

The Missing Link - Broadband Access Networks

M.E. Bray & M.J. O'Mahony

University of Essex
Department of Electronic Systems Engineering
Wivenhoe Park
Colchester
CO4 3SQ
United Kingdom
Tel 01206 872926
E-mail mebray@essex.ac.uk

Abstract

The drivers for an increase of broadband bandwidth to the home user of 2 orders of magnitude are described. Classes of user are defined along with their requirements. The available technologies are classified into fixed and wireless segments and then subdivided further and described in detail. The technologies are found to rely on each other and are complementary with each being suited for different niches. A glossary of acronyms and terms is provided.

Introduction – Building bandwidth and pushing it to consumers

The recent history of telecoms has been one of the growth of data communications. Compound annual growth rates of data of 31% have been claimed [1]. Every broadband paper gives these kinds of figures, but why are they important?

One reason is that the traditional fixed telecoms operators have seen their markets eroding. Competition from mobile operators has been fierce with revenue from mobile phones predicted to exceed that from fixed lines in 2005 [1]. The deregulation of the market has also led to price erosion and loss of market share for the incumbent operators. Standing still is not an option, so the operators are keen to develop new revenue streams. Broadband Internet services (surfing, e-mail etc) are the first of these, but we can expect operators to try to develop new services either alone or with partners and sell these to improve their profits.

One marketing phrase that is in vogue at the moment is “Triple Play” which is the provision of voice, data and TV services over a single network. Cable networks have been doing this for some time, but now traditional telecommunications operators are moving into this arena. BT recently announced their intention of providing this service following other European operators such as Swisscom (Switzerland), Belgacom (Belgium) and France Telecom (France) which have already launched some form of triple-play services; other European

firms such as Deutsche Telekom (Germany) and KPN (Holland) are working on their own full-fledged launches [2].

It is interesting to note that deregulation has played an important part of this evolution. In the early 1990's BT ran a video on demand trial to evaluate providing such services. Video on demand was necessary because regulation prevented BT from broadcasting services. In theory broadcasting did not occur because each customer would be watching time shifted portions of the video stream. Although the BT service is still expected to have video on demand capability for customer flexibility, it appears BT can now broadcast and clearly does not face the same restrictions.

As usual it is impossible to predict the ways in which people will be using networks even in the near future. For example, who could have predicted even a few years ago the growth of peer-peer networks so that their data transfers account for approximately 70% of all internet traffic. However some reasonable assumptions can be made as to some of the applications that may be used and their impact on network requirements can be evaluated.

The latest deliverable from the EC funded BREAD project lists 7 categories of use [3 - Section 10.3.1]:

- Communications e.g.
 - Email
 - Instant messaging
 - Chat rooms
- Information Seeking e.g.
 - News
 - Job-related research
 - Product information
 - Education or training research
 - Travel Information
 - Medical information
- Information Producing¹ e.g.
 - Share files with others
 - Create content e.g. web pages
 - Display photos, upload photos for developing
 - Storage/Back-up of files over the internet
 - Video upload e.g. for dissemination to family
- Downloading e.g.
 - Games, videos, pictures
 - Music
 - Movies
- Media Streaming e.g.
 - Video clip

¹ Information Producing implies a potential requirement for high bandwidth uploading of data and may benefit from symmetrical techniques to increase uplink capacity.

- Music/radio/TV station
- Movie rental
- Transactions e.g.
 - Online banking/Paying bills
 - Shopping for product/travel/service
 - Auction
 - Groceries
 - Stocks
 - Gamble
- Entertainment e.g.
 - Hobby information
 - Browse for fun
 - Game play (some interactive)
 - Adult content

It is easy to see that, as content becomes more media rich, for example video streaming for listing on auction sites instead of photos or webcam messaging rather than text based messaging, many of these applications will drive an increases requirement for bandwidth. Lepley provides a useful, realistic estimate for home based bandwidth [4]. Table 1 gives his summary. Table 2 gives a modification to show an estimate for a mobile user with a laptop.

There will be some flexibility in the numbers and there may be some statistical multiplexing to share capacity e.g. the members of a family may not be performing all functions simultaneously. However the implication is that in the near future home users may be requiring Ethernet connection bandwidths at least two order of magnitudes greater than most current offerings. Mobile users may be requiring WiFi bandwidths, but ubiquitously rather than isolated hotspots.

Most currently deployed technology will not provide these kinds of bandwidths. However any operator that is complacent with the 1-10 Mbit/s that technologies such as ADSL provide risks losing more market share to competitors as new capabilities become available.

Application	Downstream requirement	Upstream requirement
HDTV (3 per home at 20 Mbit/s each) <small>Standard TV = 4.5Mbit/s</small>	60 Mbit/s	<1 Mbit/s
Online gaming	2-20 Mbit/s	2-20 Mbit/s
VoIP Telephone (3 per home at 100kbit/s)	0.3 Mbit/s	0.3 Mbit/s
Data/ Email etc	10 Mbit/s	10 Mbit/s
DVD download for rental ² <small>Assume download must take <10 mins i.e. the time to get one from a rental store</small>	14 Mbit/s	<1 Mbit/s
Total	~100 Mbit/s	~30 Mbit/s

Table 1 Foreseeable future bandwidth requirements (fixed home user), modified from [4]

Application	Downstream requirement	Upstream requirement
HDTV (1 at 20 Mbit/s) or DVD download for rental <small>Standard TV = 4.5Mbit/s Assume DVD download must take < 10 mins Not likely to require both simultaneously</small>	20 Mbit/s	<1 Mbit/s
Online gaming	2-20 Mbit/s	2-20 Mbit/s
VoIP Telephone (1 at 100 kbit/s)	0.1 Mbit/s	0.1 Mbit/s
Data/ Email etc	10 Mbit/s	10 Mbit/s
Total	~50 Mbit/s	~30 Mbit/s

Table 2 Foreseeable future bandwidth requirements (mobile user)

² DVD download was not included in Lepley's original table

So what are the issues for carriers? Much investment has been made in the backbone and metro networks over the past 10 years and these typically have a surfeit of capacity³. The bottleneck occurs in the access network, and this is why access technologies are in focus.

The critical problem is with the legacy infrastructure. Most Western countries have fixed access networks based on twisted pair copper solutions. Typically there is a limit to the bandwidth-distance product of capacity reach using these connections. The limitations of various DSL flavours are shown in Figure 1. This is an interesting graph as it shows that VDSL performance only beats that of ADSL at loop lengths below about 1km, beyond this distance ADSL provides the best performance.

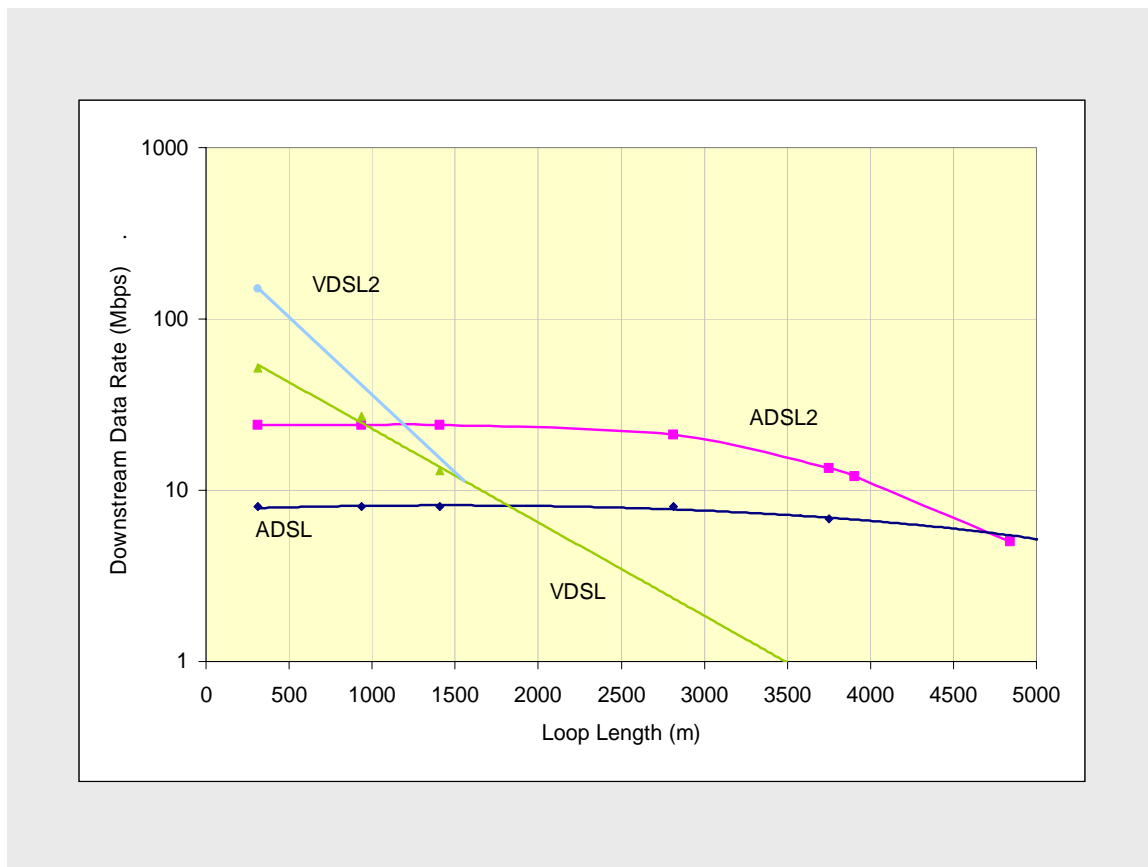


Figure 1 Relationship between downstream capacity limit and length of twisted pair for various DSL flavours, from [4]

³ This may be a short-sighted view. Desurvire recently provided a call for a return to explorative research into optical communications rather than just exploitative research. He observed that capacity requirements continue to grow exponentially, whereas existing technologies saturate, and a disruptive technology will need to be discovered to avoid a bottleneck in the next decade or so [5]. Indeed the development of access technologies and services described in this paper will feed this process and speed the predicted capacity exhaustion.

Re-building the network with new higher bandwidth connections to every home is impractical due to the cost. Hadjifotiou gives a cost of almost £1000 per residence to provide fibre to the home [6]. It is worth noting here the financial difficulties that most of the cable companies in the UK have gone through over the past few years, and they have mainly limited installing plant to urban areas with high population densities to maximise their return on investment. This gives an indication that there is a high risk in large investments in access networks. In addition incumbent operators are in jeopardy of being forced to unbundle their access networks to competitors because of the current regulatory policy. This threat impacts the decision to invest making it more hazardous⁴.

So fibre to the home (FTTH) deployment is unlikely in the current environment⁵. There are exceptions to this rule [3 - Section 7.2.7]. There are many pilot schemes within Holland (Eindhoven, Almere, Amsterdam, Appingedam, Enshede, Rotterdam, Amersfoort, Nuenen, Groningen, The Hague, Dordrecht etc). Here there is a lot of national and municipal government support. Another successful example of FTTH deployment is in Italy with the Fast Web network operating in Milan and other cities. This is a joint venture between publicly owned utilities and a private group. The involvement of publicly owned utilities may suggest cross subsidy and a skewed market. In European countries with a deregulated telecoms market (France, UK, Belgium, Spain), FTTH deployment is low or non-existent.

FTTH is not the only solution though. Many solutions that are being developed are evolutionary, re-using the existing network. Typically they install new infrastructure, such as fibre, to some intermediate point in the network such as the Principle Crossconnect Point (PCP). This is known as fibre to the cabinet (FTTCab). This reduces the distance over the last twisted pair hop, so that the bandwidth can be increased for the same bandwidth distance product e.g. [7].

FTTH discussions may seem redundant when considered from a mobile user's point of view. However, we should remember that only the final link to the terminal is wireless. The rest of the connection into the network from the transponder will still be fixed physical plant. Thus to improve the mobile user's bandwidth it is necessary to improve the bandwidth fed over the fixed network to the wireless PoP. A fibre connection may be justified in this case.

Mobility – New classes of use

Initial data access to the internet relied on (narrowband) modems. These connected to a phone line and limited users to a static location (where the connection was made to the fixed phone network) for the duration of the connection. Equipment could be moved between connections and the connection made over another fixed phone port, but to all intents and purposes the access was fixed in location.

⁴ Unbundling is a difficult issue. While it can stimulate competition, which is good for the customer, if it makes investment unattractive an industry can stagnate which is bad for the customer. Perhaps guarantees of exclusive rights or wholesale prices for new investment in the access network could be used to encourage development.

⁵ Our view may be a little controversial. BT has been trialling FTTP in the UK. Large scale unsubsidised commercial deployment will be needed to prove us wrong though.

The first broadband connections were limited to a similar fixed network. Typically this was a pre-existing phone or cable network. In this case the connection was made via a network interface box or card, colloquially (if not accurately) called a broadband modem. For the phone network this typically sent IP data over ADSL to the exchange. For cable networks the box sent the data using a different transmission protocol such as DOCSIS (Data Over Cable Service Interface Specification). The main difference between these protocols is concerned with spectrum allocation; for example, ADSL over the phone network reserves the bottom 4kHz for POTS (Plain Old Telephone System), DOCSIS currently reserves a large block of the downstream spectrum for analogue TV.

For the majority of home user and small office connections these fixed access networks still dominate the market. However there is a trend towards people unwiring their connections and becoming mobile.

The first implementation of this has been to enable pseudo-static, unwired connections via wireless technologies such as WiFi (IEEE 802.11 [8]). These typically use a WiFi enabled router connected to the phone or cable network as a broadband hub. Each computer requires a wireless capability to be connected to the hub. Wireless connections are then made between the router and the user's terminals⁶ within the home/office to create a wireless LAN. Some routers also provide Ethernet ports to allow a mixed wired/wireless LAN.

The capacity of the wireless connections currently are limited to 50-100Mbit/s; but as most residential ADSL/DOCSIS broadband connections are currently limited to 0.5-8Mbit/s, the WiFi connection is not likely to be the bottleneck in the system. The one exception of this is if the LAN regularly has large internal transfers of data.

The range of the router is limited with a typical router having a range of 45m indoors and 90m out of doors. WiFi operates in an unlicensed part of the spectrum and can suffer from interference from nearby neighbouring WiFi networks and other sources such as cordless phones.

WiFi is primarily intended to allow fast set-up of LANs within the home and small office environment without costly re-wiring. It also allows a limited mobility e.g. carrying a laptop from one room to another within a house, or even the garden. However it does not allow true mobility due to its limited range. Its big advantage outside the home environment is that it is being made available elsewhere (at a price) e.g. in airport lounges, in motorway services, or

⁶ The majority of these are still PCs at present. However it is likely that terminals will take a number of forms within the near future, such as PDAs. Indeed a new application that has appeared recently is the use of PDAs connected to a wireless network to take a customer's order in the restaurant, transmit it to the kitchen, keep track of the bill, and take payment. Other home based WiFi application examples that come to mind are baby monitoring using an inexpensive webcam; home security with video possibly streamed to an offsite storage facility; & home control with WiFi enabled heating, curtains, lights etc.

in hotels. Again the user must not migrate too far during a connection (in this paper this is termed “pseudo-static”).

So what can we predict for the future? Perhaps the best guide for near term developments is to look at phone networks. Using the development of voice communications from static to mobile to roaming we can gain some insight into the geographical flexibility users will expect providers to develop into broadband delivery networks over the next few years⁷. Users will expect to be able to use their broadband connections while dynamic e.g. in a car. Finally, perhaps the greatest technical challenges still to be solved are to provide connections for users travelling at high speeds, perhaps on high speed trains or on airplanes⁸. The classes of user we define in Table 3 are highlighted in Figure 2.

⁷ There are two terms defined by the EC project MUSE [9] that are relevant to relate here:

Nomadism - – The ability of a user who is re-connecting to the network at a new location, to recover his/her access to the network and his/her service environment. In mobile networks an example of this is making calls from different cities using the same operator

Roaming – The ability for a user to function in a serving network different from the home network. The serving network could be a shared network operated by two or more network operators. In mobile phone networks an example of this is making calls from different countries using different operators

⁸ Airlines already appear to be offering a broadband connection service on some flights e.g. the Lufthansa system uses Boeing technology [10] [11]. The system consists of an IEEE 802.11b wireless network on board, and an external satellite connection for backhaul. The bandwidth available to the plane is up to 20 Mbit/s and from the plane is up to 1 Mbit/s, but this is shared between all users so contention may well be an issue.

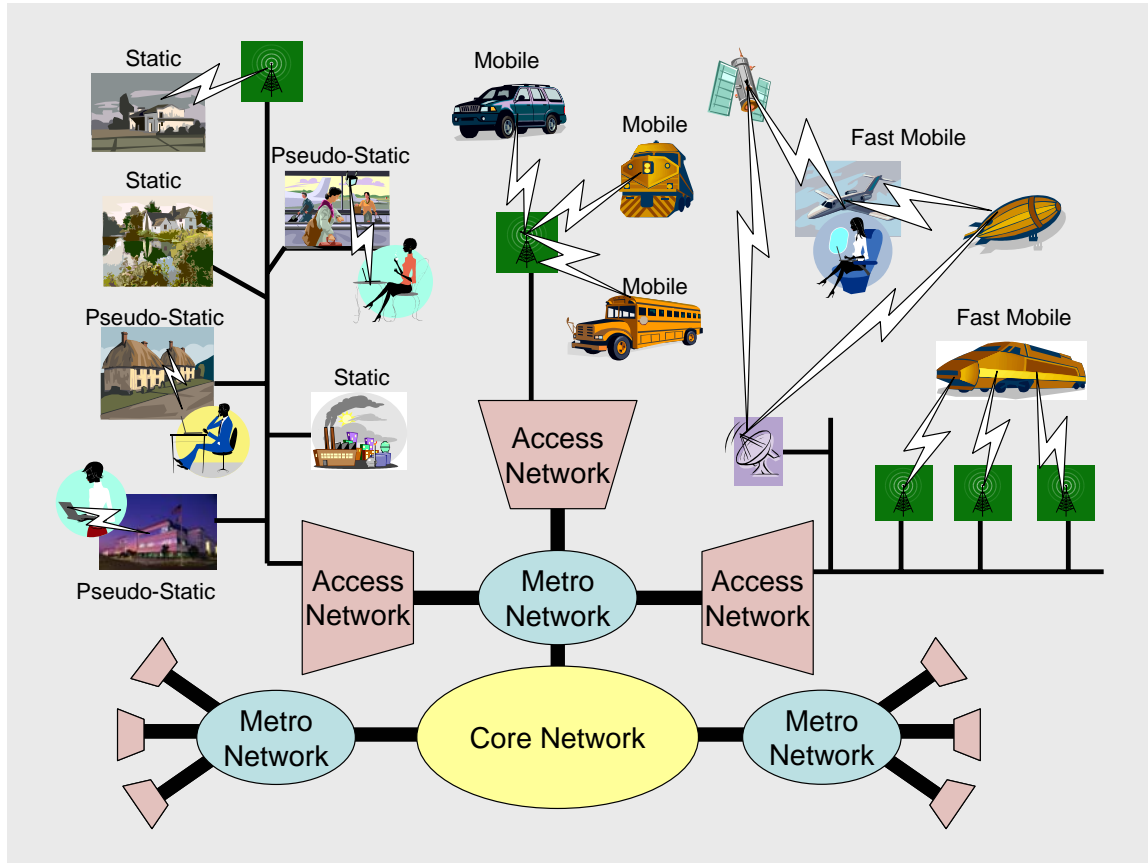


Figure 2 Mobility classes of user

The ease of use of the service will also be important. Users will expect to have a same look and feel of their connection while connected to the same network and ideally to any network. They will then expect to be able to roam to different networks and still be able to connect. The experience should be simple. Their access authorisation and accounting (AAA) should be as simple the mobile phone experience. They should only receive one bill.

As we will see below, location has an impact on technology. A small proportion of UK residences are located a long way (several km) away from the exchange. xDSL technologies are not appropriate for these customers. The exchange-customer distance limit for a 1Mbit/s service over ADSL has been set to 6km by BT following trials [12]. About 2.5% of BT's customers exceed this distance [13]⁹. A mixture of other technologies may have to be used to provide broadband to this fraction of the population. Similarly for a mobile connection the wireless method used and the access path followed will depend on location. Economics plays a part in deciding the most appropriate technology to use; for extremely remote locations

⁹ Although the numbers of customers affected by distance from exchange is small, this is an important point. By summer 2005 BT had made broadband available to 99.6% of its customers in the UK. BT stated a goal in November 2003 of 100% broadband availability by 2005 [12].

satellite or HAPs may be most cost effective to provide the down link, and possibly even the uplink.

Class of User	Static	Pseudo-Static	Mobile - Nomadic	Mobile - Roaming	Fast Mobile - Nomadic	Fast Mobile - Roaming
Range	Static	~100m	City - National	International - Global	City - National	International - Global
Typical Location	Desk	Home / Office	Car, Bus	Car, Bus	High Speed Train	High Speed Train, Plane
Speed ¹⁰	0	<~0.1mph	<~100mph	<~100mph	>~100mph	>~100mph
Carrier	Home	Home	Home mobile	Foreign mobile	Home mobile	Foreign mobile
Physical Access Technologies ¹¹	Copper (twisted pair, cable), FTTx, Wireless (WiFi, BWA, WiMax, UMTS?) with direct or Ethernet connection to gateway	Copper (twisted pair, cable), FTTx, Wireless (WiFi, BWA, WiMax) with wireless connection to gateway (Bluetooth, WiFi)	Wireless (WiFi Cells, WiMax, UMTS)	Wireless (WiFi Cells, WiMax, UMTS)	Wireless (WiFi Cells, WiMax, UMTS, Satellite, HAPs)	Wireless (WiFi Cells, WiMax, UMTS, Satellite, HAPs)
Typical Access Transmission Protocols	IP over ADSL, Ethernet or wireless	IP over ADSL to home, IP over wireless in home	IP over wireless	IP over wireless	IP over wireless	IP over wireless
Issues / Considerations	Distance from exchange / wireless PoP, interference, bandwidth	As Static	As Static and authentication, handover, barrier (e.g. tunnel)	As Mobile – Nomadic and cross-carrier signalling	As Mobile – Nomadic and acquisition tracking, Doppler	As Fast Mobile – Nomadic and cross carrier signalling

Table 3 Mobility classes of user

Technologies – How is the data transmitted?

There are various choices for physical layer infrastructure. The choices can broadly be separated into two main categories

- Wired – where the connection to the customer premises is made via a form of cable e.g. twisted pair, coaxial, fibre
- Wireless – where the connection to the customer premises is made via rf or other transmission e.g. WiFi, WiMax, UMTS

¹⁰ The speed boundary between mobile and fast mobile is fuzzy.

¹¹ Technologies are discussed in more detail below

It is interesting to note that wireless connections normally require wired networks to provide backhaul capabilities¹². For example a WiFi or UMTS cell hub or a satellite base station will be connected back through a fixed network. Thus even if wireless technology is chosen for the last link a carrier will still need a sufficiently capable fixed network.

A scenario of wired connections for networks providing the expected bandwidths described above is shown in Figure 3. Large premises such as schools, large companies, and government offices will use such bandwidth that a dedicated fibre feed to the premises may be necessary and justified. Smaller premises such as small offices and homes will not need such large bandwidth and the cost of a dedicated fibre will be prohibitive. However they will require increased bandwidth compared to the current offering.

¹² The emerging WiMax wireless technology has provision to be used for backhaul from a remote area but again a wired connection is likely at the head end of the WiMax link.

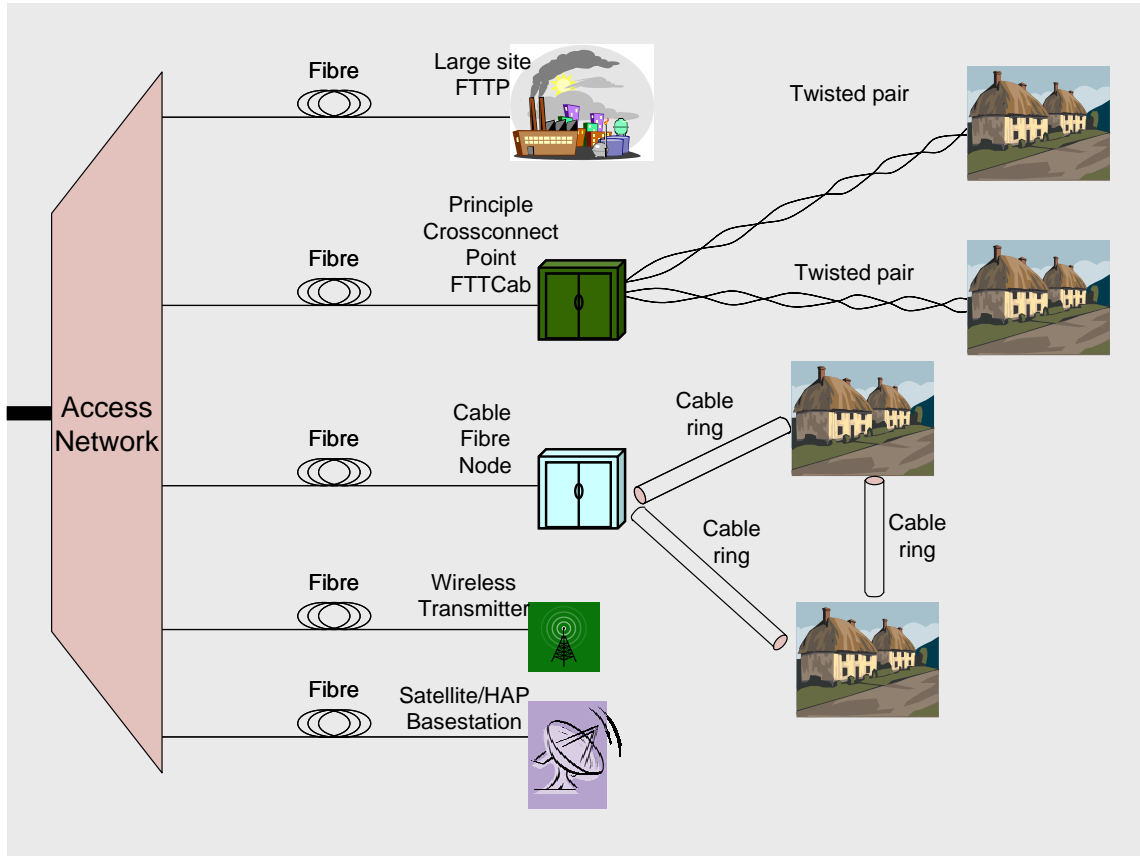


Figure 3 Scenario of wired connections

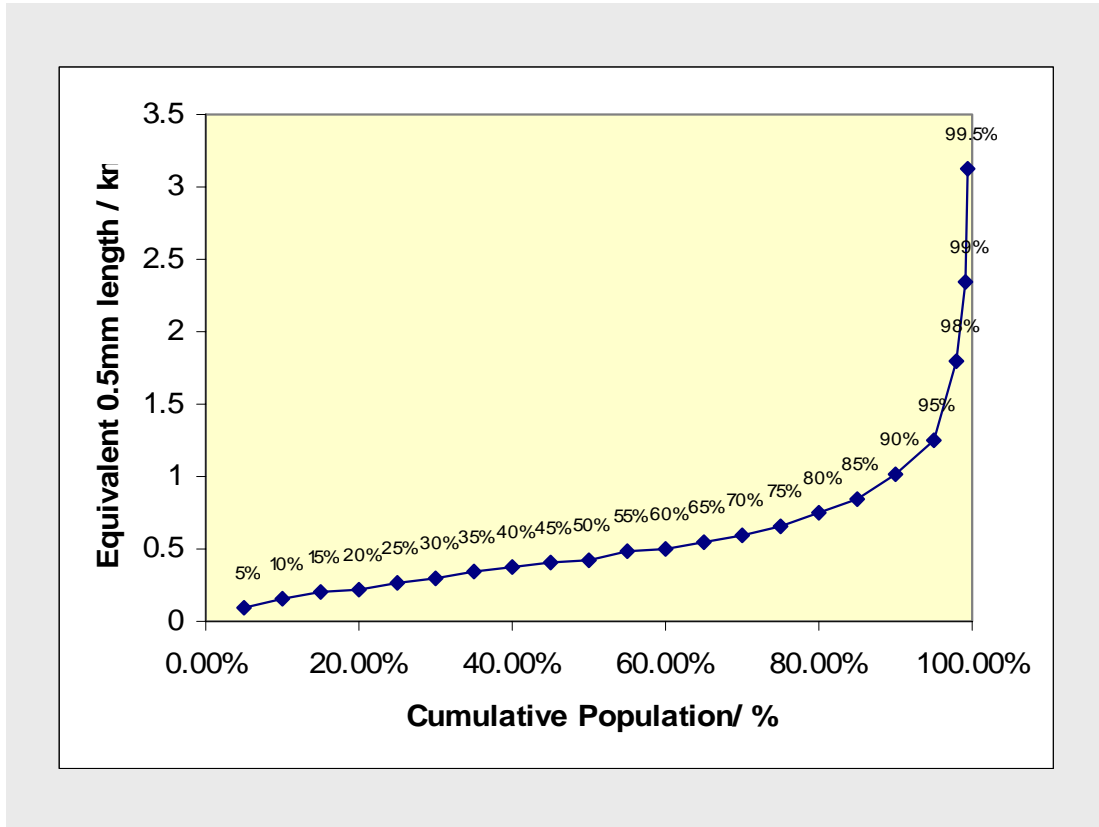


Figure 4 Cumulative graph of UK population distance from cabinet (derived from [13])

Figure 1 showed that to provide the 100 Mbit/s target derived above using VDSL 2 over twisted pair, the distance from the distribution point must be less than 500m. In order to facilitate this high capacity fibre will need to penetrate more deeply out to the cabinet. Clarke gives figures for the cabinet-copper length distribution within the UK [13]. These are duplicated in Figure 4. Only about 60% of customers are within 500m. Thus the 100 Mbit/s target is a challenge for 40% of the population using current transmission techniques. However about 85% of the population lie within 1km of the cabinet, so it may not too much of a stretch to develop techniques to feed this proportion of the population. The problem comes with the distance for the high cumulants. The last 5% of the population lies between 1.5 and >3.5km from the cabinet. These consumers may either have to settle for a reduced bandwidth (Figure 1 suggests <~30 Mbit/s) or may need to be fed by a different technology such as wireless.

Twisted pair, cable and fibre techniques are the wired techniques described here, there are other techniques such as providing the feed over electricity cables (PLC – Power Line Communications), but they are not described further since the factors are similar to those

described, and they have relatively low take-up. More information is available in the BREAD deliverable [3 – Section 7.2.1].

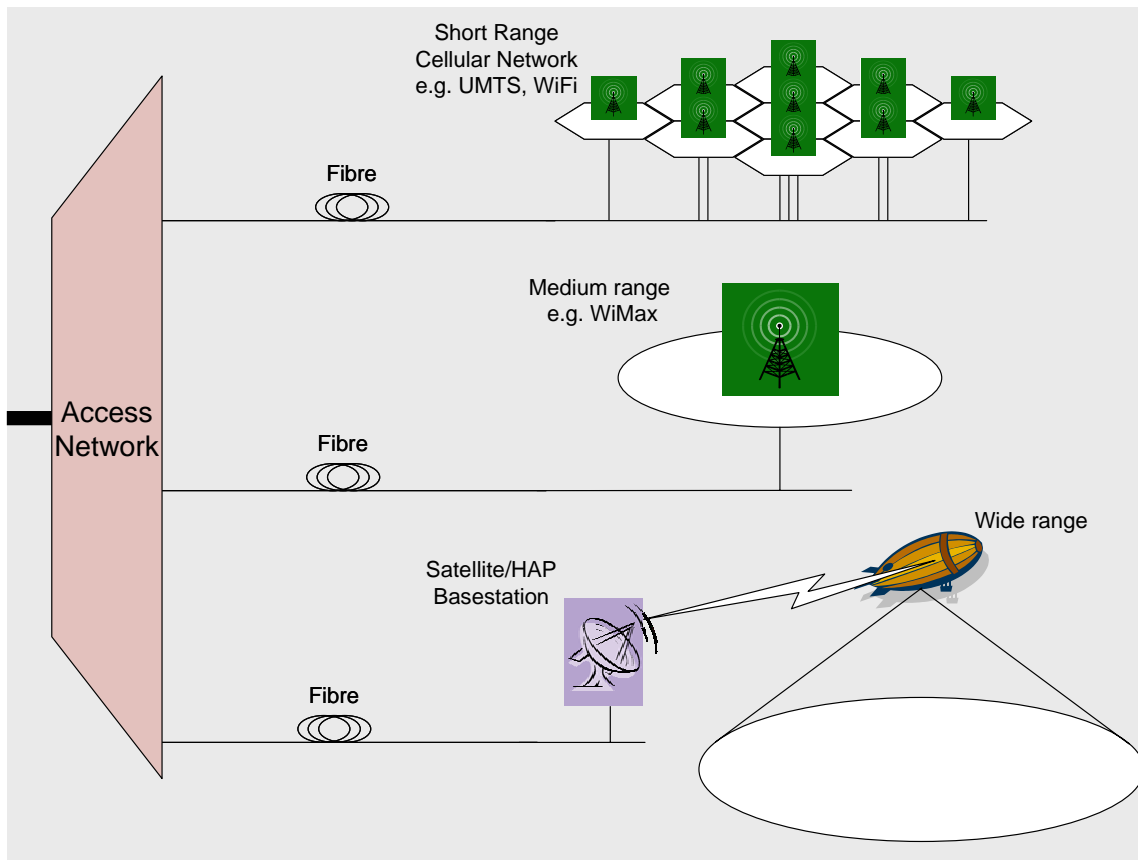


Figure 5 Scenario of wireless connections

A scenario for wireless connections is shown in Figure 5. Again here the expectation is that the feed to the base stations is through fibre cables as the base station aggregates the feed to many users and a high bandwidth is required. There are three categories of wireless access shown classified according to the range of transmission:

- **Short Range**, this is typically a cellular network and can be expected to use UMTS or WiFi or a similar technology. The short range allows high bandwidths to many users. The short range indicates the transmission range from a base station, not the total coverage which is governed by the location and size of the cells. Such networks are likely to be deployed, at least initially, in areas of high population density such as cities. Table 4 duplicates an interesting table given by Edvardsen describing the shrinking of the cells as the bandwidth increases [15]. The table also includes a new entry for WiFi for comparison.
- **Medium Range**. Here the cells are typically large enough to cover a metropolitan area. The major technology under development for this application gaining most attention is WiMax. WiMax promoters claim that a base station would beam connections over a

radius of up to 50 km (equivalent area ~8,000 km²). With non-line of sight coverage, this is likely to be greatly reduced and a rudimentary test in Michigan gave distances of about 15 km (equivalent area ~700 km²). WiMax provides shared data rates of up to 70 Mbit/s. But since this is shared the rate to an individual user is likely to be greatly reduced due to contention. Thus a single cell using this technique is unlikely to be able to provide the target bandwidth to more than a few users simultaneously. However it is a good candidate for an alternative to supply bandwidth to those limited by their cabinet-home distance.

- **Wide Range.** The signal passes through a base station to a satellite or HAP where it is sent back to the ground¹³. The range of coverage here is much larger typically covering a country. The line of sight radius of coverage of a HAP at 17-20km altitude over London is greater than the distance to Land's End (total radius ~500km) [18]. Satellite coverage is even greater. For example the SES satellite Astra 2C situated at 19.2°E covering all of Europe and the Canary Islands [16] and Astra 2D, at 28.2°E, which transmits Sky covers the whole of the UK and Ireland, but with a large ground antenna can be received in all of Belgium, Holland and France [17]. Both of these satellites are in geostationary orbit at an altitude of approximately 35,786 km. Data rates can be high. The EC funded HAP project Capanina projects downstream data rates of up to 120 Mbit/s to the user [18]. These techniques may be the only way to reach extremely remote areas. They also may be cost effective methods to develop access infrastructures for developing countries.

¹³ A HAP is an airship or plane which operates 17-20km above the earth's surface and provides a platform for communications. In essence it is a relatively low cost, maintainable substitute for a satellite. One major advantage of HAPs is their potential for rapid deployment. An evident application using this is to provide access coverage during disaster recovery, where the native communications infrastructure may have been destroyed.

Technology	Bandwidth	Coverage – Cell area	Coverage – Cell radius
GSM	14 kb/s	50 km ²	<4 km
UMTS1	384 kb/s	3 km ²	<1 km
UMTS2	2 Mb/s	1 km ²	<600 m
4G	<20 Mb/s	0.03 km ²	<100 m ¹⁴
WiFi	< 100 Mb/s	0.03 km ²	<100 m

Table 4 Diminution of cell size for mobile cellular technology, adapted from [15]

These three categories are complementary and thus rather than competing with each other could be used to provide ubiquitous service independent of location. Indeed with roaming techniques for mobile users there may well be handovers between the different categories during one connection. For example a train may be connected via a cellular network while leaving a city. The connection may migrate to a WiMax network in the countryside and if it traverses very remote areas it may then be serviced via a HAP or satellite. The interesting issue for communications engineers here is how to deal with handovers between networks seamlessly and securely.

¹⁴ The small radius of the cell provides a dilemma for operators in that they will need a multitude of PoPs to give good coverage. This requires lots of real estate. The EC funded OBAN project proposes using home gateways in private residences [15]. These gateways will have separate private and public bandwidth segments (private is limited to owners only). Presumably the owner will get some sort of discount for his co-operation.

	Wired			Wireless				
	Copper		Fibre	Ground based			Aerial	
Physical Plant	Twisted Pair	Cable	FTTx PON	WiFi	WiMax	UMTS	Satellite	HAP
Layer 1 (Physical) Protocol ¹⁵	xDSL	DOCSIS	WDM or single wavelength	IEEE 802.11	IEEE 802.16	GRAN	S-DOCSIS DVB-RCS ¹⁶	Adaptation of IEEE 802.16SC [19]
Layer 2 (Datalink) Protocol ¹⁵	PPPoA		Ethernet					
Main Layer 1 issues	Contention		Build Cost	Contention			Contention	
	Bandwidth-Distance Limits	Ingress Noise		rf Noise (Unlicensed Spectrum)	rf Noise (Unlicensed Spectrum)	rf Noise	Power management	
	NEXT	Channel Interference	Equipment Cost	MPI			Cost	rf Noise
	FEXT			Free Space Loss			Propagation Delay	MPI
	ISI	IMD	Ingress Noise (Terminal Equipment only)	Obstacles			rf Noise	Spectrum allocation
	Impulse Noise			Security			Free Space Loss	
	Bridged Taps	ISI caused by micro-reflections	IMD (Terminal Equipment only)	Range / Cell Size		Range / Cell Size ¹⁷	Security	
	rf Noise						LOS (but elevation helps)	

Table 5 Implementation of OSI layers 1 and 2 for various access technologies¹⁸

Table 5 details strong candidates for the layer 1 and 2 protocols and technologies to be used for various access methods¹⁸. Note these are not the only possibilities, but are considered the most likely to dominate. Dominance is often based on current pervasiveness rather than technical superiority. When considering access networks, we are primarily concerned with layers 1 and 2 as these cover the physical transmission and the local network connections.

¹⁵ These are not the only possibilities but seem strong candidates

¹⁶ DVB-RCS and S-DOCSIS are competing technologies for satellite protocols. There is some dissent as to which will dominate.

¹⁷ While this is not an issues for UMTS, it is likely to become an issue for 4G as described in Table 4

¹⁸ For an explanation of the OSI model see Appendix 1

Twisted Pair

For twisted pair the likely layer 1 protocol will be a form of Digital Subscriber Line (DSL). Table 6 gives information for some of the flavours that have been, are, or will be available. The layer 2 protocol is PPPoA.

It is interesting to note the impact that legacy usage of networks has on the new standards. Despite the development of VoIP, where a telephone channel is transmitted as packets within the data connection, ADSL still reserves the 0-4 kHz section of the spectrum for the legacy telephone system. Customers using alternative xDSL technologies that use this band presumably must either use a different network or a packet based telephony technique (e.g. VoIP) for their phone connections.

		Downstream Capacity kbit/s	Upstream Capacity kbit/s	Range from Exchange km	Spectrum kHz	Notes
ISDN	<u>I</u> ntegrated <u>S</u> ervices <u>D</u> igital <u>N</u> etwork	160	160	~4.5	0 - 40	
HDSL	<u>H</u> igh- <u>S</u> peed <u>D</u> SL	784 – 1,168	784 - 1168	~3.5	0 – 200 or 0 - 300	Multiple link bonding increases BW
G.SHDSL ¹⁹	<u>S</u> ingle-pair <u>H</u> igh-speed <u>D</u> SL	192 – 2,312	192 - 2312	~2.5 – 4.5	0 - 32 to 0 - 380 depending on speed	Multiple link bonding increases BW,
ADSL	<u>A</u> symmetric <u>D</u> SL	32 – 8,000	32 - 800	~1 - 5	30 - 130 upstream, 150 - 1,100 downstream	0-4kHz saved for POTS
RADSL	<u>R</u> ate <u>A</u> dapive <u>D</u> SL (variant of ADSL)	32 – 8,000	32 - 800	~1 - 5	30 - 130 Upstream adaptive, 150 - 1,100 downstream	Upstream BW adapted to maintain downstream BW
ADSL2	Improved ADSL	32 – 12,000	32 - 800	~1 - 5	30-130 upstream, 150-1,100 downstream	0-4kHz saved for POTS
ADSL2+	Improved ADSL2	32 – 24,000	32 - 800	<~3	30-130 upstream, 150-2,200 downstream	0-4kHz saved for POTS
VDSL	<u>V</u> ery-high-speed <u>D</u> SL	2,000 – 50,000	1,000-25,000	~0.5-1.5	Up to 12,000 Multiple interleaved downstream/ upstream bands	Many options included in standards

¹⁹ G.SHDSL is the standardised version of SDSL

VDSL2	Improved VDSL	100,000	100,000	~3.5	Up to 30,000 Multiple interleaved downstream/upstream bands	
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Table 6 Flavours of xDSL (mainly adapted from [13])

The most common modulation technique used in xDSL is DMT (also known as OFDM) where the transmitter transmits on many different orthogonal (independent) frequencies (typically dozens to thousands). Each sub-carrier is typically modulated by a QAM signal. RADSL (Rate Adaptive DSL) takes advantage of the ability to control the individual sub-carriers and hence bands to adapt the upstream band to maintain downstream quality and bandwidth.

Noise and range are the primary issues in the physical layer for xDSL techniques. The noise issues include:

- Contention – This is the reduction of the bandwidth to the user by sharing with others. For current UK ADSL services quoted contention ratios of 50:1 are common for home services and 20:1 for businesses. This implies that the bandwidth available could be diluted 50 times or 20 time respectively.
- NEXT – Near End Crosstalk. This is caused when a loud signal being transmitted on one pair leaks onto a received signal on a different pair at the near end of the cable. This can be a particular problem because the relative power in the noise to the received power can be high. Band separation between up and downstream signals and filtering can help here
- FEXT – Far end crosstalk. Here a signal being transmitted from one pair leaks to another pair at the far end of the cable to arrive at the wrong receiver. This is typically lower in power than NEXT. This cannot be filtered as the bands for the two pairs will normally be the same.
- ISI – Intersymbol interference. This is caused when one symbol spreads into its neighbours and causes errors in reading those bits. It can be caused by dispersion in the twisted pair medium or filters. The narrow slow channels used in DMT are naturally resistant to ISI. ISI can also be mitigated by the use of cyclic prefixes to buffer symbols or adaptive filtering in the receiver which compensates for the frequency and phase response of the transmission medium
- Impulse noise. An impairment that is short in duration but high in magnitude. Examples of causes include lightning and a power surge caused by a motor turning on. This typically will cause a burst of errors. Higher level protocols can overcome impulse noise by interleaving bits and using forward error correction. The interleaving ensures that when the FEC is applied the errors are distributed in the bit stream.
- Bridged taps. A bridged tap is a section of wire connected to the loop at one end and un-terminated at the other end. Examples of bridged taps are wires that are laid out in areas where housing is still being built. When a transmitted signal arrives at a bridged

tap, the signal divides. Part of the energy continues to the receiver and the rest of the energy reflects off of the un-terminated end. This reflection causes delayed versions of the signal to arrive at the receiver, and these reflections distort the received signal. This is mitigated by adaptive filtering the same technique used for ISI.

- rf noise – introduced because the twisted pair connection (and other equipment) can act as an antenna to pick up rf radiation either from radio sources or poorly shielded equipment

xDSL systems are adaptive. Thus if a particular sub-carrier has poor reception the size of the QAM constellation being transmitted in that carrier is reduced to allow good reception. This can be used to overcome any residual impairment.

Cable

Cable allows a far greater transmission bandwidth compared to twisted pair. This is because it inherently is less lossy with minimal radiation of the signals and conversely it suffers less from interference because of its inbuilt shielding. For comparison the total spectral bandwidth used for VDSL is 30MHz while that for DOCSIS is 860MHz.

For cable DOCSIS is the protocol which encompasses layers 1 and 2. The EuroDOCSIS spectrum allocation is described in the latest BREAD deliverable [3 – Section 7.2.2]. The upstream spectrum lies between 5-65 MHz, the downstream spectrum lies between 88-860 MHz. For DOCSIS the allocations are slightly different being 5-42 MHz and 54-860 MHz respectively.

Again legacy systems limit the allocation of the spectrum. Much of the downstream spectrum is currently occupied by legacy analogue TV transmission. Until the analogue switch off, this limits the spectrum available for broadband communications. After switchover the total capacity available will be up to 4Gbit/s downstream and 200Mbit/s upstream. With the analogue channels the downstream capacity is significantly lower (several 100 Mbit/s). However this is shared between the contending subscribers, so the bandwidth per user depends on the size of the cable ring as well as the capacity available. The BREAD deliverable quotes the ring size as consisting of 50-2000 subscribers [3 – Section 7.2.2] so the downstream bandwidth may potentially be diluted up to 2000 times.

A typical cable network architecture is shown in Figure 7. These networks are a hybrid of fibre with coaxial cable. The fibre carries the signals over most of the network, and the signal is only on the cable network for the last kilometre or so. The copper has a far lower bandwidth (~1GHz) than the fibre (potentially >1THz) so contention is only really a technical issue in the last kilometre. However cost issues may mean that it is not economical to use the whole available fibre bandwidth, thus it is possible that the fibre could also be a bottleneck.

There are many configurations for layers 1 and 2 in DOCSIS. QAM is used for downstream data modulation (64- or 256-level), and QPSK and QAM (16 level) are used for the upstream modulation. DOCSIS 1.0/1.1 allows upstream channel width to range from 400 kHz to 3.2 MHz. The upstream rate is limited to 10 Mbit/s. The downstream rate supported is up to 38Mbit/s with 256-level QAM with a 6MHz bandwidth.

DOCSIS 2.0 improves the upstream capability by various methods, including higher orders of modulation (64-level QAM) and wider channels (6.4 MHz). The improvements combine to deliver a total upstream throughput of 30.72 Mbit/s per channel. Again the downstream rate is 38 Mbit/s. The EuroDOCSIS standard supports downstream throughput of up to 51 Mbit/s per channel (due to the 8MHz channel width).

DOCSIS 3.0, currently under development is expected to permit channel bonding to allow multiple downstream and upstream channels to be used together at the same time by a single subscriber.

The modulation techniques and bandwidths are summarised in Table 7.

Standard	Direction	TDMA Carrier	Freq Range MHz	Channel Width MHz	Baud Rate MSym/s	Raw Bit Rate Mbit/s	Payload Rate Mbit/s
DOCSIS 1.0/1.1	Downstream	QAM-64 6b/Sym	54-860	6	5.057	30.34	27
		QAM-256 8b/Sym			5.3605	42.88	38
	Upstream	QPSK 2b/Sym	5-42	3.2	2.56	5.12	4.6
		QAM-16 4b/Sym			2.56	10.24	9
DOCSIS 2.0	Downstream	As DOCSIS 1.0/1.1					
	Upstream	QAM-64 4b/Sym	5-65	6.4	5.12	10.48	30.72
Euro DOCSIS	Downstream	QAM-64 6b/Sym	88-860	8	6.74	40.44	36
		QAM-256 8b/Sym			7.15	57.2	51
	Upstream	QPSK 2b/Sym	5-65	As DOCSIS 1.0/1.1/2.0			
		QAM-16 4b/Sym					
QAM-64 4b/Sym							
DOCSIS 3.0	Downstream	QAM-64 6b/Sym	54-860	$m \times 6^{20}$	$m \times 5.057$	$m \times 30.34$	$m \times 27$
		QAM-256 8b/Sym			$m \times 5.3605$	$m \times 42.88$	$m \times 38$
	Upstream	QAM-64 4b/Sym	5-65	$n \times 6.4^{21}$	$n \times 5.12$	$n \times 10.48$	$n \times 30.72$

Table 7 DOCSIS and EuroDOCSIS spectrum allocation and bit rates (adapted from [20])

²⁰ Here m indicates that m channels have been bonded together

²¹ Here n indicates that n channels have been bonded together

Noise is the primary issue in the physical layer for cable techniques. The issues include:

- Contention – After digital switchover, this will not really be an issue for current broadband bandwidths of a few Mbit/s, since 100s of channels will be supported in the available bandwidth. The quality of the channel may limit the size of the QAM constellation that can be transmitted per channel. For our target of 100Mbit/s about 3 QAM-256 channels will need to be bonded or 4 QAM-16 channels. For 4 QAM-16 channels about 32 users could be fed without contention impacting them.
- Ingress noise. This is an impairment in a cable network caused by noise entering through poorly shielded cables or communication devices attached to the cable network within the home. Ingress interference is typically impulsive and band-limited in nature as the interfering signals appear for short intervals at significant power levels within a small frequency range. Many devices emit signals in-band. These include common household appliances such as garbage disposals and blenders. Most ingress noise originates in the home. The main solution to this noise source is to eliminate the possibility of ingress. The techniques include properly designing the connected devices with suitable shielding and ensuring that cable connections are properly made with good quality joints and that ports are terminated correctly whether in use or not. Some head end equipment designs use an adaptive method to solve the problem. These look for ingress on the communication channel, and upon detection switch channel frequency to eliminate this noise source.
- Channel Interference. This is an impairment caused by other signals, such as signals from other cable modem subscribers and television signals, which interfere with packet transmission. Again this can be mitigated by an adaptive selection of the frequency of the channel. Another technique to overcome this signal quality reduction is the use of Forward Error Correction (FEC). This technique adds extra bits to a signal which can detect and correct errors introduced (the bits form parity checks). This technique can be very powerful to eliminate errors whatever the source, but it adds overhead in the bit stream and reduces the payload bandwidth.
- Intermodulation Distortion. This is an impairment caused by intermediate components in a system such as amplifiers giving a nonlinear component in their output. This is one of the reasons fibre is used for the distribution from the head end. Fiber requires fewer amplifiers than coaxial cable and optical amplifiers have better noise and distortion performance than coaxial amplifiers. Transmission at the edge of filter passbands may suffer strong IMD. The solution here is careful design of the components to minimise the nonlinearities in the operating regime, and design of the system to minimise concatenation of components. Again choice of the operating frequency may help here.
- Intersymbol interference caused by micro-reflections (imperfect impedance matching in cable joints etc). DOCSIS 1.1 cable modem systems are designed to include a pre-equalization function that counteracts the effects of micro-reflections. The head end equipment determines the pre-equalization coefficients by characterizing the micro-reflections present on the network and then transmits the coefficients to the cable modem to use in subsequent transmissions.

FTTx and PON

While cable allows gave a large increase in bandwidth compared to twisted pair to about 900MHz. This is tiny compared to fibre which in principle allows bandwidths of several THz by use of suitable wavelength division multiplexing technology. In reality for these applications such large bandwidths are not required and would need expensive components, but relatively cheap components can be used to provide capacities between 1-100Gbit/s.²²

There are several physical architectures possible. The most common and most cost effective is possibly the passive optical network shown in schematic in Figure 8. Here passive (i.e. not powered) splitters sit in the network to form a fibre tree structure from the head end to the fibre terminal. Any downstream traffic is thus naturally broadcast to all users, and security must be provided by encryption in the higher OSI layers. Upstream traffic however should be confined between the user and the central office provided there are not strong reflections.

Collisions between packets from different upstream users must be avoided. This could be achieved via an Ethernet CSMA/CD technique, although a time-slot allocation TDMA technique may be more efficient.

The passive nature of the network means that power does not have to be provided to the splitters and the sharing of the trunk and the head end equipment gives a cost benefit. However since the transmitted downstream power is shared between all the terminals the length of the fibre network is limited to about 20km depending on the splitting ratio. This is to allow each receiver enough power for good reception. A typical implementation (e.g. Alcatel's [21]) uses 1490nm for downstream data transmission and 1310nm for upstream data transmission, 1550nm is reserved for carrying broadcast video. The splitting ratio is typically limited to 1:32.

The figure shows the fibre terminals being in cabinets for the most part as we consider this a likely scenario for implementation. However there could be fibre to the premises (FTTP) for heavy users as shown and also the fibre could terminate with a junction to a cable ring as described above, rather than twisted pairs. It is useful to again estimate the required capacity for our target of 100Mbit/s per home. For the purposes of this estimate assume a network with 100 homes connected to each cabinet and 32 cabinets serviced by each fibre tree. Then the total capacity is each direction is:

²² Currently the capacity used is typically restricted to about 2.5Gbit/s in each direction [3 - Section 7.2.7]. This is expected to grow as demand expands and equipment costs fall (5 years ago the figure was more like 155Mbit/s).

Capacity per home		0.1 Gbit/s
No of homes per cabinet	X	100
No of cabinets	X	32
		<hr/>
		<u>320 Gbit/s</u>

This clearly is unlikely to be serviced economically with one laser. This suggest that either the fibre tree must be made smaller, perhaps by pushing the fibre terminals closer to the customers at distribution points (with maybe 10 customers per point), or more than one laser must be used using a WDM technique (discussed more below). For the latter solution 32 X 10 Gbit/s lasers each on different wavelengths would be a feasible solution. Commercial requirements will drive which solutions are implemented.

The PON architecture described above is a **point to multipoint** architecture as the downstream signals can be received by all users. WDM will allow a different architecture which is **point to point**. Here a downstream signal is only received by the customer (or cabinet, cable system etc) for which it is intended. An example of such an architecture is shown in Figure 9. Here a wavelength multiplex of n wavelengths corresponding to n fibre terminals is sent in either direction. These are denoted λ_{md} and λ_{pu} for the mth downstream and pth upstream wavelength respectively.

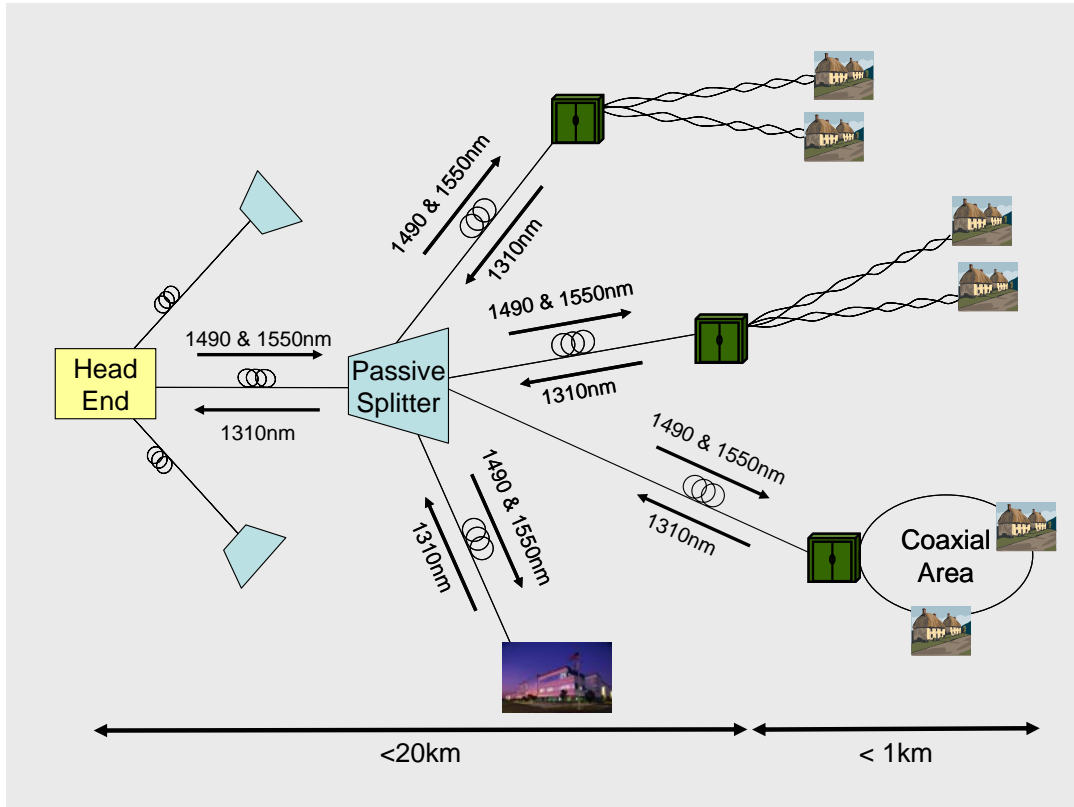


Figure 8 Simple architecture for a TDMA based PON

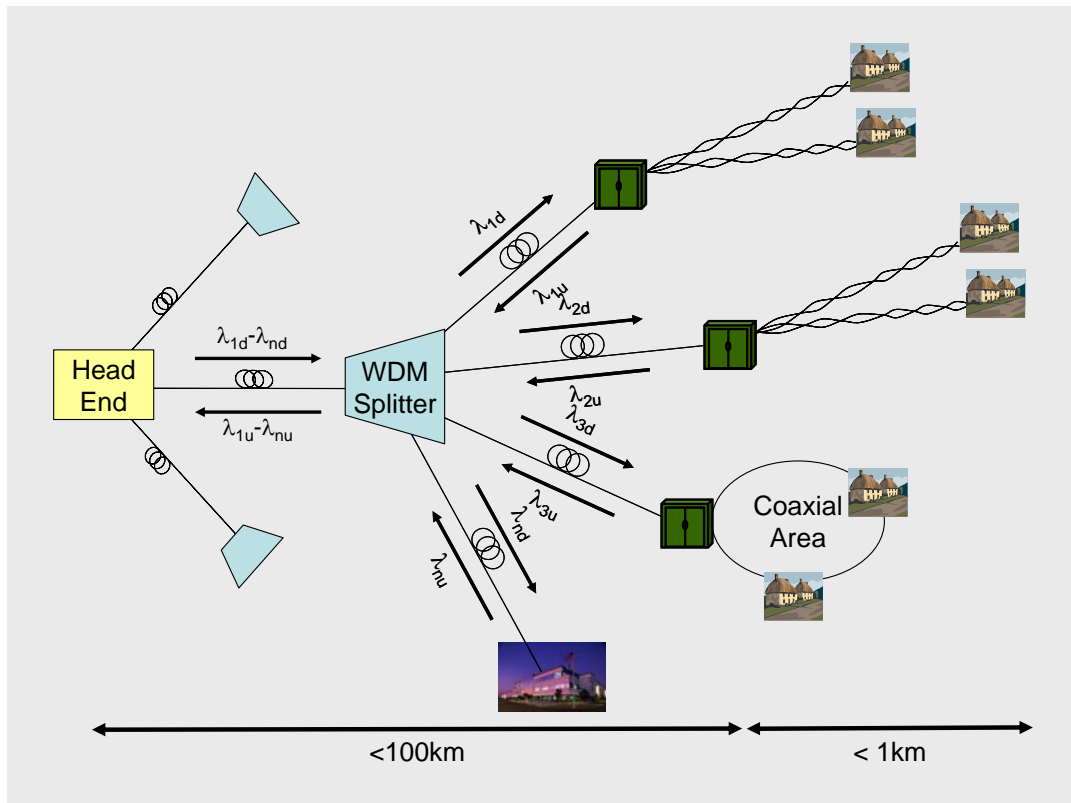


Figure 9 Simple architecture for a WDM based PON

Although the splitter is still passive it is formed by a filter which directs the light from input to output ports according to its wavelength. One benefit of this kind of architecture is that the splitting losses are reduced because the signal is now directed to its end point, thus the length limit of the network is more like 100km. Another is that the signal is not broadcast, but only is sent to its intended destination improving security. Since each wavelength pair forms a unique combination for communication to a unique destination collisions are not a problem. The disadvantage in this scheme is the increased amount of terminal equipment and the tightened wavelength requirements on the laser sources. Both of these drive increased equipment cost.

Finally PONs are not the only choice. Some solutions have active nodes. The main issue here is that power must be fed to these intermediate points, which may not be a simple thing to do. Several components could be present in an active node, but perhaps the most useful is an optical amplifier which extends the reach of the fibre network by boosting the optical power of the signal. Another possibility is a switching function to dynamically allocate capacity to users e.g. in a WDM system by allocating more wavelengths to a destination.

From a technical point of view, fibre is the medium of choice for fixed and feeder applications. The issues with fibre are minimal compared to copper and wireless methods. The medium itself is very low loss compared to other techniques. Without amplification the fibre length can be an order of magnitude greater than that for copper, with amplification the length could potentially be several hundred to thousands of km. Issues such as dispersion and non-linearities which trouble fibre system designers for backbone applications, do not really impinge on the design for the distances, bandwidths and powers under consideration for access. The fibre medium itself is impervious to noise and really the only impairments are in the electrical domain at the terminal equipment. In this equipment there is a potential for ingress noise and IMD. This can be minimised by good design of the equipment.

Cost is the issue here. The cost of laying new fibre and providing new terminal equipment is the problem. Even so the cost of laying a new fibre network is comparable with that to lay a new copper network. The cost of the equipment would also be comparable if the market sizes were similar. The problem for the carriers is how to make a return on the investment. This is the reason we believe FTTH is not a near term solution, but FTTCab may be. It is worth noting that if communications networks were being deployed from scratch now, rather than having existed for 50-100 years in most of Western Europe, they would probably be fibre!

While the equipment in the central office can be shared between multiple subscribers and its cost amortised across a large population, for the equipment in the cabinet or premises this is not the case, and cost is crucial here. The cost of the optical equipment dominates. TDMA schemes can be cheaper than WDM schemes as the wavelength stability of the lasers is not crucial. Lepley *et al* offer a potentially cheap solution with the central office sending down a CW light beam which is modulated by a semiconductor optical amplifier before returning at the far end [22]. The semiconductor optical amplifiers are all the same design even within a WDM network configuration. When supplied in bulk quantities they could be made cheaply. This is potentially far cheaper than having individual expensive wavelength stabilised lasers within each far end terminal.

The modulation in the optical network can vary:

- For example if the end connection is ADSL, the modulation may follow an ADSL style modulation on the optical carrier. This allows the equipment in the cabinet to simply take the baseband signal and rebroadcast it cutting cost. These solutions are under development (e.g. [22]) but are typically not yet commercially deployed.
- For transmission to a cable network the data modulation follows DOCSIS. TV and other signals will also share the same optical carrier. These networks are called Hybrid Fibre Coaxial (or HFC)
- For networks where the fibre terminates in the customer premises there seem to be two flavours of layer two protocol ATM and Ethernet. However due to its penetration and cost Ethernet appears to be winning this battle.

There is a move towards unifying protocols within the metro and core networks e.g. BT's 21CN network [23]. However translation equipment cost will mitigate against its deployment in customer premises, or the fibre termination points. The translation equipment will probably be deployed at the metro-access boundary where the investment can be shared between many subscribers. Within the access network many protocol may still be present.

Cellular Wireless Methods – WiFi, WiMax, UMTS

Wireless access has been one of the major growth areas in broadband communications over the last 5-10 years.

Mobile phone networks have been adding data capabilities via GSM, then GPRS and over the last 2-3 years UMTS. These enhancements seem likely to continue through 4th generation and beyond. Perhaps the major obstacle to growth in this area is the limitation of the handsets. There are competing design requirements for mobile phones of portability and battery life which affect the users' experience by limiting display size and keyboard use. Cards are now available which allow laptop users to connect via the phone network, but again the size and weight of a laptop makes it a far from ideal terminal. Perhaps PDAs are the best option currently available with a larger display than a phone, and being smaller and lighter than a laptop; however these are still not an ideal platform. Developments in flexible displays (which can be rolled away into the body of the device when not in use) and projected "virtual" keyboards may be the way forward to allow an enjoyable user experience.

While Western Europe has more or less ubiquitous mature wired phone network infrastructure, this is not true for other nations including recent entrant nations to the EU in Eastern Europe, and the big growth economies of China and India. The success of mobile phone networks may actually hinder investment in wired networks because mobile networks can already service the voice requirements of customers inexpensively, and thus the revenue streams available to finance wired networks may be restricted. Thus for nations in this situation broadband access via wireless access networks may be the only practical solution.

As well as mobile phone networks, the other big success story over recent years has been the introduction of WiFi local area networks, both for private and public use; the latter being provided via WiFi hotspots. It is now unusual to be able to buy a laptop computer without an integrated WiFi capability. The bandwidth capability of the connections has increased as number of flavours of connection covered by the IEEE 802.11 standard has been expanded.

WiFi provides small cells. "The next big thing" predicted in wireless access is the introduction of large Broadband Fixed Wireless Access cells using technologies such as WiMax. This will complement the small cells to provide coverage in areas where it is not economic to provide lots of cell hubs or wired backhaul connections. Thus whereas WiFi allows last 10m access WiMax will allow last 10km access. WiFi addresses LAN ranges whereas WiMax addresses MAN ranges.

WiFi and WiMax are both sets of protocol standards which cover level 1 and 2 (IEEE 802.11 and 802.16 respectively [8]). The different WiFi flavours have variations in the modulation techniques used. However for the higher bandwidth connections OFDM is used (as with xDSL). For WiMax either QPSK or QAM is used as the modulation technique. Finally the cellular mobile techniques typically use W-CDMA over QAM or QPSK.

The main issue with all wireless techniques are interference from other rf sources. This is particularly true of WiFi and WiMax, as they exist in the unlicensed portion of the spectrum; the same frequency bands may be used for many other uses such as cordless phones; similarly for WiFi many neighbouring WiFi cells nearby can degrade the signal quality. Some commentators such as Peter Kastner also believe that WiFi's success will become its downfall because its rapid take up will mean that a WiFi network will have to suffer noise interference from many competing, neighbouring WiFi LANs reducing its quality. Companies such as Propagate Networks are working on algorithms to improve performance [25]. Propagate's techniques include automatic selection of the channel with the best available performance, turning down of the transmit power to avoid a power arms race with competing LANs and in a multi-hub environment selection of the hub that is least used to improve performance and "flatten" the network. They aim to be the "Dolby of WiFi" licensing their algorithms to be used in each piece of equipment.

Multipath interference is similar to the impairments caused by bridged taps in twisted pair and micro-reflections in cable systems. Here the signal may take varying length paths between the transmitter and the receiver, for example reflecting off intermediate objects, and time delayed versions of the data be received. These in turn can cause intersymbol interference leading to errors in the received data. A CRC should detect the errors, but then the frames containing them will have to be re-transmitted reducing channel capacity. IEEE 802.11a, g & n and WiMax use OFDM (similar to DMT in xDSL) in which the signal is split into lots of narrow sub-channels which are then transmitted in parallel. The narrowness of the sub-channels and the corresponding longer duration of each symbol makes this technique resistant to multipath issues, since greater delays can be tolerated by each sub-channel. Multipath interference has the potential to make more of an impact on IEEE 802.11b since it uses a single broad carrier. This in turn can experience wide variations in reflectivity over its spectrum, which gives a wide range of delays, and also is less tolerant to delays. Diversity can be used to reduce the problem (diversity means having more than one spatially diverse transmitting antenna to allow the receiver to choose the one with the best signal). In this case the antenna should be widely separated so that each has a significantly different path to the receiver. UMTS and HSPDA use a property of W-CDMA to overcome the multipath interference. Essentially since the receiver correlate the codes transmitted to the codes expected it can detect the parallel paths. Each path can then be processed by a separate channel in the receiver (called a "finger" and the power of each combined to boost the signal. The receiver is known as a RAKE receiver because of a graphical representation of the multiple fingers being combined into a single connection which resembles a garden rake.

	Standard	Rf Frequency Ghz	Downlink & uplink modulation	Bandwidth Mbit/s	Typical Range km
WiFi	802.11a	5	OFDM	54	<0.1
	802.11b	2.4	CCK over QPSK	11	
	802.11g		OFDM	54	
	802.11n			>100	
WiMax	802.16	10-66 ²³	OFDM using QPSK	70	<50
	802.16a	2-11 ²⁴	16-QAM 64-QAM		
UMTS	UMTS	1.9 uplink 2.1 downlink	W-CDMA over QPSK	2	1
HSDPA ²⁵	HSDPA	1.9 uplink 2.1 downlink	W-CDMA over QPSK 16-QAM	14.4	0.5
4G	4G	Too early to say		>20?	<0.1?

Table 8 Main properties of wireless access standards

Security is also a major consideration with wireless networks. It is far easier for eavesdroppers to overhear a signal on this kind of network compared to wired networks, or even to hijack bandwidth. For WiFi hubs new terms of *wardriving* and *warchalking* have arisen. *Wardriving* consists over travelling around an area with WiFi enabled equipment to detect unsecured networks, which could be hijacked. *Warchalking* takes this one step further, chalk marks are put on the pavement near an unsecure hub to show its presence.

WiFi equipment does provide methods for security, however many users do not implement them – perhaps because of ignorance. There are two types of encryption available as part of the WiFi standard. This simply protects data in the WiFi LAN, for end-end security encryption must occur in higher layers of the OSI stack.

²³ Line of sight only

²⁴ Extension to allow non-line of sight

²⁵ Upgrade planned to UMTS networks in Japan in 2006

The first encryption technique implemented is called WEP. It uses a fixed key and is not secure. It can now be broken in a relatively short time with widely available tools. The newer type WPA uses a larger key and changes the key regularly making the security far greater. There are other measures that can be taken to enhance security in WiFi networks:

- stopping broadcasting the SSID (which means that the average user will not detect the network's presence)
- implementing MAC address filtering, so that only equipment with authorised MAC addresses can gain access to the network

No method provides 100% security to a determined attack, however implementing all of these measures will deter most assaults.

These methods provide security for a user connected to a trusted authentic network. However for mobile users connecting via hotspots there is a risk that the network may not be provided by a reputable organisation and may be pretending to be something other than it is ("spoofing"). Users of unverified networks would be well advised to pay careful consideration to the data they may be sharing on these networks.

WiMax uses an encryption protocol similar to the certified version WPA (WPA2); however the major difference is that all traffic on the network must be encrypted. There is no option to not implement the security and this should make WiMax networks more secure. Since WiMax networks are primarily intended to be public, for example they might be owned by ISPs, it may not be practical to not broadcast SSIDs or implement MAC filtering. Again users should be aware of the risks of spoofing.

The security in UMTS (3G) networks is an evolution of the security used in GSM (2G) networks. There are several components to the overall security strategy:

- Authentication and Key Agreement. Allows the network to ensure that the correct user is connected and allows the user to confirm connection to the correct network rather than a fake base-station. This last feature is new in UMTS
- Integrity. Coding of the signalling messages based on a pre shared key to ensure that the message has not be tampered with in transit. Note early GSM installations did not code control messages at all, GPRS closed this loophole.
- Confidentiality. This covers the encryption of information sent to prevent eavesdropping.

For wireless networks, cell size is also a potential problem. As the bandwidth of the connection increases the diameter of the cell covered by the hub normally shrinks, leading to the requirement of a large number of base-stations; WiMax appears to buck this trend, but contention issues may well increase the number of base-stations required.

Providing large numbers of base stations is not going to be trivial. Problems will include access to real estate and building out the infrastructure for back haul. One interesting approach is proposed by the EC funded OBAN project. Their suggestion is to use home

gateways in private residences [15]. The scheme reserves a private section of the gateway capacity for the host family while allowing roaming users access to the rest of the capacity.

A high density of cells is unlikely to be implemented in rural areas for economic reasons; other technologies such as WiMax are likely to be implemented for these customers. For extremely remote customers, satellite or HAP access methods may be used.

Finally for high speed mobile customers serviced by these networks, there will be additional problems. These include handover between cells which may occur on the timescale of seconds (or less) at these speeds (and cell sizes) rather than the more sedate pace managed currently in UMTS networks. Blondia describes an emulation where the signal power is monitored from several base stations and the strongest chosen for the active channel [26].

An important point to note is that high bandwidth wired connections will be required to backhaul data to and from each base-station and the growth of high bandwidth wireless will necessarily lead to installation of dense high bandwidth wired connections. It is interesting to note that the fates of both wired and wireless technologies may well be intertwined.

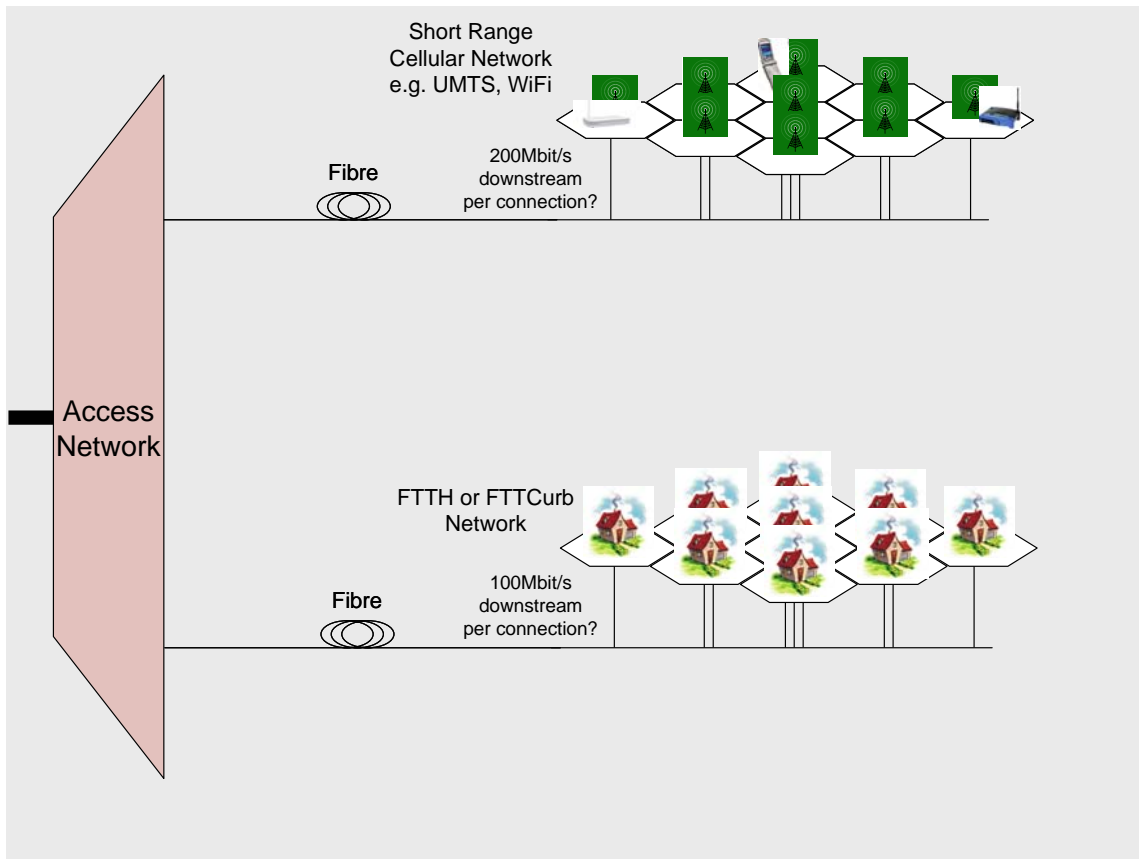


Figure 10 Similarity of backhaul networks for high density wireless cells and FTTH or FTTCurb networks

HAP and Satellite Methods

Wired networks provide access coverage for most static customers; terrestrial wireless methods extend the access to static customers in more remote areas and to mobile users. However the economics of each solution is based on the capital and operating costs of the access network and the number of customers between which these costs can be shared. For certain remote locations with few customers and long distances to the exchange these techniques may not be suitable.

The final class of access network uses satellites or high altitude platforms (HAPs) to share coverage over a huge (nation or greater) area. The costs are further amortised by their ability to also provide additional high value services.

Satellite

For satellites at least the need to spread the considerable investment across many users forces these systems primary use to be for broadcast (point to multipoint) systems. While they can be used for individual point to point datalinks, in a similar way to their use with satellite phones, using their limited spectral resource for these connections will command a premium and these systems will thus be unlikely to be competitive in areas where other methods can be used.

The limited spectral resources will exacerbate the familiar problem of contention. The problem of contention may not be too great at current broadband data rates of ~1Mbit/s however as requirements approach our target of ~100Mbit/s per customer the problem will become critical.

Satellites have three frequency bands allocated to them in the microwave region of the spectrum by the International Telecommunication Union; the allocated bands are 3.4-4.8 GHz (within the C-band), 10.7-12.75 GHz (within the Ku-band) and 19-22 GHz (within the Ka-band) [27]. These bands do not have the same characteristics:

- The C-band is virtually unaffected by rain, whereas the other bands suffer attenuation and hence fading. This can be mitigated by the use of higher gain antennas, but this adds cost (and size) to the customers' equipment. This in turn means that the C band is seen as more valuable and is more regulated. The C-band tends to be used more for broadcast services, whereas the Ku and Ka bands are expected to be used more for interactive services. If an uninterrupted connection is critical, use of the Ku and Ka bands may not be suitable.
- The bandwidths of the bands are different and hence the higher frequency bands have greater capacity.
- Above about 10 GHz the signal is line of sight only. (This was the reason that the 2-11 GHz band was introduced in the IEEE 802.16a WiMax specification). The elevation of satellites will make the requirement for LOS less of an issue than

Since the upstream bandwidth required by users is typically much lower than downstream for most applications (peer-peer file sharing being a notable exception), some systems use the satellite for downstream connectivity and a terrestrial link (phone line or other) for upstream connectivity. Given that the satellite system is only likely to be employed in areas where xDSL is not available the upstream connection will be limited to analogue modem bit rates of about 30kbit/s.

Conversely some systems use ground-satellite links in both directions. This has the advantage that the upstream link can be faster (at the expense of using the scarce spectral resource and thus incurring cost). An example of such a product is offered by Tariam in the UK [28]. The current (September 2005) price for their cheapest product (with a 512 kbit/s downstream & 128kbit/s upstream connection, contention ratio 50:1) is about £60 per month. The total installation and customer equipment cost is given as £1130.

This is clearly not cost competitive with ADSL for areas with coverage. For comparison UK ISP Demon's cheapest product (with 2Mbit/s downstream & 256 kbit/s upstream, contention ratio 50:1) costs about £20 per month²⁶ with a free modem and no installation costs [29].

There appear to be two primary orbit configurations for satellite systems:

- The first is the well known geostationary orbit where the satellite lies above the Earth's equator at an altitude of approximately 35,786 km. The orbit allows the satellite to appear stationary above a fixed point on the rotating Earth. This in turn allows ground antennas to have a fixed orientation rather than having to track the satellite.
- The second has been introduced more recently using low Earth orbits (LEOs). Since these satellites move relative to a point on the Earth's surface a constellation of many satellites must be provided to give constant coverage.
 - Perhaps the best known system is Iridium [30]. The altitude of the satellites in this system is about 780km. The system consists of 66 satellites orbiting from pole to pole with a period of about 100 minutes. This system was intended for voice communications. The service was launched in November 1998, and the original company filed for Chapter 11 bankruptcy in August 1999. Some of the reasons cited were competition from terrestrial mobile operators and the relatively high cost of using the system. The services were reinstated in 2001 by a newly founded company.
 - Teledesic was an ambitious system planned to provide broadband services [31]. The system was originally planned to use 840 active satellites in its constellation. This was gradually scaled back during the 1990s, until in 2003 the board decided its plan no longer made sense and eliminated itself [32].

Both methods suffer from latency due to the transit time of the signal on the basestation-satellite-customer path. While the delay may not impact most broadband users who use the connection for e-mail, surfing, broadcast services and the like, any time sensitive applications such as video-conferencing, VoIP etc. will be impacted. Latency is obviously less of a problem for low Earth orbit systems than geostationary systems, but is reported to be noticeable for voice calls on the Iridium system [30]. For some time-critical applications currently being discussed and developed, such as remote surgery, this delay may eliminate the possibility of using this technology.

The current main contenders for the layer 1 and 2 protocols for satellite broadband, S-DOCSIS and DVB-RCS, are both modifications of protocols used for terrestrial applications; for example the higher value products offered by Trianm use DVB-RCS. Both S-DOCSIS and DVB-RCS use QPSK for modulation.

²⁶ To use this service a customer requires a BT line and thus the full cost will include the line rental from BT, however many customers will be paying this anyway for their phone service). The cheapest line rental currently available is £10.50 per month.

HAPs

Satellite technology is expensive. Components have to meet extremely high reliability standards as they cannot be repaired after launch; launch costs are expensive, as are insurance costs against loss²⁷.

A new high altitude hub which provides many of the advantages of satellite systems, such as wide coverage and elevation, but much lower cost is the High Altitude Platform or HAP. These are airships or planes which will fly in the stratosphere at an altitude of 17-20km and provide a platform for communications. This is above the altitude that commercial airplanes fly at. The 17-20 km altitude will allow a wide coverage area e.g. the line of sight radius of coverage of a HAP situated 20 km over London is greater than the distance to Land's End (total radius ~500 km).

It is planned that the platforms will be unmanned. A big advantage is that they may be returned to ground periodically for maintenance and may also be upgraded. In the long term, the platforms are planned to have a flight duration of about a year and to be solar powered.

The access to a HAP reduces the reliability requirements of components relative to a satellite. If a component fails in a HAP it can be returned to ground for repair. With a sensible sparing policy, another HAP could be launched to replace it within a very short time. The eventual cost of a HAP is expected to be about 10% of that of a satellite.

Some developers are also proposing the use of tethered balloons as platforms. Although these are not strictly speaking high altitude, the technology is similar and should be considered as an alternative method. The discussion available implies that this may be an interim step which is realisable in a shorter term than the stratospheric solution.

A variety of beams are planned for the earth facing antennas. For broadcast services such as HDTV low gain, low directivity antennas will be employed to provide maximum coverage. Medium gain antennas will be employed to provide bi-directional broadband fixed wireless access cells for fixed users. Steer-able high gain antennas will allow dynamic allocation of large capacity for purposes such as emergency communications during a disaster, and will also service high speed mobile users.

mm-Wave are expected for platform to user connections. As well as broadcast, these may provide burst data connections of up to 120 Mbit/s. Free-space optical communications, allow higher capacity (622 Mbit/s) in clear conditions and will be used for inter-HAP communications and to supplement mm platform to ground backhaul communications.

²⁷ The risk of loss is real. For example the Astra 1K launch failed in November 2002 leaving the satellite in a useless orbit [33]. The satellite was de-orbited with the debris falling into the Pacific Ocean in December 2002 [34].

Connections to satellites and ground based hubs are planned for back haul purposes. In a scenario where many HAPs form an aerial network, inter-HAP connections will reduce the demand for terrestrial backbone network capacity and will also allow migration of high-bandwidth optical connections to the ground from HAPs where the ground links are obscured by rain or clouds to those links with clear weather. The lack of clouds at stratospheric altitudes prevents inter-HAP optical connections from being obscured.

An interesting economic factor is that the system could be deployed on a “pay as you grow” basis. Here one platform could be deployed; as its capacity is used up another could be deployed covering the same service area and sharing the same spectrum by employing the directionality of the antenna [35], and so on²⁸. This should be attractive to a network supplier

One application which the CAPANINA HAP project believes may be particularly valuable is the provision of communications links for a region where the infrastructure has been destroyed by a disaster²⁹. Similarly HAPs could be used to temporarily provide high capacity for special events such as The Olympics.

These platforms still require some development before they are available. The EC funded project CAPANINA is one which is rapidly providing credibility for these devices and recently completed trials with a stratospheric balloon providing 2Mbit/s mm-wave (28/31 GHz) data links at distances of up to 60km and a 1.25Gbit/s downlink with no errors [37]. The balloon flew for 9 hours.

Spectrum allocation may be an issue as HAPs will have to share spectrum with other services. Currently bands are available at 47/48GHz on a worldwide basis and 31/28GHz in forty countries outside of Europe. The main issue governing regulation is interference into terrestrial, satellite and other systems. The CAPANINA project is developing a radio regulatory strategy to try and ensure that spectrum is available over an appropriate timescale to fit in with the anticipated broadband roadmap from HAPs. A big factor governing availability of spectrum is the absence of HAPs systems today. The successful demonstrations provided by CAPANINA and others will help engender credibility.

CAPANINA is proposing the use of a modified form of IEEE 802.16SC as the protocol for the access link [19]. SC here refers to single carrier, where a single broadband carrier is used rather than an OFDM technique. The modulation technique can be QPSK, 16QAM or 64QAM. Adaptation of an existing standard provides cost benefits as it reduces the cost of developing equipment particularly for the customer premises.

²⁸ It is interesting to compare this with a low Earth orbit satellite system where the whole constellation must be installed at the start to avoid coverage drop-outs, or with a geostationary system where the launch of a new satellite to increase capacity must be planned years in advance.

²⁹ The Iridium satellite phone network traffic increased 6000% in the week following Hurricane Katrina recently [36]. A HAP could potentially be launched and sit over a disaster area in a very short time providing dedicated far greater capacity.

Conclusions/Summary

Broadband access has become a basic provision in homes and businesses over the past half decade. It is on a par with electricity and phone supply. As we move forward it is likely to become more pervasive, with many devices in the home requiring access, not just home computers. The services supplied over a broadband connection will multiply and a connection will become a necessity for modern life, not a luxury.

The supply of new services such as interactive HDTV will lead to capacity requirement of users increasing by at least an order of magnitude over the next few years (100Mbit/s is a reasonable estimate of the requirement per home). New technologies are being developed to provide these bandwidths, but all depend on investment on new infrastructure.

The many technologies compete in the market place, but ultimately are complementary with each technology being suited for different situations.

The technologies can be divided into three main sectors:

- **Wired** – technologies such as twisted pair, cable and PLC are probably the technology of choice for environments where the wired infrastructure already exists. Such as Western Europe. They can provide large bandwidths using existing infrastructure. However there are limits as to how much bandwidth can be provided to each customer which depend on the wire length to the exchange. Thus some investment may be necessary in fibre to the cabinet to increase capabilities. FTTH is the optimum solution from a technical point of view, but the cost of building out new FTTH networks is probably prohibitive. Some remote areas are not well served by wired networks and less-developed countries such as the new EU entrants may not have ubiquitous networks. For these the second sector may be more appropriate.
- **Terrestrial Wireless** – this technology has rapidly expanded for LAN provision through the deployment of WiFi cells, and GSM UMTS etc for mobile phone users. Wired technologies are obviously not suited for mobile users, so this technology (and aerial wireless below are needed to provide for these customers). Incipient technologies such as WiMax will lead this to be a powerful technology choice for those static communities not well served by wired networks. For the development of new infrastructure in communities poorly served by existing wired networks this may well be the favoured technology, since it is relatively quick to set up and does not require as many expensive cable runs. However the wireless hubs will still require backhaul to the core of the network. WiMax itself may be a method used to backhaul some of the way. Other choices include wired methods, but for extremely remote locations the best backhaul option may be via the third sector.
- **Aerial Wireless** – HAPs and satellites. For broadband these technologies are likely to be best suited to areas not provided for by the other sectors. An example given above relevant to the Western world is disaster recovery where the existing infrastructure has been destroyed. These technologies are also likely to be of great interest in the developing world as they can provide infrastructure over a wide area, and thus allow low population densities to have access relatively cost effectively.

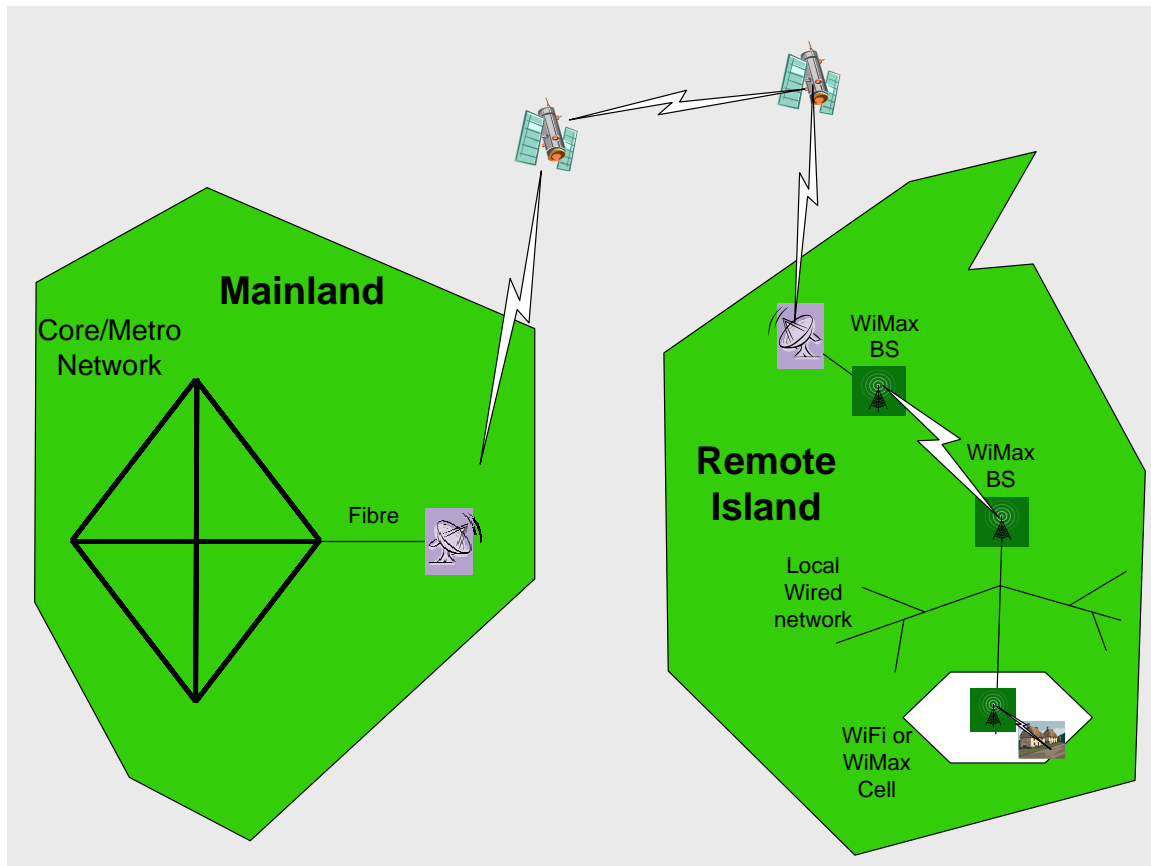


Figure 11 Use of multiple technologies to form an access link

As mentioned above the technologies are complementary. As well as using a mixture of technologies to provide access to different sectors of the population depending on location, a mixture of technologies might be used in an access link for a customer. Figure 11 shows an access network for a remote island. Here the connection from the core/metro network on the mainland to the customer on the island is shown travelling via a number of technologies:

- Wired (fibre) from the metro node to the ground satellite base station on the mainland
- Aerial wireless uplink to the satellite
- Aerial wireless from satellite to satellite
- Aerial wireless downlink from the satellite to the ground satellite base station on the island
- Terrestrial wireless (WiMax) from the satellite base station to a local network (perhaps on the other side of the island)
- Wired (perhaps twisted pair) in a feeder network to local neighbourhoods
- Terrestrial wireless (WiFi or WiMax) in a cell to provide the last connection to the user.

All the technology sectors mentioned in this article are likely to have a successful future with each having its own niche in the access market. The access market is one of the big growth areas in the communications sector and thus developments in this sector are likely to continue rapidly for the foreseeable future.

Glossary

3G	<u>3rd Generation</u> . The current generation of wireless technology. Multimedia 3G networks transmit wireless data up to 2 megabits per second making possible the integration of voice, data, and video. Started deployment in UK is 2002.
4G	<u>4th Generation</u> . The successor to 3G yet to be defined.
AAA	<u>A</u> ccess, <u>A</u> uthorisation and <u>A</u> ccounting. The security and billing functions of the operator's system. This part of the management layers of the network ensures that the user is identified, is allowed to use the services, and bills the cost to his account.
ADSL	<u>A</u> symmetric <u>D</u> igital <u>S</u> ubscriber <u>L</u> ine. A common technology that allows more data to be sent over existing copper telephone lines while still allowing independent phone communication. ADSL supports data rates of from 1.5 to 9 Mbit/s when receiving data (known as the downstream rate) and from 16 to 640 Kbit/s when sending data (known as the upstream rate). c.f. xDSL
Bridged Tap	A bridged tap is a section of wire connected to the loop at one end and un-terminated at the other end. Examples of bridged taps are wires that are laid out in areas where housing is still being built. When a transmitted signal arrives at a bridged tap, the signal divides. Part of the energy continues to the receiver and the rest of the energy reflects off of the un-terminated end. This reflection causes delayed versions of the signal to arrive at the receiver, and these reflections distort the received signal. c.f. MPI
Broadband	According to the IEEE 802.16-2004 standard, broadband means having instantaneous bandwidth greater than around 1 MHz and supporting data rates greater than about 1.5 Mbit/s'. ³⁰
BWA	<u>B</u> roadband <u>W</u> ireless <u>A</u> ccess. Proprietary or standardised methods to provide broadband to users. WiMax is an example of a BWA technology
CCK	<u>C</u> omplementary <u>C</u> ode <u>K</u> eying. Data is encoded via a set of 64 8-bit code words. As a set, these code words have unique mathematical properties that allow them to be correctly distinguished from one another by a receiver even in the presence of substantial noise and multipath interference

³⁰ According to this definition until recently most UK ISPs only provided midband with the downstream rate being limited to 512kbit/s.

CDMA	<u>C</u> ode <u>D</u> ivision <u>M</u> ultiple <u>A</u> ccess. CDMA is a "spread spectrum" technology, allowing many users to occupy the same time and frequency allocations. CDMA assigns unique codes to each communication to differentiate it from others in the same spectrum.
Channel Interference	Impairment in a cable system signal by other signals, such as signals from other cable modem subscribers and television signals, which interfere with packet transmission.
Contention	This term represents the sharing of a fixed bandwidth connection between customers. Typical home ADSL contention ratios in the UK are specified as 50:1 i.e. up to 50 customers may share the up and downstream connection. For a 2Mbit/s connection, this would mean if all possible users were simultaneously using the connection, the downstream bandwidth per user would be 40 kbit/s. For business use contention ratios of 20:1 are offered by BT Wholesale.
CRC	<u>C</u> yclic <u>R</u> edundancy <u>C</u> heck. A checksum added to a block of data to allow detection of whether or not errors have been introduced.
CSMA/CD	<u>C</u> arrier <u>S</u> ense <u>M</u> ultiple <u>A</u> ccess With <u>C</u> ollision <u>D</u> etection. This is a network control protocol for resolving contention issues, in which (a) each station listens for other transmissions and a transmitting data station that detects another signal while transmitting a frame, stops transmitting that frame, transmits a jam signal, and then backs off to wait for a random time interval before trying to send that frame again. Ethernet is the classic CSMA/CD protocol.
CW	<u>C</u> onstant <u>W</u> ave. An optical signal that has constant power as opposed to being modulated. Optical analogue to electrical DC.
DECT	<u>D</u> igital <u>E</u> nhanced (formerly <u>E</u> uropean) <u>C</u> ordless <u>T</u> elecommunications is an ETSI standard for digital portable phones, commonly used for domestic or corporate use. DECT can also be used for wireless data transfers.
DMT	<u>D</u> iscrete <u>M</u> ulti <u>T</u> one Modulation. See OFDM
DOCSIS	<u>D</u> ata <u>O</u> ver <u>C</u> able <u>S</u> ystems <u>I</u> nterface <u>S</u> pecifications. A specification for schemes and the protocol for exchanging bidirectional signals over cable. It currently supports downstream-to-the-user data rates up to 27 Mbit/s (megabits per second). This data rate is shared by a number of users so the actual downstream data rate to an individual business or home is more like 1.5 to 3 Mbit/s. The upstream aggregate data rate is 10 Mbit/s with individual data rates between 500 Kbit/s and 2.5 Mbit/s. When analogue TV services are turned off freeing spectrum these rates may change
DSLAM	<u>D</u> igital <u>S</u> ubscriber <u>L</u> ine <u>A</u> ccess <u>M</u> ultiplexer. A network device at a telephone company central office that receives signals from

	multiple customer xDSL connections and puts the signals on a high-speed backbone line using multiplexing techniques.
DVB	<u>D</u> igital <u>V</u> ideo <u>B</u> roadcasting. A suite of collaborate standards for digital video broadcasting including DVB-S for <u>S</u> atellites, DVB-C for <u>C</u> able, DVB-T for <u>T</u> errestrial, and DVB-H for <u>H</u> andhelds. Of particular interest for broadband applications are DVB-DATA is concerned with <u>d</u> ata transmission and DVB-RC is concerned with the <u>R</u> eturn <u>C</u> hannel from the customer
FEC	<u>F</u> orward <u>E</u> rror <u>C</u> orrection. A system method to control errors for data transmission wherein the receiving device has the capability to detect and correct a fraction of bits or symbols corrupted by transmission errors. FEC is accomplished by adding redundancy to the transmitted information using a predetermined algorithm. Each redundant bit is invariably a complex function of many original information bits.
FEXT	<u>F</u> ar <u>E</u> nd <u>C</u> ross(<u>X</u>) <u>T</u> alk. An impairment where signals being transmitted leak onto a different signal at the other (far) end of the wire. c.f. NEXT
FTTx	Generic term for <u>F</u> ibre <u>T</u> o <u>T</u> he ... This technology extends the fibre reach beyond the local exchange to increase bandwidth in the access network. Specific examples include FTTH - <u>F</u> ibre <u>T</u> o <u>T</u> he <u>H</u> ome, FTTC - <u>F</u> ibre <u>T</u> o <u>T</u> he <u>C</u> urb, and FTTCab - <u>F</u> ibre <u>T</u> o <u>T</u> he <u>C</u> abinet
GPRS	<u>G</u> eneral <u>P</u> acket <u>R</u> adio <u>S</u> ystem. The successor to GSM for mobile telephone systems. Sometimes known as “2.5G”
GRAN	<u>G</u> eneric <u>R</u> adio <u>A</u> ccess <u>N</u> etwork. A section of the UMTS standard that covers the lowest three layers of the OSI stack i.e. physical, datalink and network layers.
GSM	<u>G</u> lobal <u>S</u> ystem for <u>M</u> obile <u>C</u> ommunication. One of the leading digital cellular systems. GSM uses narrowband TDMA, which allows eight simultaneous calls on the same radio frequency. GSM was first introduced in 1991 and has become the de facto standard in Europe and Asia.
HAP	<u>H</u> igh <u>A</u> ltitude <u>P</u> latform. A plane or airship that flies at stratospheric altitude (~20km) to provide a platform for access communications.
HFC	<u>H</u> ybrid <u>F</u> ibre <u>C</u> oaxial. A cable network where the signal passes through fibre and coaxial media.
HSDPA	<u>H</u> igh <u>S</u> peed <u>D</u> ownload <u>P</u> acket <u>A</u> ccess. A “3.5G” W-CDMA technique boosting download for mobile systems compared to UMTS

Impulse Noise	This is an interference impairment that is short in duration but high in magnitude. Examples of causes include lightning and a power surge caused by a motor turning on
Ingress Noise	An impairment in a cable network caused by noise entering through poorly shielded cables or communication devices attached to the cable network within the home. Ingress interference is typically impulsive and bandlimited in nature as the interfering signals appear for short intervals at significant power levels within a small frequency range. Many devices emit signals in band. These include common household appliances such as garbage disposals and blenders.
IMD	<u>I</u> nter <u>m</u> odulation <u>D</u> istortion. An impairment caused by intermediate components in a system such as amplifiers giving a nonlinear component in their output. For two frequencies f_1 and f_2 , 2 nd order intermodulation products lie at $2f_1$, $2f_2$, $f_1 + f_2$ & $f_2 - f_1$. Two of the 3 rd order intermodulation products at $2f_2 - f_1$ and $2f_1 - f_2$ & are often difficult to overcome as they may lie within band and resist filtering.
IP	<u>I</u> nternet <u>P</u> rotocol. This is the standardised network layer (layer 3) for the TCP/IP Protocol Suite. IP is concerned with routing packets across a network between end-users. It is a connectionless, best-effort packet switching protocol.
ISI	<u>I</u> nter <u>S</u> ymbol <u>I</u> nterference. An impairment caused when a transmitted symbol spreads into other slots. Examples of causes include dispersive media or echoes
ISP	<u>I</u> nternet <u>S</u> ervice <u>P</u> rovider. The organisation that provides a connection to the internet for a user.
LAN	<u>L</u> ocal <u>A</u> rea <u>N</u> etwork. High-speed, low-error data network covering a relatively small geographic area, such as an office, or home
Latency	The delay that a signal experiences traversing the network from sender to receiver.
Layer x	This refers to one of the layers in the 7 layer OSI reference model. See Appendix 1 for more information.
LEO	<u>L</u> ow <u>E</u> arth <u>O</u> rbital. As the name suggests a satellite orbit which is close to the Earth (typically about 800 km)
LOS	<u>L</u> ine <u>o</u> f <u>S</u> ight. A line of sight path is free from obstructions and a signal follows a direct route.
MAC address	<u>M</u> edia <u>A</u> ccess <u>C</u> ontrol address. A unique identifier attached to networking equipment e.g. an Ethernet card. Unlike IP addresses that can be re-assigned to different servers for example, a MAC address should permanently be associated uniquely with the piece of equipment. Ethernet uses MAC-48 addressing for which the

	standard is contained within IEEE 802
MAN	<u>M</u> etropolitan <u>A</u> rea <u>N</u> etwork. Often shortened to “Metro” Network. This is a wider network than a LAN covering a city or town and typically owned and operated by a telecoms provider or ISP rather than an individual
MPI	<u>M</u> ulti <u>P</u> ath <u>I</u> nterference. An impairment caused when a transmitted signal takes more than one path to the receiver, for example a radio signal bouncing off buildings. The multiple paths cause delayed versions of the signal to arrive at the receiver, and these reflections distort the received signal. c.f. Bridged Taps.
NEXT	<u>N</u> ear <u>E</u> nd <u>C</u> ross(<u>X</u>) <u>T</u> alk. An impairment where (loud) signals being transmitted leak onto the (quiet) received signal at the same (near) end of the wire. c.f. FEXT
NLOS	<u>N</u> on <u>L</u> ine of <u>S</u> ight. A signal following a non line of sight path may experience reflections, diffraction and scattering. Components from all paths may be present simultaneously.
NRZ	<u>N</u> on <u>R</u> eturn to <u>Z</u> ero. A modulation format in which the transmitter remains in its “on” state for the whole of the bit period to transmit a “1”. c.f. RZ
OFDM	<u>O</u> rthogonal <u>F</u> requency <u>D</u> ivision <u>M</u> ultiplexing. A transmission technique in which a single transmitter transmits on many different orthogonal (independent) frequencies (typically dozens to thousands). Because the frequencies are closely spaced each one only has room for a narrowband signal. This, coupled with the use of advanced modulation techniques on each component, results in a signal with high resistance to interference.
OSI Model	The <u>O</u> pen <u>S</u> ystems <u>I</u> nterconnection Reference <u>M</u> odel. This is a seven a layered abstract description for communications and computer network protocol design. It is described in more detail in Appendix 1.
PCP	<u>P</u> rinciple <u>C</u> rossconnect <u>P</u> oint. An intermediate distribution node between the customer and the exchange. In the UK this is typically a green cabinet by the curb.
PLC	<u>P</u> ower <u>L</u> ine <u>C</u> ommunications. Broadband access networks which use the mains electricity network as the communications medium.
PON	<u>P</u> assive <u>O</u> ptical <u>N</u> etwork. A point to multipoint optical network that contains no active electronics, such as switches, between the transmitter and receiver
PoP	<u>P</u> oint of <u>P</u> resence. An artificial demarcation or interface point between communications entities. For example a carrier might wish to separate metro networks from the core networks. The interfaces are known as PoPs

POTS	<u>P</u> lain <u>O</u> ld <u>T</u> elephone <u>S</u> ystem. The legacy telephone system which has to be considered in any migration upgrade path.
PPPoA	<u>P</u> oint to <u>P</u> oint <u>P</u> rotocol over <u>A</u> TM. A layer 2 protocol used for xDSL connections
QAM	<u>Q</u> uadrature <u>A</u> mplitude <u>M</u> odulation. This is a modulation scheme which conveys data by modulating the amplitude of two carrier waves. These two waves, usually sinusoids, are out of phase with each other by 90° are called quadrature carriers — hence the name of the scheme.
QoE	<u>Q</u> uality of <u>E</u> xperience. See also QoS. A qualitative measure of the ease and satisfaction a user gets of use of the network.
QoS	<u>Q</u> uality of <u>S</u> ervice. In communications networks QoS can be defined in terms of blocking probability, network availability, set-up time, network robustness, throughput, delay, jitter, bit error rate and packet loss rate and other criteria [38]. All of these affect the Quality of Experience (QoE) of the user.
QPSK	<u>Q</u> uadrature <u>P</u> hase <u>S</u> hift <u>K</u> eying. This is a modulation scheme which conveys data by modulating the phase of two carrier waves. These two waves, usually sinusoids, are out of phase with each other by 90° are called quadrature carriers — hence the name of the scheme.
RZ	<u>R</u> eturn to <u>Z</u> ero. A modulation format in which the transmitter returns to its “off” state after transiting to its “on” state during the bit period to transmit a “1”. This has widens the spectrum of the transmission, and increases the peak power for the same average power [39]. This can have some advantages for certain transmission applications. c.f. NRZ
SCDMA	<u>S</u> ynchronous <u>C</u> ode <u>D</u> ivision <u>M</u> ultiple <u>A</u> ccess. A layer 2 protocol in which users use orthogonal code patterns to send their data, thus avoiding blocking each other.
S-DOCSIS	<u>S</u> atellite - <u>D</u> ata <u>O</u> ver <u>C</u> able <u>S</u> ystems <u>I</u> nterface <u>S</u> pecifications. S-DOCSIS is a modification of the DOCSIS (c.f.) cable-modem protocol for transmission over satellite
SSID	<u>S</u> ervice <u>S</u> et <u>I</u> dentifier. A code attached to packets on a wireless networks to identify packets as part of that networks. Essentially the name of the network.
TCP	<u>T</u> ransmission <u>C</u> ontrol <u>P</u> rotocol. . This is the standardised transport layer (layer 4) for the TCP/IP Protocol Suite. The protocol guarantees that data sent by one endpoint will be received in the same order by the other, and without any pieces missing.
TDMA	<u>T</u> ime <u>D</u> ivision <u>M</u> ultiple <u>A</u> ccess. A layer 2 protocol in which users are allocated timeslots in which to send their data, thus avoiding

	collisions.
Triple Play	The supply of voice, data and TV over a single network.
UMTS	<u>U</u> niversal <u>M</u> obile <u>T</u> elecommunications <u>S</u> ervice. A 3G standard supporting a theoretical data throughput of up to 2 Mbit/s.
VoIP	<u>V</u> oice <u>o</u> ver <u>I</u> P. A telephony method where the voice signal is digitised, converted into IP packets and transmitted as data rather than as a separate voice channel.
W-CDMA	<u>W</u> ideband <u>C</u> ode <u>D</u> ivision <u>M</u> ultiple <u>A</u> ccess. Form of CDMA used in UMTS. The “wideband” simply refers to the fact that the 5 MHz bandwidth in each direction is wider than that used for 2G CDMA communication
WDM	<u>W</u> avelength <u>D</u> ivision <u>M</u> ultiplexing. A method to increase transmission bandwidth over an optical fibre by sending different signals over different wavelength carriers.
WEP	<u>W</u> ired <u>E</u> quivalent <u>P</u> rivacy. Scheme used to secure wireless networks. Considered now to be obsolete as it can be cracked using publicly available tools. See also WPA
WiFi	<u>W</u> ireless <u>F</u> idelity, a suite of standards IEEE 802.11 for technology allowing short range wireless connectivity. Typically it allows 50-100Mbit/s over <100m
WiMax	A suite of standards IEEE 802.16 to extend the range and bandwidth of wireless connections, beyond those available with WiFi. WiMAX can transfer around 70M bit/sec over a distance of 30 miles (48 kilometers) to thousands of users from a single base station.
WPA	<u>W</u> i- <u>F</u> i <u>P</u> rotected <u>A</u> ccess. Scheme used to secure wireless networks. This is inherently more secure than WEP as the key changes dynamically as the system is used. This combined with the larger initialisation vector (essentially a larger key) defeats the key recovery attacks to which WEP is prone.
xDSL	Generic term used to refer to <u>D</u> igital <u>S</u> ubscriber <u>L</u> ine equipment and services, including ADSL, ADSL2, IDSL, SDSL, SHDSL and VDSL. All are digital technologies that provide high bandwidth over existing copper infrastructure provided by the telephone companies.

Appendix 1 – The OSI Model

Introduction

The OSI model divides the functions of a communication or computer network into seven hierarchical layers. Each layer of the stack only uses the functions of the layers below it and only exports functionality to those layers above. The main benefit of the model is that it defines the interface between the layers and allows standardisation of these interfaces. This in turn allows inter-working between equipment from different manufacturers operating in the different layers.

Layer Definition

The seven layers and their organisation are shown in Figure 12. They are:

- **Layer 1 Physical Layer:** the physical layer defines all the electrical, optical and physical specifications for transmission devices. This includes pin layout, voltages, cable specifications, modulation formats etc.

On the wired side, an examples of specifications covered within the physical layer would be wavelength standards for fibre communications; and spectrum allocation for copper communications. On the wireless side an example of the specifications covered would be allocation of the rf spectrum.

The major functions and services provided by this layer are:

- Establishment and termination of a connection e.g. connecting to a base station for a mobile call
 - Sharing of resources between users e.g. contention resolution over a cable network, for example CSMA/CD in Ethernet [40]
 - Modulation i.e. conversion of the digital data into a format by which it can be transmitted e.g. NRZ modulation of a laser in an high speed optical connection
- **Layer 2 Datalink Layer:** the datalink layer provides the functional and procedural means to transfer data between network entities and to detect and possibly correct errors introduced by the physical layer. The addressing scheme is physical, which means the addresses are hard coded into the network devices during manufacturing. The best known example of a layer 2 protocol is Ethernet which uses MAC-48 addresses.
 - **Layer 3 Network Layer:** the network layer provides the functional and procedural mean of transferring variable length data sequences from a source to a destination via one or more networks while maintaining QoS requested by the transport layer. The network layer performs:
 - Routing - routers typically maintain some form of address table to govern routing of packets according to their address labels

- Flow control – this is traffic engineering to ensure efficient use of the network and minimise congestion. Flow control might use prior reservation of resources before using a path for example.
- Network segmentation/desegmentation – this is how a large network is broken down into smaller sub-networks in a hierarchical way to allow efficient routing and control
- Error control functions.

Routing is done via a logical addressing system in contrast to the physical addressing system used in layer 2. IP is an example of a layer 3 protocol and its addressing is probably the most common form used today. IPv4 addresses used 32 bits, but these are rapidly being used up. IPv6 will provide 128 bit addressing. IP works on a best effort basis and this is the only QoS class supported

- **Layer 4 Transport Layer:** The transport layer provides transparent transfer of data between end users thus relieving higher layers from concern about reliability and cost effectiveness of data transfer. Some protocols are connection oriented and allow the transport layer to keep track of packets and re-transmit any that fail. TCP is a layer 4 protocol.
- **Layer 5 Session Layer:** The session layer provides the mechanism for managing dialogue between end users application processes. It establishes checkpointing, adjournment, termination and restart procedures. As an example this layer sets up and tears down IP sessions
- **Layer 6 Presentation Layer:** The presentation layer relieves the application of concern about syntax of data representation within end-user systems. For example MIME encoding and encryption is done on this layer. An example of a presentation layer service would be conversion of a text file to ASCII.
- **Layer 7 Applications Layer:** The applications layer interfaces with and performs common services for the application. Examples of layer 7 services include http and telnet.

Real world protocols generally do not strictly match the stack and indeed the boundaries between layers are certainly grey. Some protocols cover more than one layer such as TCP/IP.

Within access networks we are principally concerned with layers 1 and 2. Although access networks provide services for higher layers, only layer 1 and 2 connectivity is provided within the access layer. The end points of higher layer connections lie outside the access layer.

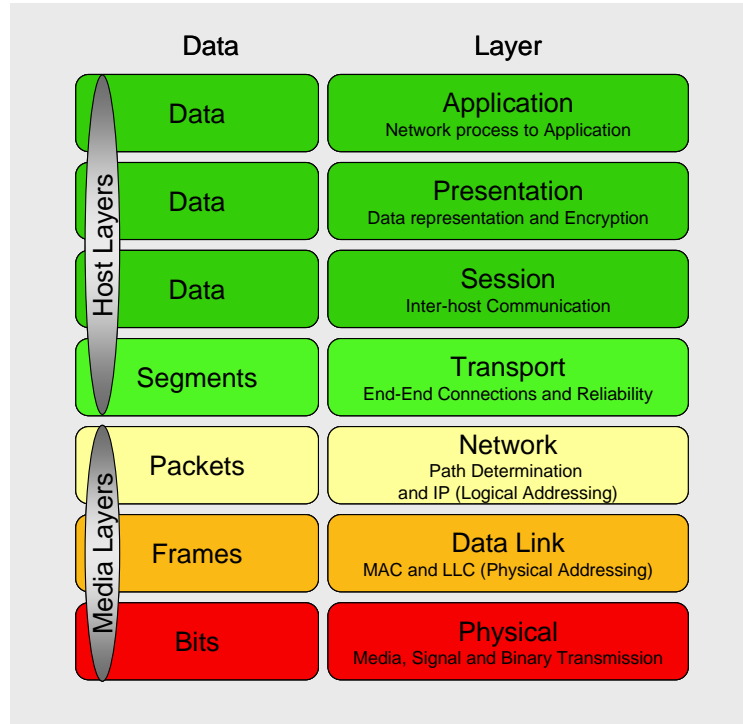


Figure 12 The seven layers of the OSI model (adapted from [41])

Analogy with Post System

Figure 13 gives an analogy of the OSI stack using an example of a manager in one company sending a message to a manager in another. As with all real implementations it does not cover everything in the model, but it does provide some useful insight. Breaking down the layers from the sender to the receiver:

Outbound

- The Application layer is not the application itself but a common process that links to the application. Here the application might be the content in the head of the manager that he needs to put into the letter, the application layer is the shorthand he uses to put the message down on paper, or his verbal skills in dictating the letter.
- The Presentation layer allows the Application layer output to be understood by the receiving end user, in this case this layer might take the dictation (which might have a heavy accent making it unrecognisable to someone at the far end) or the idiosyncratic shorthand and type in out in grammatical English. This layer is also responsible for encryption if it occurs e.g. coding the English via an Enigma machine.
- The Session layer provides the mechanism for managing the dialogue between the end user systems. In this case most of the functions, such as set-up, termination etc, are not really relevant due to the nature of the post analogy. However this layer does have to provide the final address and pack the letter accordingly

- The Transport layer provides transparent transfer of data between end users. It must control the reliability of the link. In our hypothetical example the driver at the far end must let the driver at the near end know that the letter has been received correctly or not and maybe ask for a re-transmit if it hasn't. That doesn't really apply normally to the case of sending a letter. If the manager wanted to send a bigger communication, say an encyclopaedia, it is unlikely it would all be sent in one parcel. This layer would be responsible for breaking it down to smaller units which could then be sent out in letters. It would also be responsible for labelling so that they could be re-assembled in the correct order at the far end. The transport layer is also responsible for requesting QoS. In this analogy the transport layer will select either a first or second class stamp.
- The Network layer accepts the letter and sorts it for the correct sack according to its destination. In the simple model shown here this is all it does, but it also represents the routing between networks. Thus if the letter was International, the sack might go to a sorting office at an airport. The sack would be opened and the letter sorted to another sack for transport abroad. This re-sorting of the letter would be performed in the network layer. Such layer 3 operations are shown within Figure 14.
- The Datalink layer packs the letter and sends it to the correct destination within the network. If the letter was from Plymouth to Exeter. This would mean the letter went in the Exeter sack. If the letter was from Plymouth to Glasgow and went in the Glasgow sack but had to transit the Bristol regional office. The transfer of the sack between vans in Bristol would be a layer 2 operation. This is shown in Figure 14.
- The Physical layer actually does the transport e.g. by mail van

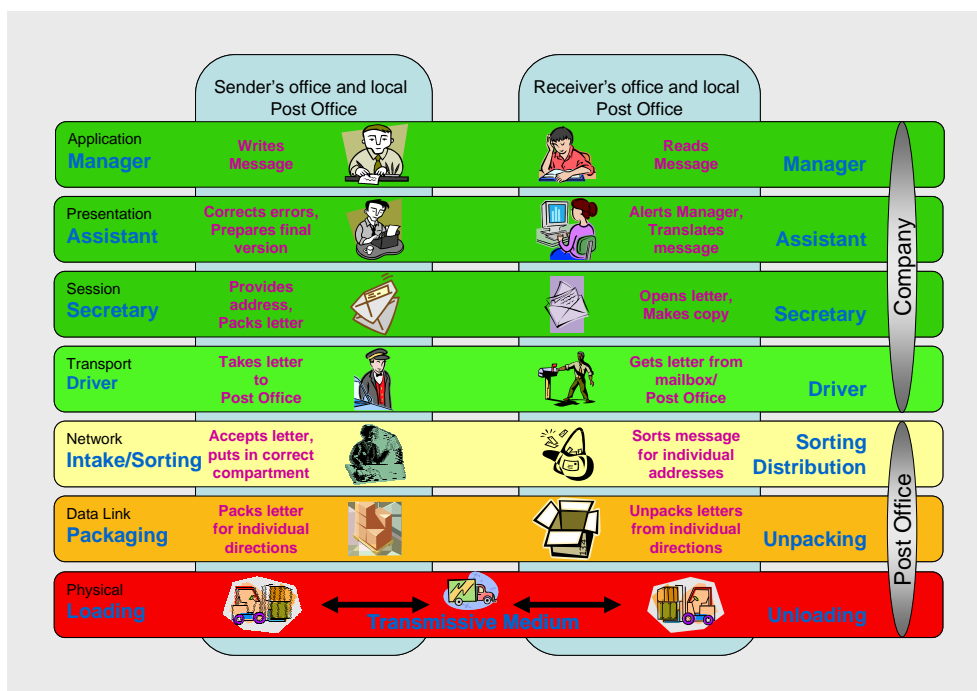


Figure 13 Analogy of the OSI model using the post system (adapted [41])

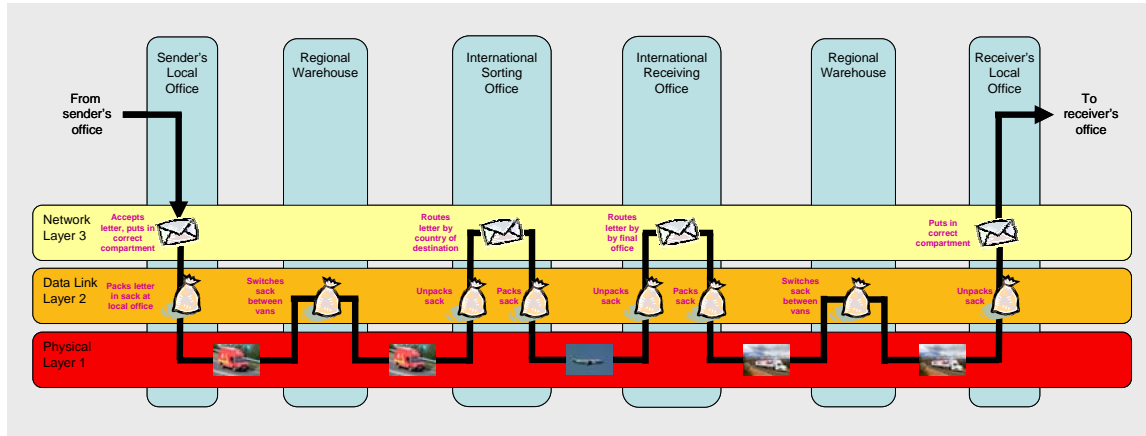


Figure 14 Media layer connections using the post system analogy in Figure 13

Inbound

- The Datalink layer unpacks the letter from the sack and hands it on.
- The Network layer sorts the message into a pigeonhole or mailbox.
- The Transport layer gathers the letter and in the case of the encyclopaedia, ensures all the parts are received and re-orders them into their correct order.
- The Session layer again is not really relevant in this analogy, but it does unpack the letter
- The Presentation layer adapts the letter for use by the Manager e.g. if the Manager was blind the Presentation layer might type the letter out in Braille.
- The Application layer reads the letter. Again this is not the final application. Here the final application might be comprehension of the content, the Application layer might be the eyesight or the touch (in the Braille case) used to read the letter.

Figure 14 extends the analogy to international traffic to show the transitions between media layers for an international letter. Here layer two is symbolised by containment within a mail sack (the sack signifies for example an Ethernet frame), layer three is characterised by taking the letter out of the sack for sorting into another sack (the sorting represents for example an IP routing). The distinction between the network and datalink layers can be hard to understand. A useful guide is to consider the datalink transmission being native to the sub-network, whereas the network layer is user at the interfaces between sub-networks. Thus in principal the datalink layer could be a non-standard proprietary solution, whereas the network layer must be standardised to allow transmission between non-compatible sub-networks.

Further Information

This description of the OSI model has been brief. Most of the information presented here has been adapted from Wikipedia which provides a good primer [41]. Much more information is available on the web. Some good sites include

- Cisco:
http://www.cisco.com/univercd/cc/td/doc/cisintwk/ito_doc/introint.htm#xtocid5
- Geocities:
<http://www.geocities.com/SiliconValley/Monitor/3131/ne/osimodel.html>
- Linux-Review:
http://www.linuxports.com/howto/intro_to_networking/c4412.htm
- LewisTechnology, (this site uses James Bond delivering a secret message to give an amusing analogy of how the layers work)
<http://www.lewistech.com/rlewis/Resources/JamesBondOSI2.aspx>

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