Systems Aspects of APON/VDSL Deployment

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ABSTRACT

The purpose of this article is to provide an overview of some system aspects allowing full service deployment over hybrid fiber-twisted pair access networks with a VDSL drop. Although VDSL and ADSL systems are similar from the point of view of transmission technology, there are differences in the architecture and implementation due to both the higher bandwidth and shorter copper loop length for VDSL. The VDSL drivers are given in the introduction. The next section describes the system architecture and the functionality of the various building blocks. Special attention is paid to optical feeder technology, for which APON is a well-suited technology. Concepts to reduce the cost of ownership are also discussed.

INTRODUCTION

While other articles in this special issue deal with various aspects of very high-rate digital subscriber line (VDSL) transmission technology, the present article covers the system architecture of a hybrid fiber-twisted pair access network with a VDSL drop. By installing optical fiber in the access network, it becomes possible to shorten the twisted pair line and use VDSL to transmit a higher bandwidth in the order of tens of megabits per second to subscribers. The introduction of this new access technology will be driven by the service requirements, as well as by the interests of the operators and end users.

SERVICES

The bandwidth of asynchronous DSL (ADSL) fits very well with the current and upcoming Internet traffic profile made of Hypertext Markup Language (HTML) graphic pages. The traffic is characterized by occasional downloads or streaming video sessions in the downstream direction and low bit rates in the upstream direction. What would trigger the need for the dramatic increase in bandwidth offered by VDSL?

A first application will probably be the delivery of symmetrical broadband services to small and medium enterprises (SMEs) and small/home offices (SOHOs). One can only imagine the possibilities of a capacity of tens of megabits per second to, for example, publishers, movie editors, engineers using computer-aided design (CAD), scientists performing complex modeling at remote supercomputers, medical doctors assisting a surgery in a remote location, LAN emulation, and high-quality video conferencing.

As for residential applications, one can perceive an expansive trend of Internet traffic and a growing interest in video-on-demand-like services. It seems that digital convergence (i.e., the combination of internetworking, consumer electronics, computers, and media contents) is an underlying factor triggering the need for abundant and inexpensive bandwidth to residential customers. The processing power of PCs and consumer goods are continuously increasing. Digital open interfaces such as Universal Serial Bus (USB) and IEEE-1394 are making their debut, together with digital video disk (DVD) technology. Television may soon be transformed into a multimedia experience thanks to broadcast-enabled computers or computer-driven TV sets. Several users within one household will simultaneously need high-bandwidth access.

VDSL fits this service model very well since it provides the several tens of megabits per second that will be necessary for these new services.

OPERATOR INTEREST

Operators owning a wireline copper plant that already passes through many homes in a serving area can prepare their access plant for the demand of the above services. However, the provision of video-rich services, allowing competition with cable operators, satellite operators, and wireless access operators, requires a minimum guaranteed bandwidth of 10 Mb/s or more available to each user.

Unlike the deployment model of ADSL, which guarantees only a few hundred kilobits per second to users located far from the central office, the delivery of several megabits per second requires an upgrade of the infrastructure. On average, even in urban areas, the majority of customers are out of reach of VDSL services deployed from central office buildings. Their lines need to be refurbished with the introduction of optical network units (ONUs) at well-planned locations in the distribution network. The copper drops to the customers can be shortened and a minimum service availability guaranteed. This unlocks revenue and reduces the risk of existing and new customers being turned away into the hands of the competition.

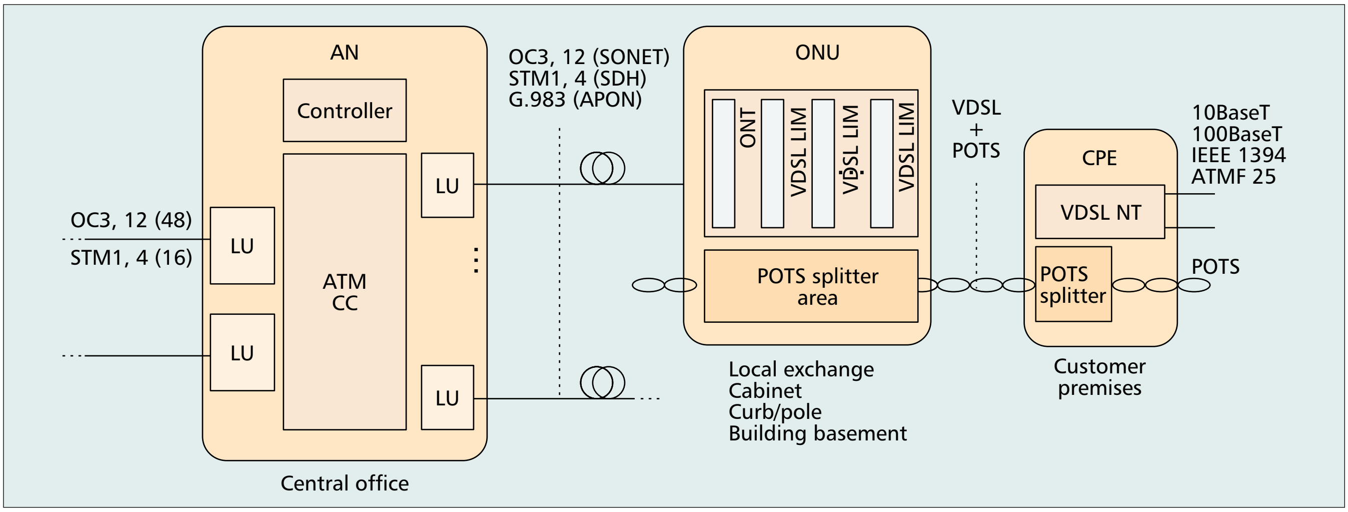

Figure 1. *The general network model for VDSL deployment.*

End-User Interest

The multiservice capability of VDSL in combination with fiber bandwidth is also beneficial for the end user. Only one access provider is required, which results in a single subscription fee. It uses the already installed phone line as the only entry point into the home. This represents a single home gateway for all home appliances that provide or need teleservices.

Architecture

General

Figure 1 shows the network model for VDSL deployment. While the line terminations (LTs) for ADSL are commonly installed in the local exchange building, VDSL LTs must be placed closer to the subscriber in an ONU. The figure depicts VDSL line interface modules (LIMs), which typically contain multiple VDSL LTs. Alternatively, the VDSL LIMs might be installed in existing digital loop carrier (DLC) cabinets or, in the case of VDSL from the exchange, in DSL access multiplexers (DSLAMs). Optical fiber is installed in the local loop to transmit sufficient bandwidth to the ONU. An access node (AN), sometimes also called an optical line terminal (OLT), concentrates the traffic of subtending ONUs and provides the interfaces to service nodes in the core network (e.g., Internet service provider, ISP; video servers; and public switched telephone network, PSTN).

Depending on the location of the ONU, one can distinguish different fiber to the x (FTTx) topologies as summarized in Fig. 2. The bandwidth delivered to the end user in the respective cases depends on the length of the copper loop and ranges from 14.5 Mb/s for long-range VDSL (1.5 km) to 58 Mb/s for short-range VDSL (0.3 km). The bit rates indicate the total capacity that can be subdivided between the downstream and upstream direction in a symmetrical or asymmetrical way. To save cost, the AN should be centralized as much as possible to eliminate the need for broadband switches at every legacy local exchange. As a result, some legacy local exchange buildings will be equipped with an ONU to deliver broadband services over ADSL or long-range VDSL. ONUs with long-range VDSL drops can also be installed at a flexibility cabinet that contains the distribution frame of copper lines for a few hundred homes passed. Higher transmission capacities can be achieved over short-range VDSL if the ONU is placed closer to the subscriber at a curb unit, on a pole, or in the basement of a building. Ultimately, the ONU can also be located at a business premises or home. Although the various FTTx topologies may look different, they consist of generic subsystems. An international group of operators meeting within the scope of the Full Service Access Networks (FSAN) initiative is generating common specifications for these subsystems in order to reduce the cost through economies of scale [1].

From a network application standpoint, there are three approaches for the support of telephony, as summarized in Fig. 3:

- In the case of a segregated broadband overlay, the narrowband system is upgraded by a broadband network element loosely coupled to the narrowband network element. Splitters are foreseen at the customer premises and at the ONU to allow for the transmission of plain old telephone service (POTS) or integrated services digital net-

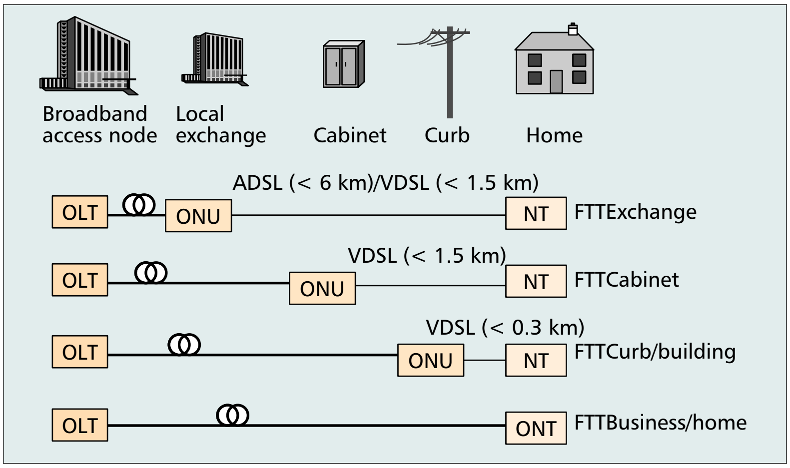

Figure 2. *Fiber to the x topologies.*

The multiservice capability and support of different QoS classes of ATM is well suited to efficiently deploy legacy narrowband and leased-line services, video streams, and IP data packets over a single full-service access network infrastructure.

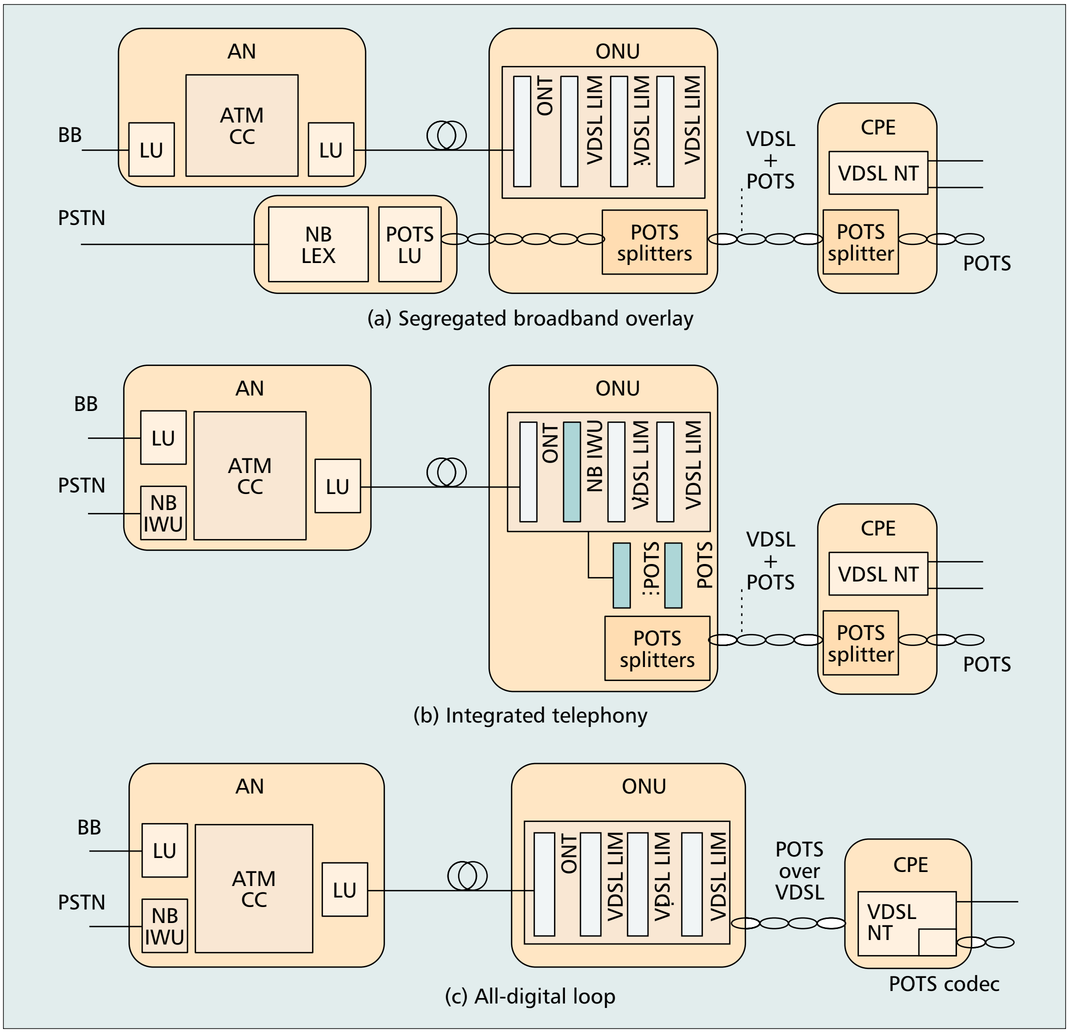

Figure 3. *Options for the integration of narrowband services.*

work (ISDN) and VDSL signals over the same twisted pair in the last drop. The broadband AN and the PSTN switch are not necessarily collocated.

- In the case of integrated telephony, the narrowband and broadband systems reside within a single network element in order to respond to a service offering combining telephony and broadband. Similar to the case above, splitters are foreseen. POTS (or ISDN) signals are, however, terminated in a NB narrowband interworking unit (IWU) at the ONU.
- In the case of an all-digital loop, PSTN services are carried digitally over the VDSL and optical link [2]. The approach results in a smaller ONU because it does not require a POTS channel bank or the use of bulky POTS splitters. The capacity of the VDSL link increases as the low-frequency bands used for POTS (or ISDN) in the previous two cases become available.

The ability to provide a POTS lifeline during a few hours of power outage is an important requirement to some operators. In the first case above, the lifeline is as reliable as in a traditional PSTN (considering passive POTS splitters at the ONU). In the second case, batteries are required at the ONU for backup in a power outage. In the third case, the power consumption of the ONU is lower than in the second, and hence the required backup battery is smaller. The POTS interface (codec) at the CPE can be made cheaply, since it should support only short distances over the in-house network. A small backup battery should be foreseen in the CPE. The first approach has the greatest operational expense because two networks need to be maintained. In the second and third approaches, POTS is carried over a reliable optical feeder, which can be made redundant (below).

While IP is the dominant network technology at the network layer, asynchronous transfer mode (ATM) remains the way to multiplex the traffic in the access network at the link layer [3]. Since the access network represents a large fraction of the total network cost and is depreciated over a longer period than equipment in the core network, it is important to invest in a mature and future-safe technology. The multiservice capability and support of different quality of service (QoS) classes of ATM is well suited to efficiently deploy legacy narrowband and leased-line services, video streams, and IP data packets over a single full-service access network infrastructure. With the current trend to IP-based network services in mind, one can optimize the throughput by making the ATM access network "frame-aware" [4].

Access Node

The AN concentrates the traffic from various ONUs and directs it to one or more service providers. In the case of integrated telephony or all-digital loop (Fig. 3b or c), the access node also provides the necessary narrowband interworking with a PSTN switch. The access node may be located at a central office or at a remote unit.

The core of the AN is an ATM cross-connect (ATM CC) and its controller, as shown in Fig. 1. Toward the service nodes, synchronous digital network/synchronous digital hierarchy (SONET/SDH) interfaces are used (OC3/STM1 at 155 Mb/s, OC12/STM4 at 622 Mb/s, or in the future also OC48/STM16 at 2.5 Gbit/s) (OC: optical container, STM: synchronous transport module). Toward the subscriber side, ATM passive optical network (APON) line units (G.983), or SONET/SDH line units at OC3/STM1 or OC12/STM4 rates can be used. The switch matrix typically has a capacity of several gigabits per second. An AN will serve around 10,000 lines. This is the typical number of homes covered by the optical feeder network in a low- to medium-density area and allows cost-effective implementation of the required cross-connect capacity. Several such ANs can be used in a modular way in the central office of a high-density area, which is more economical than developing a different type of large AN.

The Optical Network Unit

The ONU holds the VDSL LTs, the interface with the optical feeder, called the optical network termination (ONT), and the multiplexing function. In the case of integrated telephony, the ONU is also equipped with a narrowband channel unit and an interworking function that multiplexes the narrowband data onto the optical feeder transport system. The ONU typically concentrates the traffic of 10 VDSL lines for FTT building/curb (FTTB/C), a few tens to a hundred for FTT cabinet (FTTCab), and possibly 1000 for FTTEx.

Depending on the chosen feeder technology, the ONU is provided with an ONT card for an APON interface or an interface for SONET (OC3 or OC12)/SDH (STM1, STM4). Depending on the number of subscribers served by an ONU, it will consist of one or more shelves. Today, a shelf has typically around 10–20 slots, while an LIM card supports multiple DSL lines. The ONU equipment for FTTCab/B should be small in size, have low power consumption, and be provided with backup batteries. The size of an ONU, including a cable distribution frame, ranges from 50 x 50 x 50 cm^3 for a pole unit to 1 x 2 x 2 m^3 for a cabinet. The ONU can be powered locally from the net of a utility company or remotely from a shared power supply. If the ONU is installed in an outdoor cabinet, the equipment should support an extended temperature range. As for FTTEx equipment, the requirements for power consumption and space can be relaxed.

Customer Premise Equipment

At the customer premises, the VDSL network termination (NT) is the demarcation point between the access network provider and the private network or end user (Fig. 1). Considering the many possible applications, several options for the CPE can be envisaged. The simplest approach is a separate VDSL modem that provides one or more standard interfaces. For most business subscribers, the modem will be connected to a LAN and, in the case of integrated telephony, also to a private automatic branch exchange (PABX). In the case of a residential user, the modem is connected either directly to a multimedia terminal (PC, TV, or set-top box, STB), or to a residential gateway. The residential gateway is a flexible, intelligent interface to the home network that can accommodate multiple devices and different types of interfaces. It is possible to integrate the VDSL modem with the residential gateway. Another option is to integrate the modem with an STB or a PC by means of a network interface card (NIC).

Several candidate interfaces are currently being considered. Important aspects of this interface are support for multimedia, ease of configuration (plug and play), ease of cabling at the customer premises, support by residential gateway platforms, and security. The most widely used interfaces are Ethernet (10BaseT) and Fast Ethernet (100BaseT) offering 10 and 100 Mb/s, respectively. Firewire (IEEE1394) is gaining popularity in consumer electronics since it supports a mix of synchronous and asynchronous services at rates of 100, 200, or even 400 Mb/s. The 25.6 Mb/s ATM Forum interface extends the full service capabilities of the access network to the private network. In the case of an all-digital loop, one or more POTS interfaces are needed for residential users or a T1/E1 interface to a PABX for business users.

Optical Feeder Technologies

APON

Since the high-bit-rate transmission of VDSL is limited to distances of 0.3–1.5 km, optical fiber must be installed in the local loop to bring the required bandwidth closer to the customer. The search for a generic and cost-effective optical technology that can be applied to any FTTx deployment scenario has led to the concept of PONs [1]. By means of a passive star, a number of ONUs share the same feeder and LT at the AN. In the early '90s APON was developed, which uses the full service multiplexing capability of the ATM transport format. APON has been adopted by the FSAN initiative, because this optical technology is highly suitable for any FTTx architecture. It is expected that the standards specified by FSAN and approved by the International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) (G.983) will reduce the cost and accelerate the commercial deployment of APON [5].

As shown in Fig. 4, the FSAN-APON is specified to connect up to 64 ONTs to an LT over a range of maximum 20 km. The actual achievable split and range are limited by the total loss of

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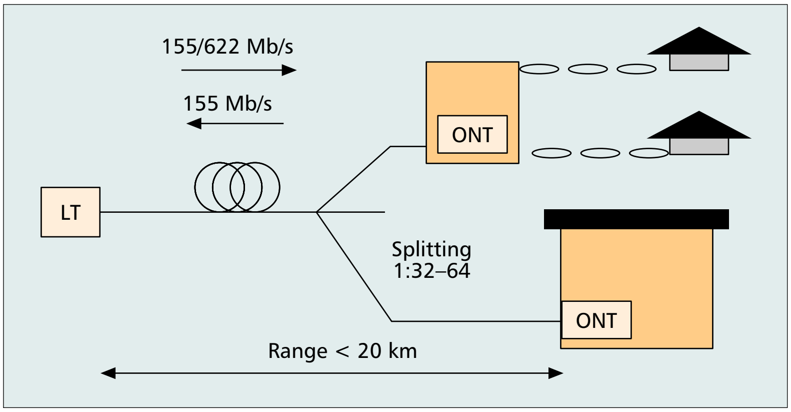

Figure 4. *APON architecture.*

optical power over the PON, which is around 30 dB. This corresponds, for example, with a split of 32 over 10 km or a split of 16 over 20 km. A downstream bandwidth of 622 or 155 Mb/s is distributed to the connected ONUs by means of time-division multiplexing (TDM), while an upstream bandwidth of 155 Mb/s is shared by means of a time-division multiple access (TDMA) protocol. It should be noted that for FTTCab applications, the split is typically 1:8 and is usually limited not by the optical budget, but by the total bandwidth.

The access of the ONUs to the common upstream channel is arbitrated by a medium access control (MAC) protocol. Conventional static MAC protocols allocate the peak bandwidth upon connection setup. More efficient multiplexing is achieved by new dynamic MAC algorithms, which take advantage of the variable or bursty bit rate inherent to some types of connections (e.g., Internet access) [4].

The APON acts as a distributed multiplexer, which can handle large peak capacities without the need for an excessive number of ports in the AN. It is also possible to serve business users directly with a fiber link and residential users via VDSL from a cabinet. The former mainly loads the APON during the day, the latter in the evening.

Another advantage of APON is that it is attractive for distributive services. An asymmetrical 622/155 Mb/s APON allows broadcasting to every connected ONU, for example, 100 video channels of 4 Mb/s that can be selected by a request signal from the CPE to the ONU. There remains a capacity of about 200 Mb/s for data services or additional broadcast channels.

It is possible to implement different levels of redundancy in an APON depending on the cost the operator is willing to incur for the service availability (Fig. 5) [6]. The cheapest step is 1:1 protection of the line termination. Double routed feeders can be connected to the two input ports of a 2:*N* optical splitter. The cable can be completely redundant up to the ONU. The highest availability is achieved by also making the network termination redundant. The first three options may be acceptable for residential multimedia services in FTTB/C. The last option is needed in the case of FTTCab to achieve sufficient availability for telephony services and to fulfill the requirement that a single point of failure should never affect more than a given number of users (e.g., 64). A PON is also more fault-tolerant than an SDH/SONET ring (see below), because power-down of one node in a PON does not affect any other node.

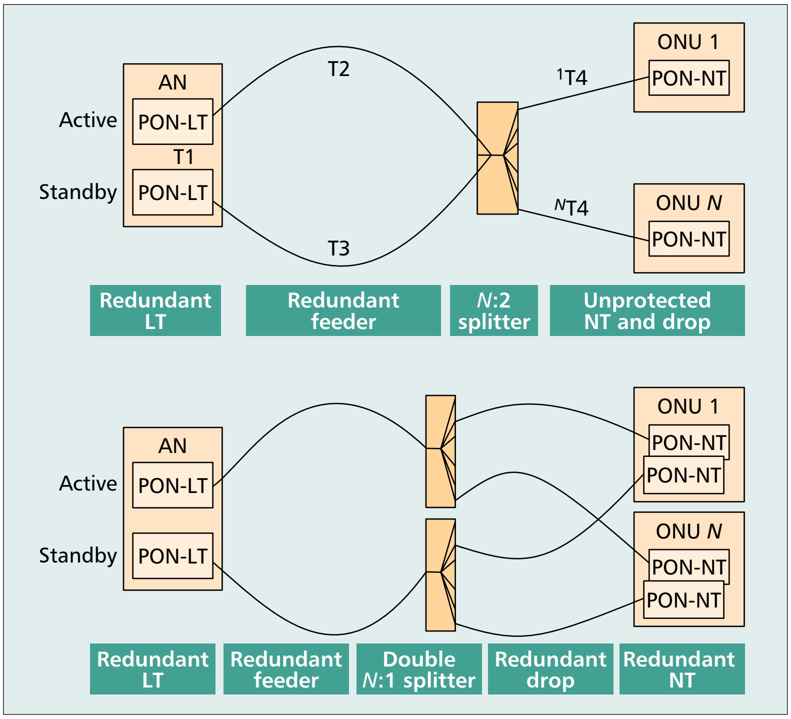

Figure 5. *Root redundancy and full redundancy of APON.*

SONET/SDH

While experience has been gained with the FSAN APON in a number of field trials [7], SONET/SDH is an alternative feeder technology for FTTCab or FTTEx in the short term. Since operators already have experience with the deployment of this proven technology in the core network, it is easily leveraged for broadband access networks as well. The bit rates for the access network are 155 Mb/s (OC3 or STM1) or 622 Mb/s (OC12 or STM4).

The most straightforward approach is a star configuration in which every ONU is connected by a point-to-point link to the AN. Compared to the APON solution, this results in a higher cost due to a larger number of optical interfaces and a larger rack space at the AN. A cross-connect port of 155 Mb/s is reserved in the AN for each ONU, which in many cases does not require such a large bandwidth.

A ring is another configuration of the feeder network in which an add/drop multiplexer (ADM) is foreseen at the AN and every ONU. This approach reduces the number of optical interfaces at the AN, improves to some extent the sharing of the capacity, and provides redundancy. An SDH ADM can drop a multiple of virtual containers (VCs): VC-11/12 (1.5 or 2 Mb/s), VC2 (6.3 Mb/s), or VC3 (44.7 Mb/s) capacity at each ONU (VC is SDH terminology, used here for simplicity). The bit rate dropped at each ADM-ONU is semi-permanently set to the expected peak rate of each ONU and is therefore not efficiently used in the case of variable or bursty bit rate services.

Two techniques can be applied to improve statistical multiplexing on a SONET/SDH ring: inverse multiplexing for ATM (IMA) and integrated SDH-ATM (ISA) [8]. IMA enables the transport of a high-bit-rate ATM cell stream onto a multiple of lower-bit-rate SONET/SDH VCs (e.g., n x T1/E1) between one ADM-ONU and the AN. In the ISA implementation, the capacity of a large SONET/SDH VC (normally VC3 or an entire STM1) is shared over the entire ring and each node is able to add and drop, pass through, and discard ATM cells in the link.

The multiplexing efficiency of the three approaches is illustrated in Fig. 6. The example has been calculated for a video-on-demand service (6 Mb/s), assuming an FTTCab deployment in an area of 30,000 homes passed. Figure 6 shows the required number of 155 Mb/s ports in the AN as a function of the service penetration. Only ISA performs as well as APON, since it also has an ATM cell as the smallest multiplexing granularity.

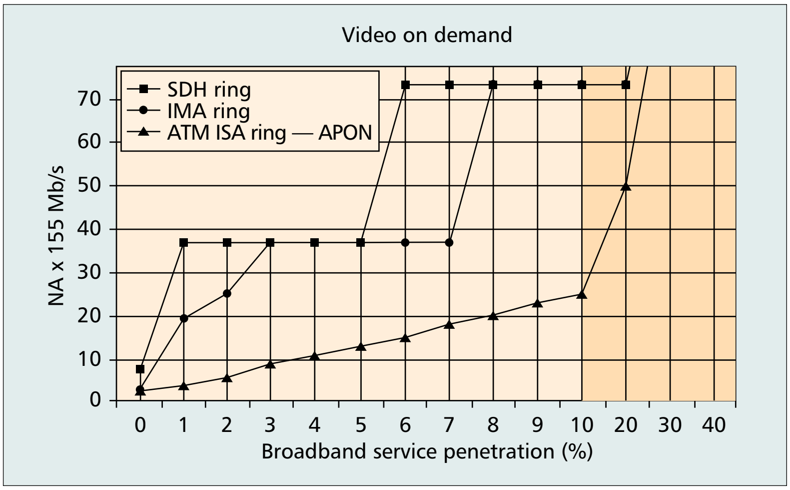

Figure 6. *A comparison of APON with various multiplexing approaches on SDH rings.*

FUTURE EVOLUTION

Besides the commercially available APON and SDH systems, new optical access technologies for the long term are being investigated. In the European Advanced Communications Technologies and Services (ACTS) projects PLANET and PELICAN, a SuperPON has been demonstrated that features a large splitting factor (2048), long range (100 km), and high bandwidth (2488/311 Mb/s) [9]. At these bit rates, a TDM/TDMA transport system is still the most cost-effective solution. Optical amplifiers are inserted in both transmission directions to compensate for fiber attenuation and splitting losses. The longer range allows for an extensive reduction in the number of switching nodes, thereby saving operating and maintenance costs. Although the full splitting factor of SuperPON is probably not needed for FTTCab, the increased bit rate may become of interest to supply sufficient bandwidth to more ONU cabinets with a larger number of VDSL drops than a conventional APON or provide additional capacity for video broadcast services.

Dense wavelength-division multiplexing (DWDM) techniques are currently being introduced in core networks. As the required bandwidth increases and the cost of optical components decreases, DWDM will also find applications in metropolitan and access networks [10].

DEPLOYMENT ASPECTS

COST OF OWNERSHIP

While the costs associated with ADSL deployment scale rather well with the number of subscribers, VDSL requires an initial investment in the cable infrastructure and street cabinets. Progress in optical technologies have made the introduction of fiber in the access network a viable solution. Integrated electro-optical transceivers are becoming available at low cost if produced in sufficient volume. Also, the civil works cost for cable installation could be significantly reduced when using available rights of way (existing poles or ducts, sewers, pipes).

Whether the fiber should be installed up to an active unit from where services are delivered over the existing twisted pair or up to the home is extremely dependent on the business case, which takes into account the first installed cost, operational cost, and service revenues. Although the initial investment for FTTH is more expensive, it is in some cases offset by reduced operational cost [11]. The systematic use of active remote nodes for VDSL represents a burden of expenses for maintenance and powering. The investment for an FTTx network can be justified where the penetration of broadband users is expected to become large enough to create sufficient revenues.

A VDSL "BRICK"

Concepts have been proposed to lower the first installed cost of VDSL for low penetration. A VDSL brick consists of a small-size ONU in a sealed can with, say, eight VDSL lines [12]. Instead of investing in a new cabinet with active equipment next to the existing flexibility cabinet, the VDSL brick is installed in the footway box together with the power supply. As demand increases, additional bricks can be connected to an optical splitter in a modular way.

SERVICE PROVISIONING

In considering upfront investments, operators should not forget that connecting individual customers when they request the new service entails major costs. This is particularly true if it requires service visits by field personnel at the street cabinet and customer premises. In order to allow for automated provisioning, the ONU can be equipped with a small automated main distribution frame (MDF). One spare VDSL LT is foreseen in the ONU for a given number of eligible PSTN customers. The automated MDF switches a new broadband user to the spare LT upon service activation. As such the interventions at the street cabinet can be restricted to regularly scheduled visits, during which a newly activated VDSL line is replaced by a fixed configuration

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and new spare capacity is created. The number of candidate lines per spare VDSL LT is dependent on the expected service growth, the planned site visit cycle, and the acceptable intervention ratio.

An automated MDF would enable the following model to reduce the cost of service activation. The VDSL NT is a standard product for sale in more or less every PC/TV retail shop. If the retailer has access to a database of the operator, he can check whether the customer's PSTN line is prepared and qualified for VDSL. The customer, with support of the retailer, is able to install the NT and the required software in the PC or home terminal. Connecting an individual customer to the VDSL service must be possible with little effort and at minimum cost.

SUMMARY

Due to the short loop length, the VDSL LT must be placed in an ONU at a cabinet or curb unit, or in the basement of a building. Traffic from ONUs is transported over optical fiber and concentrated in an access node. Although different locations and sizes are possible for the ONU, generic subsystems have been defined and standardised.

APON is a well-suited optical feeder technology. Since it is a distributed multiplexer with a granularity as small as an ATM cell, it enables efficient use of port capacity at the access node. The broadcast nature of APON can save bandwidth when delivering distributive services. Various redundancy schemes, including ring topologies, can be implemented.

Concepts have been proposed to reduce the cost of ownership. A VDSL brick may reduce the up-front investment in case of low penetration. An automated MDF at the ONU is a possible solution to reduce service activation cost. The choice for a specific FTTx option will depend on the business case of the operator, taking into account the initial installed cost, the operational cost, and the service revenues.

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BIOGRAPHIES

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