HFC

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1 Requirements

1.1 High level requirements

Referring to cable MSO issues [EurocableLabs Antwerp 9 June 2004], the first priority issue is to offer more bandwidth per customers in a more efficient and cost effective way; this can be translated in a set of technical requirements:

- Increase downstream capacity per subscriber, including both network capacity and terminal capacity
- Increase upstream network capacity, including more efficient use of the upstream
- Allow flexible sharing ratio between upstream and downstream traffic
- Load balancing in upstream and downstream
- Evolve to a full IP architecture including video services, and supporting QoS, billing, security.
- Extend the framework to home network

To define the requirements produced by the services, applications, or regulatory constraints is necessary to build a coherent technology roadmap. This is still more pertinent since these requirements are evolving rapidly; examples of such changes are the rapid deployment of VOIP, the explosion of high bit rate access with a rapid increase of the bit rate, and the increasing demand for nomadic and mobiles services. The table below represents a first sketch of requirements and their effect on technology roadmap.

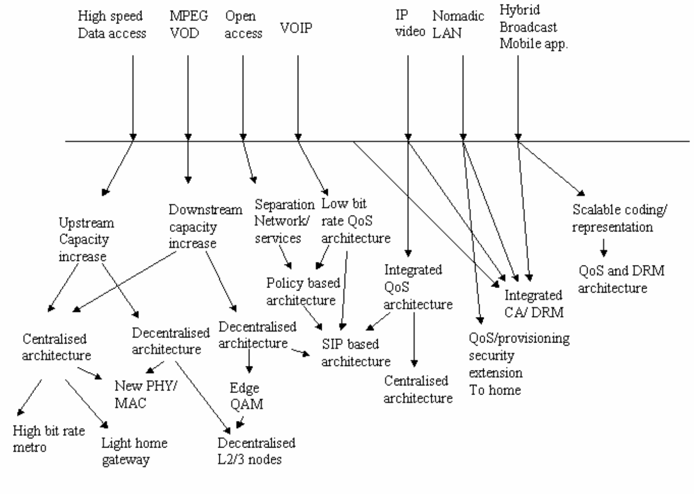

Figure 1: requirement and roadmap

High speed data access: Both Peer to Peer application or fast download, and competition between operators are pushing the average bit rate offered to the subscriber to an rapid increase; a basis for the average bit rate per subscriber can be taken from the MUSE project [MUSE MA 2.4 road mapping].

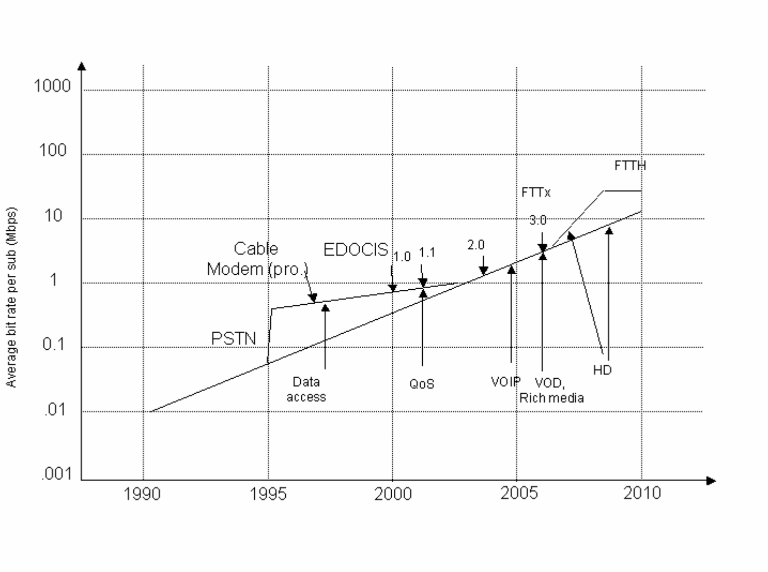

Figure 2: bit rate evolution

VOIP is now deployed together with high speed data. VOIP is introducing a requirement for low bit rate QoS architecture, signaling, security and provisioning, as well as interconnection with metro/backbone networks. VOIP can be deployed using 2 different paradigms (centralized or decentralized), which are developed later in this document.

Video on Demand, or more generally rich media content, is a clear roadmap from the cable operators; one short term solution based on legacy MPEG video, and one longer term video over IP paradigm.

Open access is a regulatory requirement to unbundle the network from the services and applications, and requires to define a clear interface between the network operator, the service provider, and the application provider.

Extension of the cable access network to the home is necessary to provide an end to end service to the subscriber; whether the cable operator will have the control of the wireless home network is subject to regulation; the features provided to the home will include QoS, provisioning, DRM, home devices management.

Hybrid broadcast/fixed applications: there is a clear trend towards applications using cooperating networks (cooperation of a broadcast and a mobile network); as the cable network can be terminated by a WLAN network, the user with a mobile terminal can use the cable network as a cooperating network by itself (as the cable network support broadcast, multicast and unicast services).

1.2 Roadmaps

Different technological choices choice are possible, mainly based on evolution to a centralized or decentralized architectures:

- A centralized architecture corresponds to today cable access networks implementations, and has the following classical advantages:
    - Network easy to maintain and reliable, as all the “intelligent” (layer 3 and above) elements are centralized
    - Cheap user terminal, as the signaling protocols are very light (like MGCP for instance)

The network capacity increase can be imagined under these assumptions.

- The current trend is to evolve to a decentralized architectures where the network elements are placed closer to the subscriber. It is based on a peer to peer signaling paradigms like SIP. The current economical drawbacks of this architecture (reliability and maintainability, network elements and terminal costs) will no longer apply in the future, and the complexity is compensated by the scalability of the architecture.

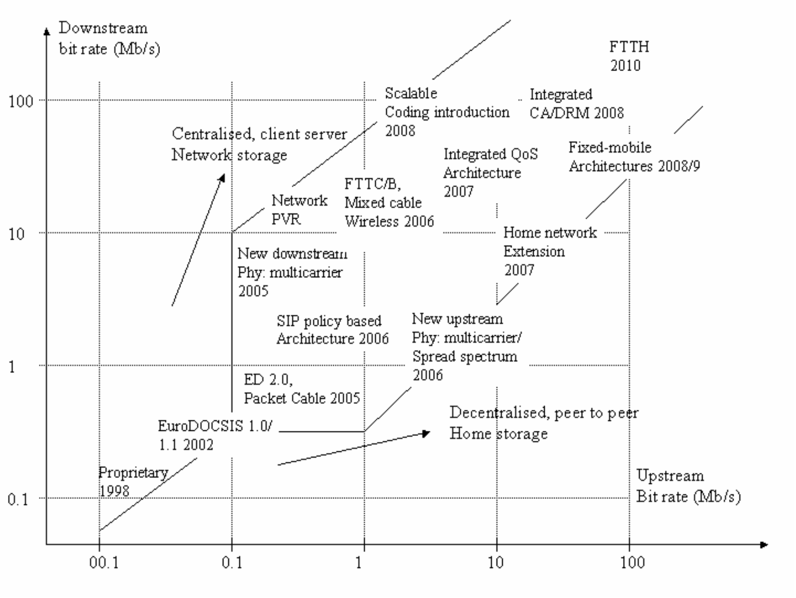

Figure 3: roadmap related with network capacity

Different technology roadmaps can be deduced according to the 2 categories of paradigms which will prevail in the future (centralized or decentralized), corresponding to different application scenarios (peer to peer will most probably lead to decentralized architectures, whereas client server types of applications would lead to centralized architectures); the different technology concepts are developed in the next paragraphs. Note that upper layer and lower layers centralized and decentralized architecture can be uncorrelated (upper layer decentralized model can be implemented over a centralized architecture).

2 HFC cable network deployment situation

Broadband access via cable is without contest one of the 2 main deployed technologies; the main figures being given below:

Cable networks current architecture

The view below summarizes the architecture of a modern HFC (Hybrid Fiber Coaxial network). Many variants can exist but in general the architecture includes several levels:

A Main Head-end (Central Node) where all broadcast services are aggregated. The main HE feeds the secondary Nodes (or Local Nodes), generally through secured fiber optic links.

The local nodes feed medium size cities or small regions ; many variants like shown in can apply. The local node serves a number of coaxial area via fiber links using usually analogue transmission. The boundary node between fiber and each coaxial area is called a Fiber Node. The coaxial area size will determine the ultimate traffic capacity available per user.

The coaxial area architecture can be either a star network with different levels, or more commonly a tree and branch network; this part becomes critical when very high bit rates have to be conveyed

The HFC specific part of the network begins at the Local node (the MAN or WAN between the DN and the LNs not being specific to HFC); optical transport is usually analogue, transmitting transparently the upstream and downstream spectrum.
The RF spectrum allocation downstream and upstream are respectively 88-860 MHz and 5-65 MHz (many local variants exist), the downstream spectrum is occupied by analogue broadcast TV carriers and digital QAM 64 or QAM256 carries conveying digital TV MPEG signal or data payload.

The ultimate cell capacity (assuming that digital switchover has occurred) can be up to 4.8 Gbps downstream, and 200 Mbps upstream; this capacity can be shared between broadcast, unicast and multicast traffic. In practice, when taking into account the broadcast analogue channels, the unicast downstream available capacity is significantly lower These figures show that very high bit rate access is possible at the expense of segmenting the network into small cells, which introduces a series of technical challenges.

In summary Cable access provides an competitive alternative to XDSL, as it offers the same kind of capacity, and allows in addition to deliver multicast / broadcast services; it provides an interesting cost effective alternative to FTTH. The problem is to find good evolutionary scenarios for cable network in order to increase significantly their capacity, on an economical way so that it can still compete with XDSL and FWA alternative technologies.

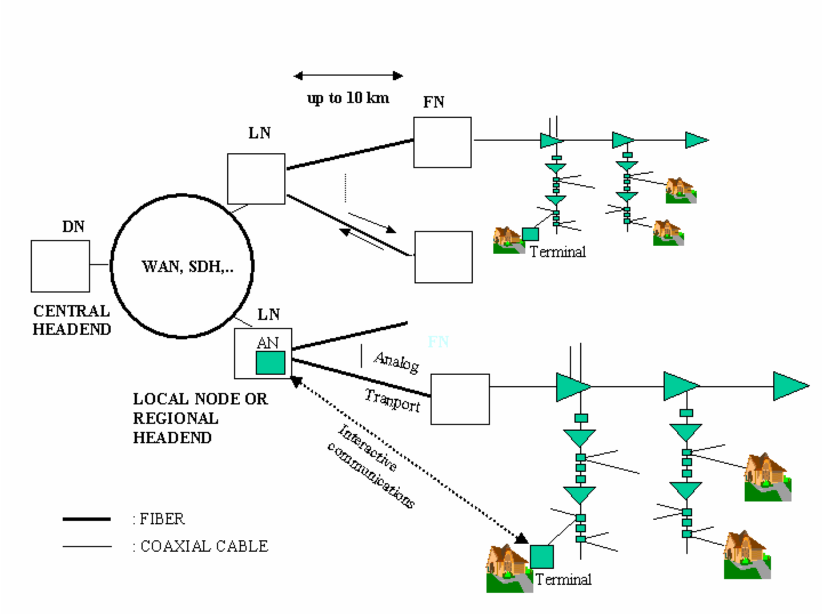

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Figure 4: HFC architecture 1

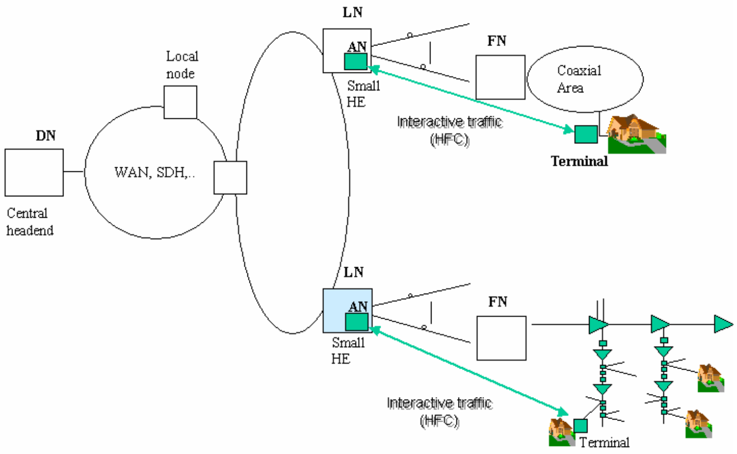


Figure 5: HFC architecture 2

2.1 *Current spectrum situation*

Most of the downstream spectrum is occupied by analog legacy channels as shown in the example below; in consequence the cable network paradigm is significantly different before and after the digital switchover:

- before the digital switchover the spectrum resource is limited, and spreaded around the whole downstream spectrum (usually 88-860 MHz).

- After the digital switchover the available spectrum will enable the delivery of the capacity mentioned in fig. 3-3

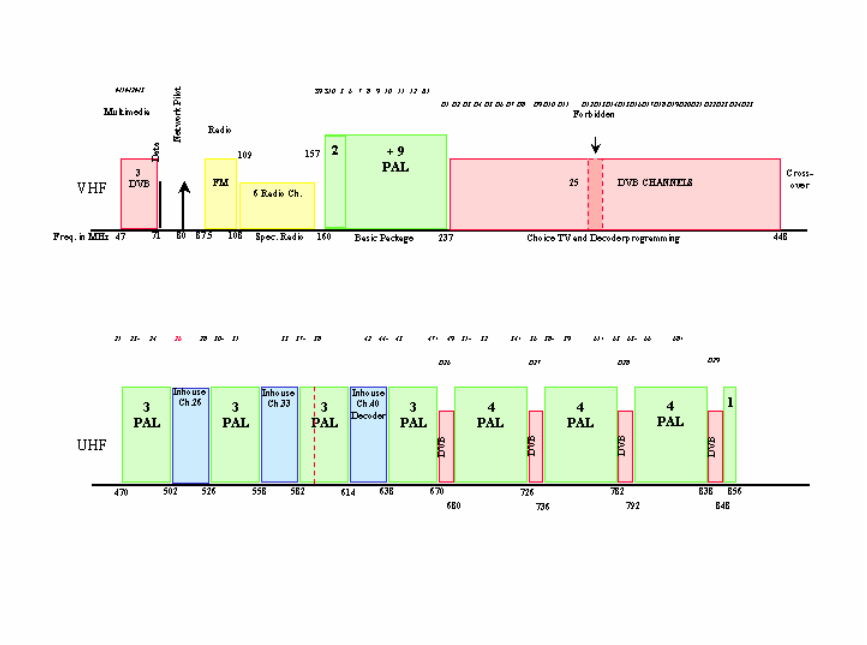


Figure 6: Example of downstream spectrum allocation

Upstream spectrum

The upstream spectrum has been analyzed by academic R&D centers and European R&D projects like Interact (http://www.cordis.lu/infowin/acts/rus/projects/ac086.htm), as the upstream spectrum availability can really be a bottleneck to deliver broadband access. The usable band (5- 25 to 5-65 MHz, depending on the plant), is subject to a number of disturbances like Impulse and Ingress noise which can severely limit the upstream capacity by preventing the use of some bands, or limiting the bandwidth efficiency.

The 4 mains categories of disturbances that have to be considered are Impulse noise, Ingress noise, Common path distortion, and Gaussian noise. Impulse noise and Common path distortion are localized disturbances, whereas there is an accumulated additive process for Ingress and Gaussian noise, due to the tree and branch architecture of the coaxial network. Another important disturbance is clipping in upstream (and downstream, which creates bursts of errors in the digital transmission); as disturbance are a crucial issue for upstream capacity, further analysis of disturbances is made in annex 1.

3 Plant capacity

The total HFC plant capacity is represented below; in downstream, efficiencies in the order of 4-5 bits/s/Hz can be achieved, whereas in upstream, 2-3 bits/s/Hz is possible. As shown, most of the downstream band is used by current legacy analogue video, therefore part of the band only can be utilized for IP communication, assuming that digital broadcast video is deployed in parallel with analogue programs. Ultimately (after

2010), the whole band can be utilized for IP unicast and multicast/broadcast communications.

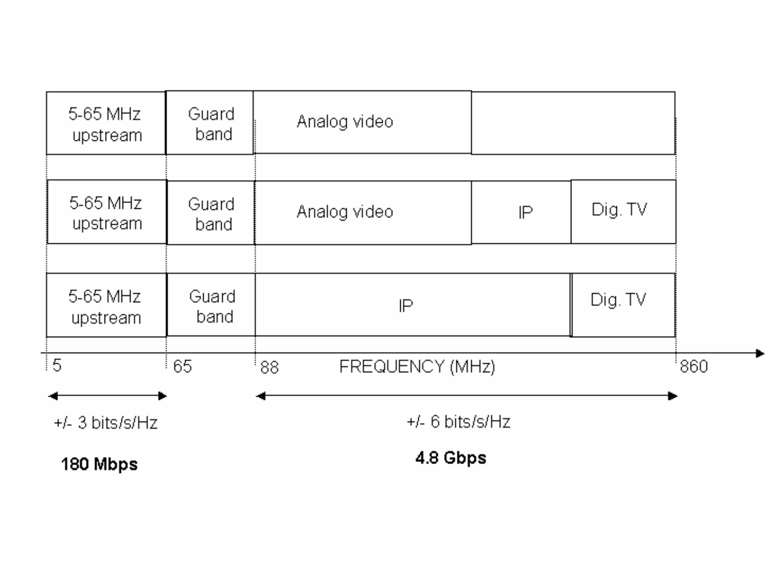
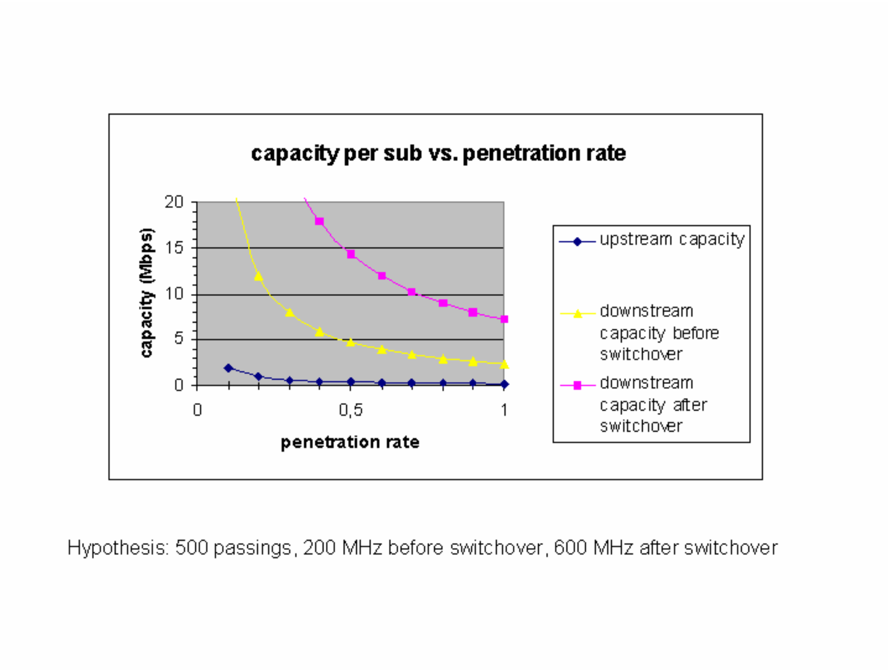


Figure 7: bandwidth allocation and capacity

Translating this into average subscriber capacity gives the following figure:



Hypothesis: 500 passings, 200 MHz before switchover, 600 MHz after switchover

Figure 8: upstream and downstream subscriber capacity

The upstream capacity is clearly insufficient for the high bit rate requirements described above, whereas downstream average capacity (before switchover occurs) is not sufficient at high penetration rates.

3.1 Alternatives for increasing the plant capacity

3.1.1 Changing the split between upstream and downstream

If more traffic is required for upstream communications, the solution of extending the upstream band to 200 MHz can be chosen, at the expense of the upgrade of upstream and downstream filters in the coaxial amplifiers, and assuming that upstream digital tuner is possible in this frequency range. The solution does not solve the overall capacity issue, but allows to adapt the sharing between upstream and downstream traffic.

Technical challenges are related to the realization of a low cost system, i.e. to realize a 200 MHz Modem without RF tuner.

3.1.2 Cell segmentation

Simple cell segmentation can be done to increase both downstream and upstream traffic; the advantage of the solution is to keep a centralized architecture, which presents major advantages ion term of cost and maintainability. However keeping an analogue architecture is not a priori optimal, as it requires the use of expensive optical components (especially as C or DWDM techniques have to be used if the number of fibers must be spared).

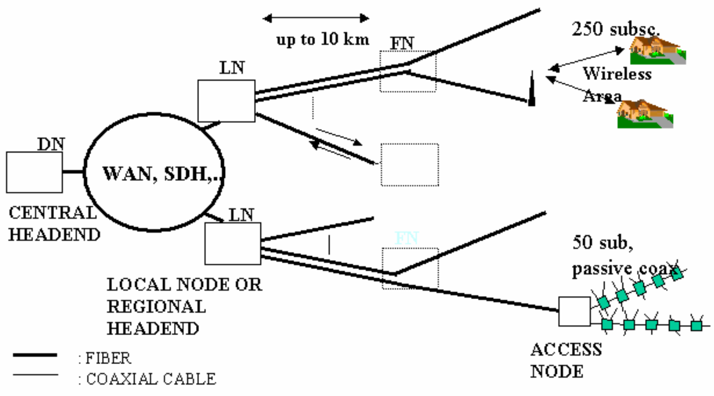


Figure 9: cell segmentation

In the downstream, the existing RF channels (6 to 8 MHz wide) can be aggregated in order to provide higher bit rate pipes to the subscriber, and maintain compatibility with legacy customer equipments. 100 to 144 MHz band blocks are considered to be achievable in the future to provide up to 1 Gbps pipe to the user, both at the terminal and the HE equipment side.

The second challenge is the optical technologies needed to use as efficiently as possible the fiber bandwidth and reduce the spacing between optical carriers. Spacing of 100-200 GHz can be considered in the middle term, and disruptive optical technologies [cveyres] may allow to reduce the spacing between carrier to 6.25-12.5 GHz, using either analogue or digital (in this case an A/D and a D/A are used in conjunction with the optical transmitter and receiver respectively, see paragraph below).
In the case of analogue transmission, QAM modulation used for downstream carrier will require good C/N, CSO, CTB, and Cross modulation performances, which will be limited both by the optical components and optical phenomena's in the link, like Stimulated Brillion scattering, Stimulated Raman Scattering, Interferometric noise, Polarisation mode dispersion. These later phenomenas can be modeled and counter measures can be applied (like external phase modulation when using MZI based external modulation).

3.1.3 Channel Digitization

In order to overcome the cost and performance issues introduced by analog optical components, the whole return band can be digitized like in the diagram shown in figure 4; the 2 main issues associated with this solution are the sub-optimal use of the bandwidth (as high order constellation (up to 256 QAM) and mixed TDMA and SCDMA techniques are used in upstream, 12 bit digitization is required, requiring 2 Gb/s links for each upstream), and a short spacing between optical carriers in order to spare the number of fibers used (developed above).

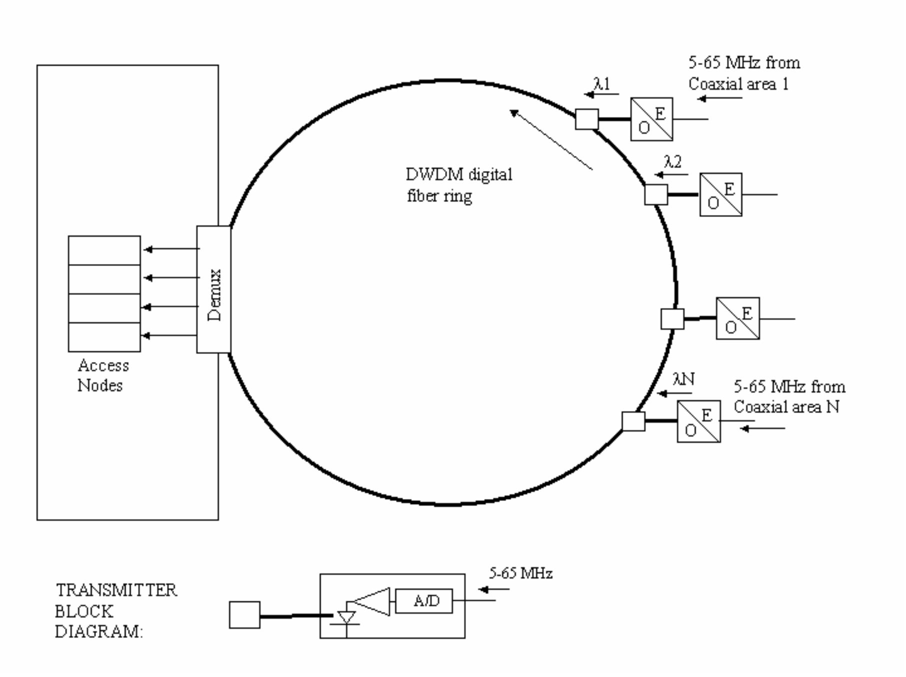


Figure 10: **Return channel architecture**

The downstream band can also be segmented and digitized, but the capacity is in this case limited to around 100-150 MHz bandwidth, which gives a capacity of around 900 Mbps per cell. When high unicast bit rates are targeted, the challenge is to implement such interfaces for small cells, which creates both cost an envirnemental issues for the interface.

3.1.4 FTTC/Mini Fiber Node Architecture

Classical analog HFC has the advantage to support legacy broadcast video, and of a centralized architecture, but the architecture can suffers from some issues like:

- The optical transport network is analog in both directions, leading to relatively high cost, especially if the architecture evolves from a broadcast to a narrowcast model;
- In the upstream, the cost of analog optical return links can become significant, even if return channel digitization is made, as described above.

In the FTTC, also called Mini Fiber node architecture, the HFC can be now separated into 2 separate networks:

- The optical network which ensures digital bidirectional data communication between the Local Node, and the Mini Fiber Node;
- The coaxial local network, using classical DOCSIS FDMA/TDMA-SCDMA access in the RF spectrum.

However classical FTTC architectures do not scale well for HFC, as they do not support legacy broadcast video; a more scalable alternative is the hybrid architecture shown below, which preserves the legacy analogue architecture, and introduces progressively broadband “islands” in the network.

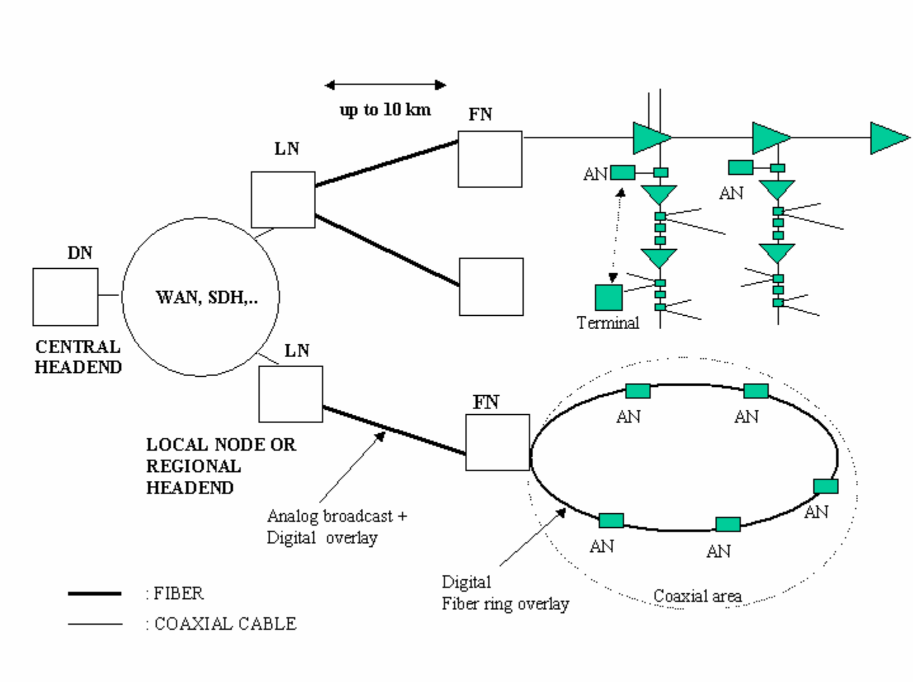


Figure 11: Hybrid architecture with digital overlay for interactive services

Both "mini-fiber node" architectures introduce important technological and cost challenges, the main one being to integrate the Access Node very close to the subscriber. As the access node serves a low number of subscribers (50 to 200), the product cost is critical and requires the integration of all the Access Node functions in a "System on chip" architecture. Recent studies and realizations show that this SOC is achievable by using the next available (10 µm and below) technologies and multi CPU integration.

Let us note that (Euro)DOCSIS standard was designed for large cable areas, and it is appropriate in this new situation where the AN serves "micro-cells" to evolve current standards; new projects are now investigating both backward compatible solutions, and new solutions (different use of the cable bands, new physical layers, baseband Ethernet,..).

Use of Ethernet MAC layer

More particularly the low cost of Ethernet based components make this technology particularly cost attractive; moreover when the cable network is based on a star topology, it is easily possible to have baseband (10 base T or 100 base T) Ethernet transport over the last cable segment as shown in the figure below.

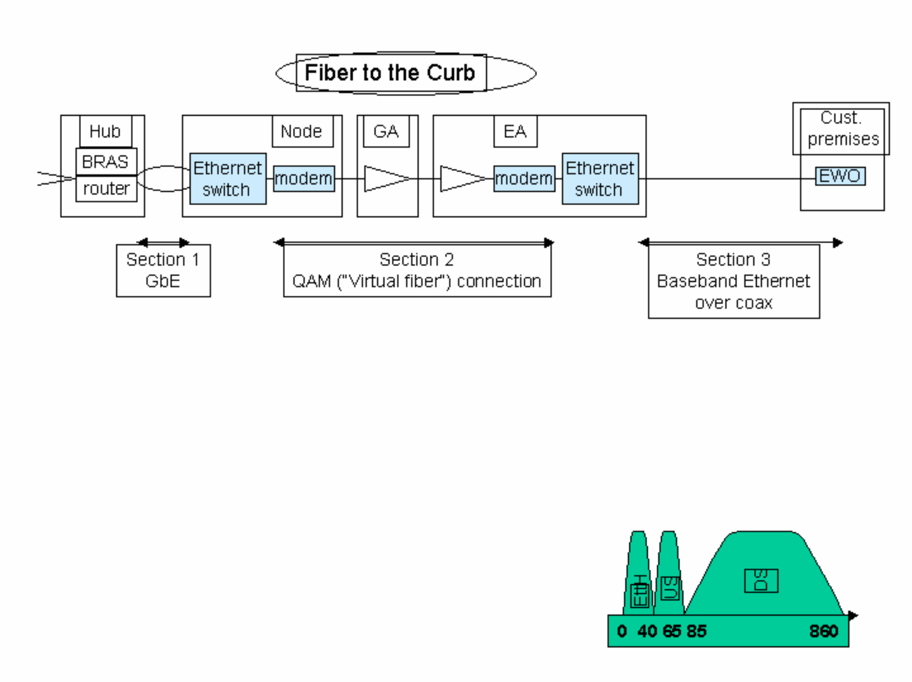


Figure 12: Ethernet on cable

The use of baseband Ethernet is adequate in the lower band, as it has a good resistance against impairments like Ingress and Impulse. Moreover the technology is scalable as it allows to remain compatible with DOCSIS and Eurodocis (used for the upper part of the upstream band), and allows to use keep a coaxial segment for low penetration rates, or fiber segment is higher bit rate per cell is needed.
The solution however has still to be proven for tree and branch network, which constitute most of the current cable architectures. Another issue is that unlike DOCSIS 1.1, 2.0 and the future 3.0, which provide layer 2 QoS mechanisms, this solution does not provide QoS and bandwidth over-provisioning has to be done to respect the QoS constraints introduced by voice and rich media services.

4 Physical and MAC layers

4.1 Current upstream physical and MAC layers:

The standard of choice for upstream physical and MAC layer is DOCSIS (standardized in the USA by CableLabs) and its European variant, Eurodocsis, standardized in ETSI as EN 201 488.
There are 3 versions of the standard: 1.0, 1.1, and 2.0.
Version 2.0, which has been designed to mitigate efficiently the plant disturbances uses both single carrier TDMA and SCDMA access techniques, the maximum bit rate per RF carrier being 30 Mbps.

As the Cable network is a shared medium, the MAC layer is a point to multipoint type of MAC layer, where the subscribers are sharing an upstream channel using ATDMA; the slot allocation is determined by the central station, called AN (Access Node), which is the interface between the HFC network and the backbone.

The standard is based on IP packet transmission, but IP packet fragmentation is possible to respect the jitter constraints of services like IP telephony, when mixing data and voice services. Eurodocsis defines also a per flow QoS description, which allows to support both an Intserv and diffserv type of architectures in the access network (a mapping between RSVP QoS parameters, and the MAC layer QoS parameters is defined).

Multicast connection and mapping with IGMP are also described at the MAC level; furthermore the standard includes layer 2 unicast and multicast encryption and authentication tools to ensure subscriber privacy, and prevent terminal cloning. Security is therefore supported both for unicast and multicast sessions.

For future capacity requirement, if 100 Mbps peak bit rates upstream and Gbps downstream are targeted, some adaptations and changes in the downstream and upstream physical and MAC layers are necessary.

4.2 Downstream evolution

DVB-C physical layer which is used in downstream can evolve as follows:

In the downstream higher order constellations (256QAM, 1024QAM) single carriers can be used if the plant is of good quality (limited CSO and CTB), and has limited clipping disturbances; however the bit rate achieved remains limited. A better/complementary solution may be to use multiple carriers assembly to stay compatible with legacy DVB-C systems. A new terminal would have the capability to decode multiple single channels simultaneously (a block of 16 channels would correspond to a Gbps capacity). Issues related to this evolution are the realization of a one chip – one tuner solution with 100 – 150 MHz channel bandwidth.

4.3 Upstream and MAC layer evolutions

In the upstream single carrier will be difficult to achieve with bandwidth exceeding 6 MHz, due to Ingress and Impulse noise limitations in the lower part of the band. Multi carrier technique is the right solution to solve both the Ingress (frequency granularity) and Impulse noise (larger symbol width) limitations; filtered multitone (FMT) techniques like DWMT or DMT are more efficient at they limit both the Ingress noise effect on adjacent carriers, and the ICI of unsynchronized carriers during ranging [JCP], [IBM]. Upstream total channel bandwidth of 25-30 MHz can be achievable, leading to upstream peak bit rates of 100-150 Mbps. Additional clipping can be an issue as compared to single carrier, but the use of non synchronized carriers can solve this issue.

A mixed TDMA/SCDMA access scheme can be applied to bring an optimum efficiency to the channel, as TDMA is well adapted to burst transmission over a clean sub-channel, whereas CDMA optimizes the throughput. Turbo codes or capacity approaching codes [JCP] will bring an additional gain to the system.

The MAC layer can be derived from the current DOCSIS MAC layer and its current mechanisms (ranging, slot allocation) adapted to the new physical layer.

The MAC layer is adapted to a mix of data and VOIP services, the later using fixed bit rate coding with silences (G711, G729, G723-1). The small bit rate required by voice telephony services does not require more optimization.

However video services will occupy a significant part of the upstream and downstream channel, and the coding schemes are VBR based with high short term and long term variations (when constant video quality is targeted). In the case of MPEG, [DOCSIS_video], the produced streams are VBR, and bursty over different time scales. Current DOCSIS mechanisms are not optimal for these hybrid CBR/VBR streams, and need some adaptation. Second issue occurs with scalable coding schemes: MPEG2 and MPEG4 (including H264) schemes are not very scalable as they use block transform, whereas wavelet transform based schemes enable fine grain scalability. In the case where video services can be dominant in the downstream of upstream traffic, a second parameter which is the class of service (or an equivalent parameter), and will allow in case of network congestion to discard certain class of traffic (like WRED); for upstream traffic, this type of mechanism has to be managed by the terminal (queue management), or better as a layer 2 mechanism by the CMTS (in that last case, either different flows per class of service have to be available to the terminal, or special priority tags have to be set on the requests coming from the terminal within a service flow. More generally investigation is needed to find what is the best overall scheme for QoS reservation in the cable network (or in any point to multipoint architecture).

4.4 Data plane QoS features

As mentioned above, the cable access architecture support an Intserv model for QoS. As it is critical to optimize the downstream and upstream utilization, a generic layer 2 mechanism of Payload Header suppression in defined In EuroDocsis, which can allow to optimize the traffic on a per session basis; some more efficient proprietary techniques (Broadcom), or some TCP related mechanisms (TI) are used.
Certainly further study is needed in that field, which can be made in common with other point to multipoint architectures (wireless, satellite, terrestrial).

5 Open access and related issues

There is a requirement to mandate the ILEC which has a significant market power to open their access network to CLEC; this is called "open access", or local loop unbundling.
To enable a subscriber dynamic open access to any ISP, a tunnel has to be created between the subscriber CPE and the ISP router; moreover the subscriber has to be dynamically provisioned with the corresponding IP and QoS parameters. Several solutions are possible:

- Using PPP to establish a tunnel: Layer 2 (PPPOE) or layer 3 (L2TP) tunnel can be established, or a combination of both. PPPOE can be a logical solution, since DOCSIS is based on Ethernet, but the solution cannot cross layer 3 devices; moreover the overhead (8 bytes) introduced by this technique is limited, and multiple links with different ISP can be established by the same subscriber. The drawbacks of the PPPOE protocol are the following:
    - QoS and multicast are not supported;
    - In principle the CPE software has to be supported
    - All communications are centralized (Peer to Peer communications between subscribers owning to the same network have to proceed through the ISP)
    - Difficulty to monitor and classify the traffic

- L2TP is another solution which has the advantage to support layer 3 device, but is not largely supported, and introduces large overhead. L2TP can be used between the BAS (PPPOE aggregation router) and the ISP router to create aggregated ISP tunnels
- Policy based routing is a possible solution, where the access router checks the source address of an uplink traffic packet, and routes the packet to the right ISP according to this information. The advantages are a full compatibility with DOCSIS 1.1/2.0, support of QoS, multicast; the drawback are the scalability, complex processing at the CMTS side, and requirement to pre-provision the cable network with public IP addresses owning to all the ISPs.
- VLAN based solutions present major advantages of the 2 mentioned solutions: they are compatible with DOCSIS, introduce low packet overhead (2 bytes), and reduce the cable devices (CMTS) complexity. They support QoS and multicast paradigms. Authentication and connection to the right ISP domain can be provided by 802.1x. Drawback is the number of available VLAN tags (limited to 4096), but this issues could in principle be solved by cascaded tagging.

At the Cable network side, when connecting the CM can receive its VLAN tag during provisioning, avoiding the use of any particular protocol.

5.1 Impact of open access on layer 1 / layer 2 architectures:

The L1 issue related to multi-ISP provisioning has 2 aspects: the first one is related to the upstream and downstream resource limitations for a given cable area; the resource allocation can be divided into 2 levels: the aggregated bandwidth reserved for the ISP and the bandwidth contract for each subscriber. Additional complexity is introduced by upstream disturbances, which may require dynamic resources reallocation between RF channels. The second simple issue is the total bandwidth limitation in one area, which may introduce important limitations in the ISP potential subscriber coverage. The requirement to introduce equal treatment between ISP, and between subscribers, is introducing additional complexity in the network.

In conclusion it is difficult to segment the upstream bandwidth per RF channel and dedicate RF channels to ISPs, as sometimes RF channel dynamic reallocation is necessary; moreover the QoS offered to a subscriber may depend on the channel used by the subscriber at a given time.

Concerning layer 2 issues, the requirement mentioned above has to be considered and introduces as well additional complexity for admission and control, and MAC layer resources management. In principle the requirement to support different types of SLA is covered by a DQOS architecture, but introduces of course additional complexity in the admission and control process.

The impact on the network architecture is significant as the operator has to set-up a tunnel architecture as described in figure NNN, and to provision the sets of IP addresses and services descriptions for each ISP.

Once open access has been set-up, IP architecture for voice and multimedia services can be defined independently, as described below.

6 IP architecture

A complete IP architecture is defined in the access network for voice communication, and could be extended in general to multimedia services requiring QoS.

Signaling is based on a centralized architecture and thin client model (MGCP), and mostly applicable to telephony services. 2 QoS models are defined: the most applicable one (called dynamic QoS) relies on Intserv, and define the access QoS architecture using RSVP. Another variant assumed a diffserv architecture. COPS is the protocol of choice for communication between the CMTS and the CMS for policy enforcement and authorization purpose.

Interdomain signaling defines SIP or H248 for signaling between different domains; interdomain QoS is obviously not precisely defined yet.

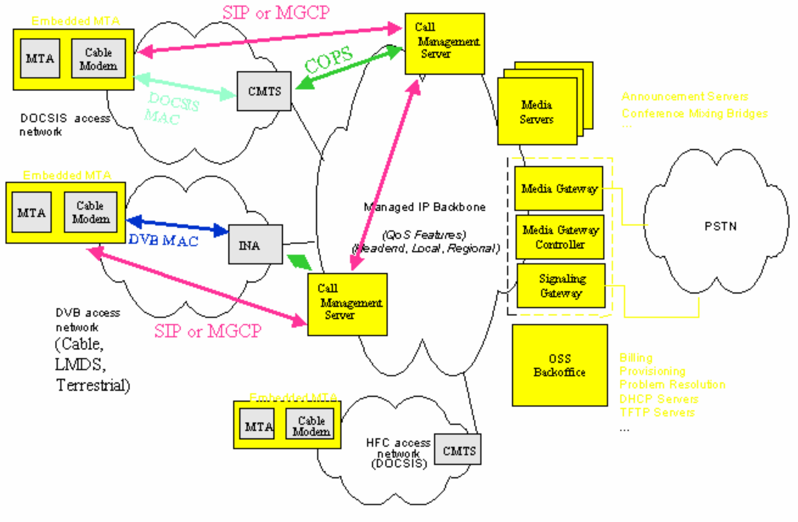


Figure 13: VOIP architecture

6.1 *Extension to multimedia services*

The current HFC networks QoS architecture is based on an Intserv paradigm, supporting a per flow QoS. The DOCSIS MAC layer uses a reservation scheme where the subscriber terminal can request transmission opportunities to the Access Node, and therefore can supports CBR and VBR type of services; moreover a MAC service flow can be associated to a particular session of group of sessions. Initial resources reservation for a session can be made either directly via RSVP (more particularly a variant of RSVP optimized for cable access networks), or indirectly via signaling (like SIP or RTSP) where the session description can be translated into MAC QoS parameters.

Current Packet Cable VOIP architectures are built on a centralized model based on a variant of MGCP signaling adapted for cable ;

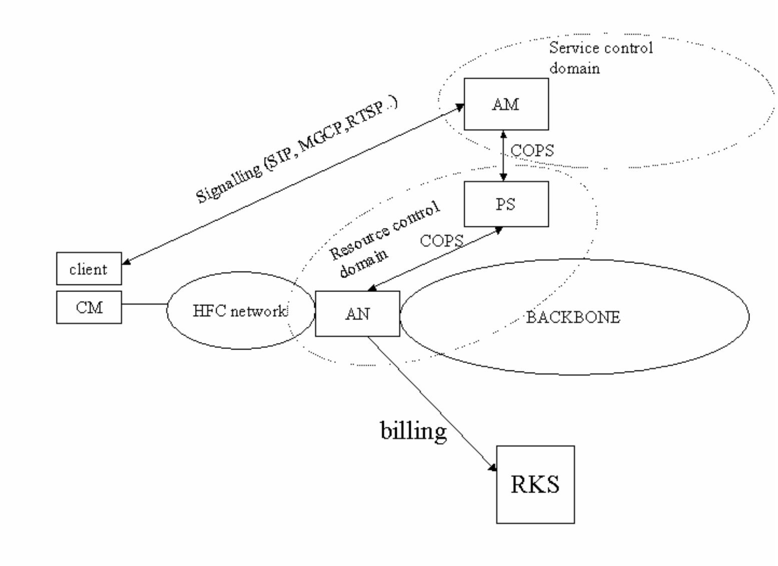


Figure 14: Packet Cable Multimedia policy architecture

More generally for multimedia services, the ongoing Packet cable Multimedia project (see figure 6) is defining a policy architecture, which recognizes that a variety of signaling protocols will be used (MGCP, SIP, proprietary), and allows to differentiate clearly between network provider and applications provider.

2 distinct domains are defined:

- The Resource Control Domain (RCD) which is defined as a logical grouping of elements that provide connectivity and network resource level policy management in the access cable network domain. The Resource Control Domain includes the AN and the Policy Server (PS).
- The Service Control Domain (SCD), which is defined as a logical grouping of elements that offer applications and content to service subscribers. The Application Manager resides in the SCD. Note that there may be one or more SCDs related to a single RCD. Conversely, each RCD may interact with one or more SCDs.

Fundamentally, the roles of the various PacketCable Multimedia components are the following:

- The Application manager is responsible for application or session-level state, and applying SCD policy.
- The Policy Server is responsible for applying RCD policy and for managing relationships between Application Managers and AN (therefore the PS acts as a PEP for SCD and a PDP for RCD)~~.~~
- The AN is responsible for performing admission control and managing network resources through DOCSIS Service Flows.

Currently the interface which are defined by Packet Cable Multimedia are related to QoS (using COPS between AM and PS, and between PS and AN) and resource accounting (using radius between AN and Record Keeping Server).

When looking at the Packet Cable and Packet Cable Multimedia architectures, and the general trends in access, an architecture like PC MM covering a limited set of signaling and session control protocols (like SIP and RTSP for instance) have to be defined, as logically the client paradigms is shifting from a thin a thick client, making more logical a solution based on SIP (for both telephony and multimedia) rather then MGCP. Recent analyses of different signaling evolutions for multimedia [CASSIC] have shown that SIP or similar protocols are the most appropriate solution.

6.2 Extension to video

Legacy video architectures are based on MPEG transport and use DVB standards both for transport (DVB-C, DVB-TS), encryption (DVB-CA), CA architectures and interfaces (DVB-Simulcrypt), signaling (DVB-SI), middleware (DVB-TAM using MHP). (E)DOCSIS protocol is used for transport of interactive information and IP traffic.

No precise extension is defined at this stage as digital video and data-voice architectures were defined and standardized separately. The introduction of video in IP services is still to be addressed for cable. An FP5 project (CASSIC) has begun to analyze this aspect (the project has focused on interface between middleware (MHP) and IPCABLECOM architecture.

Different issues can be investigated:

- How to migrate video services in an IP architecture, ensuring transition paths with coexistence of MPEG and IP
- Definition of a common framework for:
    - Content security (including protection and right management)
    - Network security
    - QoS
    - Signaling
    - Provisioning (network, service and application)
    - Billing
- Defining an open access architecture separating network resources from application.

Centralized versus decentralized architectures for video
Network PVR

As the cable network media is bidirectional one can apply the concept of “network terminal” to a video architecture, where the storage is centralized instead of being distributed, and the customer equipment has no storage and low processing power; the middleware is very primitive. Most of the applications are executed in the central server place (at the extreme the STB is sending to the server very primitive information like positioning on the screen).
In addition, the storage capacity issue and the STB price is not necessarily a major problem:

- Storage capacity: 2 arguments can be in favor of local storage; the price of local storage decreases regularly and is now at a reasonable level. In addition the subscriber may prefer to have the content available locally.
- STB price: STB are evolving to a one chip architecture including signal processing, MPEG decoding and processing, and all the broadband access (including routing, provisioning, and signaling stacks); if a good yield is achieved, the price difference between low level and high level chips can be insignificant. The resulting STB price range can become small between “thin client” and “thick client” STB. The figure below represents an example of price range estimation of thin and thick client STB, and storage additional price.

FIGURE

Decentralized architecture for VOD

There are several options for a decentralized architectures; 2 significantly different architectures are with or without local storage. Although local storage is not necessarily required currently, the home network segment traffic can become significantly higher, especially when HD services and user mobility are introduced. The whole network can be considered as a content delivery network with the main server in the Central Headend, and proxy servers in the Local Headend and subscriber Home Network.

A decentralized architecture can be set-up with both thin and thick clients, and the application part can be split-up between the terminal storage and the different servers.

7 security

There are several distinct levels of security in the HFC network:

7.1 HFC network security:

DOCSIS BPI+ provides a layer 2 security mechanism, which enables the user terminal authentication, payload content encryption (using secret key algorithms, e.g. DES or triple DES), and key exchange mechanisms (using public key algorithms and hashing). This layer 2 security ensures the user authentication and privacy in the HFC network (as HFC is a shared medium), and provides a layer 2 reliable mechanism which can be used by end to end services and applications.

7.2 *Service/application level security*

For voice services, Packet cable defines in summary IPSEC mechanisms for signaling, and secret key algorithms (based on RC4) for end to end voice content encryption.

For SD/HD broadcast video (and other services like data), Conditional access systems are used according to DVB-CA and DVB-Simulcrypt standards. Content encryption use secret key encryption (based on DVB-CS algorithms), whereas the key exchange and billing mechanisms are proprietary.
Interfacing between the different functional elements of the conditional access system, and the video network elements (video multiplexer) is defined by the DVB-Simulcrypt standard. This allows network openness, i.e. several conditional access system to interoperate with the same network. CA systems are designed to operate in a uni-directional system.

For multimedia services in general, different systems are defined or under definition (DVB, 3GPP, OMA, MPEG21, IETF, ISMA, see[techno_synthes._table]).

As mentioned above, whereas the network level security is defined and stable, a variety of solutions are used for service/application level security, and specific to the application (point to point or point to multipoint voice services do not have the same requirements as video broadcast for instance..). However it appears possible to define a unique security system (which handles encryption and right management) with the following requirements:

- suitable both to unicast and multicast type of applications
- allowing different levels of security and right management
- linkage of security and right management with QoS (for scalable content right management and encryption has to be dynamically adaptable to the QoS effectively delivered to the user).
- Supporting unidirectional medium but optimized for bidirectional transmission.

Definition of

8 Home network

Home networking can be considered as a general topic, but has also some specific aspects which are related to cable; part of these aspects are covered by the CableLabs Cable Home project:

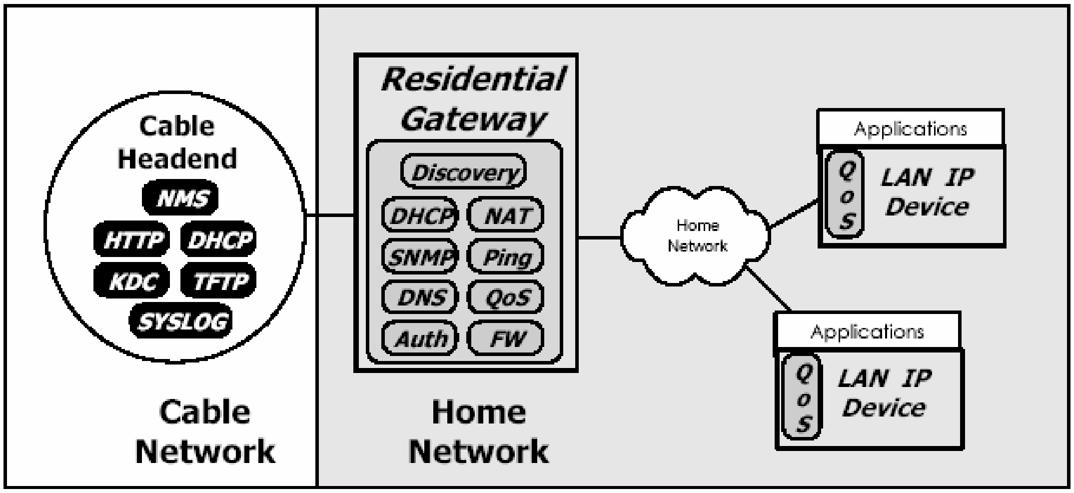


Figure 1 - CableHome Architecture

Figure 15: Cable home architecture

The CableHome architecture [W223White] consists of network elements, and functionality within those network elements at the Headend, the residential gateway, and IP devices in the Home LAN. CableHome 1.0 defines function for provisioning, management, security, and packet handling within the residential gateway. CableHome 1.1 adds the QoS, firewall, and discovery (including home network elements and services) functionality to Cable Home 1.0.

CableHome 1.0

CableHome 1.0 defines functions for provisioning, management, security, and packet handling within the residential gateway. Following are descriptions of these functions.

Provisioning

The CableHome 1.0 provisioning functions consist of a DHCP client, a DHCP server, configuration file processing, and a time of day client. CableHome 1.0 defines two provisioning modes, the DHCP Provisioning Mode and the SNMP provisioning mode. The DHCP provisioning mode is compatible with the DOCSIS 1.0 provisioning infrastructure, and requires no authentication. In this mode, DHCP messages contain information about where the RG can find its configuration file. The SNMP provisioning mode is similar to the PacketCable provisioning process, and the RG is authenticated via a Kerberos Server. In this mode, configuration file name and location information is passed to the RG via secure SNMPv3. In both modes, the RG then initiates a TFTP session to download the specified configuration file. CableHome 1.0 configuration files are comprised of TLVs (like DOCSIS) and include a hash to verify file integrity.
The DHCP client in the RG acquires IP address leases from the DHCP server in the cable operator’s data network, and the DHCP server implemented by the RG assigns

private IP addresses to networked elements in the home. CableHome 1.0 defines two WAN side interfaces for the residential gateway, the WAN-Management IP interface, and the WAN-Data IP interface, each requiring a unique MAC address.

Management

Like DOCIS, CableHome management is SNMP based, and consists of a wide variety of RG MIBs that allow for configuration and control of the CableHome suite of functionality. Via the NMS system in the headend, the cable operator can configure the RG functionally as most appropriate for their particular home-networking service and to satisfy specific customer needs.
Like DOCSIS 1.1 & 2.0, CableHome 1.0 defines two management modes (NmAccess and SNMPv3 Coexistence), and a number of standard SNMP traps for event reporting.
In addition, LAN IP Device connectivity and throughput test functionality has been defined for the RG, which employs ping-like exchanges between the RG and LAN IP Devices.

Security

CableHome 1.0 security consists of secure software and configuration file download, mutual authentication, a firewall, and secure SNMPv3 management messaging. Configuration file integrity is ensured via a hash function, and the residential gateway authenticates downloaded images using code verification checks supplied within the configuration file. The residential gateway is authenticated via KDC servers and device certificates. The keying material for SNMPv3 is provided via Diffie-Hellman in DHCP Provisioning Mode, and via Kerberos in SNMP Provisioning Mode.
The firewall functionality consists of a standardized download mechanism, triggered in the configuration file, or via SNMP. The integrity of the firewall configuration files is ensured via a hash within the firewall configuration file. In addition, firewall event monitoring is provided via SNMP MIB variables and event messages, which indicate suspicious activities.

Packet Handling

CableHome 1.0 provides NAT and NAPT functions within the residential gateway. These functions allow for IP address conservation and also provide a common logical IP sub-network in the home. In addition “Passthrough” addressing is defined, whereby public IP address are served directly to devices in the home from the headend DHCP server. Passthrough addressing is meant to support applications that do not work well with NAT (such as PacketCable telephony applications). Mixed mode addressing is also supported, which allows a combination of NAT/NAPT and Passthrough addressing simultaneously. Finally, an “Upstream Selective Forwarding Switch” function is defined in the RG, which keep home traffic local to the LAN.

CableHome 1.1

CableHome 1.1 builds upon CableHome 1.0, the primary additions being QoS, firewall, and discovery functionality. These additional CableHome 1.1 features are described below.

QoS

CableHome 1.1 defines a QoS system for LAN IP devices, meant for services for which quality assurances are important. CableHome 1.1 QoS employs a priorities based solution, which allows specified applications to have priority access to the home network physical media. The priorities are also used in forwarding decisions within the residential gateway.

Applications on the home network are identified by the IP address and port upon which they communicate. The cable operator assigns priorities for these applications via a QoS MIB in the RG. LAN IP devices pass a list of pertinent resident applications, to the RG, via SOAP/XML/HTTP [7] messaging, and the RG replies with the assigned priorities for each of the applications advertised. The LAN IP devices use these assigned priorities when sending traffic, and the RG uses the assigned priorities when forwarding LAN IP traffic within the home.

Firewall

The CableHome 1.1 firewall definition includes standardized firewall configuration, a minimum set of firewall functionality, a list of applications that are required to work through the firewall, and a set of MIBs to support all of this functionality.

While CableHome 1.0 requires firewall functionality and a policy download mechanism, it does not specify the format or contents of the firewall policy file. CableHome 1.1 standardizes the firewall configuration to provide a uniform firewall management scheme. The firewall configuration is accomplished via a filter MIB in the RG, which is modeled after the DOCSIS IP filter table. IP packets are filtered based upon packet attributes, or by RG interface they arrive though. The firewall configuration also allows limits to be placed on day and time, which can serve as the basis for simple parental control applications. A minimum set of filters rules are defined as a default firewall policy.

Discovery

CableHome 1.1 also defines a discovery feature, whereby the cable operator is provided with information about devices and applications in the home. The information is passed from LAN IP Devices to the RG via SOAP/XML/HTTP messaging, and includes information such as device type, manufacturer, hardware revision, serial number, model name and number, software version, physical address, and resident applications (via port ID.) The RG saves this information and makes it available to the MSO via MIBs.

Miscellaneous Additions

CableHome 1.1 requires the RG to receive and process SNMP traffic arriving from the LAN interfaces. Also defined is static port forwarding, which supports servers in the home. Incoming traffic, that is not in response to a LAN IP Device initiated

message, is routed to a configured private LAN IP address.
CableHome 1.1 also defines VPN support in the form of smart port recognition.
VPN applications typically require key exchange communications to occur on port 500, and if port translation occurs at the RG, the key exchange messaging is broken.
CableHome 1.1 RGs are required to recognize, and not translate port 500.
Configuration file authentication, and optional encryption has also been added in CableHome 1.1, for DHCP provisioning mode. This is accomplished via Transport Layer Security (TLS) (RFC-2246).

Again how to integrate video in this architecture is not defined yet, and the different issues related to DRM in the home, content location, storage, user mobility have to be added.

Cable home network

As an important proportion of home networks are cabled, and the cable bandwidth is adequate for wireless signal transmission, work is in progress in CENELEC (committee number) to define physical interface for wireless LAN transmission through cable.

9 Related standard bodies

CableLabs (Packet Cable, DOCSIS, CableHome, OCAP, Open Cable) in charge of several projects:
Cable Modem for cable network physical and MAC layer standardization (DOCSIS); main releases are DOCSIS 1.0 (for best effort services), DOCSIS 1.1 (supporting QoS and Intserv model), and DOCSIS 2.0 (providing additional mechanism to mitigate the upstream disturbances).
Packet cable to define an VOIP architecture; main release are packet cable 1.0 specifications
Cable Home to provide an architecture for end to end QoS
Packet Cable multimedia to define an IP architecture for multimedia services.

SCTE in charge of ratifying the standards for cable.
ECCA: European Cable Communication Association (URL), including MSOs and defining requirements for cable networks
DVB
CENELEC: producing standards for physical layer related issues in cable network.

Related projects and initiatives

CASSIC (FP5 R&D project extending a decentralized IPCABLECOM architecture to video services).
Packet Cable Multimedia project (CableLabs, USA): generalization of IPCABLECOM voice over IP architecture to multimedia services
NGNA: Next Generation Network Architecture launched recently in the US to address service convergence with video in cable network

10 Potential issues and topics to develop

As a summary of the different issues and gaps identified and developed in the document, the following R&D topics have to be investigated for HFC:

- Techno economical analysis of the HFC network architectural evolution for high downstream and upstream bit rate access: decentralized and centralized architectures,
- related technological issue: optical components, terminals and cable routers, tuners, RF components.
- Analysis and modeling of the upstream band (5-55MHz) for upstream capacity optimization (Noise, Ingress, non-linear effects). Work has been performed on the topic, but modeling and measurement methods, i. e. how to dynamically characterize the upstream disturbance dynamically in an operational situation) have still to be investigated.
- Optimization of the upstream physical layer and dynamic adaptation to the upstream condition (spectrum management)
- IP architecture including video service and providing QoS, provisioning, security, AAA, open access:
    - Signaling architecture definition
    - Interface definitions for QoS and security between application, service, and network layers: evolution of the Packet Cable multimedia architecture
- Extension of the framework to the Home environment, related to home storage and video support:
    -

References

[DOCSIS_video]: Dennis Bushmitch, , Sarit Mukherjee, Sathya Narayanan, Muthukumar Ratty, and Qun Shi: “Supporting MPEG Video Transport on DOCSIS-Compliant Cable Networks”, Ieee Journal On Selected Areas In Communications, Vol. 18, No. 9, September 2000, p. 1581-1596.

[EurocableLabs Antwerp 9 June 2004]:

[cveyres]:

[JCP]:

[jcnossens]:

11 ANNEX 1: analysis of disturbances in cable upstream.

4.1 Impulse noise

Impulse noise is defined as including Impulse length of limited duration (<300 sec for instance). The impulses are therefore broadband in nature and disturb the whole return band. The impulse amplitude can be high enough to saturate the return amplifier or the return laser transmitter and destroy all the information transmitted in the band during the impulse; but also medium amplitude Impulse can exist, acting more like a temporary gaussian noise added to the signal.

The impulsive noise is mainly generated by man-made devices and to a minor extent by Nature. Among the man-made noise sources, we can mention power switching, high power dimmers, electrical motors, engine ignitions, digital equipment, switching of domestic equipment. The rate of occurrence of such Impulse has been observed as being multiple of the AC line frequency, i.e. relatively low repetition rate.
A second type of Impulse noise can also be created by bad contacts in the cable network interrupting from time to time the cable amplifiers AC power supply, lightning, atmospherics, and galactic noise.
A third type of Impulse is produced by the upstream optical transmitter clipping as explained below.

Extensive analysis [1] of Impulse noise has been performed in other papers and supports the following characterization of impulse noise statistics:

- Impulse length of less then 10 sec occur most frequently with a low repetition rate (< 1 kHz); the Impulse length limitation can be explained by the fact that most of the Impulses are filtered by the upstream band;
- Impulse length of 10 sec to 100 sec occur less frequently;
- Impulse noise can be sometimes observed to occur at given time in the day;
- The spectrum of these Impulses is not flat across frequency but can have a repetitive nature [1] as shown below.

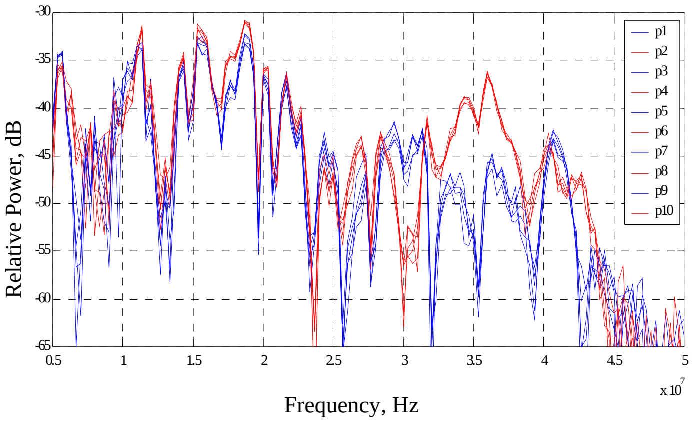


Figure 16: example of consecutive Impulse spectrum measurements[1]

4.2 Ingress noise

Ingress is defined as frequency selective impairment in contrast with Impulse noise, and can be categorized as follows:

- Narrowband Ingress injected in the cable network itself: the major causes are identified as being AM short-wave, amateur band, maritime radio transmission; the amplitude of the injected Ingress vary during the day according to the propagation condition; this slow amplitude variation can be as high as 20 dB
- Location specific interference: electronic equipment in the subscriber premise can inject a high level of Ingress in a poorly shielded coaxial installation.

The relative degree of importance of these 2 sources of Ingress will vary according to the cable network architecture; for instance:

- A cable network with aerial cabling will be more sensitive to Narrowband ingress, whereas man made noise will be of primary importance in an “underground” network;
- Some networks with a passive return path (working therefore at low operating levels) will be more sensitive to Narrowband Ingress.

4.3 Common Path Distortion

Common Path distortion (CPD) is produced by poor contacts in the cable network; these contacts create a rectifier effect, which produces mainly second order non-linear distortion product (and to a minor extent third order products) coming from downstream carriers. The main frequencies at which CPD will occur will are the multiple of channel frequency spacing (multiple of 6, 7 or 8 MHZ according to the frequency plan).

In general the CPD effects can be accurately calculated using a limited Volterra series (see [2]); in practice a good simplified model has been developed in [1], assuming that the non linear behavior did not depend on frequency (Taylor-expansion), and that the major part of the analog channels energy is located at the vision and sound carrier frequencies.

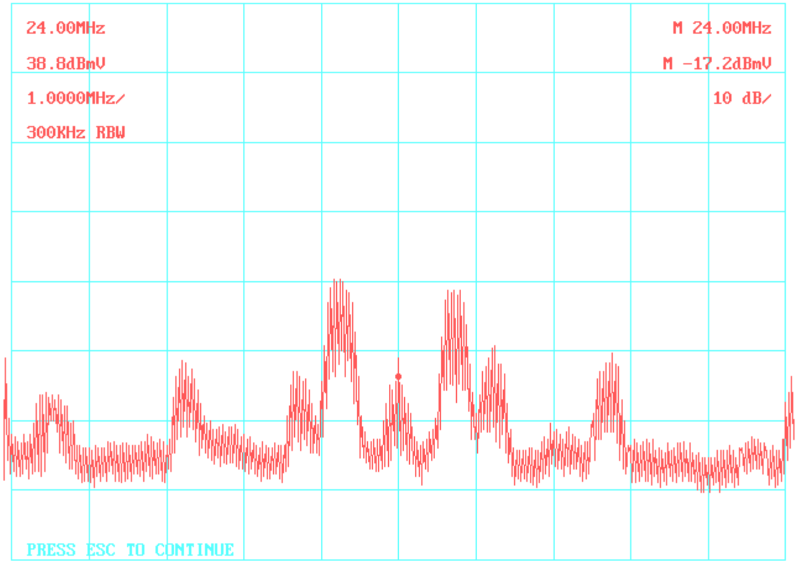


Figure 17: example of CPD spectrum measurement at 24 MHz (SCTE)

In summary the CPD frequencies are well determined as fixed by the downstream frequency plan, and the level of CPD can vary broadly during the day.

4.4 Clipping

Two non-linear devices will contribute to distortion and clipping in the upstream:

- Upstream amplifiers, which can be characterized by CTB, CSO and noise figure for 2nd and 3rd order non-linear distortion and noise respectively.
- Upstream laser transmitters can use uncooled Fabry-Perot or DFB, with and without optical isolators. A detailed description is out of scope but let us recall that:
  - Lasers diode show a hard clipping behavior under the threshold current;
  - The noise and non linear distortion behavior of the laser diode is complex and will depend on both on the amplitude and frequency of the incoming signals according to the following optical phenomena:
    - Discrete reflections to the laser diode can change both the noise and distortion characteristics;
    - Fabry-Perot external cavity created by 2 reflections will create non linear effect (due to the laser chirping);
    - Fiber combined double backscattering associated with homodyne detection at the receiver will induce an 1/f frequency dependant noise in the lower part of the spectrum;
    - Mode partition noise associated by Fiber dispersion and Polarization mode dispersion can also affect the optical transmission characteristic.

As a result a return path optical system is better characterized by its Noise Power ratio (the NPR) which will determine the range of total input power that is acceptable for a given C/(N+I).

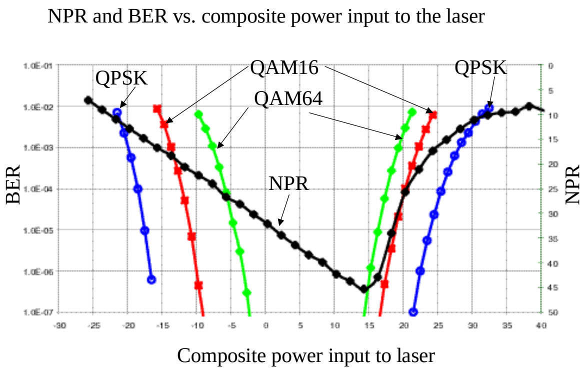


Figure 18: curve showing example of NPR, and BER for different constellations

The NPR approximates the acceptable operating level for a given spectral efficiency (via the C/(N+I) requirement).

The NPR estimation is accurate when the input signal to the laser is gaussian, i.e. for instance if the signal is composed of a sufficient number of similar QAM carriers;
Some slight corrections be made in the following cases:

- The additional power introduced by Ingress and Impulse noise may be significant and may require to add an additional margin;
- The total signal can differ slightly from a gaussian profile. This can be the case of an heterogeneous upstream spectrum containing different type of carriers, for example CDMA and TDMA carriers;
- The amount of Error correction applied on each carrier, linked with the service availability requirement, will also require some correction.

An enhanced NPR curve can take into account these situations, and will determine more exactly the required laser operating level.

The Ingress noise power can be significantly higher than the useful carrier power; in such case:

- The most frequent situation is where the Ingress situated between 5 and 10 MHz is the most disturbing; a low pass filter can be placed at the input of the impaired transmitters;
- If Ingress is mainly produced by the subscriber, Filters or Noise blockers can be used at the subscriber premises.

In conclusion the described disturbances affect mainly the low frequency (5-25 Mhz) upstream band, and each creates different kind of impairments.

The situation is particularly critical in the 5-20 MHz band where both Impulse and Ingress noise are important. Optimization of the upstream capacity even in that band is necessary, as it delays a costly plant upgrade for the operator (refer to economical analysis).

Glossary

QoS	
CSO	
CTB	
CDMA	
TDMA	
NPR	
CPD	
DVB	
SCTE	
CENELEC	
ECCA	
VLAN	
L2TP	
PPP	
PPPOE	
C/N	
C/(N+I)	
BPI	
SD	
HD	
SIP	
MGCP	
HFC	
MHP	
DOSCIS	
ETSI	
IP	
MPEG	
DN	
LN	
WAN	
LAN	
OMA	
DES	

DVB-DCA	
DVB-CA	
A/D	
D/A	
FTTH/B/C	
VOIP	
DRM	
CMTS	
CMS	
Diffserv	
IntServ	
3 GPP	
ISMA	
MHz	
A/D	
D/A	
QAM	
MZI	
MSO	
MAC	
ATDMA	
AM	
PS	
SOC	
CPU	
IETF	