Literature Survey Report for the Broadband

Cable Modem Service (IEEE 802.16)

For

Advanced Networking (ADNET)

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1. Concept
1.1 Background - Richard Hanley

Cable Modems came into existence as one answer to the issue regarding the lack of bandwidth and speed available to home users. Home users traditionally used the analogue telephone system to transmit and send data across the Internet. The fastest they could connect on a standard connection was limited by the poor infrastructure (wiring etc) of a system designed to support voice communication not computer data transmission. The 56k dialup modems were the fastest achievable on such setups. Due to the boom in cable Television, brought about in part by the deregulation of the cable television stations but the 1984 Cable Act (allowing the stations to broadcast popular sports programs etc), it is estimated that by the end of the 80’s 53 million households were cable subscribers. With the infrastructure of cable already in place and cable of high speed communications via the coaxial cabling and fibre optical cables (far superior to the analogue telephone system) it is of no surprise that the Cable Modems, allowing the home user to connect to the Internet via their cable connections, proved popular and a viable success economically. The new Cable Modems allowed connections far in excess of that available on the old 56k dialups.

[CABLETVNY]

The cable business rational for implementing broadband on their networks was mainly to fight off competition from direct broadcast satellite operators. The ability to offer Internet access being the added incentive for the subscriber to use cable instead of the alternatives. The cable network has other advantages, as well as speed mention earlier, that contribute to its popularity and use:

- The cable infrastructure is already present in lots of homes and so easily available (one of the issues with its take up in the UK was lack of funding laying the cables in rural areas).
- The use of coaxial cable enables a larger bandwidth than the twisted pair copper cables in telephone networks.
- The service is ‘always on’ there is no need to dial up as there is with the telephone dialup modem.
- The cost of Cable is easy to budget for the subscriber as they are charges a flat fee per month. However this has become less of an incentive as dialup operators began offering a similar service.
- The business incentive to operators is that they can use one connection to support thousands of subscribers; with dialup you need one port per each subscriber.
- The final issue is content. The Cable Operators have close ties with big name content providers (like Time Warner Entertainment). This gives unique content to cable users and provides content providers with an easy way of distributing their output.

The standard used in the operation of Cable Modems today is called DOCSIS (Data Over Cable Service); developed in 1995. The rational behind DOCSIS being developed was as way of reducing production costs by using a common development platform. The work on DOCSIS was begun by a group of north American companies collectively referred to as “Multimedia Cable Network System Partners Ltd” (MCNS) who joined with CableLabs research group. Some companies use proprietary systems but DOCSIS is the most wide spread. Come version 1.1 of DOCSIS QoS (Quality of Service) was also implemented, this will be discussed later.

[GABE99c]

1.2 Other alternatives **- Nathalie Philippon**

1.2.1 ADSL (Asymmetric Digital Subscriber Line)

Originally created to permit the transmission of voice and data through copper wires, since a pair of copper wires can support voice and data at the same time. So it is possible to have a phone call while the computer is connected to the Internet. The data are travelling through the original wires used for the phone calls. The first use of ADSL was only to transmit a lot of data, because ISDN was overcrowded.

With ADSL, there is one specific network for the transmission of voice and another specific network for the data. There are two modems for each line, one is located at the host and the other is at the local exchange in the network, the exchange modem can be used by many lines. This technology became popular very quickly, users were offered ADSL thanks to telephone companies, which were interested in providing this type of access to the Internet. It is moreover quite cheap, if we consider the services offered with it, and it concurrences Cable Modems because of the price and the speed.

The ADSL modem can adapt the rate of transmission to the line (when it is a low rate line or if it is very busy) and it can check the noise along the line. It is possible to download voice files from the Internet at a rate of 1 Mbps, up to 8 Mbps. But the main advantage with ADSL, compared to Dialup Modem, is the fact that the computer is always connected to the network. There is no need to wait for the line when everyone in the area is connecting at the same time. There is a splitter in each modem, which check if the voice and the data were transmitted properly, without interfering one on the other.

ADSL is taking only a few seconds to find the line. This short time is only the time needed to reach the router. To transmit at very high rate, we cannot use very long distances with the same pair of copper wires, there is the need to reconfigure the message and in the same time check if it does not contain errors. Security is better with ADSL than with cable modem because a user does not share the same coaxial lines with its neighbours, he is directly linked to the Central Office (CO). There exist some troubles in security, but less than with dialup modems.

[GETECH03]

1.2.2 VDSL (Very high bit-rate DSL) **- Nathalie Philippon**

VDSL is like ADSL but is faster because it can transmit messages with a high rate. In both cases, data is transmitted in a short time, the bandwidth is always enough to carry the whole message or voice with high speed. The downstream is 8 Mbps but the upstream is 1 Mbps, that is why this system is called asymmetric. As a consequence of this difference of rate, ADSL uses FDM (Frequency Division Multiplexing) so we can know if the line is downloading or uploading by seeing the rate of transmission. Another variant exists called RADSL, which is ADSL that is able to adapt the rate of transmission to the business of the line, checked regularly. For example, it can consider the length of the line to transmit at the best rate, reducing it when necessary.

[SANJ_LEE02]

1.2.3 ISDN (Integrated Services Digital Network) **- Nathalie Philippon**

Uses two channels to transmit on the one hand voice and on the other hand data. The speed can be very high if we only want to send data, we can therefore use the two channels to transmit data, twice faster. That is why ISDN is a good alternative to Dialup Modem if the main use of being connected to the network is to download or upload pure data. ISDN works with digital signals, this is a gain of time because messages are originally digital, and all hosts use the same rate for the line. But it is not convenient because ISDN uses the phone line, which needs to be switched on. Moreover, the phone line will be congested during the time the computer is connected to the Internet.

[SANJ_LEE02]

1.3 Cable Modem Model - Richard Hanley

In figure 1.3a you will see the model that was developed for the cable modem.

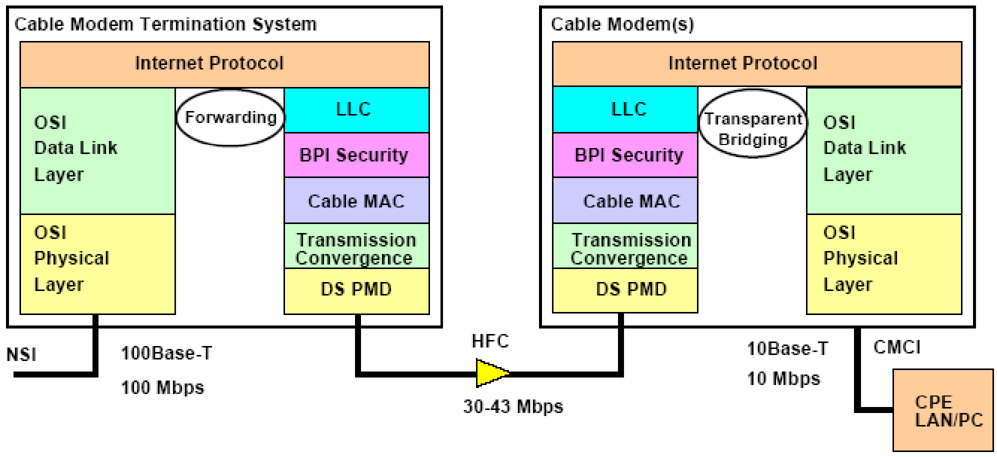


Fig 1.3a – Protocol Stack
Source: [AGILENT03]

This is the DOCSIS model (the one shown above is represents downstream but the upstream is the same but in reverse). The cable modem model lends its self to the OSI (Open Systems Interconnect) [see Appendix B]. The highest layers on the figure are the applications and the data flows downward from these.

The cable modem termination system (CMTS) takes the information from the web through the standard OSI layers to the universally known IP protocol. Then back down through its' own MAC layer; this adds cable modem specific headers. The data is then passed through the cable system through the MPEG-2 for downstream (PMD layers are used for the upstream). This data is passed through hybrid fibre cable (HFC) and then the reverse to the CMTS occurs in the cable modem until the data is brought to the IP layer. Here it can be transferred via the OSI to the subscribers LAN or PC depending on their setup.

[AGILENT03]

2. Architecture - Physical Layer

2.1 Technology - Evan Davies

Cable Modems work like a standard dialup modems except that it has a permanent connection to the Internet. Cable Modems also share their bandwidth with the local area. This is known as the neighbourhood node.

Cable Modems come in various shapes and sizes, from internal PCI cards to exterior modem to being included into the set-top box itself. Setting aside the physical appearance, all Cable Modems have the same basic components.

Standard Coaxial cable networks operate within 350 MHz to 450 MHz of capacity, which can provide around 60 channels, standard coaxial network doesn't have the capacity to handle both upstream and downstream traffic. Recently cable companies have upgraded their infrastructure and replaced their coaxial backbone with fibre optic. This is called Hybrid fibre-coaxial or HFC for short, fibre is used in the backbone and coaxial going to the homes, this new system provides bandwidth from 5 to 750 MHz or more. This allows for more TV channels, video on demand and Pay-TV. Cable Modems take advantage of the extra frequency and use frequency modulation to send and receive IP traffic.

Source: [ehards]

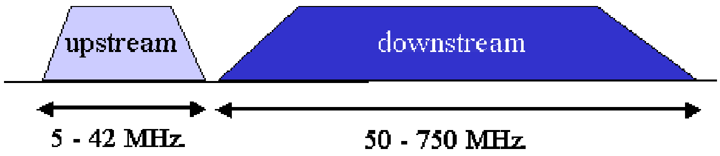


Fig 2.1a – Cable Modem Frequency Ranges
Source: [NextGen03c]

2.2 Inside the Cable Modem - Evan Davies

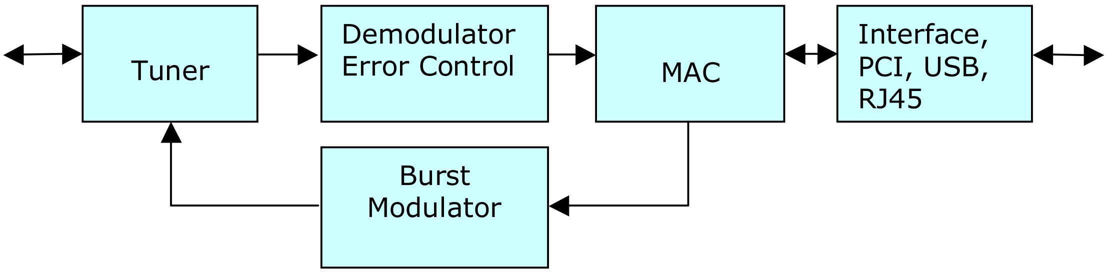


Fig 2.2a – Inside the Cable Modem Block Diagram
Source: [CableModem3]

2.2.1 Tuner

The tuner connects to the cable outlet. With the use of a splitter it receives the Internet data rather than all the data. The data comes through an unused cable channel [see 3.1 Protocols] and therefore the tuner simply passes it over to the demodulator.

2.2.2 Demodulator

The demodulator receives the modulated QAM-64/256 signal, It is then broken down into 0 and 1s by the Analogue/Digital converter. The frames are then checked by MPEG-2 frame synchronisation to make sure the data packets are synchronised. Then the data is checked for errors using Reed-Solomon error correction, corrupted packets are also corrected using this formula. [See 2.6 Error Control for more information].

2.2.3 Burst Modulator

Transmitted data is encoded using QPSK/QAM-16 on the specified frequency, and performs the digital/analogue conversion.

2.2.4 MAC

The Media Access Control system is located between the upstream and downstream section of the modem, MAC for Cable Modems are much more complex then the Ethernet MAC and requires some help of the CPU.

2.2.5 Interface

This is usually Ethernet RJ45 connection but can also be USB or PCI.

2.2.6 CPU

While not shown on the diagram a CPU is required, it mostly handles the MAC functions of the MAC system.

Source: [CableModem3]
[PCWorldM]

2.3 Downstream - Evan Davies

As explained earlier Cable Modems have more bandwidth downstream than upstream.

Frequency	42-850 MHz in USA and 65-850 MHz in Europe
Bandwidth	6 MHz in USA and 8 MHz in Europe
Modulation	64-QAM with 6 bits per symbol (normal) 256-QAM with 8 bits per symbol (faster, but more sensitive to noise)

	64-QAM	256-QAM
6 MHz	31.2 Mbit/s	41.6 Mbit/s
8 MHz	41.4 Mbit/s	55.2 Mbit/s

As you can see the European 8MHz cable runs a little faster than the USA.

This downstream data is the raw throuput only, in real life after the headers and error correction etc you lose a sizable chunk of it. Also similar to Ethernet all modems will receive all the download data, the cable modem then filters out the relevant data.

Source: [CableModem2]

2.4 Upstream - Evan Davies

2.4.1 Reserved Slots

Upstream bandwidth is shared with multiple users, but unlike Ethernet which uses collision detection Cable Modems must use collision avoidance techniques. Every cable modem transmits in timed bursts (also known as mini-slots), and each slot is reserved for specific modems. No other modems can transmit on another modems time slot.

2.4.2 Contention Slots

These slots are available for any modem to transmit within, if two modems transmit the same time then a collision occurs, when the head end receives the corrupted slot of data it will send a signal that no data was received. Then both modems will wait a random amount of time before retransmitting.

These slots can not be used for large amounts of data, they are used to send little short amounts, an example is to ask the head end for more time slots to transmit.

2.4.3 Ranging Slots

Cable Modems are all different distances away from the head end, to try and make the Cable Modems all work together properly; ranging slots are used to modify their clock speeds. The cable modem is given three slots and is told to transmit in the second slot, the head end receives the slot and does some tests to see if its in the correct position and signals the modem to alter its clock speed and try again until its perfect. Another outcome of this is to make the power level of the signal that reaches the head end the same level as the others.

Source: [CableModem1]

2.5 Modulation - Evan Davies

2.5.1 Quadratic Phase Shift Keying

Quadratic Phase Shift Keying transmits two waves with common frequencies which are offset by 90 degrees, each of which is amplitude modulated. This achieves 2 bits per symbol time and works in harsh and noisy environments.

2.5.2 Quadratic Amplitude Modulation

Like QPSK, QAM uses two waves, the I and the Q. One version of QAM is QAM-64 where each wave is amplitude-modulated independently with eight levels thus yielding 64 different amplitudes jointly.

While QAM-64 manages to encode six encoded bits per symbol, QAM-256 manages eight bits per symbol, while it offers better compression rates its more susceptible to noise and corruption.

2.6 Error Control - Evan Davies and James Saunders

Cables being what they are, are susceptible to interference and noise. Errors could be introduced into the Cable Modem signal for a number of reasons including signal degradation, bad cabling, interference or delays.

Because cable is used to transmit video and data services its not a viable option to have corrupted packets. Current error correction techniques used by TCP detect minimal number of errors and in most cases will ask for the packet to be retransmitted. Obviously retransmitting for a real time, live video stream of packets and data will take too long so a way was devised to allow the receiver to correct a large number of errors and making retransmission a thing of the past.

There are a couple of different techniques used within the DOCSIS Cable Modem system to either detect or correct errors.

Both upstream and downstream packets have a FEC (Forward Error Correction) trailer containing Reed-Solomon codes; these are additional redundant bits (like parity) that are used to aid in correcting any bits that are received in error.

Also as each upstream or downstream packet is essentially a broken down Ethernet frame at the point where the Ethernet frame is rejoined it automatically contains an Ethernet CRC (Cyclic Redundancy Check) field which can be used to detect errors.

2.6.1 FEC (Forward Error Correction) RS - Reed-Solomon

RS codes are block based correction codes used within a wide range of digital communication and storage including CD's, DVD's, Barcodes, Mobile Phones, Satellite Communication and Broadband technologies such as ADSL including Cable Modems.

FEC is used by filling up the left over space in the frame with a hamming code. The receiver can then do some calculations to work out if there are any errors and if so correct them. This technique works well if the errors are spread out along the data, if too many are in one location the algorithm fails. The number and type of errors which can be detected and corrected depends on the depth of the RS code.

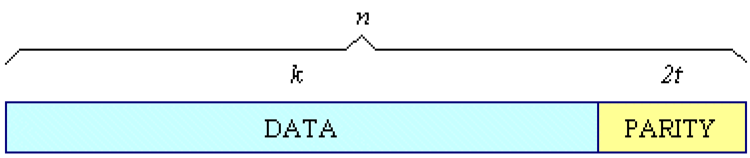


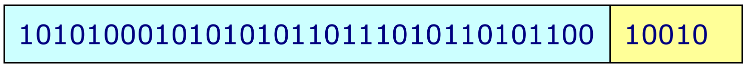
Fig 2.6.1a – Packet with Reed-Solomon trailer
Source: [4I2I]

"A RS code is specified as RS(n,k) with s-bit symbols. This means that the encoder takes k data symbols (MPEG or PDM packets) of s bits each and adds parity symbols to make an n symbol codeword.
There are n-k parity symbols of s bits each. A Reed-Solomon decoder can correct up to t symbols that contain errors in a codeword, where 2t = n-k.
The following diagram shows a typical Reed-Solomon codeword (this is known as a Systematic code because the data is left unchanged and the parity symbols are appended):"

Direct Quote from: [4I2I]

2.6.2 CRC (Cyclic Redundancy Check)

CRC is part of the Ethernet Packet Specification, In CRC, the sender takes the sum of all the binary 1's in the Ethernet payload and adds them together; the result is stored as a hexadecimal value in a 32bit packet trailer. The receiver again adds up all the binary 1's in the payload and compares the result to the value stored in the trailer. If the values are the same the packet is good.



Number of Bits in packet = 34
Number of 1's = 18
18 = 0x12 = 10010

Fig 2.6.2a – Packet with CRC trailer
Source: [RAD]

This is not totally fool proof, for example if an error were to cause a 1 to be changed to a 0 and somewhere else in the packet a 0 was changed to a 1 this error would not be detected, as to the CRC check it till has the right number of 1's even though the message may be wrong.

2.6.3 Interleaving

In addition to these Error Detection and Correction techniques interleaving is used to spread out the amount off errors within chunks of data, with the hope that they would be easier to correct. As errors often occur in one place from bursts of noise, the interleaving process reorders bits on transmission, if a chunk of data is damaged when the data is reordered by the receiver, the errors will be more spread out e.g. Where Red = Bad Bits!

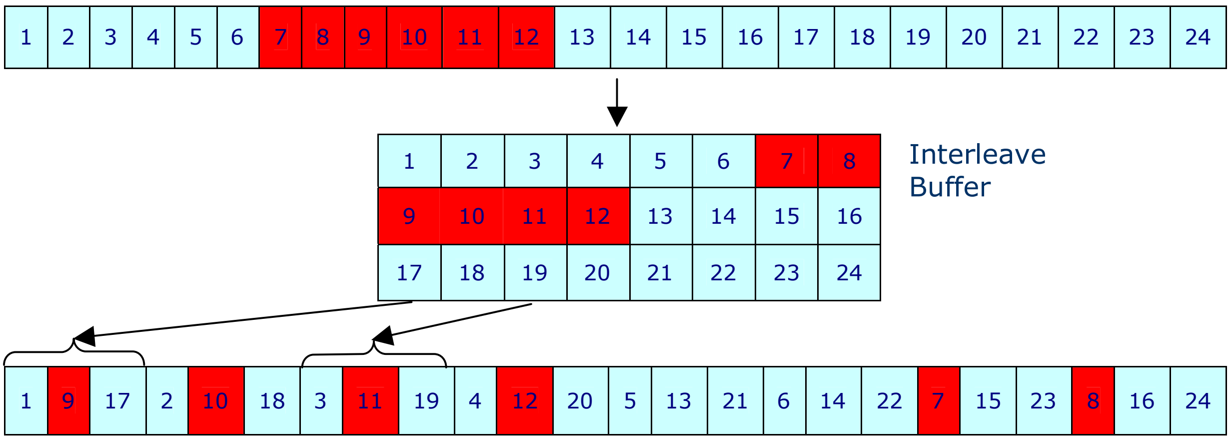


Fig 2.6.3a - Interleaving

Spread out errors, are easier to detect and change by the likes of CRC and Reed-Solomon.

The stream of data to be sent is rearranged in the Interleave buffer and then re-arranged into a new order known to both the sender and the receiver. The price of using Interleaving is latency, the bit stream will experience delay due to processing time; as the bits are put in and taken out of the Interleave Buffer.

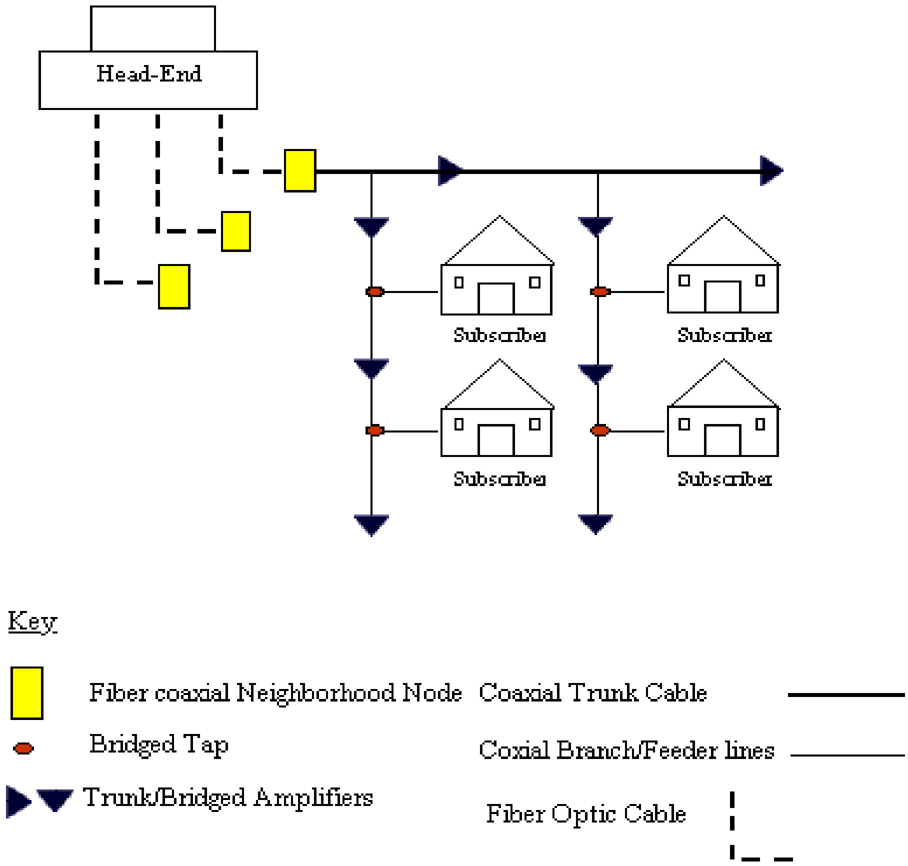
[GABE99b]

3. Architecture - Protocols
3.1 Access Methods - Nathalie Philippon

To log on the Internet when using a cable modem connection, we have to use the television network because it can receive some data (video) from a wide range area. There is in the network a Head-end linked to the television, so to the computer thanks to the cable between the computer and the television. Even if the name does not say so, there is no modem in this system. A cable modem can be seen as a Local Area Network, because the Head-end is most of the time situated in a local range, this Head-end is a bridge to the Internet.

The three main types of Cable Modems are set-top box, external and internal and their ways of running differ slightly [see 2.2 Inside the Cable Modem].

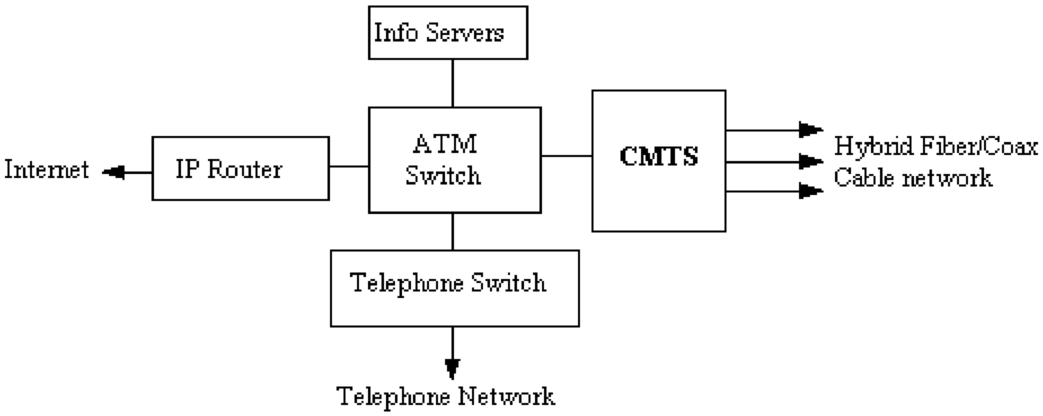
- Set-top box is a device that allows the user to connect to the Internet with any type of screen to watch the result, it can be a computer but also a television. It uses the POTS (Plain Old Telephone System). Through the same line, it is possible to take some data from the Internet or to send data to the Internet, so these two operations do not execute themselves at the same frequencies (FDM).
- External cable modem is when the computer is linked to the network via a wire in a wall socket. It uses a 10Base-T-Ethernet card.
- Finally, the internal version is a card inside the computer unit, it is essentially designed to desktop PCs. Cable Modems are linked with a socket or a television to a Head-end, which is then connected to other Head-ends.



Between the different subscribers, the wires are coaxial trunk cables, whereas fibre optic cables connect the Head-ends together. So there are numerous small networks and they are linked to create a Wide Area Network: a few houses share the same coaxial feeder line so neighbours can see the operations other people are doing, these groups of houses belong to a bigger network linked with coaxial trunk cables, which are connected to a FCNN (Fibre Coaxial Neighbourhood Node). There are several FCNN in the same Head-end. This scheme is called FTTN (Fibre To The Neighbourhood) because they use a mix of wires, such as trunk cables, fibre optic cables.

Cable modem architecture uses television lines, but those are only to download data, there was no need, when it was created, to send data from your house (television) to the network. So some radio frequencies were added to allow upstream. There are moreover so numerous subscribers that some other devices were added to the running of Cable Modems: servers, security systems, backbone connectivity and routers. Fibre optic cables increase the speed of transmission and it is very easy to transmit at 750 MHz. With Frequency Division Multiplexing, the line is divided into numerous bandwidths for television channels, downstream and upstream.

For each Fibre Coaxial Neighbourhood Node, there is one CMTS (Cable Modem Termination System) in the Head-end. The CMTS reads the destination of the packet it received and tries to find the best way to reach the computer hosting the site of this address. The path is then reserved and the real transmission can begin. At the end of the transmission, the sender is informed that the packet was sent and received properly. Moreover, a unique CMTS can deal with numerous transmissions at the same time. If the CMTS is always busy, it should be a good point to add a channel to it, to increase the number of packets sent in the same time with this CMTS.



Downstream signals are sent on the line where the end user, who has to receive the signal, is hosted, but all his neighbours are able to pick the signal up and keep it for them. So Cable Modems know if the signal is for them or not. In upstream direction, either Frequency Division Multiplexing technique or Time Division Multiplexing technique is used. The use of fibre optic cables increased the speed of transmission, because these cables replace coaxial cables, which were used along the whole path to the network.

Nevertheless, coaxial cables are still employed to connect end users to FCNNs in order to reduce the cost of lines. It could be possible to transmit data at higher speed by using fibre optic cables on the entire Internet, and there could be less routers because we can transmit on longer distances with fibre optic cables. That is why telephone companies are replacing coaxial cables by fibre optic cables, where subscribers have the most need of it for instance.

Fibre Coaxial Neighbourhood Nodes are situated between coaxial cables and fibre optic cables, one side is linked to end-users and the other side is linked to the Internet. Moreover, FCNNs can transform the signal received from coaxial cables to signals that can travel through fibre optic cables. Downstream signal are transmitted as optical signals and are then converted to go through coaxial trunk cables, whereas it is the inverse for upstream signals. And there is no possibility to neighbours to send data to each other unless going through the Fibre Coaxial Neighbourhood Node.

When we look at the configuration of the cable modem network, we can wonder how the message can reach the right end user, because there are several houses linked to the same coaxial cable. It is the job of Cable Modems to check if the message, which is going through the line, is intended to them or to their neighbours. When two Cable Modems are transmitting data to the Head-end and are using the same line, they have to share the line and to avoid interfering one with the other. To do so, they do not work on the same bandwidth, so it is supposed not to be any trouble during the transmission. The two most used ways to share a line are using different bandwidths or dividing the line into slots of time. Cable Modems are produced by companies such as Hybrid Networks, Terayon or Motorola.

3.2 Routing

- James Saunders

At the Cable Operator end, there is a device called a CMTS (Cable Modem Termination Service) this provides much the same functionality as a Dialup Router or DSLAM Router provides in other ISP alternatives – A Gateway to the Internet.

The CMTS routes the traffic coming to and from a number of different users – This traffic may not just be Internet IP Data it may also be contain Video and Interactive TV Messages. The Internet Data is merged in one direction and split in the other from Video Data and routed to an ISP (Internet Service Provider) destined for the Internet.

[HSW03]

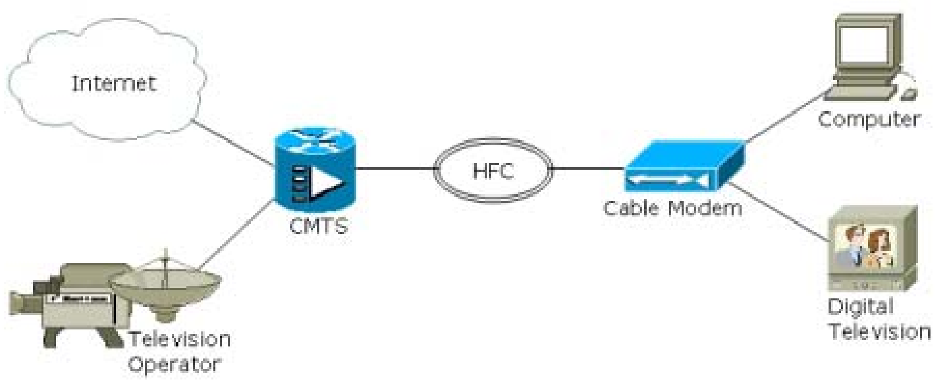


Fig 3.2a – Cable Modem Infrastructure
Source: [CISCO03a]

To transfer data quicker over longer distances – Cable Operators started using specially designed combined Coaxial and Fibre Optic cables, HFC (Hybrid Fibre Coaxial) made it possible to transfer data along fibre while still been compatible with the original Coaxial system.

In some cases the HFC may run all the way from the CMTS to the end of the subscribers road, where is would be converted to normal Coaxial signals running into the home.

3.2.1 Routing Block Diagram

A more in depth look at the Cable Operators backend showing the CMTS and how it routes data can be seen in the following block diagram.

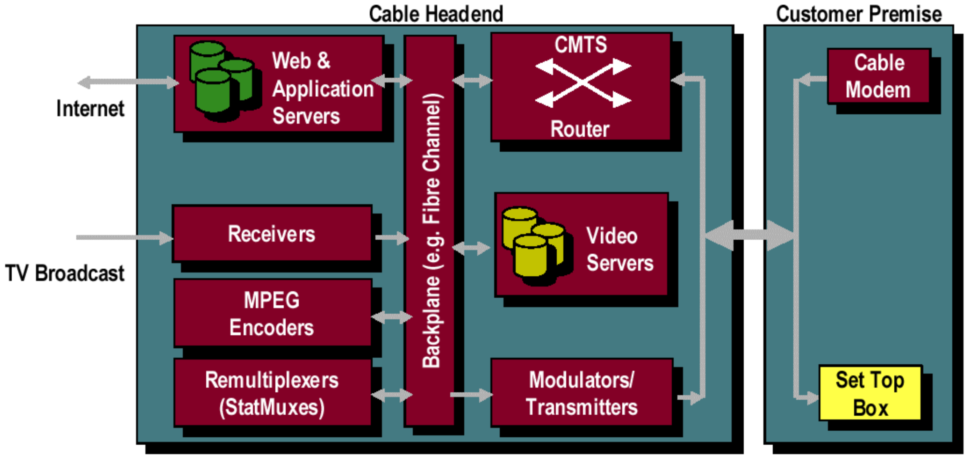


Fig 3.2.1a – Block Diagram of Cable Modem system
Source: [XILINX03]

3.2.2 CMTS

As discussed there is usually one CMTS providing connection for a number of subscribers in a Neighbourhood (FCNN). The CMTS reads MPEG-2 data streams [see 3.4 and 3.5.4 on MPEG-2] and determines the destination /source as video or data and routes accordingly, in Fig 3.2.1a the CMTS is connected to:

- Web Servers and the Internet, where IP packets are routed to and from. (Upstream and Downstream)
- Receivers, MPEG Encoders and Television Operators. These are used to provider video stream for TV, in a downstream direction (out from the CMTS towards to modem)

A single CMTS can cope with multiple transmissions at the same time, while also granting and denying Cable Modems the ability to transmit back, this enables the CMTS to control the routing of all packets to receive them as and when it wants them.

3.3 Management - James Saunders

Cable Modems have been designed to be as user friendly as possible without the need for subscribers to have to configure them. When a new cable modem is taken from its box for the first time and plugged in, it has no way of knowing how to connect to the Internet, there are two levels of learning which the Cable Modem must go through for it to successfully be able to start transferring data to and from the Internet. All management of cable modem configuration is done at the Cable Operators end.

At the first level of learning - Initially the Cable Modem needs to learn some Physical Layer information; which frequencies it will be sending and receiving data on with the Cable Operator.

The modem does this by scanning across downstream frequencies (frequencies coming into the modem) with the eventual aim to read special control packets called Upstream Channel Descriptors, these packets are broadcast by the CMTS solely for newly attached Cable Modems. The scanning procedure is done by starting with the relatively low frequencies (some Cable Modems jump to starting scanning at 350Mhz as it is assumed that below this frequency are analog TV signals) and slowly increasing in 6MHz steps to 850Mhz at each step testing whether it is a Digital TV signal or Data by examining the packets for a value called a PID (Program Identifier). Each TV channel would have a unique PID and a special PID of "1111111111110" (0x1FFE) has been set aside by DOCSIS (Data over Cable Service Interface Specifications) for Cable Modems. This PID is not allowed to be used by TV operators to broadcast standard channels on. Once the correct frequency is reached with the correct PID, the Upstream Channel Descriptor can be read.

3.3.1 Upstream Channel Descriptor

The Upstream Channel Descriptor contains amongst other information the following configuration information:

- Frequency, on which the cable modem is allowed to transmit, ranges between 5 - 42 MHz.
- Initial Rate of Transmission
- Maximum number of bytes that can be transmitted the next time permission to send is granted
- Modulation Techniques (QPSK or QAM-16)

Once the Cable modem knows which upstream and downstream frequencies it can use it then has permission to transmit and must learn one more physical piece of information through a process called 'ranging' in which the cable modem attempts to learn how far it is to the CMTS – this is needed to synchronise the timeslots on which it is to send. Ranging is done by sending a short packet to the CMTS and measuring the response time [see 2.4.3 Ranging Slots].

[GABE99a]

At the second level of learning - The Cable Operator is responsible for providing two configuration services to the Cable Modems, Assigning IP addresses via DHCP and Assigning Configuration Scripts via TFTP.

3.3.2 DHCP (Dynamic Host Control Protocol) Address Assignment

An Internet protocol responsible for automating the configuration of computers which use TCP/IP. DHCP can be used to automatically assign IP addresses to Cable Modems, to deliver TCP/IP configuration addresses such as the subnet mask and default router and TFTP server and to provide other configuration information such as the addresses for time, news and TFTP servers.

```
option domain-name            "cableoperator.net";
option domain-name-servers    123.123.123.1, 123.123.123.2;
option time-offset            0;
default-lease-time            21600;
max-lease-time 43200;
option tftp-server-name       "123.123.123.10"; #tftp server

subnet 123.123.123.0 netmask 255.255.255.0 {
      option routers 123.123.123.254;         #default gateway
      option subnet-mask 255.255.255.0;
      default-lease-time 86400;
      max-lease-time 604800;
      range 123.123.123.50 123.123.123.250;
}
```

Fig 3.3.2a – Example of DHCP script showing configuration sent to Cable Modem

3.3.3 TFTP (Trivial File Transfer Protocol) Configuration Assignment

A Simple UDP protocol used by Internet devices to transfer files. Specifically, it is one of the most popular methods used for "remote booting". In the case of Cable Modems it is used to upload/download a configuration script to the Cable Modem called a DOCSIS Config. The script MUST contain the following configuration information:

- Network Access
- Class of Service – Subscriber connection speed cap. (e.g. 600K)

The following settings are optional:

- Vendor ID
- Firmware Software Upgrade filename & Software Server IP
- CMTS Ethernet MAC Address
- Telephone Settings (if applicable)
- Vendor Specific Configuration (if applicable)
- Downstream Frequency
- Upstream Channel ID [MOTOROLA03]

```
DownstreamFrequency     123000000;
UpstreamChannelId       1;
NetworkAccess           1;
ClassOfService {
      ClassID           1;
      MaxRateDown       512000;
      MaxRateUp         64000;
      PriorityUp        3;
      GuaranteedUp      32000;
      MaxBurstUp        54314;
      PrivacyEnable     1;
}
```

Fig 3.3.3a – Example of DOCSIS Config Script sent to Cable Modem
Source: [SOURCEFORGE]

The learning stages above are only needed for a newly attached Cable Modem. As it can take some time to gather, all the information in the stages above (e.g. Frequencies, Addresses, Configurations, Ranging Information etc.) are stored on NVRAM (Non Volatile RAM) which means that even after a reset or power down the modem will still remember this information.

The Cable modem will finally ask for the current time of day, sets up access to network, assigns IDs and slots and establishes the encryption and decryption keys see [4.1 Authentication].

By allowing all the configuration information to be based at the Cable Operators end, it means that management is made easier with operators storing all configurations centrally and being able to ‘push’ new DOCSIS Configs onto Cable Modems to adjust Cable Modem operation such as Class of Service, used to slow down or speed up the subscribers’ bandwidth. The act of slowing down a Cable Modem through this method is also known as ‘Capping’.

3.4 Encapsulation - James Saunders

To make the cable modem data service compatible with the digital TV service, the DOCSIS standard specifies MPEG-2 packets as the framing protocol for downstream data; that is IP packets are placed in the payload section of MPEG-2 frames. Using MPEG-2 means that other types of information also encapsulated with MPEG-2 (e.g., voice and video) can all be sent on the same Radio Frequency carrier as DOCSIS Cable Modem data maximising radio bandwidth.

3.5 Frame Formats

- James Saunders

3.5.1 DOCSIS MAC Header

Within the DOCSIS system the MAC frame is the standard 'transfer unit' between the Cable Modem and the CMTS, the same frame is used for both upstream and downstream communications. MAC frames can be variable in length. The first part of the MAC frame is the MAC header, this header identifies the contents of the Data filed.

Frame Control (8 bits)	MAC Parameter (8 bits)
Length (16 bits)	
Extended Header (0-240 bytes) …	
Header Check Sequence (16 bits)	
Data	

- **Frame Control FC (8 bits)**
  Identifies type of MAC Header, split into 3 parts:
  - **FC Control Type field (2 bits)**
    00: Packet PDU MAC Header
    01: ATM PDU MAC Header
    10: Reserved PDU MAC Header
    11: MAC Specific Header
  - **FC Parameter Field (5 bits)**
    Parameter bits, use dependent on FC Type.
  - **Extended Header Toggle (1 bit)**
    When = 1, indicates that EHDR field is present. And the length of the EHDR would be determined in the MAC Parameter Field.
- **MAC Parameter (8 bits)**
  Parameter field whose use is dependent on FC:
  if EHDR_ON=1; used for EHDR field length (ELEN) else if for concatenated frames (see Table 6-9) used for MAC frame count else (for Requests only) indicates the number of mini-slots and/or ATM cells requested
- **Length (16 bits)**
  The length of the MAC frame. The length is defined to be the sum of the number of bytes in the extended header (if present) and the number of bytes following the HCS field. (For a REQ Header, this field is the Service ID instead)
- **Extended MAC Header EHDR (optional; variable size 0-240 bytes)**
  The Extended Header (EHDR) field provides extensions to the MAC frame format. It is used to implement datalink security and can be extended to add support for additional functions in future releases. Initial implementations SHOULD pass this field to the processor. This will allow future software upgrades to take advantage of this capability. (Refer to Section 6.2.6, "Extended MAC Headers" for details.)
- **Header Check Sequence (2 bytes)**
  The HCS field is a 16-bit CRC that ensures the integrity of the MAC Header, even in a collision environment. The HCS field coverage MUST include the entire MAC Header, starting with the FC field and including any EHDR field that may be present.

[DOCSIS03]

MAC frames may contain Internet data, control messages or signalling. The way in which these Frames are transported to and from the Cable Modem differs, frame formats can be divided into two types; MPEG-2 packets, used in downstream direction only and PMD (Physical Media Dependent) packets used for upstream and signalling.

The upstream transmission is done at a different frequency than the downstream data, these frequencies are learnt in the learning stages described above in the [Management Section] and also transmitted using different modulation techniques (FDMA, QPSK, TDMA, QAM). Because of this frequency sharing mechanism, it is possible for the Cable Modem to use a single cable to transmit and receive simultaneously.

For example:

- Downstream – 88 - 860 MHz using QAM
- Upstream – 5 – 42 MHz using QPSK

3.5.2 Downstream Frames **- James Saunders**

As mentioned above [3.4 Encapsulation], the MPEG-2 transport layer which is present in the downstream flow only, is used to provide a common platform for the transfer of video and data over the Cable Modem network. IP packets are transferred in continuous 188 byte MPEG-2 packets containing the following header information:

<table>
<tr><td colspan="8">Sync Byte
(8 bits)</td></tr>
<tr><td>T Error
(1 bit)</td><td>Payload
(1 bit)</td><td>Priority
(1 bit)</td><td colspan="5">PID
(first 4 bits)</td></tr>
<tr><td colspan="8">PID
(last 8 bits)</td></tr>
<tr><td colspan="2">Scrambling
(2 bits)</td><td colspan="2">Adaptation
(2 bits)</td><td colspan="4">Continuity Counter
(4 bits)</td></tr>
<tr><td colspan="8">Pointer
(8 bits)</td></tr>
<tr><td colspan="8">Data</td></tr>
</table>

- **MPEG header (4 bytes)**
  Identifies packets carrying Data Over Cable, Broken down the MPEG-2 Header Contains:
  - **Sync Byte (8 bits)**
    0x47; MPEG Packet Sync byte
  - **Transport Error Indicator (1 bit)**
    Indicates an error has occurred in the reception of the packet. This bit is reset to zero by the sender, and set to one whenever an error occurs in transmission of the packet
  - **Payload Start Indicator (1 bit)**
    A value of one indicates the presence of a Pointer field as the first byte of the payload (fifth byte of the packet)
  - **Transport Priority (1 bit)**
    Reserved, set to 0
  - **PID (13 bits)**
    This is the PID value [see 3.3 Management] and would ordinarily contain the 0x1FFE string, to ensure that both the Cable Modem and CMTS know it holds data and not video.
  - **Transport Scrambling Control (2 bits)**
    Reserved, set to 00
  - **Adaptation Field Control (2 bits)**
    Use of the Adaptation Field is NOT ALLOWED in a DOCSIS PID, set to 01
  - **Continuity Counter (4 bits)**
    Counter for packets within the PID

- **Pointer (1 byte)**
  Used for MAC messages that extend over multiple MPEG frames. (Unused pointer locations are filled with data).

- **The data payload is 183 bytes long (184 without the pointer)**
  If the data does not need the entire payload capacity, padding bytes of binary 1's are used to fill the packet to make it a total of 188 including headers.

[CABLELABS]

These MPEG-2 packets are continuously sent even if there is no data to send, this is done so that the stream is kept in synchronization.

The data being sent downstream may have been corrupted and may contain errors, instead of asking for a retransmission, a special mechanism is used to correct errors. This mechanism, known as a Forward Error Correction (FEC) code is the last 16 bytes of the frame, [see 2.6 Error Control]

The payload portion takes the Ethernet frame and breaks it into segments of 184 bytes. Some bits in the header identify the payload as being the start of the Ethernet frame, in the middle of the Ethernet frame, or the end of the Ethernet frame.

MAC frames may begin anywhere within an MPEG packet, MAC frames may span many MPEG packets, and several MAC frames may exist within an MPEG packet.

3.5.3 Upstream Frames **- James Saunders**

Upstream flow is transported as units also known as PMD (Physical Media-Dependent) packets, these are measured in terms of time instead of bytes and each unit is 6.25 microseconds long and each unit is known as a mini-slot. The amount of data transferred in each mini-slot can be variable as it is depended on the upstream speed. In order for a Cable Modem to transmit data, it must request with the CMTS enough mini-slots to send the packet; again the number of mini-slots needed is dependent on upstream speed.

Unique Word (16 bit)	ATM Header	Data

- **Unique Word (16 bit)**
  Since the upstream data is just a short burst of data, the demodulator needs something to trigger on. That is the unique word, that is appended to the beginning of the data.
- **ATM Header**
  Header used for Transport within the ATM network.

A cable modem may have a Data Packet to transmit to the CMTS, it would request from the CMTS the number of mini-slots needed to transfer the whole packet.

It is the job of the CMTS to decide on what data is to be sent downstream and to decide when to give a Cable Modem permission to transmit and how much data the Cable Modem should transmit. Because the CMTS has such complete control of the system, it can accurately schedule the delivery of data.

[IEEE802]

3.5.4 Frame Life **- James Saunders**

Below is the breakdown of data for both upstream and downstream data. User data is first broken down into TCP/IP packets and then put in an Ethernet frame, this Ethernet frame has the DOSCIS header appended to it.

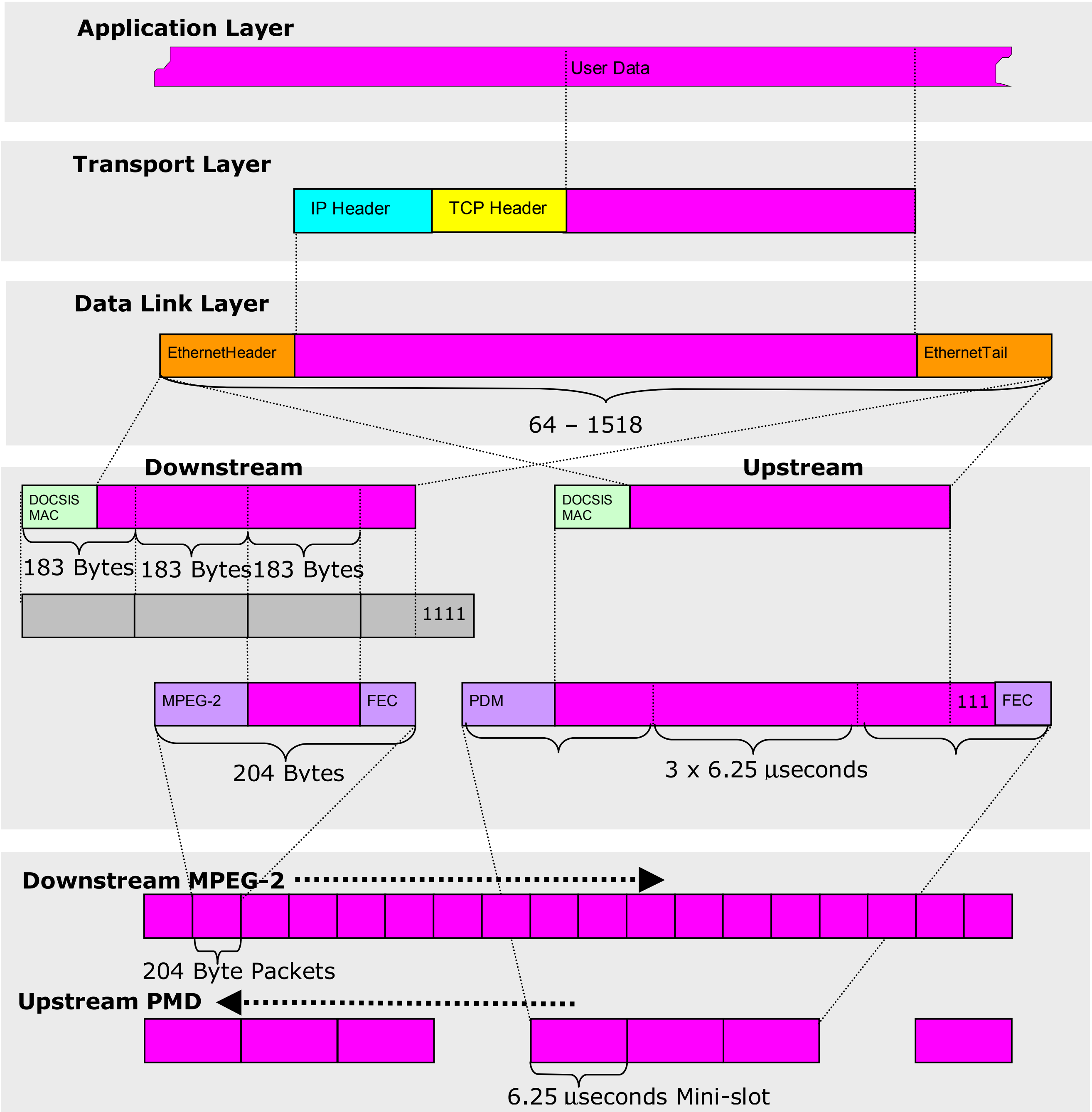


Fig 3.5.4a – Breakdown of IP Packets into Upstream and Downstream Packets
Source: [NextGen03b]

Depending on direction of stream the DOCSIS MAC frame is broken down in two different ways:

For downstream DOCSIS MAC frame is broken down into 183 Byte packet chunks and encapsulated in MPEG-2 Packets.
For upstream the DOCSIS MAC frame is broken down into 6.25 µsecond packet chunks. If any packets are not full they are filled with binary 1's to make the packet its full size

4. Security - Richard Hanley

With Cable Modems it would be possible for your neighbours to view, with some kind of packet sniffing tool or similar, the data your are sending and receiving. To counter this problem the cable operators employ a system known as Baseline Privacy Plus (BPI+). This encrypts all your data to ensure that anyone can not snoop on your transmissions. The BPI+ also stops the illegal use of someone's connection to gain free access.

The encryption used must travel with the information where ever it goes. The US has laws on the level of encryption that is allowed to be exported. As such the maximum encryption available is 128 bit. To have a data exchange there is first key exchange. The key exchange uses triple DES as its encryption. This is quite a strong encryption and provides a satisfactory protection to the key exchange. The algorithm used is a public key exchange. [GABE99d]

4.1 Authentication - Richard Hanley

Cable Modems do not require a username and password in the same way the dial up connections do. The authentication is actually hard coded into the Cable Modems when they are built. This is called the X.509 digital certificate it is built up of the following items:

- A serial number
- Cryptographic public key
- Ethernet MAC address
- The Manufacture's Identification

The X.509 is verified by the head end also known as distribution hub. Once this has been verified the following data sent by that user is encrypted using their public key.

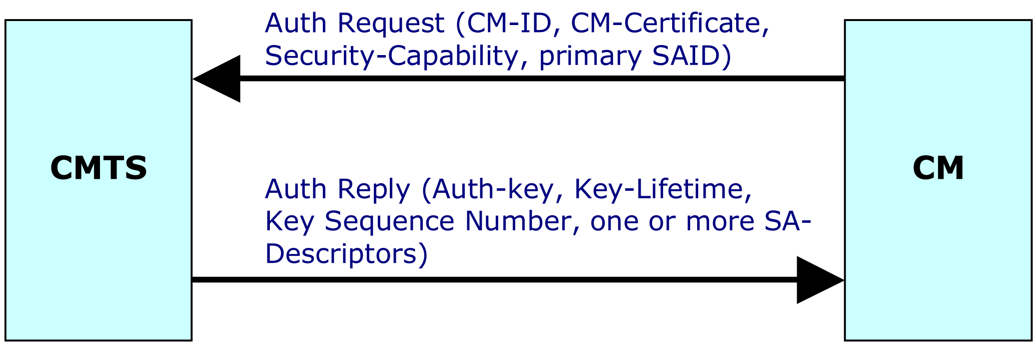


Fig 4.1a – Authentication
Source: [MOTOROLA03]

Figure 4.1 shows how a basic authentication is carried out between the cable modem and cable modem termination system. The CM Certificate is the X.509 certificate and the CM-ID is the serial number, manufacture ID, MAC address and RSA public key.

The cable modem first sends its X.509 certificate and manufactures certificate. This is verified by checking its expiration date, ensuring issuer name is the same as manufactures name and finally that the X.509 signature is valid using the manufactures certificate public key. The CMTS also verifies the manufacturer certificate but using DOCSIS root public key to test signature. Once the CMTS has verified the x.509 certificate it responds to ensure the owner is actually the correct owner.

To do this the CMTS will encrypt the authorization key with the CM public key. The CM uses it private key (if it was an impostor it would not have the matching private key) to get the authorization key. Using this it will generate a Hash-based Message Authentication Code (HMAC) key and reply to the CMTS with this. The verification of this HMAC key proves the CM has the private key to match the public key.

[MOTOROLA03]

4.2 QoS (Quality of Service) - Richard Hanley

QoS or Quality of Service was added to the DOCSIS standard in version 1.1. In order to implement Quality of Service, the following features where added into DOCSIS 1.1:

- Packet Priorities
- CMTS
- Unsolicited Grants
- Packet Fragmentation
- Payload Header Suppression

4.2.1 Packet Priorities

The packets are assigned a priority, those with higher priorities are dealt with first and can jump ahead of queues on routers etc.

4.2.2 CMTS Control

The CMTS instructs the modem how much data and for what period of time it may transmit its data.

4.2.3 Unsolicited Grants

The issue with CMTS is that everyone might transmit at the same time; the data would overlap and become confused and muddled. The UCG (Unsolicited Grant Service) solves this problem. Essentially what the UGS does is have the cable modem transmit the requirements of it's session. This information is used to assign a slot of time to this transmission so that the different Cable Modems do not overlap and collide.

4.2.4 Packet Fragmentation

Large packets of information are broken up. This is done so that more important transmission (those with a higher priority) can interrupt and be transmitting without waiting for the whole of the large packet to be sent.

4.2.5 Payload Header Suppression

The payload header suppression works to improve QoS by decreasing the amount of data that is sent. It does this by removing duplicate information that will not change from one packet to another, for example the destination address may be the same for multiple packets so it will remove any duplicates of the address.

Another form of QoS used by Cable Modems (although not strictly a QoS method) is the implementation of capping. Capping limits the bandwidth available to a subscriber depending on what subscription price they pay. Examples of such bandwidths are 150kbs (it has been argued this is not true broadband), 600kbs, 1mbs. This means that a user can only use as much bandwidth as they have paid for. In the past there have been issues of subscribers "uncapping" [see 3.3.3 TFTP Configuration Assignment] the limit and increasing their bandwidth illegally. This is not so much an issue these days as it is now well protected.

One issue with Cable Modems is if neighbouring subscribers are using a lot of their bandwidth it can effect the whole street (or subscribers connected to same port).

[NextGen03a]

5. Conclusion

5.1 Future Uses for Cable Modems - Nathalie Philippon

Cable Modems are now using a combination of fibre optic cables and coaxial trunk cables. The first ones are the fastest and they do not need a lot of amplifiers along the path. But the second ones are the cheapest and they are very useful to connect millions of houses anywhere on Earth to the network. In the future, if fibre optic cables become cheaper than now, it will be very interesting to replace coaxial trunk cables with fibre optic cables. In doing this, speed of transmission will be faster and with better quality because there is less noise in fibre optic cables than in coaxial trunk cables.

Cable companies aim to extend the bandwidth for downstream to reach higher rate of transmission and they might want to use two different cables to transmit data, one for upstream and one for downstream. Other important purposes are making the network become safer in protecting data to be read by neighbours, or using new cables with clusters, to reach much higher speeds of transmission in both ways.

5.2 VoIP (Voice over IP) - Nathalie Philippon

We can assume that in the few next years telephone communications will be done with IP addresses, the scheme will be reversed. Internet was developed over telephone lines, but because now Internet is more performing than telephone lines, it would be a great idea to transpose telephone lines to something similar to the Internet. The Hybrid Fibre Coax (HFC) can easily support the transmission of voice, so Cable Modems have made the voice communications become better than before. Numerous researchers are working to find out how to transmit voice on a packet switching network, because the whole voice message need to be reconstructed before being open by the receiver.

[BCR03]

5.3 End Conclusion (The Comparison to Other Broadband Technologies) - James Saunders

Cable Modems offer a cost effective way for Cable TV Providers to offer a high speed data service to its already large subscriber base, with relatively low change to its architecture.

As the Cable TV architecture needs to be of higher quality than the telephone architecture (in terms of cabling) it is already at a greater advantage for offering a better data service.

Cable Modems greatest competitor ADSL [see 1.2.1 ADSL] can offer a similar service in terms of always on and speed, but ADSL is offered at a greater cost to its operator - the telephone company, due to the need for separate lines for all subscribers, and with the lower quality twisted pair cable of telephone lines, the telephone companies are unable to provide ADSL to certain areas due to bad cabling or long distances.

To the casual user there is no difference between Cable and ADSL, the real advantage is with the Service Operator, and its architecture.

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Glossary of Terms

ADSL	Asymmetric Digital Subscriber Line – Type of Broadband
BPI+	Baseline Privacy Plus
CM	Cable Modem
CMTS	Cable Modem Termination Service
CO	Central Office
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check – Form of Parity Checking
DHCP	Dynamic Host Configuration Protocol
DOCSIS	Data Over Cable Service Interface Specifications Specification for transmission of data over a cable network that has been approved by the ITU as an international standard.
DSLAM	Digital Subscriber Line Access Multiplexer
FCNN	Fibre Coaxial Neighbourhood Node
FEC	Forward Error Correction
FTTN	Fibre To The Neighbourhood
HFC	Hybrid Fibre Coaxial – Type of Fibre, Coaxial Combo
IP	Internet Protocol
ISDN	Integrated Services Digital Network
ISP	Internet Service Provider
MAC	Media Address Control
MHz	Megahertz – One million cycles per second. Used especially as a radio-frequency unit.
MPEG-2	Motion Picture Expert Group - a set of protocols designed for encoding, compressing, storing and transmitting audio, video and data in digital form.
OSI	Open Systems Interconnect
PCI	Peripheral Component Interconnect, Currently by far the most popular local I/O bus, developed by Intel and introduced in 1993
PID	Program Identifier / Packet Identifier
PMD	Physical Media Dependent
QAM-16	Quadrature Amplitude Modulation – a frequency modulation technique
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying - a digital frequency modulation technique used for sending data over coaxial cable networks. Since it's both easy to implement and fairly resistant to noise, QPSK is used primarily for sending data from the cable subscriber upstream to the Internet.
RADSL	Rate Adaptive Digital Subscriber Line – Type of Broadband
RJ45	Type Of Network Cable Plug commonly used in Ethernet Networks
RS	Reed-Solomon – Forward Error Correction
TCP/IP	Transmission Control Protocol / Internet Protocol
TFTP	Trivial File Transfer Protocol – Simple Protocol for transferring files
TV	Television
USB	Universal Serial Bus – Type of Serial Data Port on Computers
VoIP	Voice Over IP – Transmission of Voice over Data Network
UGS	Unsolicited Grant Service (QOS)

Appendix A - Packet Headers

IP Header [STEVENS94]

<table>
<tr><td>Version
(4 bit)</td><td colspan="2">Header
Length (4bit)</td><td>Type of Service (TOS)
(8 bit)</td><td colspan="2">Size of Datagram
(16 bit)</td></tr>
<tr><td colspan="4">Identification
(16 bit)</td><td>Flags
(3 bit)</td><td>Fragment Offset
(13 bit)</td></tr>
<tr><td colspan="2">Time to Live (TTL)
(8 bit)</td><td colspan="2">Protocol
(8 bit)</td><td colspan="2">Header Checksum
(16 bit)</td></tr>
<tr><td colspan="6">Source IP Address
(32 bit)</td></tr>
<tr><td colspan="6">Destination IP Address
(32 bit)</td></tr>
<tr><td colspan="6">Options</td></tr>
<tr><td colspan="6">Data</td></tr>
</table>

- **Version**
  (always set to the value 4, which is the current version of IP)
- **Header Length**
  (number of 32 -bit words forming the header, usually five)
- **Type of Service**
  now known as Differentiated Services Code Point (DSCP) (usually set to 0, but may indicate particular Quality of Service needs from the network, the DSCP defines one of a set of class of service)
- **Size of Datagram**
  (in bytes, this is the combined length of the header and the data)
- **Identification**
  (16-bit number which together with the source address uniquely identifies this packet - used during reassembly of fragmented datagrams)
- **Flags**
  (a sequence of three flags (one of the 4 bits is unused) used to control whether routers are allowed to fragment a packet (i.e. the Don't Fragment, DF, flag), and to indicate the parts of a packet to the receiver)
- **Fragment Offset**
  (a byte count from the start of the original sent packet, set by any router which performs IP router fragmentation)
- **Time To Live**
  (Number of hops /links which the packet may be routed over, decremented by most routers - used to prevent accidental routing loops)
- **Protocol**
  (Service Access Point (SAP) which indicates the type of transport packet being carried (e.g. 1 = ICMP; 2= IGMP; 4 = IpinIP; 6 = TCP; 17= UDP; 94 = IPinIP).
- **Header Checksum**
  (A 2's complement checksum inserted by the sender and updated whenever the packet header is modified by a router - Used to detect processing errors introduced into the packet inside a router or bridge where the packet is not protected by a link layer cyclic redundancy check. Packets with an invalid checksum are discarded by all nodes in an IP network)
- **Source IP Address**
  (the IP address of the original sender of the packet)
- **Destination IP Address**
  (the IP address of the final destination of the packet)
- **Options**
  (not normally used, but when used the IP header length will be > 5 32-bit words to indicate the size of the options field)

Appendix A - Packet Headers

TCP Header [STEVENS94]

<table>
<tr><td colspan="8">Source Port Number
(16 bit)</td><td>Destination Port Number
(16 bit)</td></tr>
<tr><td colspan="9">Sequence Number
(32 bit)</td></tr>
<tr><td colspan="9">Acknowledgement Number
(32 bit)</td></tr>
<tr><td>Header Len
(4 bit)</td><td>Reserved
(6 bit)</td><td>U
R
G</td><td>A
C
K</td><td>P
S
H</td><td>R
S
T</td><td>S
Y
N</td><td>F
I
N</td><td>Window Size
(16 bit)</td></tr>
<tr><td colspan="8">TCP Checksum
(16 bit)</td><td>Urgent Pointer
(16 bit)</td></tr>
<tr><td colspan="9">Options</td></tr>
<tr><td colspan="9">Data</td></tr>
</table>

- **Source Port Number**
  16 bits The source port number.
- **Destination Port Number**
  16 bits The destination port number.
- **Sequence Number**
  32 bits The sequence number of the first data octet in this segment (except when SYN is present). If SYN is present the sequence number is the initial sequence number (ISN) and the first data octet is ISN+1.
- **Acknowledgment Number**
  32 bits If the ACK control bit is set this field contains the value of the next sequence number the sender of the segment is expecting to receive. Once a connection is established this is always sent.
- **Header Length**
  4 bits The number of 32 bit words in the TCP Header. This indicates where the data begins. The TCP header (even one including options) is an integral number of 32 bits long.
- **Reserved**
  6 bits Reserved for future use. Must be zero.
- **Control Bits**
  6 bits (from left to right):
  URG: Urgent Pointer field significant
  ACK: Acknowledgment field significant
  PSH: Push Function
  RST: Reset the connection
  SYN: Synchronize sequence numbers
  FIN: No more data from sender
- **Window**
  16 bits The number of data octets beginning with the one indicated in the acknowledgment field which the sender of this segment is willing to accept.
- **TCP Checksum**
  16 bits The checksum field is the 16 bit one's complement of the one's complement sum of all 16 bit words in the header and text. If a segment contains an odd number of header and text octets to be check summed, the last octet is padded on the right with zeros to form a 16 bit word for checksum purposes. The pad is not transmitted as part of the segment. While computing the checksum, the checksum field itself is replaced with zeros.

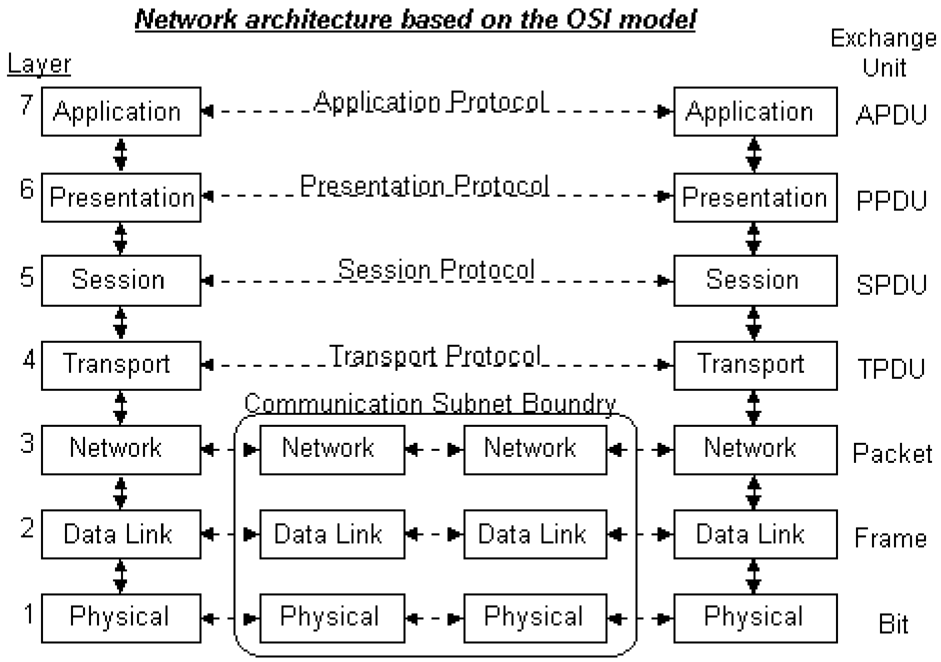
  The checksum also covers a 96 bit pseudo header conceptually prefixed to the TCP header. This pseudo header contains the Source Address, the Destination Address, the Protocol, and TCP length. This gives the TCP protection against misrouted segments. This information is carried in the Internet Protocol and is transferred across the TCP/Network interface in the arguments or results of calls by the TCP on the IP.

The TCP Length is the TCP header length plus the data length in octets (this is not an explicitly transmitted quantity, but is computed), and it does not count the 12 octets of the pseudo header.

- **Urgent Pointer**
  16 bits This field communicates the current value of the urgent pointer as a positive offset from the sequence number in this segment. The urgent pointer points to the sequence number of the octet following the urgent data. This field is only be interpreted in segments with the URG control bit set.
- **Options**

Appendix B - OSI Layers

Seven layers are defined:
7) Application : Provides different services to the applications
6) Presentation : Converts the information
5) Session : Handles problems which are not communication issues
4) Transport : Provides end to end communication control
3) Network : Routes the information in the network
2) Data Link : Provides error control between adjacent nodes
1) Physical : Connects the entity to the transmission media



Source [http://www2.rad.com/networks/1994/osi/layers.htm]