White Paper: Broadband Access Technologies

A White Paper by the

Deployment & Operations Committee

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Table of Contents

Introduction

To keep up with increasing bandwidth demands, telecoms operators are migrating from copper-based telephone and cable television networks to fibre-based networks, which promise to deliver higher speeds *. However, migration to an all-fibre network infrastructure requires major investment and takes considerable time to complete – probably at least a decade in most countries.

Operators and vendors have been working together to increase the broadband bit rates achievable using copper-based access technologies, making faster speeds available more quickly, and extending the lifetime of copper networks. In the short term, therefore, copper-based technologies will continue to play an important role in providing access to high-speed broadband services.

But will these developments enable copper-based networks to compete with all-fibre access networks in the medium and longer term?

In this white paper we compare the performance characteristics of fibre-based access technologies with those of the latest copper-based access technologies.

The following copper-based access technologies are considered:

- **Digital Subscriber Line** (DSL) family of technologies, including asymmetric digital subscriber line (ADSL) and very high speed digital subscriber line (VDSL), as well as acceleration techniques such as bonding, vectoring (G.Vector) and "phantom mode".

- **Coaxial cable networks** based on Data Over Cable Service Interface Specification (DOCSIS), including current generation DOCSIS 3.0 and the next-generation standard DOCSIS 3.1.

Other technologies also provide broadband services, including mobile network technologies such as third generation (3G) and long term evolution (LTE), satellite communication networks, and broadband over power line. These technologies have fundamentally different architectures, characteristics and limitations from wireline access networks. Therefore, we confined our discussion to the main technologies being used in wireline access networks.

The Deployment & Operations Committee has also published a white paper about the relationship between wireless and wireline technologies, which is available to download at www.ftthcouncil.eu.

* Notes on terminology: The term "speed" is used synonymously with "bit rate".

The need for speed: Nielsen's Law

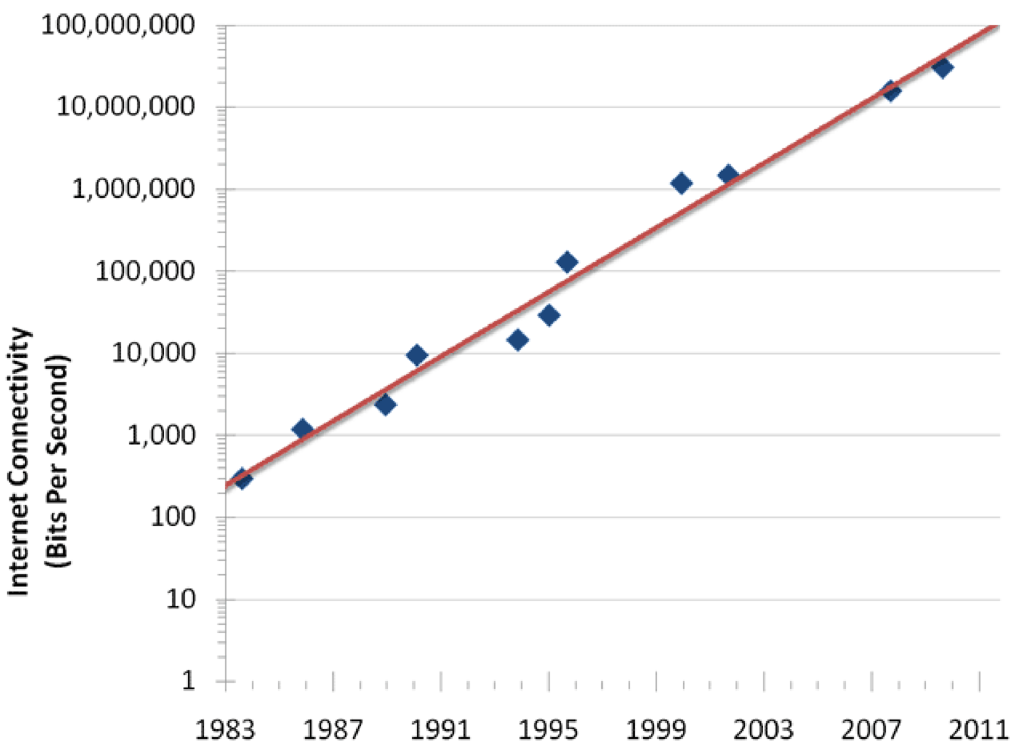
Over the past twenty years, Internet connection speeds have steadily increased. This has been driven by Moore's Law, which increases computer processing power, and also by the move to higher-resolution displays, and the greater use of images and video rather than just plain text.

This growth in Internet connection speeds is expected to continue for the foreseeable future, just as it has in the past. The trend is encapsulated in "Nielsen's Law of Internet bandwidth", an empirical observation which states that a high-end user's connection speed grows by 50 percent per year, or doubles every 21 months.

Originally expressed in 1984, Internet bandwidth has followed Nielsen's Law up to the present day. Nielsen's data point for 2010 is a connection speed of 31 Mbps, a speed that is already familiar to many, but by no means the highest available to consumers.

In future, the growing popularity of existing services combined with the introduction of bandwidth-hungry new services such as videoconferencing and e-health, will continue to increase the bit-rate requirements of residential and small business Internet users.

Figure 1: Nielsen's Law of Internet Bandwidth



Source: Jakob Nielsen, http://www.useit.com/alertbox/980405.html

As more information becomes available in digital form, data will need to be accessed more quickly. And as the capabilities of the network improve, new applications will be developed to take advantage of the improved capabilities, which will continue to push the requirements even higher.

The aggregate bit-rate requirements of all the applications in a "connected home" could easily exceed 200 Mbps by 2020, according to a recent study by WIK Consult for German broadband association Bundesverband Breitbandkommunikation (Breko).

Digital Agenda 2020

Recognising the importance of Internet access to Europe's economic development, in May 2010 the European Commission set out clear broadband objectives as part of its Digital Agenda for Europe initiative, which states:

> *"To match world leaders like South Korea and Japan, Europe needs download rates of 30 Mbps for all of its citizens and at least 50% of European households subscribing to internet connections above 100 Mbps by 2020."*

These targets support the roll out of high-speed broadband networks across Europe. However, it is necessary to look beyond the targets set in the Digital Agenda to include all the necessary parameters to ensure that Europe's broadband dreams are realised.

The Digital Agenda targets relate to downstream speeds (from the Internet to the end user). It will also be important to provide high speeds in the upstream direction (from the user to the Internet). The digital economy will be based on active information exchange that will require better upload speeds than are commonly available today. Many legacy (i.e. copper-based) broadband connections are asymmetric by design, which means that the upload speed is typically much lower than the download speed.

While it is commonly accepted that *traffic volumes* will remain asymmetric – on average, subscribers will continue to consume more data than they produce – there is no reason to assume that broadband *speeds* should remain asymmetric. Both download and upload bit rates affect the latency (the time delay) associated with a particular networking task. The need for faster upload speeds is already apparent as applications requiring two-way video communication become commonplace, which demand equal speeds both upstream and down.

The ability of technologies to evolve to meet future needs is also of paramount importance. Infrastructure upgrades should be carried out with a long-term view, especially where they are supported by public funding. In this white paper we will identify the current and future technical capabilities and limitations of the various network technologies.

Back to basics: FTTx architectures

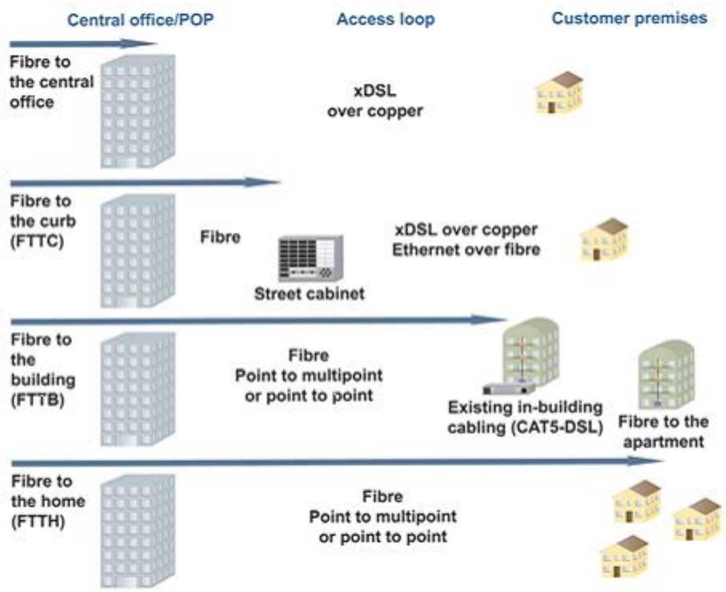
The network architecture refers to the design of a communications network, and provides a framework for the specification of the network from physical components to services. The access network is the piece of the communications network that directly connects to end users. Depending on the architecture, parts of the network can be copper cable or optical fibre, as shown in Figure 2.

The network itself comprises the transmission medium (twisted-pair, coaxial or fibre-optic cable) and the electronic equipment used to transmit the signal. The topology of the network describes the positioning of the various elements – links, nodes, etc. – within the network.

In a traditional telephone network, twisted-pair copper cables connect the central office to homes and other buildings, while the link from the central office to the core network is usually optical fibre. A telephone network uses copper cable over relatively long distances ("line lengths"), with the central office serving homes and buildings within a radius of up to 5.5 km.

Other architectures bring fibre closer to the end-user, and these are called hybrid fibre networks, or fibre to the x (FTTx). In fibre to the curb or cabinet (FTTC), optical fibre is installed from the central office to a street cabinet, typically located within 1000 m of homes.

Figure 2: Different types of FTTx networks



Source: FTTH Council Europe, FTTH Handbook, 5th edition, Figure 4

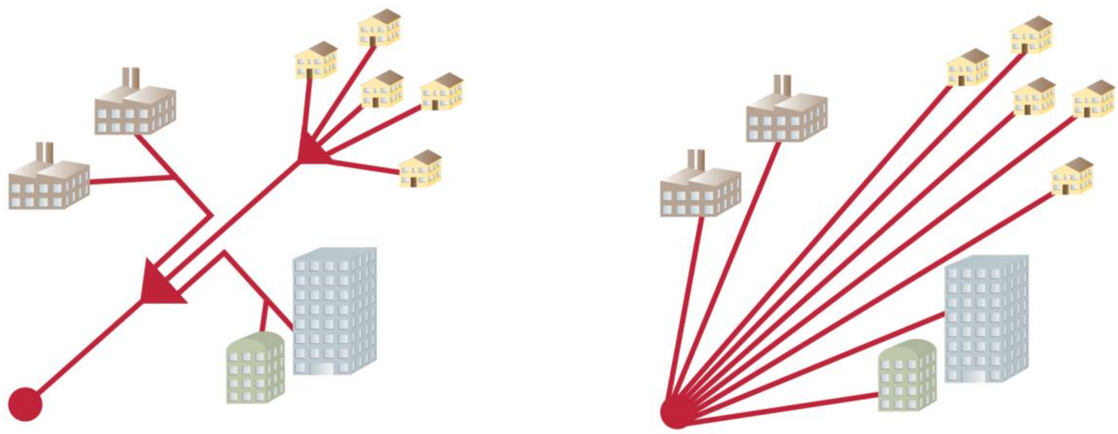
Recently (not shown) operators and equipment vendors have been developing fibre to the distribution point (FTTdp), also called fibre to the street (FTTS), which brings fibre cable even closer to subscriber premises, and uses compact equipment, possibly located on a pole or in an underground enclosue, to send signals over the final tens of metres of telephone cable. Most line lengths would be between 30 to 50m, and all must be less than 250m.

Fibre to the building (FTTB) brings fibre as far as the building itself, usually a multi-dwelling unit such as an apartment block, and uses any new or existing medium – including copper and fibre cables – inside the building to distribute the network to individual residences.

Fibre to the home (FTTH) provides a full fibre network from the central office directly to the customers' premises. There are two main types of FTTH network: point-to-point (usually Ethernet technology) or point-to-multipoint (usually GPON technology) – see Figure 3 for details.

Modern cable networks use an architecture that is similar to FTTC, with optical fibre installed to nodes in the street, and coaxial cable connecting those nodes to individual customers' homes. This architecture is also called hybrid fibre-coax.

Figure 3: Point-to-multipoint and point-to-point network topologies.



Source: FTTH Council Europe Business Guide

What is the maximum speed?

It is important to know the maximum speed that any network can provide, either now or in the future, because bit-rate requirements are growing and choices made today will affect the technical capabilities of the network tomorrow. Although it is difficult to predict the future, Nielsen's law of Internet bandwidth described earlier provides a guide to future bit-rate requirements.

A combination of factors determines the speed or bit rate achievable on the network. The transmission medium is one of the most critical factors – the type of cable, its length and layout will determine the theoretical maximum speed. The choice of electronic equipment determines the actual maximum speed as well as the number of subscribers on a port.

The Shannon Limit

Every transmission medium has a physical bandwidth limitation, which can be determined using the Shannon–Hartley theorem.

As stated by Claude Shannon in 1948, the theorem provides a means to calculate the maximum achievable bit rate over a transmission medium as a function of the frequency-specific signal-to-noise ratio (SNR) values. The following formula defines the maximum channel capacity C:

$$C = B\log_2\left(1+\frac{S}{N}\right)$$

where:

- C is the channel capacity in bits per second (bps),
- B is the bandwidth of the channel in Hertz (Hz),
- S is the average received signal power in Watts (W),
- N is the average noise power in W,
- S/N is the signal-to-noise ratio expressed as a linear ratio (not logarithmic scale in decibel, dB).

The maximum theoretical capacity of a communications channel, as determined by this equation, is called the Shannon Limit.

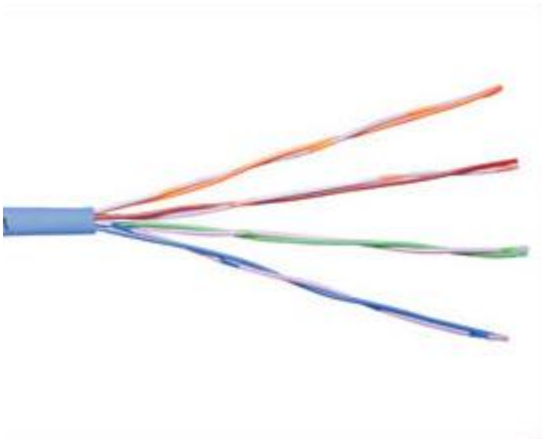
The SNR decreases with increasing attenuation (the gradual loss of signal intensity as the signal travels along the medium) and crosstalk (noise from interfering signals). Conversely, reducing crosstalk or attenuation can increase SNR and channel capacity. As attenuation accumulates rapidly over distance, the length of the copper cable is a significant constraint.

The aim of developing new transmission technologies is to move closer to the theoretical channel capacity given by the Shannon theorem. Improvements can be made by developing more efficient modulation schemes to encode the data, or reducing the impact of crosstalk.

DSL technologies

Digital Subscriber Line (DSL) is the family of technologies that provide digital data over the wires of a local telephone network. The transmission medium is the twisted-pair cable, where the two wires are twisted together into a helix to reduce interference.

Figure 4: A typical twisted-pair cable design

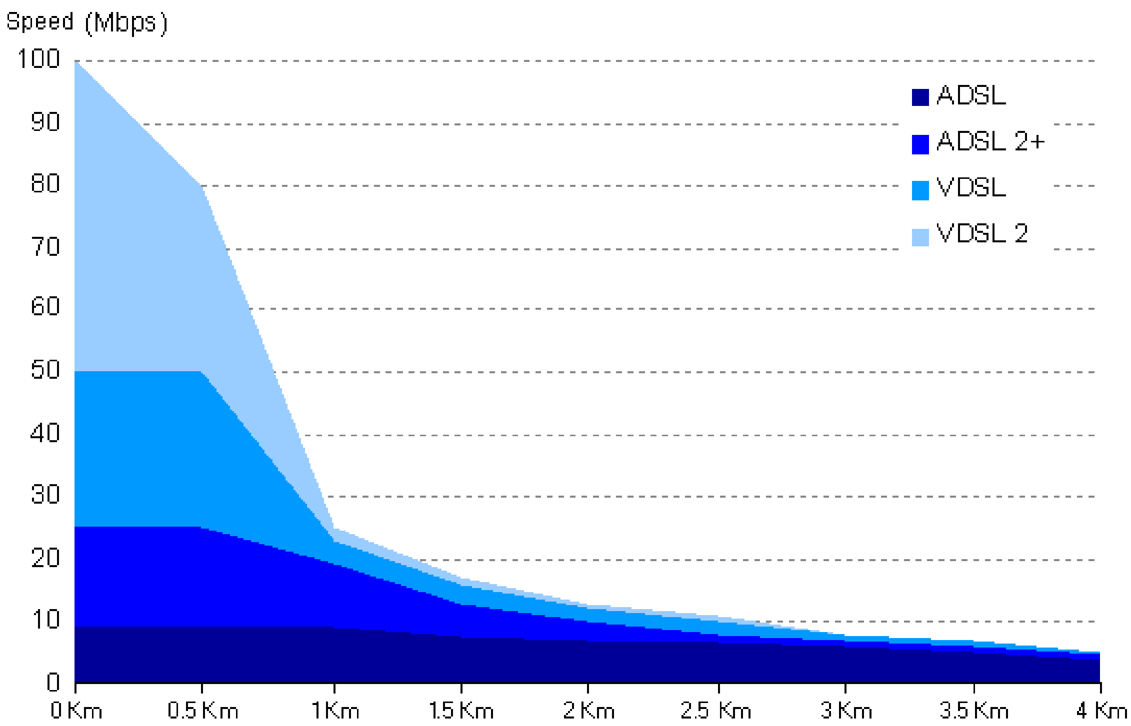


Source: Prysmian Group

This transmission medium was originally chosen to transport analogue voice signals with a maximum frequency of 3.4 kHz. All DSL technologies exceed this maximum frequency by several orders of magnitude, for example, ADSL2+ supports frequencies up to 2.2 MHz, and VDSL2 supports frequencies up to 30 MHz.

High frequencies, which are required to transmit higher bit rates, are strongly attenuated by the twisted-pair cable, which places severe restrictions on the achievable length and speed. Higher speeds are only possible over short lengths of cable; homes located some distance away from the central office will not be able to access the higher speeds.

Figure 5: Theoretical performance of DSL technologies



Source: IDATE

DSL speeds decrease with increasing distance from the transmission equipment, as shown in above. At distances greater than 500 m, the speed delivered by VDSL2 decreases rapidly. Hence, VDSL2 is best suited to short line lengths and is usually combined with FTTC. The feeder portion of the network must be upgraded from copper to fibre to maintain performance.

Although some varieties of VDSL2 (e.g. 30a profile) can achieve speeds of up to 100 Mbps in theory for both download and upload, this can also be heavily affected by interference from nearby copper pairs located in the same binder. This will further reduce the speed delivered by VDSL2.

DSL acceleration techniques

In recent years, DSL acceleration techniques have been developed, such as vectoring, bonding and phantom mode. These technologies increase the maximum speed over copper twisted-pair cable, but it is never possible to exceed the physical limit imposed by the Shannon theorem.

- Bonding combines multiple copper pairs into a single transmission channel;
- Vectoring reduces the far-end and near-end crosstalk (FEXT and NEXT);
- Phantom mode technologies mimic additional copper pairs.

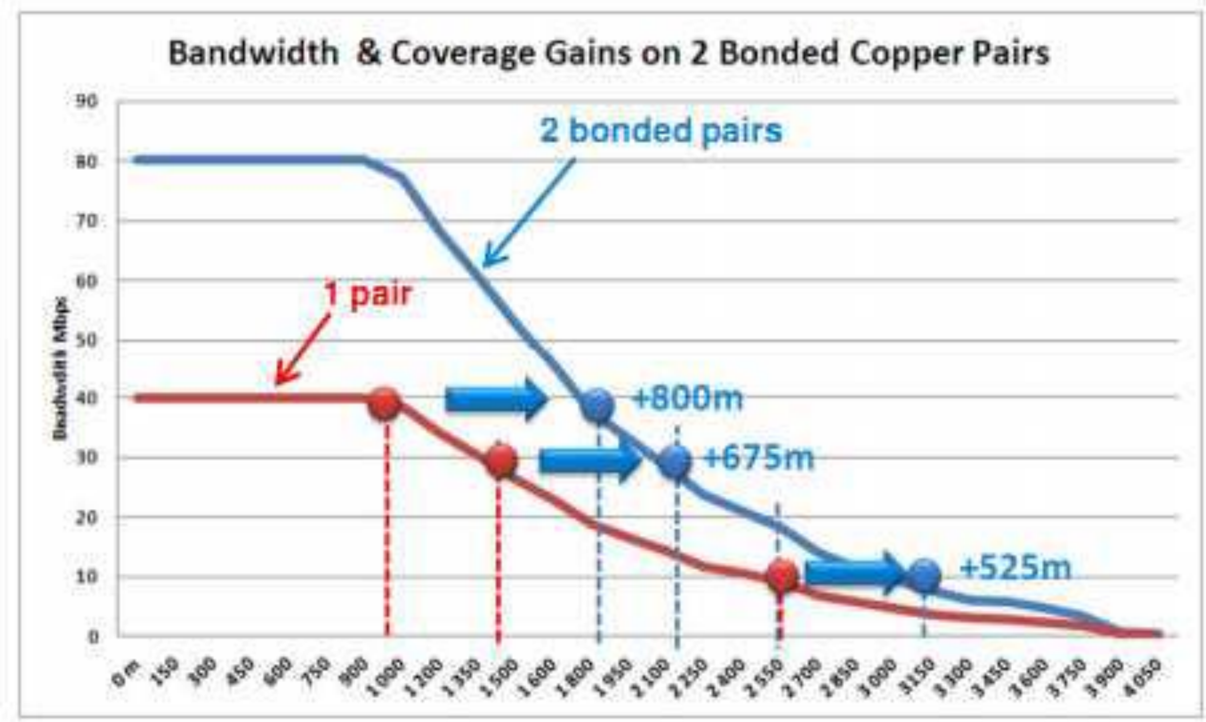
Bonding

Bonding is the term applied to combining multiple copper pairs (e.g. in a quad copper telecom cable) to increase the total capacity of the communications channel.

In general by bonding two pairs, either speeds or reach can be improved as shown in Figure 6:

- Increasing the speed: e.g. 80 Mbps at 500m, or
- Extending the reach: e.g. 40 Mbps at 1000m

Figure 6: Bonding gains using two copper pairs.



Source: ZTE

Commercially available equipment currently supports VDSL2 bonding of up to eight copper pairs to achieve speeds of up to 400 Mbps.

Of course, the viability of bonding relies largely on the availability of households connected to two or more copper pairs. However, most residential deployments are limited to two pairs, and this is not available everywhere, and in some countries not at all, which makes it difficult to create ubiquitous services based on bonding.

Vectoring

Vectoring is an active technology that reduces crosstalk between signals travelling down nearby copper pairs. By reducing the noise, the performance of the copper is optimized towards the Shannon Limit to provide up to 100Mbps over 500 m. By eliminating crosstalk the theoretical performance of a VDSL2 system with only one active user can be approximated in a real deployment with multiple users on the system.

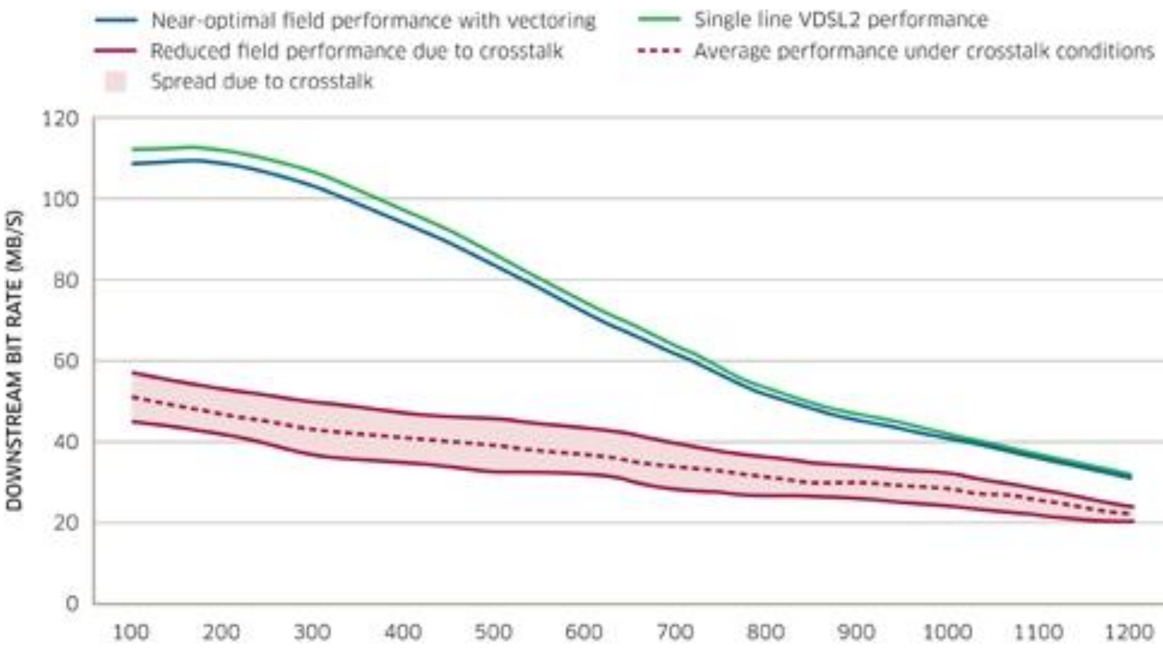
However, to obtain the best results from vectoring, all VDSL2 lines in a cable must be controlled by the same equipment/operator; otherwise the noise cancellation will be less effective. Vectoring does not allow physical (local or sub-loop) unbundling and third parties are limited to bitstream services, which can present regulatory challenges.

Vectoring has been standardized by the ITU Standards Association as G.Vector. ITU-T G.933.5 supports far-end crosstalk cancellation in the downstream and upstream directions.

G.fast is a new standard, still several years from completion, that is being developed to provide higher speeds using frequencies above 30 MHz combined with vectoring in a FTTdp scenario.

Note that vectoring does not require additional copper pairs (i.e., bonding) to be effective.

Figure 7: Typical gains achieved with VDSL2 vectoring



Source Alcatel-Lucent

Phantom mode

Phantom mode signals can be used, in combination with vectoring and bonding, to increase the capacity of a single communications channel using multiple copper pairs. This approach is called "Phantom Mode" by Alcatel-Lucent and "SuperFast" by Nokia Siemens Networks.

Phantom mode is based on an old concept used in analogue telephony to save copper pairs. If multiple twisted copper pairs are available, then it is possible to define additional pairs – the phantom mode – by applying a differential signal across two pairs to create a third, virtual pair. Next, vectoring cancels the cross talk generated between the physical and virtual pairs. Finally, the two physical pairs and the virtual pair are combined into a single communications channel.

The performance of the phantom pair will always be inferior to the performance of the real pairs because the lines constituting this pair are not twisted.

The maximum bandwidth successfully reached in prototype, laboratory based experiments is:

- **Alcatel-Lucent** (Phantom Mode) has showed 300 Mbps at 400m (or 100 Mbps at 1000m) using two pairs of 0.6-mm twisted-pair cable. Alcatel-Lucent says its approach enables bit rates that are 2.5 times greater than two bonded pairs.

- **Nokia Siemens Network** (SuperFast) has demonstrated connection speeds of 825 Mbps over 400m and 750 Mbps over 500m for its "SuperFast" technology.

- **Huawei** (SuperMIMO) has achieved speeds of 700 Mbps over 400m using four copper pairs. Huawei says this approach boosts DSL bandwidth by 75%, from an average of 100 Mbps per twisted pair to about 175 Mbps

To implement phantom mode technology, a hardware swap in the central office or the street cabinet would be required, while two copper pairs per subscriber are also necessary.

In addition, phantom mode techniques have not been standardized, which is a drawback to wider adoption of the technology.

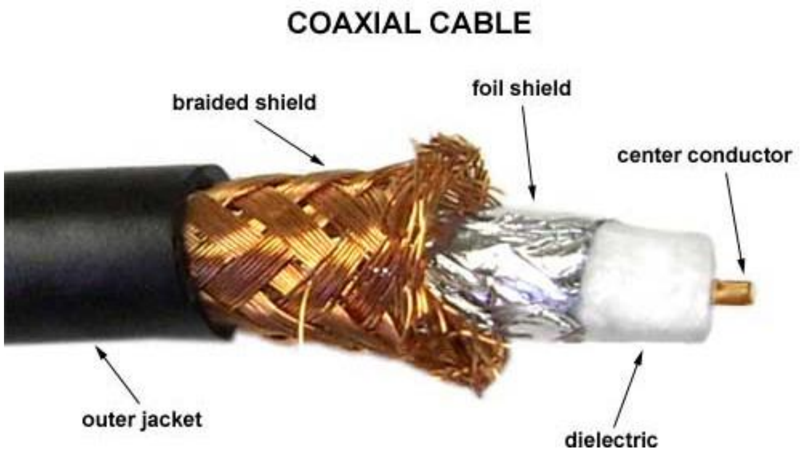
Cable technologies

Cable networks were originally established as unidirectional networks to deliver television into customers' homes, as a high-quality alternative to terrestrial television broadcasting that was often subject to interference. The networks were later upgraded to provide two-way communication.

The old cable networks were fully coaxial cable based, but modern cable networks are based on an architecture that is similar to fibre to the cabinet. Optical fibre has been installed to nodes in the street, and coaxial cable connects those nodes to individual customers' homes.

Coaxial cable was always intended to carry high frequency signals. The coaxial portion of the network also includes electronic amplifiers to boost the signal relative to the noise, and so the maximum frequency supported by the cable is determined by the distance between amplifiers.

Figure 8: Structure of a coaxial cable.



Source: Prysmian.

DOCSIS 3.0

Data transmission over cable networks uses the Data Over Cable Service Interface Specification (DOCSIS), which has been standardized by ITU-T. The current generation, DOCSIS 3.0, was ratified as ITU-T Recommendation J.222.

When broadband was introduced, a single television channel was replaced by a data channel in the downstream direction. The frequency range was also split and the lower part of the range allocated to upstream data transmission.

In Europe each downstream channel has a usable broadband capacity of 50 Mbps, and in North America the capacity per channel is 38 Mbps. With DOCSIS 3.0 multiple channels can be bonded to achieve higher speeds – note that these are radio frequency (RF) channels on the coaxial cable spectrum rather than physical cables. DOCSIS 3.0 has no limit on the number of channels that can be aggregated, as long as they fit into the available RF spectrum.

Limits arise from the capabilities of the cable modem termination system (CMTS) and customer premises equipment (CPE). The cable operator must also decide on the most appropriate (and profitable) split between television and broadband services.

Commercially available DOCSIS 3.0 equipment can provide:

- Download capacity of 400 Mbps (8 channels) on the DOCSIS CPE
- Upload capacity of 120 Mbps (4 channels) on the DOCSIS CPE

Cable operators have several upgrade options. They can allocate more RF channels to broadband. Analogue television channels occupy significantly more cable spectrum than the equivalent digital services. Converting television delivery to all-digital frees up additional spectrum that can be used to provide broadband.

The downstream broadband channel in a DOCSIS network is a shared medium. The service level and sustainable bit rate will depend on the number of concurrently active subscribers on the segment of coaxial cable. A single optical node in a big city can serve up to several thousand homes, connected over the same optical fibre. As a result, operators needing to upgrade the cable plant to cope with bandwidth growth are segmenting the network into smaller sharing groups of 500 homes, and even only 250 or 100 homes in some cases, by:

- connecting individual fibres to each fibre node,
- dividing the fibre nodes into two or more smaller fibre nodes, or
- bringing fibre to the last amplifier (FTTLA) to service an even smaller group of homes.

DOCSIS 3.1

To improve the download and upload speed over cable networks, several suppliers are preparing the next generation of standards, DOCSIS 3.1. The goal is to achieve at least 5 Gbps for the download bit rate, as well as more than 1 Gbps for the upload. (This is shared capacity used by all homes on the same coaxial cable segment.)

DOCSIS 3.1 will increase the available cable spectrum and aim to use it more efficiently by:

- employing new, more efficient modulation and error-correction schemes, including orthogonal frequency-division multiplexing (OFDM) and low-density parity-check (LDPC) codes;
- creating additional downstream RF spectrum by using higher frequencies, and
- creating additional upstream RF spectrum by moving the "split" between upstream and downstream transmissions..

The available RF spectrum in cable networks depends on plant design. Most cable systems have at least 750 MHz of spectrum, while some reach 860 MHz, and a few have expanded to 1 GHz. DOCSIS 3.1 aims to increase the upper limit to 1.15 GHz, and eventually push it even further to 1.7 GHz, but this increase would require some changes to the installed plant.

The split between upstream and downstream spectrum is at 42 MHz in North America while cable systems in Europe use 65 MHz. This is known as a low split or sub-split. In the short term the aim is to move to a mid or extended sub-split at 85 MHz, which would triple upstream throughput using DOCSIS 3.0. The longer-term recommendations are for a high split at 230 or even 400 MHz.

A summary of these proposals is shown in the following table:

Figure 9: The potential of DOCSIS 3.0 and 3.1 technologies.

	DOCSIS 3.0		**DOCSIS 3.1**	
	Now	**Phase 1**	**Phase 2**	**Phase 3**
DS Range (MHz)	54 – 1002	108 – 1002	300* – 1152	500* – 1700
DS QAM Level	256	256	≥ 1024	≥ 1024
# DS Channels	8	24	116*	200*
DS Capacity (bps)	300M	1G	5G	10G
US Range (MHz)	5 – 42	5 – 85	5 – 230*	5 – 400*
US QAM Level	64	64	≥ 256	≥ 1024
# US Channels	4	12	33*	55*
US Capacity (bps)	100M	300M	1G	2G*

DS = downstream; US = upstream; * = to be determined. Source: Cisco

The specification of DOCSIS 3.1 is underway, and expected to be complete in the next few years.

Optical fibre technologies

Optical fibre has incredibly low loss coupled with extremely high capacity, making it a unique transmission medium. From the point of view of the access network The Shannon Limit can effectively be ignored. Distance is not an inherent limitation as optical signals can travel 70–80 km before they need to be amplified. Instead the limitations on bit rate arise from the pace of development of transmission equipment.

In 1995, the Full Service Access Network (FSAN) organization was formed by network operators wanting to build high-speed broadband access networks, and their work has been standardized through the International Telecommunications Association (ITU).

FSAN developed the passive optical network (PON), which uses inexpensive optical splitters to share the optical signal from a single fibre out among the separate fibre strands feeding individual subscribers. PONs are called “passive” because, other than at the central office and subscriber end points, there are no active electronics within the access network. Standards-based activity began with ATM PON (APON), which evolved into Broadband PON (BPON) and then into Gigabit PON (GPON). Described by ITU-T G.984 in 2004, GPON provides 2.5 Gbps downstream and 1.25 Gbps upstream shared between up to 64 users over distances of at least 20 km.

At around the same time, Ethernet PON (EPON) was established as a result of work from the Ethernet in the First Mile (EFM) group in the IEEE Standards Association (IEEE 802.3ah). The group also developed standards for Fast Ethernet and Gigabit Ethernet over singlemode fibre for use in point-to-point fibre access networks, offering speeds of 100 Mbps and 1 Gbps, respectively, over distances of 10 or 20 km.

Both the ITU and IEEE standards continue to evolve. The IEEE 802.3av Task Force finished work on the 10-Gigabit Ethernet PON standard in September 2009. The following year, the ITU approved 10-Gbps GPON, or XG-PON, which offers 10 Gbps downstream and 2.5 Gbps upstream for up to 128 users. Equipment vendors are currently working towards NG-PON2, which will increase speeds by a factor of four to 40 Gbps downstream and 10 Gbps upstream.

In the longer term WDM-PON promises to bring even higher speeds, with each user receiving a dedicated wavelength at speeds of 1 Gbps (unshared capacity).

Although the exact broadband speed provided depends on the technical choices made by the operator, the potential exceeds that of other technologies by a wide margin. Equipment is commercially available today that can provide up to 1 Gbps per user, not per group of users.

Conclusion: FTTH Council Europe position

Copper-based access networks are widely available and can provide broadband at speeds that meet most customer requirements at the present time. Network operators are providing download bit rates of 50 Mbps or even more using VDSL2+ and DOCSIS 3.0 technologies. These copper-based technologies are likely to coexist with fibre-based technologies for some time to come.

As bit-rate requirements continue to grow, the ability of broadband technologies to evolve to meet future needs is of paramount importance. Infrastructure upgrades should be carried out with a long-term view, taking into account the expected lifetime of the network.

FTTH and FTTB are future-proof network architectures, and they have been clearly identified as the target solutions for wireline broadband networks.

Using the acceleration techniques of bonding, vectoring and phantom mode, DSL could provide maximum bit rates of several hundred Mbps over short distances. However, these solutions still have significant limitations compared to all-fibre networks, especially the need for multiple copper pairs, the limited range at maximum speed, and much slower upload speeds.

VDSL2 can be favourably applied in FTTB scenarios where the distance is only tens of meters and where two copper pairs are available per apartment to make bonding a viable option.

Cable networks using DOCSIS 3.0 can provide download speeds comparable to VDSL2. However, the upload speed is restricted compared to the download speed, and total capacity must be shared among many subscribers, which can result in poor performance at busy times.

Technological advances in copper-based technologies will extend the potential lifetime of operators' existing infrastructure. However, this approach could delay the implementation of the more desirable architecture: FTTH.

References

The main information sources for this position paper are:

- FTTH Handbook (Edition 5, February 6th 2012)
- FTTH Business Guide (Edition 3, February 8th 2012)
- Report M11317, "VDSL2 bonding, vectoring and beyond". IDATE (January 2012)

Input from FTTH Council Europe members was also used.