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The Emerging WDM EPON

ACADEMIC MIND
University of Belgrade, Faculty of Electrical Engineering
Belgrade, 2012.

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Publisher

ACADEMIC MIND, Belgrade, Serbia

Lecturer
Maja Stevanović

Design of cover page
Zorica Marković, Academic Painter

Printed in Serbia by

ACADEMIC MIND, Belgrade

Circulation
50 copies

ISBN 978-86-7466-449-0

Dedicated to my parents,
Milanka and Ratko Mirković,
and to my family -
my husband Goran and our sons Dušan and Bogdan,
M.R.

Dedicated to my family,
P.M.

Content

Preface

Motivation

Data transmission and networking technologies have witnessed tremendous growth over the past decade. However, much of this development and growth has been primarily in the core networks where high capacity routers and ultra-high-capacity optical links have created a truly broadband infrastructure. The so-called first mile – the access network connecting end-users to backhaul infrastructure – remains a bottleneck in terms of the bandwidth and quality of service it affords to the end-users.

Until recently the lack of broadband Internet access has been an inconvenience, but today this type of Internet access is truly essential for further development of many aspects of life. High-speed Internet expands our ability to communicate, learn and entertain. Nowadays, Internet access is commonly associated with entertainment and information browsing, where most end-users use Internet connection for exchanging information, online gaming and applications like Facebook and Twitter. On the other side, the number of business users has dramatically increased as network infrastructure is becoming the necessity for successful business operations. Service providers are mainly focused on the development and implementation of applications like video on demand (VoD), high definition TV (HDTV), and online gaming which further increases the need for higher access speeds.

Moreover, broadband infrastructure is able to improve the quality of life in addition to supporting and improving business operations. Broadband online learning, video conferencing, online education for people with disabilities, national health network and electronic health records are only a few examples that demonstrate the importance of the further development of broadband infrastructure.

In last decade, Ethernet passive optical networks (EPONs) were considered as a potential optimized architecture for the access network. EPONs are designed to carry Ethernet frames at standard Ethernet rates where architecture is passive with only active the end terminating equipment. Propelled by rapid price declines of fiber optic and Ethernet components, these access networks combine the latest in optical and electronic technology and become the dominant players for delivering gigabit broadband connectivity to homes over a unified single platform. A major feature for this architecture is the use of a shared transmission media between all users; hence, medium access control arbitration mechanism is essential for the successful implementation of EPON. This mechanism ensures a contention-free transmission and provides end-users with an equal access to the shared media. Moreover, with the development of different multimedia based applications like HDTV, internet protocol TV (IPTV), and many others, the related quality of service (QoS) issues are also becoming a key concern. Namely, together with an increasing number of users in the access network, the number of bandwidth-hungry applications is increasing as well.

Until today, different models for incremental migration from TDM (Time Division Multiplexing) to TDM/WDM (Wavelength Division Multiplexing) EPON networks have been proposed but most attention has been given to those solutions that support QoS implementation. Moreover, with the rapid development of different bandwidth applications, QoS support is becoming a key concern in WDM EPON network as it was the case with EPON networks.

Organization

Throughout the chapters of this book, we address many of the specified issues and present models and algorithms that we believe could resolve these issues. Moreover, we are convinced that the hardware implementation of the presented models and algorithms would operate in a foreseen manner and would not involve any additional implementation complexity. In the first place, we present a theory of differentiated services that essentially represents a basis for the QoS implementation in Ethernet-based networks since the QoS support has become a crucial requirement for a converged broadband access network with heterogeneous traffic. Furthermore, we present a detailed analysis and discuss the most important aspects of QoS support and implementation in networks that are based on optical transmission, particularly EPONs and WDM EPONs.

Following the outline of the theory of differentiated services, we present the overview of the EPON technology and introduce the readers with the challenges and unresolved issues in currently deployed EPON networks. We propose to use the multipoint control protocol (MPCP) defined within the IEEE (Institute of Electrical and Electronics Engineers) 802.3ah Task Force to arbitrate the transmission of different users, and we discuss the implementation of different dynamic bandwidth allocation (DBA) algorithms to effectively and fairly allocate bandwidths between end-users. In our first main contribution, we propose a novel dynamic Intra-ONU (Optical Network Unit) scheduling algorithm for single-channel EPON systems, termed hybrid granting protocol (HGP), with full QoS support in accordance with the theory of differentiated services. For the presented model we analyze how new scheduling algorithm can be combined with existing dynamic bandwidth allocation schemes in order to minimize packet delay and jitter. Specifically, the presented dynamic scheduling algorithm minimizes packet delay and jitter for delay and delay-variation sensitive traffic (e.g. voice transmissions) by allocating bandwidth in a grant-before-report (GBR) fashion. This considerably improves their performance without degrading QoS guarantees for other service types. Detailed simulation experiments are presented for studying the performance and validating the effectiveness of the presented solutions.

However, given the steadily increasing number of users and bandwidth-hungry applications, although standardized, the current single-channel systems will not be able to satisfy the growing traffic demands in the future. Accordingly, we further suggest the implementation of wavelength division multiplexing technology in Ethernet passive optical networks in order to overcome problems that exist in the classical single-channel systems. Implementation of WDM technology would allow access network operators to respond to user requests for service upgrades and network evolution. Moreover, the deployment of WDM technology adds a new dimension to current TDM EPONs whereby the benefits of the new wavelength dimension are manifold. Among others, it may be exploited to increase network capacity, improve network scalability by accommodating more end-users and separate services and service providers.

As previously discussed, the development of various multimedia applications requires QoS implementation in WDM EPONs just as it was the case with EPONs. In our next main contribution we further present and analyze two models for wavelength and bandwidth allocation in the hybrid TDM/WDM EPON system with full QoS support, namely the fixed wavelength priority bandwidth allocation (FWPBA) model, and the dynamic wavelength priority bandwidth allocation (DWPBA) model. In order to implement QoS support we present a new approach for QoS analysis and implementation in WDM EPON in which wavelength assignment takes place per service class and not per ONU, as suggested by the common approach in literature. In this way, the need for implementation of additional complex algorithms in order to support QoS, which increases system cost and increases the overall system efficiency, is avoided. Additionally, we propose a method for providing an upgrade to WDM in EPONs that includes an extension of the MPCP. In this way, the presented architecture and models will allow an incremental upgrade from TDM EPON to TDM/WDM EPONs. For each of the proposed models, wavelength and bandwidth allocation algorithms with full QoS support have been presented in order to fulfill all the requirements of new applications and services in a converged triple-play network. The presented models and algorithms are then compared in terms of average and maximum packet delay, packet variation delay (jitter), queue occupancy, packet loss rate, throughput and overall system performance. Once again, detailed simulation experiments are presented for studying the performance and validating the effectiveness of the presented solutions.

In addition to FWPBA and DWPBA models, we present the future development of the proposed model that includes further segregation of medium priority traffic class according to the IEEE 802.1d standard and add another wavelength to be used for transmission of medium priority traffic, i.e. multimedia applications.

In the last chapter of the book, we conclude our work and present guidelines for future developments within this field.

Instruction for readers

This book is intended to resolve misunderstood facts, equations, algorithms and routines connected with EPONs, especially those directly connected to QoS and overall quality of traffic transmission in access networks. It may be very useful for students studying communication sciences, telecom operators, professionals in fields of optical networks and, of course, academic educators and scientists.

The first part of the book, namely Chapters I to IV, are intended to introduce readers to the field of EPON and describe and explain the most important facts about EPONs and the extension to WDM EPONs. These chapters recapitulate EPONs and QoS support in EPON and are more appropriate for students and readers which study EPONs for the first time. The second part of book, Chapters V to VII, are more advanced and introduce a novel concept of WDM EPON (wavelength assignment per service class) which may be designated as new generation EPON; a name which may seem more appropriate than "next generation EPON" which has been commonly used for WDM EPON and 10G EPON within the classical approach (wavelength assignment per ONU). These chapters are intended for readers with knowledge of basic architecture of PONs and EPONs, professionals in the field as well as for university educators at advanced levels of postgraduate studies (Master and PhD courses).

We hope that the following text will be very useful for all readers and that it will open new frontiers for the future development of optical access networks.

Verba volant, scripta manent.

Authors

Chapter 1: Introduction

1.1Traffic growth and first mile evolution

Broadband Internet access, (or just "broadband") is a high data rate connection to the Internet that is typically contrasted with the dial-up access using a 56 kbps modem. Dial-up modems are limited to a bit rate of about 60 kbps and require the dedicated use of a telephone line whereas broadband technologies supply more than this rate generally without disrupting telephone use. Broadband is a term that is used consistently with different types of internet connections. Broadband in telecommunications means a wide range of frequencies that are available to transmit information. This eventually means that the wider the range of frequencies available, the higher the amount of information that can be sent at any given point of time will be. Since data transmission and networking technologies have witnessed tremendous growth over the past decade, the number of users and bandwidth-hungry applications has significantly increased as well.

However, much of this development and growth has been primarily in the core networks where high capacity routers and ultra-high-capacity optical links have created a truly broadband infrastructure. Namely, with the expansion of services offered over the Internet, a dramatic increase of bandwidth has been facilitated in the backbone network through the use of wavelength division multiplexing (WDM), providing tens of gigabits per second per wavelength. Moreover, a wide range of increasingly bandwidth-intensive services are continuing to emerge, e.g. storage extension/virtualization, grid computing, packet video teleconferencing, and many more. At the same time, end-user local area networks (LANs) have also seen their tributary speeds progressively increase from 100 Mbps upwards to 1Gbps and beyond. Such a growing gap between the capacity of the backbone network and end-users' needs results in a serious bottleneck in the access network between them [1], i.e. "access bottleneck," Figure 1.1. The term 'last mile' used in the literature to describe the access network is now often replaced by the 'first mile' in order to emphasize the role and importance of this network segment for the further development of information-communication networks.

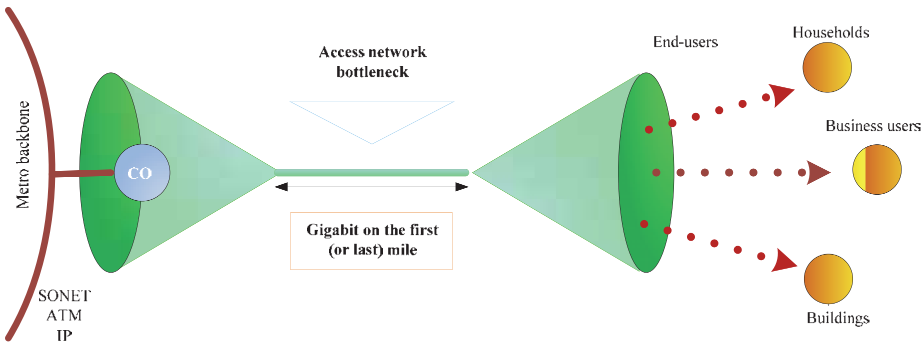

Figure 1.1 Access network bottleneck

Today, the term 'residential broadband' describes the group of technologies that provide high-bandwidth connection to the Internet for residential consumers. The replacement for the now fading residential dial-up technology should allow end-users to use different services such as watching video stream, downloading music in seconds, video and voice chats, real-time gaming, and many others.

Broadband is often called high-speed Internet access, because it usually has a high rate of data transmission. As shown in Figure 1.2, average broadband speed can go up to 60 Mbps. In general, any connection to the customer of 256 kbps or greater is more concisely considered broadband Internet access. The ITU-T (International Telecommunication Union Standardization Sector) recommendation I.113 has defined broadband as a transmission capacity that is faster than primary rate ISDN, at 1.5 to 2 Mbps. The US Federal Communications Commission definition of broadband amounts to 4.0 Mbps. The OECD (Organization for Economic Co-operation and Development) has defined broadband as 256 kbps in at least one direction and this bit rate is the most common baseline that is marketed as "broadband" around the world. Many countries have already projected the increase in broadband access speed and penetration. USA expects that every household should have the access speed of 4 Mbps by 2020, UK expects to provide everyone with at least 2 Mbps by 2015, Korea expects to raise average speeds to 10 Mbps by 2012, EU to provide at least 30 Mbps for every EU citizens by 2020, Russia to have 35% broadband penetration by 2015, and Serbia to have 20% broadband penetration with 4 Mbps by 2012. [2, 3].

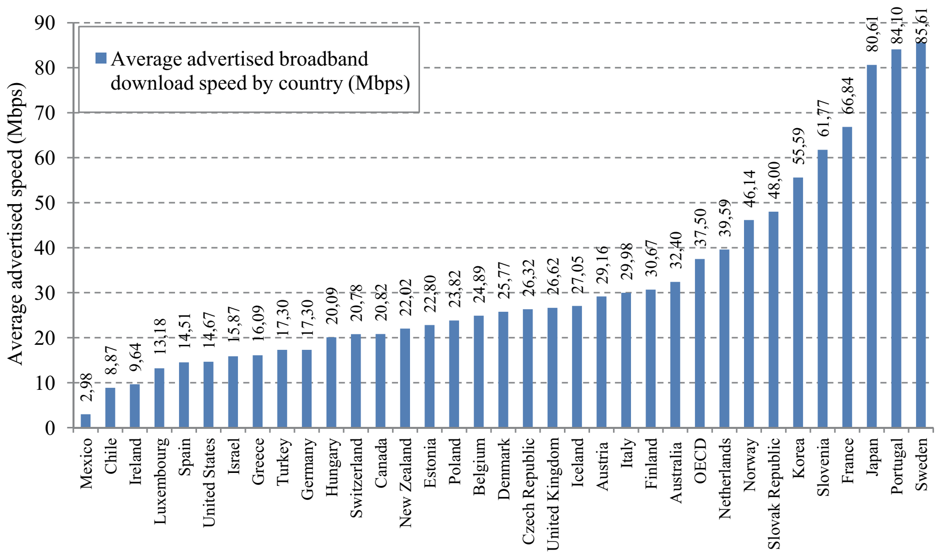

Figure 1.2 Average advertised broadband download speed by country (*Source: Information technology and innovation foundation,* September *2010)*

In practice, the advertised maximum bandwidth is not always reliably available to the customer. Namely, physical link quality can vary, and Internet service providers (ISPs) usually allow a greater number of subscribers than their backbone connection or neighborhood access network can handle, under the assumption that most users will not be using their full connection capacity very frequently. This aggregation strategy known as a contended service works more often than not, so users can typically burst to their full bandwidth most of the time. However, applications like peer-to-peer (P2P) file sharing systems often require extended durations of high bandwidth usage and consequently violate these assumptions and most probably cause major problems for ISPs.

In general, broadband solutions can be classified into two groups: fixed line technologies and wireless technologies. The fixed line solutions communicate via a physical network that provides a direct wired connection from the customer to the service supplier. Wireless solutions use radio or microwave frequencies to provide a connection between the customer and ISP network.

Fixed line broadband technologies rely on direct physical connection between subscribers and service suppliers. Many broadband technologies such as cable modem, digital subscriber line (DSL) technologies and broadband over power line (BPL) have evolved to use an existing form of subscriber connection as the medium for communication. Namely, xDSL systems use the twisted copper pair traditionally used for voice services like plain old telephone service (POTS). BPL technology uses the power lines installed in subscriber homes to carry broadband signals. On the other hand, cable modems use existing hybrid fiber-coax (HFC) Cable TV networks. When the above mentioned technologies are not available, satellite connections can be used instead.

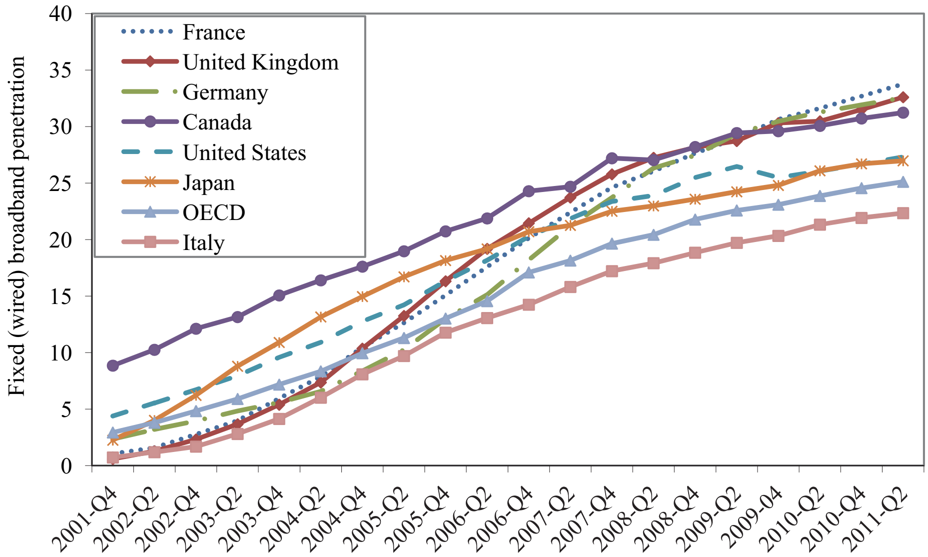

Figure 1.3 Fixed (wired) broadband penetration, G7 countries (Source: OECD June 2011 www.oecd.org/sti/ict/broadband)

For example, Figure 1.3 shows the growth and penetration of residential broadband technologies including DSL, BPL, and cable technologies for the US market in the last eight years. The development of broadband market is characterized by:

- ✓ Fast growth, 11% increase per year;
- ✓ More than 50% penetration already reached across Internet households;
- ✓ Several competing broadband service providers;
- ✓ Telephone companies, wireless carriers, cable TV service providers and satellite providers.

In addition to the stated technology, a lot of attention nowadays is given to optical networks as a possible solution for the bottleneck problem in the access network. Namely, none of the aforementioned technologies, including xDSL, BPL, HFC, as well as wireless technologies, are able to offer sufficient bandwidth for the successful transmission of different video and multimedia applications. Consequently, a lot of attention in the Telco industry and market is given to the FTTx technologies as the main candidate for the successful realization of a truly broadband infrastructure.

Fiber to the x (FTTx) is a generic term for any broadband network architecture using optical fiber to replace all or part of the usual copper local loop used for last mile, Figure 1.4. Today, the FTTx term includes several configurations of fiber deployment, where x stands for node (FTTN), premises (FTTP), building (FTTB), curb (FTTC), and home (FTTH).

These solutions require the installation of new fiber (link) from the local exchange (central office) directly to or closer to the subscriber. Fiber installation can offer the ultimate in broadband bandwidth capability, but installation cost of such network must be taken into account.

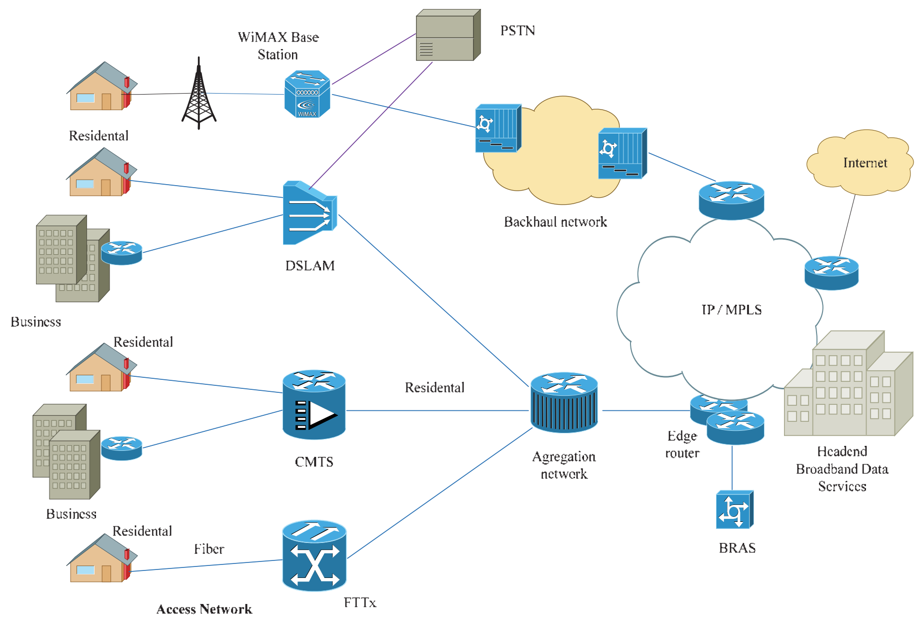

Figure 1.4 Broadband network

1.1.1 DSL technologies

Digital subscriber line (DSL) is a family of technologies that provides digital data transmission over the wires of a local telephone network. DSL originally stood for 'digital subscriber loop'. DSL service is delivered simultaneously with the regular telephone service on the same telephone line i.e. using the existing copper telephone infrastructure to facilitate high-speed data connections. When using a modem on a regular telephone line, the line is busy and cannot be used to make or receive a phone call at the same time. With DSL technology, the phone line can carry two signals at the same time (Figure 1.5):

- ✓ a phone-call / fax / analog-modem connection;
- ✓ a high-speed digital signal for Internet access.

DSL achieves this by dividing the voice and data signals on the telephone line into three distinct frequency bands. These frequency bands are subsequently separated by filtering on the customer side. On the service provider's side, DSL access modules (DSLAM) are placed in the local exchange or at nodes in the access network in order to transmit and receive data signals.

Today, there are various DSL technology options as shown in Table 1.1 [4-9]. In practice, actual speeds may be reduced depending on line quality where the most significant factor in line quality lies in the distance from the DSLAM to the customer's equipment.The key technologies are asymmetric DSL (ADSL), symmetric DSL (SDSL), very high bit rate DSL (VDSL) and ADSL2+. The data throughput of consumer DSL services typically ranges from 256 kbps to 100 Mbps in the direction to the customer (downstream), depending on the DSL technology, line conditions, and service-level implementation.

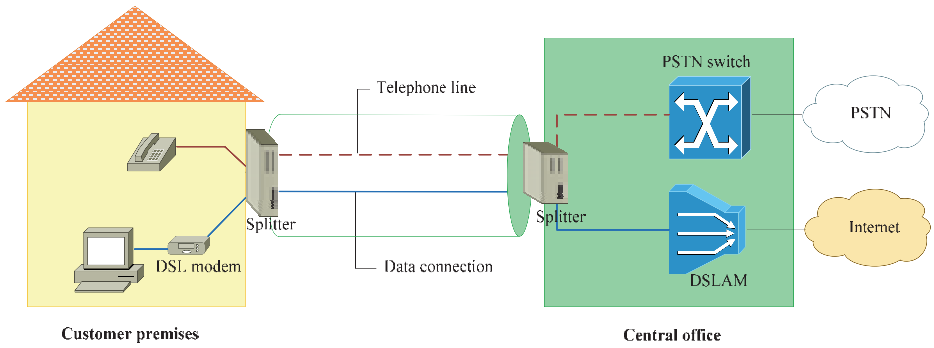

Figure 1.5 DSL technology implementation

Table 1.1 DSL technology characteristics *(*at maximum distance, the achieved rates are significantly smaller than the maximum rates defined in the fifth column; actual speeds may vary based on factors such as line quality, distance from exchange (for ADSL/ADSL2+), technology used, hardware capabilities, server route and network congestion)*

Family	ITU	Name	Ratified	Maximum speed capabilities*	Maximum distance
ADSL	G.992.1	G.dmt	1999	8 Mbps down, 1 Mbps up	5.4 km
ADSL2	G.992.3	G.dmt.bis	2009	12 Mbps down, 1.4 Mbps up ITU G.992.3 annex M: 3.3 Mbps up	5.6 km
ADSL2+	G.992.5	G.adslplus	2009	24 Mbps down, 1 Mbps up	1.5 km
G.SHDSL	G.991.2	G.shdsl	2003	2.3 Mbps down, 2.3Mbps up (two wires) 4.6 Mbps down / 4.6 Mbps up (four wires)	Up to 6 km (two wires) Up to 5 km (four wires)
VDSL	G.993.1	G.vdsl	2004	50 Mbps down, 6.4Mbps up	1.5 km
VDSL2-12 MHz long reach	G.993.2	G.vdsl2	2006	50 Mbps down, 30 Mbps up	1.0 km
VDSL2-30 MHz short reach	G.993.2	G.vdsl2	2006	100 Mbps down/30 Mbps up	0.3 km

DSL is currently the most prevailing broadband choice in the world with over 65% market share and more than 200 million users. DSL is available in every region of the world, and ADSL owns the majority of the market, even though VDSL and ADSL2+ are gaining ground. However, DSL is a distance sensitive technology where the signal quality decreases and the connection speed goes down with the increase in the distance between the DSLAM and users, Figures 1.6-1.7.

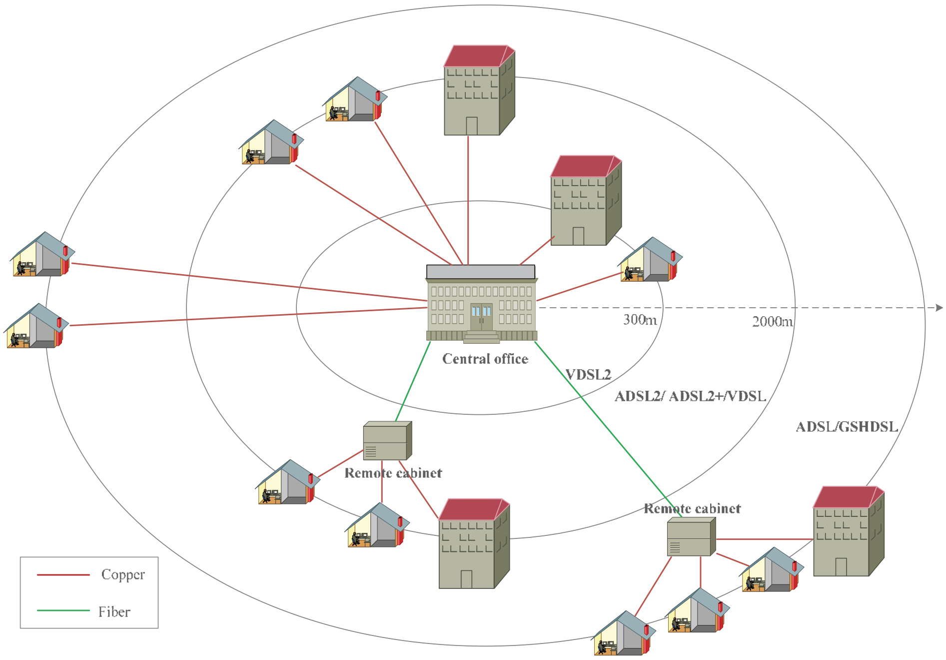

Figure 1.6 DSL technologies – distance vs. speed

Since the most popular DSL technologies including ADSL, ADSL2, and ADSL2+ have not solved the problem of bottlenecks and they are not able to offer sufficient amount of bandwidth for the successful transmission of different multimedia applications, Figure 1.7. This resulted in VDSL and VDSL2 technologies gaining a lot of attention as these technologies are seen as a possible key for enabling real competition between Telco's and cable operators.

Table 1.1 shows that ADSL technology can provide maximum downstream speeds of up to 8 Mbps and upstream speeds of up to 1Mbps. The maximum distance for ADSL service is 5.4 km, but at this distance, transmission speeds are limited to approximately 500 Kbps. For different business applications, customers could use GSHDSL which allows high speed download and upload, but again the maximum available bandwidth is approximately 3 Mbps. With, for example, video-on-demand (VoD) service requiring at least 3 Mbps and high-definition television (HDTV) requiring approximately 15 to 20 Mbps, it is clear that neither ADSL nor GSHDSL can meet the bandwidth requirements for HDTV or even basic video service over the full network. However, VDSL and ADSL2+ can offer enough bandwidth to allow video services. VDSL can offer up to 52 Mbps, but only at very short distances. In order to offer VDSL to the significant proportion of customers, the DSLAM needs to be relocated to street cabinets, closer to the subscriber (fiber feeds are now installed in the street cabinets). The cost of this upgrade is equal to the cost of laying fiber to cabinets, i.e. VDSL is prohibitively expensive relative to ADSL and therefore VDSL deployments are limited.

The latest technologies to emerge from the DSL family are ADSL2+ and ADSL2++. ADSL2++ is not yet supported with the appropriate standard. ADSL2+ is standardized and allows transmission of sufficient bandwidth for some video services over greater distances than VDSL without the need for DSLAM reallocation. As a result, ADSL2+ is becoming the upgrade path for operators wishing to improve their standard ADSL offerings.

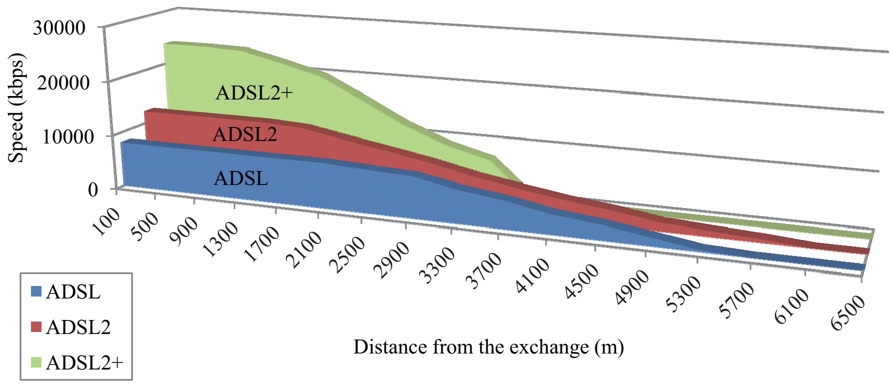

Figure 1.7 Characteristics of various ADSL technologies

DSL technologies are currently dominant in Europe, Figure 1.8. Research conducted by European Cable Association during 2010 shows that different variants of DSL technology are used by the majority of the population in European Union.

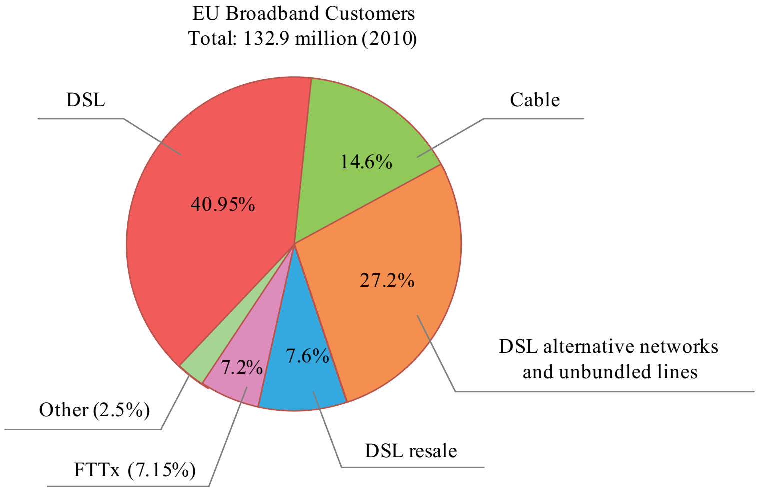

Figure 1.8 Deployment of DSL technologies in the European Union (Source: European Cable Association, http://www.cableeurope.eu/index.php?page=ff-2009-broadband-in-europe)