Optical Network (APON/EPON)
Some years back, when the introduction of fibre in the access network was foreseen, the Full Service Access Network consortium (FSAN) designed a fibre access architecture called 'Passive Optical Network' (PON). The network makes use of an underground splitter coupling one fibre signal half way in the access network onto more fibres, resulting in fewer fibres to be used than is the case with Optical Ethernet. This point-to-multipoint topology means however that the bandwidth of one fibre is shared with a number of users (typically 16 to 32 users, which is the maximum splitting factor).
Already a few years back FSAN adapted and standardised ATM to be transmitted on the PON architecture, the advantage of ATM being that certain QoS mechanisms are available in this protocol for provisioning different services (like voice, video and internet) with different priorities. Although the data rate of the first FSAN compliant ATM PON systems was 155 Mbit/s, current systems support a symmetrical data rate of 622 Mbit/s (and proprietary implementations go up to 1 Gbit/s). The *distance* that can be reached with an APON system is 20 km.

The main cost drivers of PON systems are the optical transceivers. The *price* of the APON systems continue to stay relatively high due to the fact that the technique is designed for specific type of market (FttH or FttB market), which is still relatively small in size.
With the increase in business use of Optical Ethernet systems also the Ethernet protocol has been adapted for use over a PON. The IEEE 802ah 'Ethernet in the First Mile' task force is working towards an update of the standard (IEEE 802 ah 1.3) that will enable the EPON components to be manufactured at significantly less *cost* than their APON rivals.
As the EPON standard now reaches a more mature level, several EPON products are currently coming to the market, delivering 1 Gbit/s of PON transmission speed (typically to be shared with 1-16 subscribers). Mainly in the U.S. some Commercial Local Exchange Carriers have regionally implemented EPON and APON technologies in their access network.

3.3 Case of an urban municipality
On behalf of the City Council of The Hague and the ministry of economic affairs, the general requirements have been made more specific in order to evaluate which of the mentioned potential access network techniques (as mentioned in all of § 3.2.) would be suitable for implementation in an urban environment [2].

The main conclusions are:
Fixed Wireless Access technologies
LMDS, Satellite and Free Space Optics are less suited for use in a densely populated urban area (with many buildings and apartment complexes) because of the restrictions in line-of-sight. MMDS has some 'near Line of Sight' restrictions.
WLAN has the risk of being more susceptible to other radio users due to its use of an unlicensed frequency band. The geographical reach of WLAN is also restricted to several hundred meters and therefore would need a sizable broadband feeder network.
Although these technologies are less suitable for realising an access network, it can be said that Fixed Wireless Access technologies are good alternatives to fixed connections, when used as hotspot connections or as alternative for specific 'leased line' concepts. The process of licensing LMDS and MMDS in the Netherlands is almost finished, making it a better alternative for WLAN.

Full Copper technologies (xDSL-technologies)
DSL-technologies have been designed for use in an access network, making these technologies generally more suitable.
At lower bit rates ADSL(2+) and SDSL have usually sufficient geographical reach to cover the complete distance in an access network. When higher data rates are needed and e.g. VDSL is used, the distance realised is lower than what is needed in an access network (when the objective is to reach the

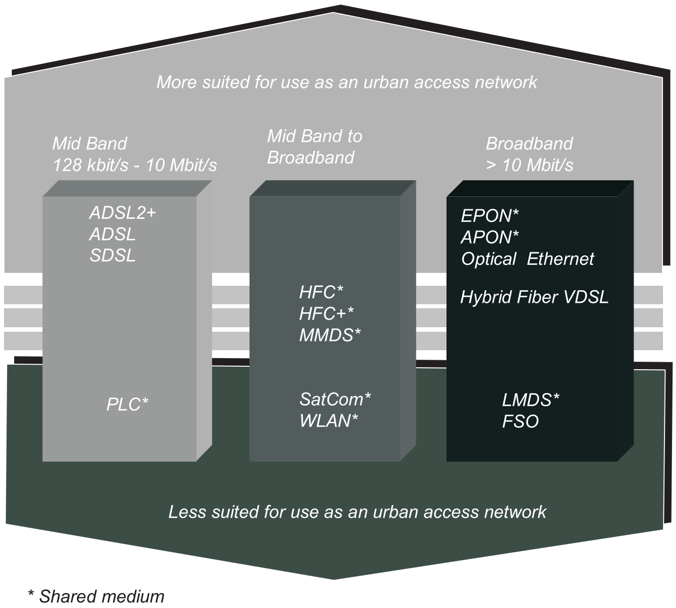

Figure 3: Suitability of access infrastructure solutions for urban access network environment.

majority of households) and should be complemented by a broadband feeder network (e.g. based on optical fibre). In that case it becomes a Hybrid Fibre technology.

Since legislation regarding unbundled local loop access is in place in most countries, several operators can implement a DSL access network over the same fixed (telephony) copper infrastructure.

Hybrid Fibre technologies

In this case fibre is used as a broadband feeder network to extend the reach of technologies like (V)DSL, EuroDocsis or PLC systems. In all cases these technologies use the existing telephony-network, cable network or energy network to realise the 'first mile' from the subscriber towards a first aggregation point where the conversion to fibre transmission is done. The fibre network will cover the rest of the 'miles' towards a switch at "telephony exchange level".

As it is expensive to perform digging in an urban environment (especially the first mile from the user towards street cabinet) these hybrid technologies have some advantage over full fibre network technologies.

Generally speaking, Hybrid Fibre VDSL and Hybrid Fibre Coax are suitable technologies to be used in an urban access network environment.

However regarding *openness* it should be noted that with Hybrid Fibre (V)DSL there is no legislation in place regarding the sub-loop unbundling (on street cabinet level).

Hybrid Fibre Coax networks in the Netherlands are currently working towards making their networks more open for other (internet) service providers, but this process will take some time to result in a truly open cable market. PLC however is not suited for implementation as an urban access network, since it is far from being standardised and not open for other operators; only energy operators can use PLC on their own network using proprietary solutions.

Full Fibre technologies (Passive Optical Network and Optical Ethernet)

ATM or Ethernet based Passive Optical Network and Optical Ethernet is suited to be used as an urban access network.

The maturity of Ethernet and ATM PON is a somewhat lower than most copper-based technologies, because it is only implemented on a small scale (not a large market) and ongoing standardisation process of EPON. Optical Ethernet is already commonly used in the LAN/WAN/MAN market, therefore products are readily available and maturity is high.

In figure 3 a summary is given of all access solutions and their suitability for the urban case.

4 Services and their requirements on access infrastructures

When evaluating the potential of a certain access network technology, it is also important to check what type of services can be transported. In this chapter we identify several service packages, determine their requirements (bandwidth and QoS) towards the network and match this against the characteristics of the different types of access networks.

4.1 Identifying current and future broadband services in to service packages

We performed research on existing and prospective broadband applications and created an extensive list of more than 200 concrete examples. These broadband applications have been grouped together in [12], showing their relevance for different application domains and matching this with the underlying generic services.

It is assumed that broadband subscribers will not use just one application, but will use a complete package of services (depending on the domain where it is used). They will start with web browsing and e-mail and step-by-step the number of

applications they use will expand. Another important assumption we have made is that in time the use of these applications will grow from one user to multiple users in the home.
These basic assumptions have led to the definition of four service packages with an increasing demand to the network resources. These are:

1. Innovative individual
- Internet, email, newsgroup access, gaming and internet quality videoconference with standard webcam, basic Teleworking (access to email and calendar) (512 kbit/s)
- Pre-recorded video content ;VHS-quality (2 Mbit/s)

2. Heavy usage individual
- Internet, email, newsgroup access, gaming and peer to peer filesharing (1 Mbit/s)
- Videoconference with high resolution webcam and 'wire line' voice quality (384 kbit/s)
- Advanced Teleworking; full access to email, calendar, files on server and remote desktop (1 Mbit/s)
- Live or pre-recorded video content; TV-quality (5 Mbit/s)

3. Innovative family
- Internet, email, newsgroup access, gaming and peer to peer file sharing (1 Mbit/s)
- Two Videoconference connections with high resolution webcam (2 x 384 kbit/s)
- Four Voice over IP channels (VoIP) with 'wire line' voice quality (4 x 64 kbit/s)
- Advanced Teleworking; full access to email, calendar, files on server and remote desktop (1 Mbit/s)
- Three concurrent live or pre-recorded video content channels/streams; TV-quality (3 x 5 Mbit/s)

4. Heavy usage family
Same as the previous "Innovative family" but added:
- One Surround sound HDTV channel/stream (19 Mbit/s)

For these service packages the requirements on the underlying network are identified in the form of 'network performance parameters' in the following paragraph.

4.2 Expressing service requirements in to network performance requirements

The network performance requirements of services have been expressed in QoS classes, delay, delay variation, packet loss ratio and the peak/sustained data rate. These results are completely listed in several tables in [12]. In this paragraph we will summarise the main results.
Regarding the QoS requirements service package 1 only needs two QoS priority classes (to differentiate between its basic internet access service and the pre-recorded video stream) and has no specific delay (variation) requirements. Packages 2 to 4 need four QoS priority classes (to differentiate between Internet, videoconference, teleworking and live or pre-recorded video content), in combination with a delay less than 50 ms and a delay variation less than 20 ms in order to support good quality teleconferencing and VoIP.

The requirements, regarding the data rate needed to transport a service, are split up into a needed 'peak' data rate and a 'sustained' data rate. The peak data rate is the maximum instantaneously needed data rate, while 'sustained' data rate is the average data rate needed to transport a service, taking into account a certain statistical multiplexing factor.
The sustained data rate calculation has been done on specific service usage assumptions (expressed in 'overbooking factor').
The peak data rate is calculated by using the sum of the data rates per service. Table 2 lists the service requirements for Live-TV/VoD content (unicast), Teleworking, HDTV (using an overbooking factor of 1:5), Internet (overbooking factor of 1:10) and Telephony (overbooking factor of 1:4).
It should be mentioned that the overbooking factor used here applies only for dimensioning the access network part of a total network. In reality an operator will overbook certain traffic/services even

Table 2: Peak and sustained data rate requirements for various service packages.

	Downstream (Mbit/s)		Upstream (Mbit/s)	
	Peak	Sust.	Peak	Sust.
Package 1	2.5	0.45	0.26	0.03
Package 2	7.4	1.4	2.3	0.4
Package 3	18	3.6	3.0	0.55
Package 4	37	7.4	3.0	0.55

more when transporting this through its core network.

4.3 Matching network performance requirements with access infrastructure characteristics

The characteristics of the different type of infrastructures have been expressed in the same network performance parameters as used to express the requirements of the services. Using this information a comparison is possible on how well a certain access infrastructure can accommodate all the service requirements.

Regarding ensuring a stable level of QoS and bandwidth, Wireless LAN has a disadvantage because it uses a license free frequency band. Interference of other users and operators in this band will heavily influence the delay (variation) and effective bandwidth on a day-to-day basis. Satellite communications is not suitable for use to transmit service packages 2 to 4 because of the (standard) transmission delay of a geostationary satellite hop of around 240 ms, which is to high to provide 'wire line quality' voice with the telephony and videoconferencing service.

Table 3: Access infrastructure capacity

	Downstream (Mbit/s)		Upstream (Mbit/s)		
Infra	Peak	Sust.	Peak	Sust.	Remark
ADSL	*8*		*0.640*		Theoretical max
SDSL	*2.3*		*2.3*		
ADSL2+	*25*		*3.58*		G.992.3 Annex J
VDSL	*28.3*		*28.3*		Theoretical max
HFC	38	0.48	5	0.03	80 users/ch down 160 users/ch up
HFC+	52	4.3	30	1.25	12 users/ch down 24 users/ch up
PLC	4.5	0.05	4.5	0.05	100 users /PLC - headend
WLAN	37	3.7	37	3.7	10 users per 802.11g/a channel; 70% effective data
LMDS	84*	2.1	84*	2.1	40 users per sector channel of 84 Mbit/s
MMDS	26*	0.65	26*	0.65	40 users per sector channel 26 Mbit/s
FSO	*100-622*				
Satcom	38	0.5	2	0.03	75 users per DVB-channel
APON	622	38.9	622	38.9	16 users
EPON	1000	62	1000	62	on a splitter
OE	*1000-10,000*				

* Effective peak data rate might be limited by lower interface speed at CPE; *Cursive* infrastructures are point-to-point technologies; assumptions on users sharing capacity with point-to-multipoint might vary in practice.

Next to the Quality of Service, another important network performance parameter is the data rate that an access infrastructure can deliver to the user.
For the point-to-point technologies the peak data rate is equal to the sustained data rate (no sharing), which are derived from the maximum 'line or channel speed' that can be realised by the user modem (or transmitter).
For the point-to-multipoint technologies the (shared) 'line or channel data rate' is the peak data rate. The sustained data rate is the 'line or channel data rate' divided by the number of users sharing this resource. Although the number of users that are assigned to share a certain channel capacity differs greatly between operators, some assumptions regarding our urban case have been made for the point-to-multipoint technologies, this is listed in table 3.

Using the figures from tables 2 and 3 an indication can be given how the different infrastructures are suitable to transport a certain service package. This is shown in the figure 4.

When taking into account the suitability of the infrastructures regarding general urban requirements as discussed in paragraph 3.3 it was concluded that PLC, SatCom, WLAN, LMDS and FSO where not suitable to be used as urban access network technology. This was because either concerns about Line of Sight, maturity or guaranteed spectrum use. Also regarding QoS (low delay and guaranteed bandwidth) SatCom and WLAN were found less suitable.

Combining these results the following can be concluded about the technologies "found suitable for the urban case":

- Midband to Broadband technologies: Full Copper xDSL-technologies deliver support for service package 1 (ADSL), package 2 (SDSL) to package 3 (ADSL2+).

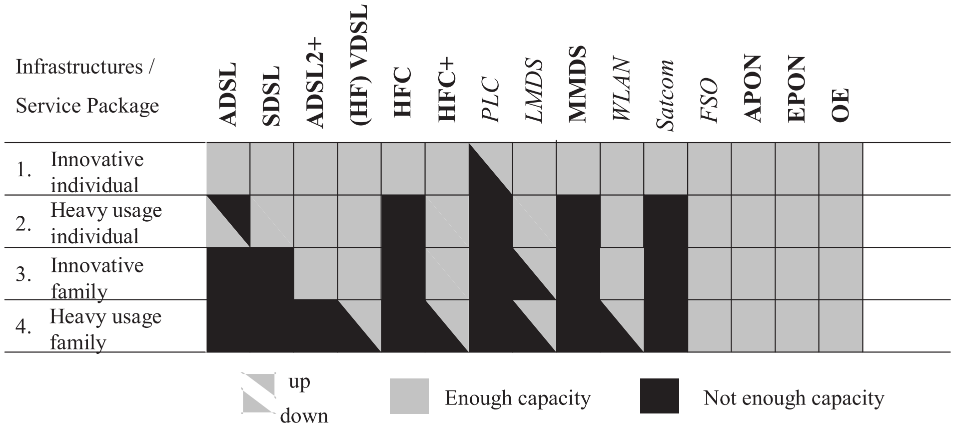

Figure 4: Suitability of transport-infrastructures for different service packages.

- The HFC scenario and MMDS can only support service package 1.
- Hybrid Fiber broadband technologies (FttC): Hybrid Fibre -VDSL and the HFC+ scenario - can support up to package 3.
- Full Fibre (FttH) broadband technologies like Ethernet PON, ATM PON and Optical Ethernet support all four packages.

5 Providing information, best practices and guidelines by an expertise centre.

The Dutch national government wants to play a stimulating role in the development of broadband in the Netherlands. They recognise the role city councils and public organisations want to play.
To make knowledge about broadband more readily available they intend to participate in a market initiative for a Broadband Expertise Centre (BEC). The BEC will be a public-private partnership offering its services to cities, public organisations, small, medium and larger enterprises. The BEC should be independent and professional. Examples of services of this centre are:

- Quick scan of the policy of a city council.
- An evaluation of best practices of roles of governments.
- Information, best practices and guidelines about legal, technical and economical aspects.
- Examples of business and collaboration models that work.

The stablishment of this BEC will be part of a comprehensive Broadband Action package to be delivered by the ministry of economic affairs early in 2004.

6 Conclusions

In the Netherlands we see public organisations being active in the stimulation and introduction of broadband services, using different policies. We have shown the different roles they may take (§ 2). Depending of these roles, a lower or higher degree of influence on the choice of the technology for the infrastructure is needed.
In the decision-making process, it is helpful to take 5 clusters of 'general requirements' towards the technology for infrastructure: reach and penetration factor, future proof, maturity, openness and price (§ 3.1).
We evaluated 15 technologies with a potential for realising an access network (§ 3.2). Their characteristics were matched against the generic requirements of an access network in an urban environment (§ 3.3). We concluded that Power Line, Fixed Wireless (based on LMDS or WLAN), Satcom and Free Space Optics are less suitable if a "broadband-to-all" policy is followed.
If the policy is related to a desired profile of present and future broadband services, the relation between the service and the network requirements should be made as well. In order to give an indication four service packages have been defined, with an increasing demand to the network resources (§ 4).

Not surprisingly the Fibre-to-the-Home infrastructures are able to support all packages of services we may dare to think of. We have shown also that the modern hybrid fibre-copper and fibre-cable infrastructures are able to support service packages for heavy usage individuals and innovative families as well.
Depending on the ambition or realism level and the time horizon, city councils and public organisa-

tions will strive for either fibre-to-the-home (full fibre) or fibre-to-the-cabinet (hybrid fibre) solutions in their cities.

Acknowledgements

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Novel signal multiplexing methods for integration of services in in-building broadband multimode fibre networks

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Keywords: Service integration, multimode fibre, mode group diversity, subcarrier multiplexing, optical frequency multiplying, radio over fibre

Abstract

Many different services with widely ranging signal characteristics are to be supported in in-building networks: fast data transport (e.g. Gbit Ethernet), video, high-Q audio, and control signals. These services may use wired or wireless connection to the end user. In order to support them in parallel at low cost, cost-effective methods for multiplexing signals independently on a multimode optical fibre inbuilding network have to be devised. In particular multimode polymer optical fibre is attractive for easy installation. This paper reports recent results in exploring novel multiplexing methods applicable on multimode fibre: mode group diversity multiplexing, adaptive subcarrier multiplexing using higherorder fibre passbands in combination with multilevel coding, and optical frequency multiplying for transporting microwave signals for e.g. broadband wireless local area networks and personal area networks. The applications in broadband multiservice scalable in-building networks are highlighted.

Introduction

In-building, there presently is a wide variety of networks, each optimised for transporting a particular set of services (such as CATV services, voice telephony ones, high-speed data services, fast internet access, etc.). In-building networks may comprise quite a diversity of networks: not only networks within residential homes, but also networks inside office buildings, hospitals, and even more extensive ones such as networks in airport departure buildings and shopping malls. Thus, the reach of in-building networks may range from less than 100 metres up to a few kilometres.

The lack of a common in-building network infrastructure hampers the introduction of new services, and the creation of mutual relations between the services. Optical fibre may open the way towards such a common network, as it is transparent for any signal format, and it may offer low losses together with sufficient bandwidth in order to multiplex a wide variety of services.

For widespread in-building usage, however, fibre installation costs should be low. The installation of single-mode silica fibre, as commonly used in core and metro networks, requires delicate high-precision equipment and highly skilled personnel. Multimode silica fibre is more attractive for inbuilding usage, as it is far easier to install due to its large core diameter. As illustrated in Fig. 1, its large core diameter makes it far easier to launch light from the transmitter's laser diode, thus avoiding complex optical imaging systems. Also, the tolerance against lateral misalignment in fibre-fibre connections is much better; thus there is no need for expensive high-precision connectors and delicate mounting techniques.

Multimode fibre is already widely accepted for short-range data communications in broadband LANs, benefiting from low-cost multimode fibre transceiver modules. E.g. several Ethernet standards have been set using multimode fibre; the Fast Ethernet 100 Mbit/s IEEE 802.3u standard

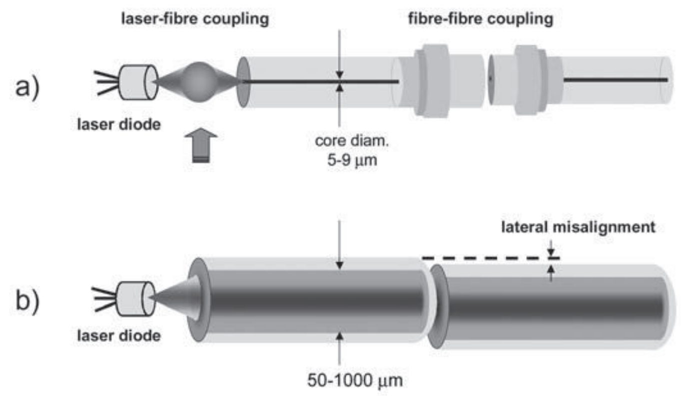


Fig. 1 Installing fibre links
a) using single-mode fibre (core diameter 5 to 9 µm)
b) using multi-mode fibre (core diameter 50 to 1000 µm).

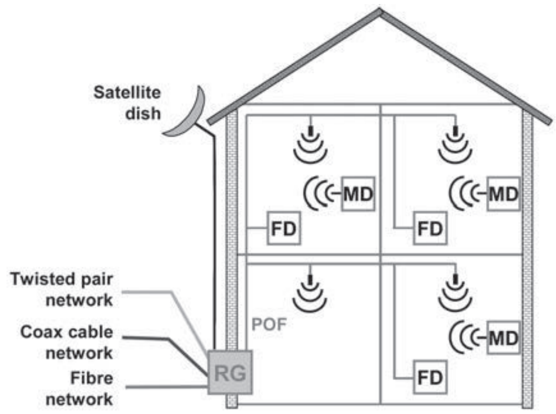


Fig. 2 Transparent in-building network with Polymer Optical Fibre (POF), integrating fixed-wired and wireless services in a common infrastructure (MD = Mobile Device; FD = Fixed Device; RG = Residential Gateway).

100BASE-SX can span up to 2 km of multimode silica fibre at a wavelength of 850 nm, and 100BASE-FX up to 2 km at 1310 nm. The Gigabit Ethernet IEEE 802.3z standard 1000BASE-SX has been set to bridge up to 550 m multimode silica fibre at 850 nm wavelength, and the 1000BASE-LX standard up to 550 m at 1310 nm.

In comparison to multimode silica fibre, multimode Polymer Optical Fibre (POF) offers a larger flexibility and ductility, which further reduces installation costs in often less accessible customer locations [1, 2]. Its attenuation per unit length is being reduced steadily, as production technology improves; presently, losses below 10 dB/km have been obtained.

The major disadvantage of multimode fibre as compared with single-mode fibre is its reduced bandwidth, which is caused by the dispersion in the propagation delays among the various modes. The bandwidth figures can be significantly improved by an accurate control of the graded refractive index profile in the core of the fibre, which thus can equalize the propagation delay differences. Thus, for POF bandwidth-times-length products have reached some 1 to 5 GHz-km, and for silica multimode fibre even beyond 10 GHz-km; however, these figures inevitably will remain much lower than those of single-mode fibre.

The limited bandwidth obstructs the desired integration of multiple broadband services into a single in-building fibre network. Therefore new methods are being investigated to overcome the bandwidth limitation. This paper reports on three techniques for this:

- *Mode group diversity multiplexing*, for realising a number of independent parallel communication channels by deploying subsets of the many guided modes in multimode flbre,
- *Subcarrier multiplexing using the higher-order transmission lobes of multimode fibre*, in order to adaptively position services in appropriate passbands of the multimode fibre network, and
- *Optical frequency multiplying*, for carrying microwave signals in order to feed wireless base stations.

Fig. 2 illustrates how a single POF in-building network could be used to feed broadband services to wireless and to wired user terminals, where the multiplexing of the services can be done in a centralised site such as the residential gateway, which connects to the various outdoor access networks.

Mode group diversity multiplexing

The modal dispersion resulting from the different propagation times of the modes guided in a multimode fibre (MMF) is the main cause of its limited bandwidth. However, one may get benefits from launching not all the guided modes simultaneously. Firstly, with restricted launching of just a subset of the modes, the bandwidth is increased due to the reduced propagation time differences; gains of up to a factor 4 in bandwidth have been achieved [3]. Secondly, one may launch different signals into different mode groups, thus creating parallel transmission channels. This novel method, which we have termed mode group diversity multiplexing, is illustrated in Fig. 3 [4].

The concept is based on using a number N of independent optical transmitters at one end of the

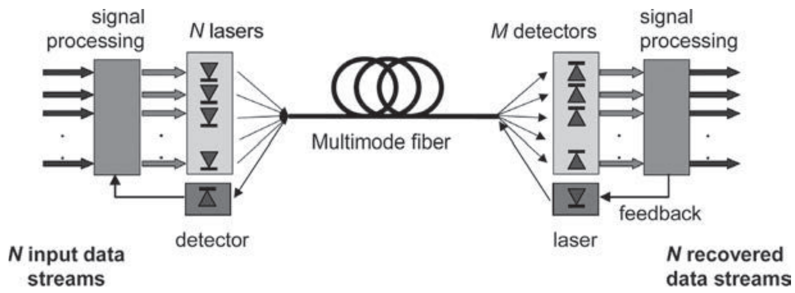


Fig. 3 Mode group diversity multiplexing.

system, and M receivers at the other end. Each transmitter launches a data signal into a different group of modes. Each spatially selective receiver detects a mixture of the N signals, and in a subsequent electrical signal processor the mixtures are unravelled in order to produce the N signals separately again. For this, the signal processor needs to invert the transmission matrix that describes the signal transfer from the N transmitters to the M receivers (see Fig. 4 for the basic case $N = M = 2$). Actually, this problem is related to the Multiple-Input Multiple-Output (MIMO) techniques that are investigated for improving the throughput and robustness of wireless LAN systems. The coefficients of the system's transmission matrix may be determined by initialising the system through sending some training sequences known by the receiving site. The fluctuating mode mixing conditions in the multimode fibre will cause variations in the transmission matrix coefficients. Assuming that these fluctuations are much slower than the bit rates of the signals, strategies to adapt the coefficients dynamically may be devised. E.g., the fluctuations may be monitored by adding some redundancy to the transmitted signals by means of line coding in a signal processing stage at the transmitter site, which enables the detection of transmission errors at the receiver site. A feedback channel may instruct the transmitter site to optimise the mode group launching conditions, and to restart the initialising training period in case of loss of the adaptation process.

An analysis has been made how mode groups can be excited separately, and thus how different near-field patterns (NFPs) of light intensity can be generated at the output of the fibre link. The propagation of light rays in multimode fibre can geometrically be described using the eikonal equation [5]; a light ray congruence solution is characterised by the parameters h and k given by

$$k = n(r) \cdot \cos\theta(r)$$

$$h = n(r) \cdot \frac{r}{a} \cdot \sin\theta(r) \cdot \sin\psi(r)$$

where $n(r)$ is the local refractive index as a function of the radial co-ordinate r, θ is the angle of the light ray with the z-axis of the fibre, and ψ is the azimuth of the ray; see Fig. 5.

It can be shown that at the fibre output annular NFPs are generated; for a parabolic refractive index profile, the inner radius r_0 and outer radius r_1 of the annular NFP can be calculated to be

$$r_0 / a = \frac{1}{NA\sqrt{2}} \left\{ n_0^2 - k^2 - \sqrt{\left(n_0^2 - k^2\right)^2 - (2hNA)^2} \right\}^{1/2}$$

$$r_1 / a = \frac{1}{NA\sqrt{2}} \left\{ n_0^2 - k^2 + \sqrt{\left(n_0^2 - k^2\right)^2 - (2hNA)^2} \right\}^{1/2}$$

where NA is the numerical aperture of the fibre, a is the core radius, and $n_0 = n(0)$. For meridional rays crossing the fibre axis, $h = 0$ and thus $r_0 = 0$ mea-

Fig. 4 Modelling the system's transmission matrix (for N=M=2).

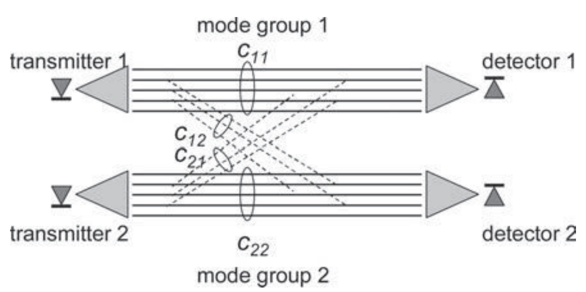
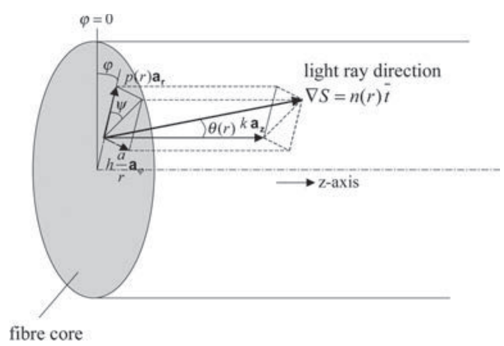


Fig. 5 Ray propagation in a multimode fibre.



ning that the NFP radially extends from the core centre to an outer radius r_1 depending on k.
Non-meridional rays follow a helix-shaped path centred around the fibre axis, confined between a cylinder with radius r_0 and one with radius r_1.

The radial intensity distribution $\Phi_r(r,h,k)$ for a (h,k) light ray congruence in the region $[r, r + \mathrm{d}r]$ is proportional to the time which the light ray spends in transversing this region, and therefore inversely proportional to the radial speed component $v_r(r)$. Due to the light spreading over the annular ring, it will furthermore be inversely proportional to the ring circumference $2\pi \cdot r$. As the light ray speed at the radial position r is given by $v(r) = c_0/n(r)$ where c_0 is the light speed in vacuum, using Fig. 5 it can be seen that

$$v_z(r)=v(r)\cdot\cos(\theta)=\frac{c_0}{n^2(r)}\cdot k$$
$$v_r(r)=v(r)\cdot\sin(\theta)\cdot\cos(\psi)=\frac{c_0}{n^2(r)}\cdot p(r)$$
$$v_\varphi(r)=v(r)\cdot\sin(\theta)\cdot\sin(\psi)=\frac{c_0}{n^2(r)}\cdot\frac{h}{r}$$

where $v_z(r)$ is the axial speed component, and $v_\varphi(r)$ the tangential speed component. The time it takes for the light ray to move from the inner caustic plane $r = r_0$ to the outer one $r = r_1$ is given by

$$\tau_s(h,k)=\int_{r_0}^{r_1}\frac{dr}{v_r(r)}=\frac{1}{c_0}\int_{r_0}^{r_1}\frac{n^2(r)}{p(r)}dr$$

The normalised radial light intensity distribution (normalised on the total light power between the two caustic planes) for a (h,k) light ray congruence is therefore given by

$$\Phi_{nr}(r,h,k)=\frac{1}{2\pi r\cdot v_r(r)\cdot\tau_s(h,k)}=\frac{n^2(r)}{2\pi\ c_0\cdot p(r)\cdot\tau_s(h,k)}$$

Using

$$p(r)=\sqrt{n^2(r)-k^2-\frac{h^2a^2}{r^2}}$$

for a parabolic refractive index profile given by

$$n^2(r)=n_0^2\left\{1-2\Delta\left(\frac{r}{a}\right)^2\right\}\quad\text{for}\ \ 0\le r\le a$$
$$=n_0^2\,(1-2\Delta)=n_1^2\quad\text{for}\ \ \mathrm{r}>a$$

which allows $p(r)$ to be expressed as

$$p(r)=\frac{n_0\sqrt{2\Delta}}{a\,r}\sqrt{(r^2-r_0^2)(r_1^2-r^2)}$$

and the theoretical numerical aperture as

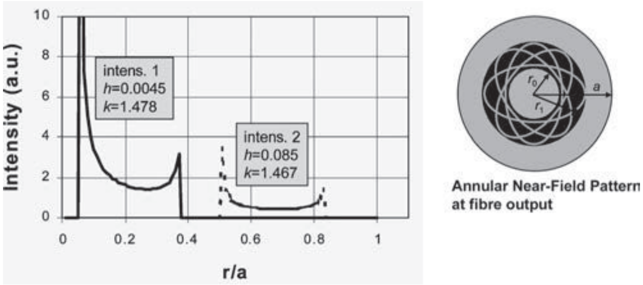


Fig. 6 Radial distribution of NFP for non-meridional rays, for different launching condition parameters (h, k) ; NA = 0.2, n_0 = 1.48

$$NA=\sqrt{n_0^2-n_1^2}=n_0\sqrt{2\Delta}$$

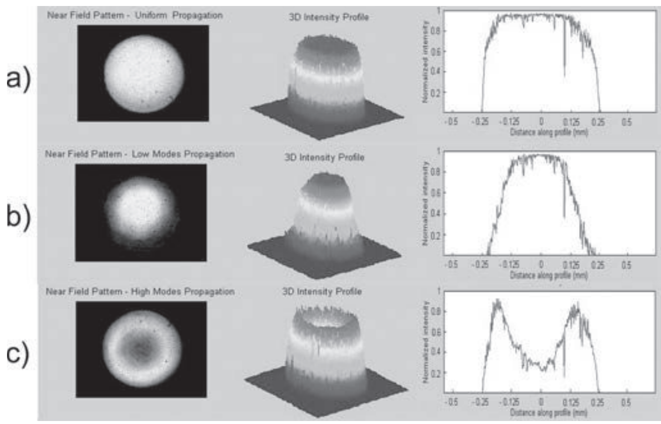
it can be derived that

$$\tau_s(h,k)=\frac{\pi}{4c_0}\cdot\frac{a}{NA}\cdot(n_0^2+k^2)$$

As an example, Fig. 6 shows the radial intensity distributions for two different pairs of launching parameter sets (h, k).

To confirm the analysis, measurements with restricted mode group launching have been performed of the NFPs at the output of a 100 metres PMMA graded index POF; see Fig. 7. These results confirm the annular shape of the NFPs (in accordance with [6]). There is some central overlap in the intensity patterns due to the meridional rays in the mode groups, which will generate non-zero terms outside the diagonal of the system's transmission matrix. However, the NFPs in Fig. 7 b) and c) show sufficient complementarity in order to support different communication channels after elimination of this crosstalk by the matrix inversion in the signal processing circuit at the receiver site.

Fig. 7 NFP measured at output of 100 metres PMMA GI-POF, with 500 μm core diameter
a) with excitation of all modes
b) with excitation of low-order modes (high k) only
c) with excitation of high-order modes (low k) only



Knowing the transmission matrix coefficients, these may also be used for selective mode group transmission in the upstream direction, thus enabling bi-directional communication.

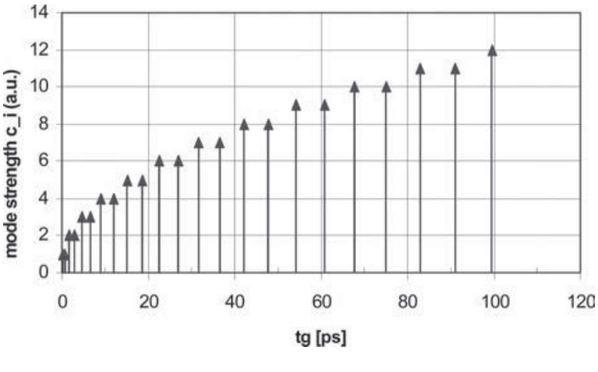
The system functionality that can be achieved with this mode group diversity multiplexing method is basically similar as wavelength division multiplexing. However, no (costly) wavelength-specific sources and wavelength (de-)multiplexer modules are needed. Instead, electronic signal processing is needed to separate the various channels, and an array of laser diodes and one of photodetectors. Provided that low-cost electrical integrated circuits and integrated optical sources (e.g. VCSEL, vertical cavity surface emitting laser, array) and detectors can be used, mode group diversity multiplexing may thus be an economically attractive alternative for wavelength multiplexing in short-range integrated-services networks.

Subcarrier multiplexing using the higherorder transmission lobes of multimode fibre

In multimode fibre systems, usually only the low-pass part of the multimode fibre transfer characteristics is deployed. However, in case of small chromatic dispersion and negligible mode coupling, the impulse response of a multimode fibre link consists of a number of subsequent Dirac pulses, corresponding to the different propagation times of the finite number of individual guided modes [7]; cf. Fig. 8.

Therefore, the transfer characteristic of the multimode fibre also may show bandpass lobes at higher frequencies, as has been confirmed by measurements such as those shown in Fig. 9 [8].

Fig. 8 Calculated impulse response of 500 m parabolic graded-index multimode fibre (core diameter 62.5 μm, NA = 0.2), using a monochromatic light source at 850 nm wavelength



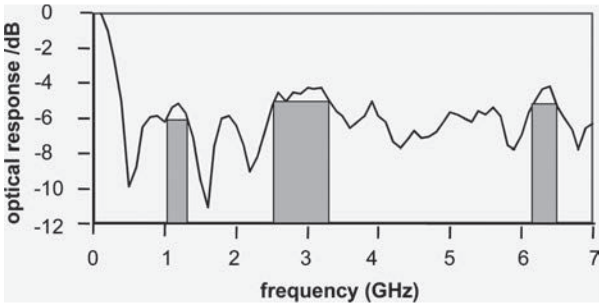


Fig. 9 High-frequency transmission lobes of 500 m 62.5 μm core diameter silica multimode fibre, measured with an 850 nm VCSEL (from [9])

By means of subcarrier multiplexing techniques, the various services to be integrated can be put on separate carrier frequencies, which are positioned in such a way that they fit optimally to the bandpass characteristics of the fibre. E.g., in [8] two subcarriers are used at 1 and 3 GHz respectively, each carrying 625 Mbit/s in BPSK format over a link of 500 metres of multimode fibre.

More comprehensive signal modulation techniques (such as multi-level quadrature amplitude modulation, x-level QAM) may be used for bandwidth compression, in order to match the service capacity requirements to the width of a passband lobe. These modulation formats, however, also put more stringent requirements on the linearity of the system.

The subcarrier frequencies may be adapted in order to match the actual position of the lobes, which depend on the actual fibre length and may also change due to variations in the environmental conditions. The position of these lobes can be monitored by measuring the strengths of some weak injected pilot tones, or those of the (partially suppressed) subcarrier tones. The strengths of the tones are detected at the user side, and are used to adapt the subcarrier frequencies. Thus the subcarrier frequencies can be optimised to match the transmission lobes of the multimode fibre links. Fig. 10 shows a system concept of this approach, with tunable local oscillators for setting the subcarrier frequencies. Bidirectional transmission is implemented on the single-fibre network by using separate wavelengths for up- and downstream transmission, respectively. Choosing the wavelengths sufficiently far apart (e.g., 1540 nm for downstream and 1310 nm for upstream) allows to use lowcost coarse wavelength multiplexing techniques.

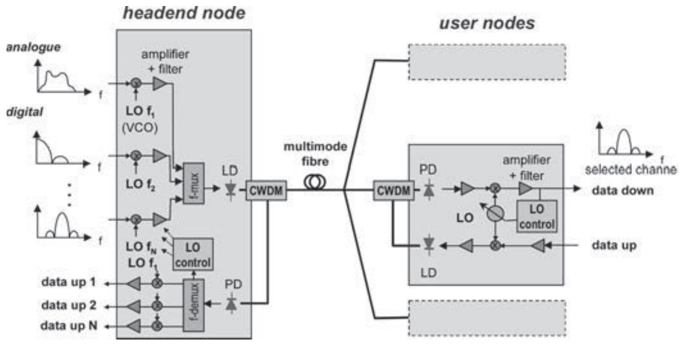


Fig. 10 Bi-directional subcarrier multiplexing point-tomultipoint access network, adaptively deploying higher-order MMF transmission lobes (LD=laser diode, PD=photodiode, CWDM=coarse wavelength (de-)multiplexer, LO=local oscillator)

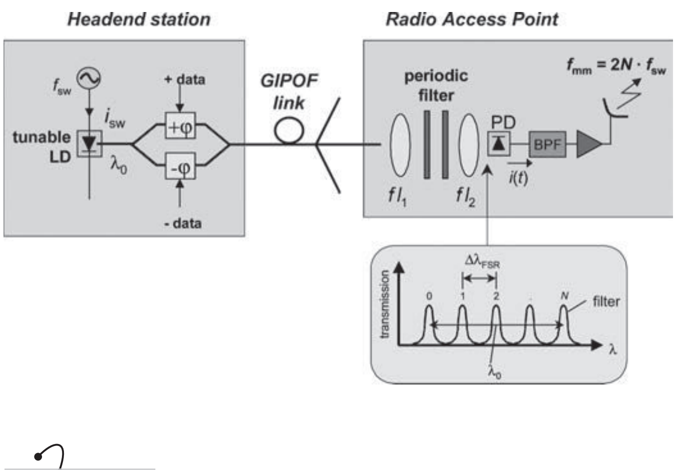
Modal noise may seriously disturb the transmission performance of a multimode fibre system. An effective countermeasure is decreasing the light source coherence time, which can be efficiently achieved by high frequency modulation of a laser diode. This is done in the system already by the subcarrier modulation techniques used for creating the information transfer channels.

Like the mode group diversity multiplexing technique, this subcarrier multiplexing technique does not need wavelengthspecific sources nor highly-selective wavelength (de-)multiplexing modules, but relies on electrical signal processing instead, which may be cheaper when a sufficient level of circuit integration is achieved.

Optical frequency multiplying

In addition to offering mobility to users, wireless communications are increasingly offering higher bandwidths. Consequently, the radio carrier frequencies need to increase, which leads also to smaller radio cell coverage due to the increased propagation losses. Wireless LANs in the 2.4 GHz frequency range are evolving from the IEEE 802.11b standard offering up to 11 Mbit/s to the IEEE 802.11g standard offering up to 54 Mbit/s. In

Fig. 11 Feeding microwave data signals over a multimode GIPOF network by optical frequency multiplying



the IEEE 802.11a standard, up to 54 Mbit/s is provided in the 5.4 GHz range. Research is ongoing into systems providing more than 100 Mbit/s in the range well above 10 GHz (LMDS at 28 GHz, HyperAccess at 17 GHz and 42 GHz, MVDS at 40 GHz, MBS at 60 GHz, …). When the radio cell sizes shrink with increasing radio frequencies, ever more antenna sites are needed to cover a certain area. Thus it becomes increasingly important to simplify the antenna stations and to consolidate the radio signals processing in a centralised site. Carrying radio signals over optical fibre is a very interesting solution to achieve this. Single-mode fibre has adequate characteristics for e.g. supporting optical heterodyning to remotely generate microwave carriers [10], but entails high installation costs. Therefore techniques for carrying microwave signals over multimode fibre while overcoming its limited bandwidth are being investigated. The so-called optical frequency multiplying method relies on periodic wavelength sweeping of the optical source across multiple transmission peaks of an optical comb filter at the receiver [11, 12].

As illustrated in Fig. 11, sweeping the source wavelength back and forth at a sweep frequency f_{sw} across N bandpass peaks of the filter results in a microwave signal with fundamental frequency $2N \cdot f_{sw}$, containing also the higher harmonics. The bandpass filter (BPF) selects the desired frequency for radiation by the antenna. The data signal is chirp-free intensity-modulated on the frequency-swept optical carrier by using e.g. a differentially driven Mach Zehnder modulator. It should be noted that the sweep frequency is limited by the GIPOF link's baseband bandwidth, but that the microwave frequency can exceed this bandwidth by far due to the realised optical multiplication factor $2N$.

Simulations and experiments have shown that extremely pure microwave signals can be generated, notwithstanding a moderate laser spectral linewidth, due to the inherent phase noise cancellation in the optical frequency multiplying process. Fig. 12 shows that a microwave carrier at 16 GHz can be generated having a FWHM spectral width of only 18 Hz, whereas the laser FWHM linewidth was 1 MHz. Qualitatively, this may be understood from Fig. 13, showing for example how the optical frequency is swept linearly across the transmission characteristics of a Fabry-Perot (FP) cavity. When the frequency is increasing along a rising slope of

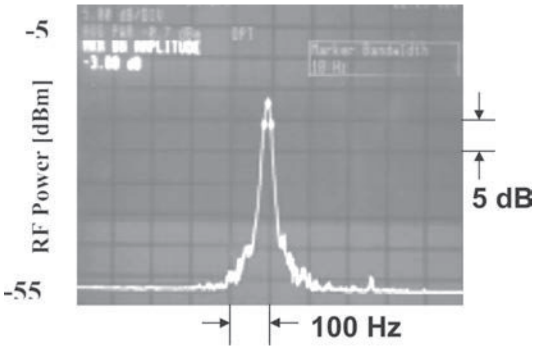


Fig. 12 Generated microwave at 16 GHz.

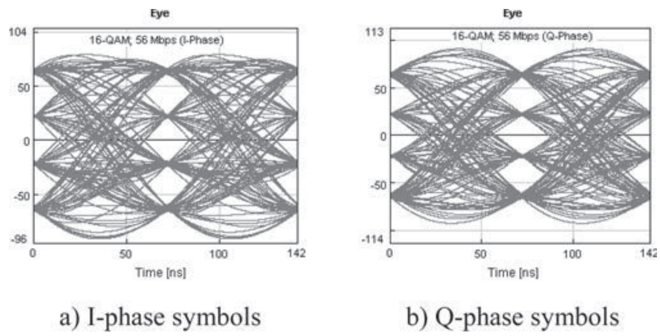


Fig. 14 Eye patterns of 16-QAM demodulated data at 56 Mbit/s.

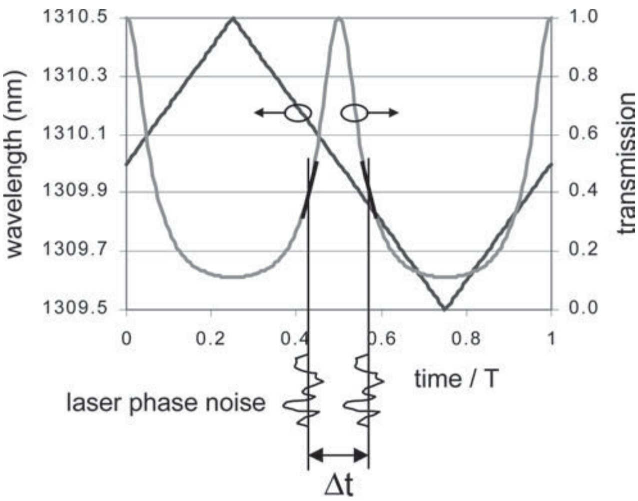
the FP curve, the laser phase noise is FM-to-AM converted with a positive sign, whereas along a falling slope it is converted with a negative sign. When the laser coherence time is much larger than the frequency sweep time needed to cross one period of the FP filter, then the FM-to-AM converted noise terms generated at the opposite slopes cancel each other, thus yielding a strong laser phase noise cancellation effect.

Comprehensive data modulation formats such as QPSK or 16-level QAM can be carried by putting these first on a subcarrier, which subsequently is fed to the MZ modulator.

Simulations have shown the feasibility of carrying 56 Mbit/s in 16-QAM on a subcarrier of 225 MHz and a microwave carrier of 5.4 GHz [11, 12]; clear eye openings were obtained, as shown in Fig. 14, pointing out successful data transmission at a very low error rate.

Also a bi-directional system can be realised by using the generated microwave and a frequency shifter at the antenna station for downmixing the upstream signal, and an IF laser transmitter for conveying the data upstream [11, 12].

Fig. 13 Cancellation of laser phase noise.



Conclusions

A number of novel signal multiplexing methods suitable for multimode fibre may remarkably increase the capacity of multimode (polymer optical) fibre networks beyond its baseband capabilities. These techniques are promising for cost-effective integrated-services broadband in-building networks, supporting wired as well as wireless broadband user terminals.

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