Integrated MSc in Electrical and Computer Engineering

Hybrid Networks and DOCSIS 3.0

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CONTENTS

INTRODUCTION

In the following chapters, hybrid networks and Data Over Cable System Interface Specification (DOCSIS) 3.0 are discussed.

The main motivation behind this document is to provide an insight into the realm of cable networks. In order to achieve this, the study focuses on how the network is built, its major limitations, evolution of the DOCSIS specification and the structure and major benefits of the latest iteration.

In chapter 1, is given an introduction to the cable networks. The chapter starts with a bit of history in order to understand the roots of the actual architecture of today's networks.

Chapter 2 starts off with the reasons behind the appearance of fibre in the cable networks. As it progresses, some examples of network topologies are given and it ends with the introduction of DOCSIS and the elements needed to provide a DOCSIS service.

As for chapter 3, the evolution of DOCSIS is presented throughout the chapter. Each version has a small description with the main advantages over the last one, as well as the key benefits and features of it. In the end of the chapter, two tables sum up the information presented in this chapter.

Approaching the final chapter, DOCSIS 3.0 fills in the entire chapter 4 with a physical and MAC layer overview. The chapter end with a section dedicated to highlight the major benefits and advantages of DOCSIS 3.0. Along this section, the reason behind the improvements of data throughput in cable networks is presented.

The last chapter finishes the study with a small summary of these four chapters alongside with some conclusions.

1. CABLE NETWORKS

After the World War II (1946), Television gained a new strength, with TV broadcasting being resumed and people wanting to spend the economies they saved during the war. This led to an increase and perfection of television sets. Although it was desired by many, TV signal was still inaccessible to people farther from the signal's origin. Because of this, people started to look for alternatives for their lack of signal. Some people who had knowledge in the domain of electronics, started to search for a TV signal somewhere around their homes. Most of them found themselves travelling hundreds of kilometres and spending most of their weekends travelling in search of a TV signal (1).

This was the case of Mr. Ed Parsons. Mr. Parsons wanted to make his wife happy, who wished to see what the new radio with images was all about. Unfortunately, Parsons lived in a rocky town in the outskirts of Astoria, where TV couldn't reach. At least until he found out, that an antenna in the top of his rooftop was able to pick up the TV signal. Being this lucky, Mr. Parsons soon started to gain popularity and his town was seen as an opportunity to see the radio with images. Quickly, Mr. Parsons was looking for a way to regain his privacy and started to think about ways of distributing the signal he received to his neighbours (2).

Transmitting it through air was out of the question, because he would need to get FCC's authorization. This led him to the coaxial cable, since there were no legal obstacles to do this. Soon he was passing meters of cable from his house to their neighbours, which shared the costs of his system. Community antenna television (CATV) was born, being Mr. Parsons one of the pioneers of cable TV in America, along with several people from the rural valleys of Pennsylvania (1) (2).

Defining cable networks

From the beginning, cable networks started to appear as a way to deliver entertainment content to towns, where TV signal was not available, either due to their distance from the emitting station or terrain's characteristics. These networks were built upon coaxial cable and most of them used proprietary systems to provided access to the network. (1) (2) (3).

These first networks, as shown in figure 1, were mostly used to broadcast television signals that were received at the head end of the network through satellite dishes (tree-and-branch topology). On its way to the customer several amplifiers compensate the attenuation of the coaxial cables, which must not be too far apart in order for the input signal to be below the minimum noise level. In figure 2 attenuation versus frequency plot for two kinds of coaxial cables is presented. In the plot it is possible to see that a 1GHz the attenuation is very high, thus this is a limitation on cable networks. As operators reach closer to the 1GHz, the networks need to have more amplifiers and more close to each other. This an important factor to take into mind when updating a network (4) (5).

With the nineties also came the digitalization of most subscriber's telephone line and new services like DSL started to appear, offering voice and data at the same time. Cable operators also saw this as an important way to increase their revenues leading them to start offering data and telephony services on their network. To offer this kind of service, operators needed to update their networks to add a second cable for the return path, from customers to the head end of the network. This also meant updating all the amplifiers on the network, to provide amplification in both downstream and upstream channels (5) (4).

As operators needed to update their network to offer new services, fibre optics started to appear in the networks, in order to reduce the number of needed amplifiers and costs of operation. Throughout the nineties, most operators had their networks updated with a hybrid fibre-coax (HFC) network (5) (6).

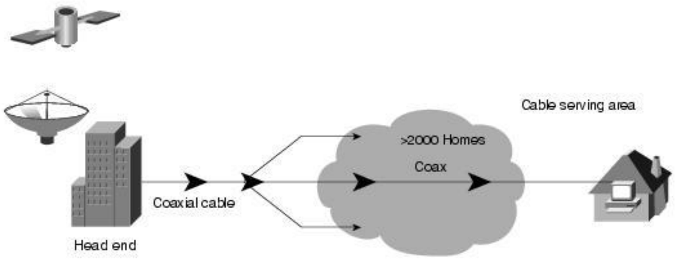

Figure 1 – A one way coax-only CATV network (4)

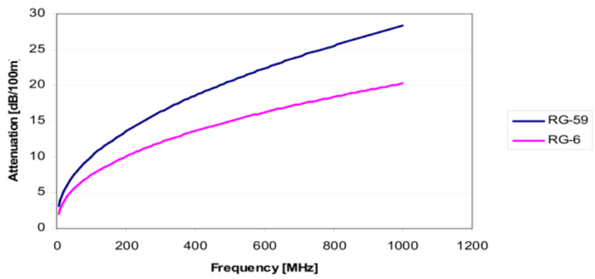

Figure 2 – Attenuation on coaxial cables (5)

2. HYBRID NETWORKS

In order to improve the connectivity of end users to the big cloud, the Internet, service providers strive for new technology that can provide higher bitrates to their customers. In order to achieve this, research is done in the field of modulation, synchronization techniques and development of new materials and so on.

2.1 Adding fibre to cable networks

As mentioned in the chapter I, the use of fibre-optic technology provides an increase of quality to the existing cable networks. The first portions to upgrade on the networks are those which experience heavy traffic loads. The coaxial cable is then substituted by multi fibre optic cable from a head end or a hub location. The most common architecture used nowadays is a ring topology, where the head end is connected to several optical nodes or optical hubs (figure 3). In these nodes, the optic signal is converted into an electric signal in order to be transmitted through the coaxial cable to the subscriber's home. The optical nodes serve a few hundreds or thousands of homes, although this number is decreasing as fibre gets closer to the subscriber home.

The optical node is connected by two optical fibres to the optical ring, one with the upstream signal and one with the downstream signal, which also adds redundancy to the network. In the optical node, the downstream signal is converted to an electrical signal on the coaxial cable, via a photodetector. As for the upstream channel, the node needs to convert the electrical signal into an optical signal. This conversion is done directly by putting the electrical signal as input to the laser, to modulate the light signal in the upstream fibre.

2.2 Network topologies

In Europe there are two common topologies that are employed in HFC networks, tree-and-branch and star topology.

The tree-and-branch topology is the most common one for the coaxial distribution plant. The main trunk cable is split into branches through splitters (passive bi-directional components). At regular times the bi-directional amplifiers amplify both the upstream and downstream signals. To connect a subscriber a tap is used to connect the drop cable to the home. Taps are like splitters and can multiplex one input into several outputs (5).

In a star topology, splitters with multiple outputs are used to connect several houses. This can be seen in figure 5 on the coax part of the network.

Note that these topologies are regarding the connection of the subscribers to the optical node.

2.3 HFC and the DOCSIS network

Updating the networks is not the only concern for the cable operators. For costumers to have access to the network, they also need to provide the equipment necessary to do that. This was a very important issue when they started offering data and telephony services, because the price of the equipment was very high as every company had its own solution. To keep up with the competition, cable operators had to unity and try to reach a consensus on how to access a HFC medium. The answer came with the version 1.0 of the Data Over Cable Service Interface Specifications (DOCSIS), which provided a *best effort* service but introduce interoperable cable modems, along with an important reduction on the price of the equipment.

To provide a DOCSIS service, the network needs to have several elements such as provisioning systems, network management service (NMS), cable modem termination system (CMTS), cable modem (CM) and customer premises equipment (CPE) (figure 6). The service might also be provided in a coaxial only network, but it is more common to use a HFC networks, because of the mentioned benefits in the previous section.

Starting with the CPE (customer equipment that connects to the Interne), this equipment connects to the HFC through a CM either by using IPv4 or IPv6 (only on DOCSIS 3.0). Then the HFC network connects to the CMTS that connects the back office and the core network, forwarding packets between them. The provisioning systems provide several back office configurations such as DHCP, Certificate Revocation server, software updates for the CM, configuration files for the CM, among other. Finally, the NMS provides the operator to monitor and configure Simple Network Management Protocol (SNMP) Agents, such as CM and CMTS. For example, this allows the operator to allow or disallow a device in a network. A syslog is also present in the NMS to obtain operation data from the devices. Statistics are also collected through an IP service (7).

The frequency spectrum is another concern, as the bandwidth is limit, mostly by the presence of coaxial cable, limiting the frequency operation to 1GHz. For a DOCSIS network the spectrum is divided into the upstream and downstream spectrum. The upstream spectrum is limited to the range of 5MHz to 42MHz or 5MHz to 85MHz in DOCSIS 3.0. On the other hand, the downstream spectrum is limited to the range of 108MHz to 1002MHz.

In this division of the spectrum, several services are supported by the cable operator, analog TV, digital TV, video on demand (VoD) and operation for the DOCSIS. The spectrum's division in use in Europe is presented in figure 7.

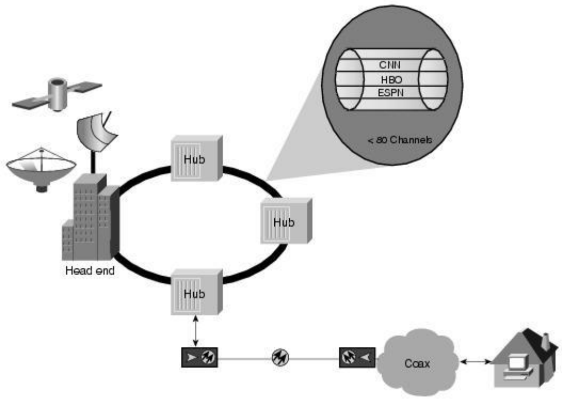

Figure 3 – RING topology of a HFC distribution network (4)

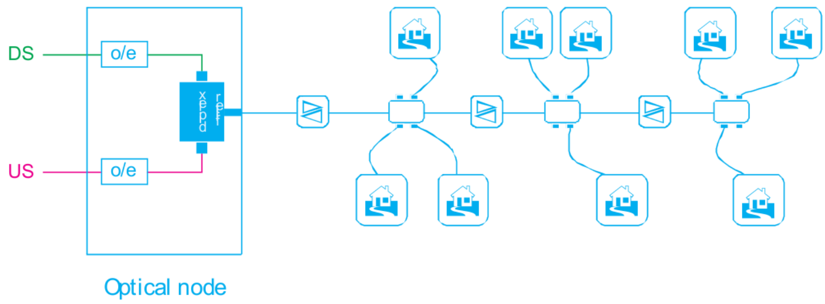

Figure 4 – Tree-and-branch topology in a HFC network (5)

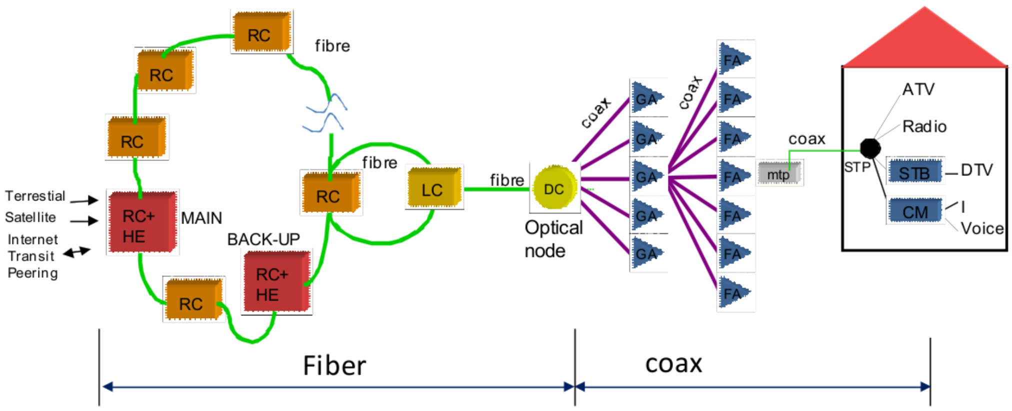

Figure 5 – Star topology in a HFC network (5). In the figure, RC, LC, DC: Regional, Local and District centers; GA,FA: Group and Final amplifiers; HE: head end; CM: cable modem; STB: set top box; mtp: multiple output taps

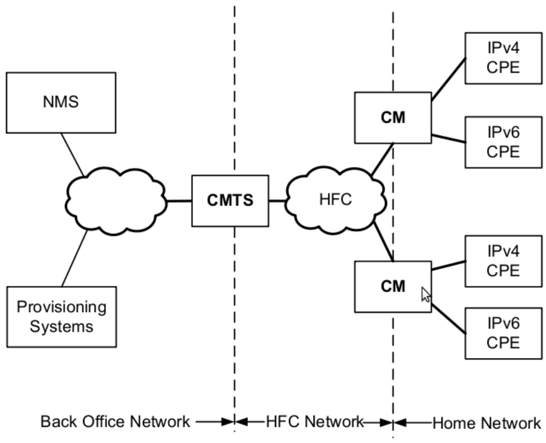

Figure 6 – The DOCSIS network (7)

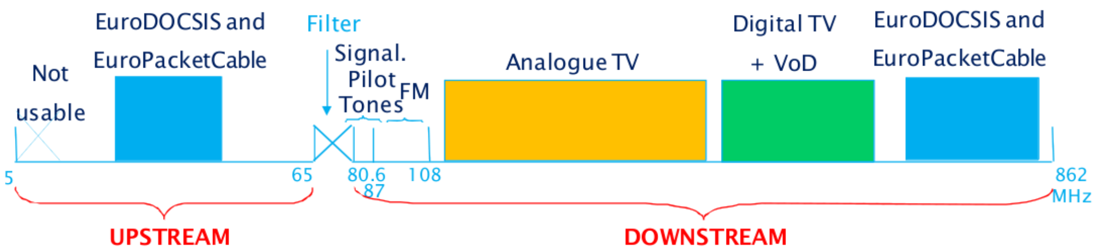

Figure 7 – Spectrum division on a EuroDOCSIS system. (Compatible with DOCSIS 3.0) (5)

3. Evolution of DOCSIS

As already mentioned in the previous sections, DOCSIS stands for Data Over Cable Specification. This specification resulted of a convergence made by cable companies in order to keep competition with the DSL market. This was what led to the creation of Cable Labs, a non profit organization that is focused on providing DOCSIS specifications for the United States of America. This specification includes the physical and MAC layer of the Open Systems Interconnection (OSI) model. As for Europe, DOCIS is known as euroDOCSI and is maintained by EuroCableLabs. As of 29 August of 2006, EuroDOCSIS was fully integrated into DOCSIS 3.0 as a joint effort of these two organizations (8).

Over the years, the improvements in the HFC networks of the companies and the increasing demand of users, led to significant changes to the DOCSIS specification. It was this what led to the evolution of DOCSIS through the several specifications, DOCSIS 1.0 (March 1997), DOCSIS 1.1 (April 1999), DOCSIS 2.0 (December 2001) and DOCSIS 3.0.

Comparison between DOCSIS versions

To fully understand the meaning of DOCSIS 3.0 one needs to comprehend the benefits ad features of the previous versions. A brief summary of the key features, benefits and advantages of each version of DOCSIS is presented in tables 1 and 2 (6).

Starting with DOCSIS 1.0, this specification allowed clients to have a basic broadband internet service, where there was no guarantee of service, which means DOCSIS 1.0 provided networks a *best effort* service. Although it did not provide quality of service (QoS), this version brought a huge benefit to cable operators, interoperability between vendors. This led the cost of the CMs from hundreds of Euros down to a few dozen dollars (9).The **QoS** would only be implemented over DOCSIS 1.1. Besides the introduction o QoS, this version provided many more advantages regarding its former one. In order to provide QoS several methods were implemented in this version, such as packet classification, service flows and dynamic services. With packet classification the packets can be classified regarding its origin, where it is going, type of packet and can be associated to a service flow. Therefore, service flow defines the specific guarantees (maximum and minimum throughputs, latency, jitter, among others) and limits to a type of traffic, for example, P2P (10).

Dynamic Services, such as Dynamic Service Addition (DSA), Dynamic Service Change (DSC) and Dynamic Service Delete (DSD) consist of a set of MAC messages that allow the CM and CMTS to communicate in order to create, change or delete a service flow. Note that this allows the association of different service flows to the same CM, which can be associated to a different kind of traffic (9) (10).

MAC layer fragmentation was also implemented. This is especially important as the return path of a cable network is shared among several users and the traffic in it becomes heavy. MAC layer fragmentation allows the CMTS to instruct a CM to fragment a large upstream data packet into several smaller ones. These smaller packets can then be scheduled to be sent after giving opportunity to other users that are trying to access the medium. Note that concatenation of packet can also be issued by the CMTS when the traffic on the network is light (10) (10).

IP multicasting was also introduced, providing a better usage of the available network through an efficient use of Internet Group Membership Protocol (IGMP) and IP multicast services. This allows the packets to be sent only once but may be received by several users. IP multicast services can then be delivered, such as audio, video, news headlines, among others (10).

In the field of **security** DOCSIS 1.1 provides also a set of new encryption characteristics to the already existing baseline privacy interface (BPI) in DOCSIS 1.0, through BPI plus (BPI+). BPI+ adds certificate-based authentication, describes how encryption works when CMs are able to provide several services as well as when fragmentation occurs (10).

To sum up, DOCSIS 1.1 provides several and important advantages over DOCSIS 1.0 and is still being used by operators all over the world, being ZON Portugal one example (11).

Continuing with DOCSIS 2.0, the biggest introduction of this specification is the increase of the upstream channel maximum throughput. By allowing the use of a 6MHz channel with a 64-QAM Modulation, a CM can achieve a maximum throughput of 30.72Mbps (9) (12).

With the increasing of the maximum upstream rate, this version had to set up defences against channel noise and interference. To accomplish that in this version is possible to use different **error correction codes**, such as a Reed-Solomon FEC with a 128/122 code (6 symbols of overhead for every 128 symbols, 4.7%) or a Trellis coding (1 byte for every 15 bytes, for 64-QAM, and 1 byte per 20 bytes, for 256-QAM. This is 6.7 percent and 5 percent, respectively). With the overhead introduced by Ethernet packets (18 bytes) DOCSIS and IP (6 bytes each) and an additional 2% of overhead for DOCSIS MAC traffic, the actual throughput is lowered down close to 27 Mbps. **Advanced Time Division Multiplex Access** (**ATDMA) and Synchronous Code Division Multiple Access (SCDMA)** are also presented in this version as new and better alternatives over the FDMA access in the versions 1.x. ATDMA is a direct evolution of the previous specification using time instead of frequency to multiplex the several accesses. As for SCDMA, the transmission to the medium is made simultaneously by the use of 128 orthogonal codes during the same time slot. To achieve compliance with DOCSIS 2.0 these two access methods must be supported (9) (12).

As for DOCSIS 3.0, the latest version of DOCSIS builds upon its predecessors and provides the highest throughput so far, with the use of channel bonding. New IP services are also present in this version, such as IPv6 and IPTV. Security is also enhanced through the use of Advanced Encryption Standard (AES). This version will be better discussed in chapter IV (9) (7).

To sum up, versions 1.1 was the version that introduced more enhancements to the DOCSIS specification, making it really competitive with other communication solutions in the market. Although version 1.0 managed to build low budget CMs, the evolution of this rather simple specification led to the version 3.0 which allows a continuous function between USA and Europe.

Table 1 - Key differences between each DOCSIS version *(9)*

DOCSIS 1.1 over 1.0	- Quality of Service - Dynamic Services - Fragmentation and concatenation - IP Multicast - Payload Header Suppression - CM Authentication - CM Account Management
DOCSIS 2.0 over 1.1	- 6.4 MHz maximum upstream channel width - 27 Mbps maximum upstream channel capacity (64 QAM) - Synchronous-CDMA operation (S-CDMA) - Increased robustness to upstream noise and channel impairments - Enhanced Reed-Solomon error correction - Trellis Coded Modulation - Channel utilization statistics
DOCSIS 3.0 over 2.0	- Channel bonding to increase possible upstream and downstream data rates by a factor of 4 or more - Support for IPv6 - Enhanced security features, including the Advanced Encryption Standard (AES) - Support for IPTV - Support for HFC systems other than low-split - Enhanced reporting to manage traffic - Enhanced tools to detect plant problems

Table 2 – Features and benefits of the several DOCSIS versions (9)

DOCSIS Version	Features	Benefits
DOCSIS 1.0	Basic broadband internet connectivity (*best effort*). Allows to rate limit a customer's data rate to a value selected by the cable operator	Made the Interoperability of cable technology a reality, through the use of cable modems. Standardization was then possible reducing the prices from 500€ to 50€.
DOCSIS 1.1	Improved operational flexibility, security, and quality-of-service (QoS).	Enables the cable operator to configure guarantees on the data rates and/or the latency of the service
DOCSIS 2.0	Upstream reliability and throughput for symmetric services	Increases upstream throughput to 27 Mbps of capability.
DOCSIS 3.0	Channel bonding, enhanced multicast, IPv6 support and security and management enhancements.	Allows cable operators to provide data rates in the hundreds of megabits

4. DOCSIS 3.0

The key drivers for DOCSIS 3.0 are competitive threats, migration planning and premium services. DOCSIS 3.0 stands as an answer from the cable operators to the competitors on the DSL space. Thus, DOCSIS 3.0 brings with it higher throughputs as well as new and better IP services.

While it brings important changes to the DOCSIS environment, this version is still compatible with devices that are still functioning with an older version.

4.1 Physical layer overview

A more detailed discussion on the physical layer will be presented throughout this section. More detailed information can be found in the specification provided by cable labs (7).

4.1.1 Radio frequency (RF) channel

In the RF channel, the normal downstream transmission must be supported in the range of 50MHz to 1002MHz. Though, the specification only provides parameters for an operation on the range of 108MHz to 1002MHz. The maximum downstream channel width is 6MHz in the USA and 8MHz in Europe. As for upstream operation, the RF channel must support operation in the range of 5 to 42MHz or 5 to 85MHz. The maximum channel width is also 6MHz.

4.1.2 Upstream

The upstream Physical Media Dependent (PMD) sublayer uses a FDMA/TDMA (TDMA mode) or FDMA/TDMA/S-CDMA (S-CDMA mode) burst type format, which provide six modulation rates and multiple modulation formats. The use of TDMA or S-CDMA is configured by the CMTS via MAC messaging (7).

In FDMA multiple channels in the RF channel are assigned in the upstream band. A CM transmits on one or more RF channels and can be reconfigured to change channels. The CM must support at least four active upstream channels. As the number of upstream channels can change due to request of the CMTS, the CM has to report to the CMTS its maximum number of upstream to ease negotiations with the CMTS. These upstream channels can be apart in the upstream band and the CM must be able to operate under this conditions.

In S-CDMA multiple CM can transmit in the same RF channel during the same TDMA time slot, using orthogonal codes to distinguish them in the reception.

Signal Processing Requirements

Before sending the signal in the upstream channel, the CM has to process the signal as depicted in figure 8.

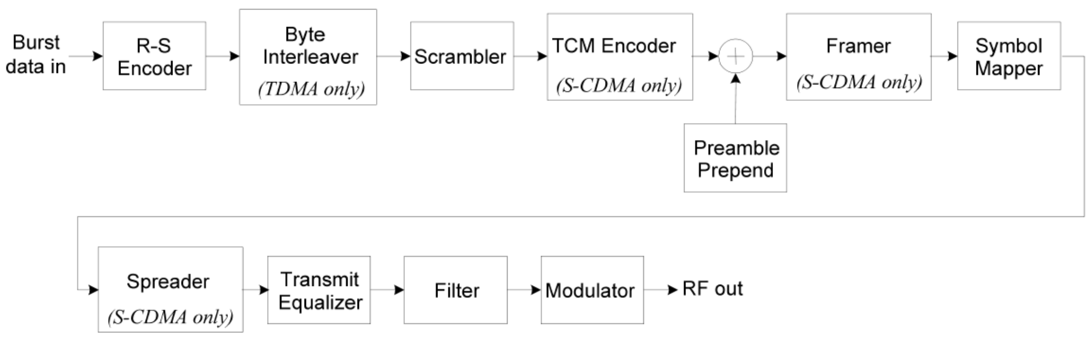

Figure 8 – Upstream signal-processing sequence (7)

The same sequencing was already done in DOCSIS 2.0. Note that the overhead is different in TDMA mode and S-CDMA mode. On the former, there's only an overhead imposed by the Reed Solomon encoder (R-S encoder), opposed to the later where there's an extra overhead imposed by the Trellis code modulation.

The Reed Solomon encoder (R-S encoder)

The R-S encoder must provide over a Gallois Field of 256, meaning a maximum of 255 bytes (253 bytes of information for 1 error correction). Note that the R-S encoder can also provide up to 16 corrections, meaning that in 255 bytes, only 223 bytes would contain information. This value is configured by the CMTS. The minimum number of corrections is zero, meaning that the R-S encoder can be disabled.

The encoder can function with fix-length codeword or shortened-last codeword. In either mode the minimum size for the codeword is 16. In left side of figure 9, the packet data length is always equal to the codeword length. Opposed to this is the second example in the right side of figure 9. In this case, the packets can have different lengths of data. The data that can not fit into the first packet is put on a second packet with one padding until the codeword size (k bytes).

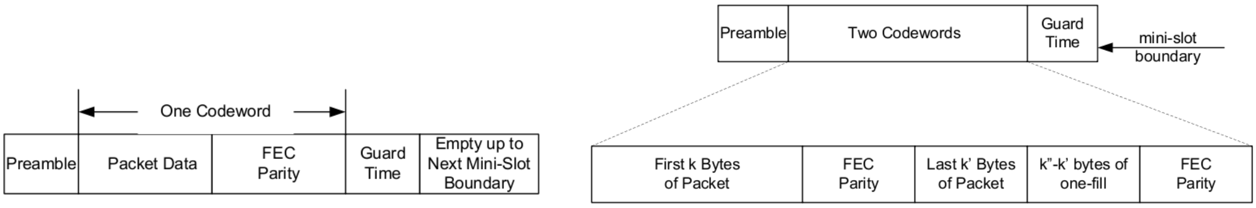

Figure 9 – Fix-length codeword (left) and shortened-last codeword (right) examples

The frames on figure 9 represent a mini slot that is sent to the CMTS, with the agreed burst size of 2.

Byte interleaver

The function of the byte interleaver is to provide additional protection against noise. The encoded data bytes of the R-S encoder are written in each row of a matrix. Afterwards, every column is read and sent to the scrambler. As errors usually occur in bursts, if a sequence is damaged only one bit in each packet will be damaged.

Scrambler

This consists of a LSFR with a seed configured by the CMTS. LSFR produce a pseudo random sequence with a period given by the polynomial that is used. In this case the polynomial in use is $x^{15}+x^{14}+1$. Every output of the LSFR is combined with each bit of the byte interleaver. This is used for security reasons.

TCM encoder

Used only with S-CDMA systems, this block provides a trellis code modulation for transmission of m bits per symbol with QPSK 0, 8QAM, 16QAM, 32QAM, 64QAM and 128QAM constellations. This generates an overhead of one bit, as m input bits are mapped into m+1 bits.

Preamble prepend

The preamble has not a fixed size and has specifics rules regarding modulation for each version of DOCIS. Therefore this sequence must be programmable by the CMTS. For DOCSIS 3.0, the minimum size of the preamble is 0 and the maximum is 192 bytes. A QPSK0 or QPSK1 modulation must be used, which means a maximum of 768 QPSK symbols. The preamble is a well know pattern that eases the symbol lock and recovery by the burst modulator.

Modulation rates

In TDMA and S-CDMA, the CM upstream modulator must support all modulations at 1280, 2560 and 5120 kHz.

S-CDMA framer and interleaver

These two blocks provide that the input mini-slots are matched with a spreading code and a spreading interval, arranging them in an S-CDMA frame. Protection against impulse noise is provided by the interleaver. Some notes should be taken regarding the numbering of minislots, the delay introduced by the framing operation and transmission time.

Minislots are numbered according to the available codes to the CM. Although, the spreading interval, which is the time each frame last, may not me a power of two multiple of the 10.24 MHz reference Therefore, an additional synchronization step is required. This is done through a timestamp snapshot that contains the information required for the CM to calculate the number of time counts per S-CDMA frame.

Regarding transmission times, each frame (with m minislots) is supposed to arrive at the same time in the CMTS. Each CMs can send at least one frame which depends on the bandwidth that was allocate. Using S-CDMA, there is a delay approximately equal to the duration of a frame. Considering a burst profile with 10 spreading intervals (number of counts) per frame and a sampling rate of 2.56Hz, this would result in a frame duration of 500 µs as obtained in (1).

$$\mathrm{T_f} = 10 * 128 * \ (2.56 * 10^6\ ) = \ 500\ \mu\mathrm{s}\ (1), \text{where 128 is the code length}$$

Symbol mapper

This block maps the symbols to the constellations of the modulation that was configured by the CMTS. In both TDMA and S-CDMA modulations QPSK 0, 8QAM, 16QAM, 32 QAM, 64 QAM are possible, although S-CDMA also provides 128 QAM.

Spreader

This block spreads the vector of 128 symbols from the previous block into a 128x128 code matrix. Each row of the matrix is an orthogonal code. Code hoping is available through the use of a LSFR. This consists of changing the code matrix every time a frame is sent according to the pseudo random output of the LSFR.

SPECTRAL SHAPING

In this block the CM upstream transmitter uses a Nyquist square-root raised-cosine pulse-shaping filter with roll-off factor α =0.25. Therefore, the channel width can be calculated through (2)

$$Channel\,Width = Modulation\,Rate * (\,1 + \,\alpha)\;(2)$$

Being 5120kHz the highest modulation rate, this implies a 6,4MHz maximum channel width.

Relative processing delays

When a CM is using upstream channel bonding, it is said to function on the Multiple Transmit Channel (MTC) mode. In this more the CM and CMTS can exchange Bandwidth Allocation Messages (MAP) in order to balance the load on the network. Although there is a certain delay while processing these messages. The processing delay, D_p, is given by equations (3) and (4).

$$D_p = 600 + \frac{M}{5.12}\,\mu s\;(3)$$

$$M = \begin{cases} I_r N_r, & I \neq 0 \\ B_r, & I = 0 \end{cases}\;(4)$$

In equation (4), M represents the number of elements on the interleavers (in TDMA mode) and framers (in S-CDMA mode). In both cases, the minimum processing delay happens when there is no interleaving or framing, meaning M=0, therefore a delay o 600 µs. For S-CDMA, M = 128(K+1) with K=32 being the maximum number of spreading intervals per frame. This means a delay of ***1.425 s***.

4.1.3 Downstream

To comply with DOCSIS 3.0 operation the CM must work with at least for active downstream channels in frequency ranged specified before. The specification states the minimum signal to noise ratio that should be observed by the CM.

Downstream Multiple Receiver Capabilities

For each CM, the CMTS needs to know its constraints in order to keep the downstream synchronised and prevent data disruption. Then, each CM reports to the CMTS by sending its Receive Channel Profiles (RCP). In response, the CMTS configures the CM by sending a Receive Channel Configuration (RCC).

STANDARD RECEIVE CHANNEL PROFILE

To keep the complexity down in RCP, DOCSIS defines a set of standard RCP that are to be used by the CM when reporting its constraints to the CMTS. A CM will at least report one standard RCP to the CMTS alongside its manufacturer RCP, which provides the RCP with more details. The CMTS will then issue a RCC back to the CM. If this is based on the standard RCP, some capabilities of the CM might be unavailable.

Note that in case of load balancing, the CMTS might need to change the bounding configuration of the CM. When something like this happens, the CMTS will analyse the RCPs that were sent to him by the CM, before sending out a new RCC. With this, the CMTS can minimize and/or schedule the disruption of downstream traffic and any perturbations to DOCSIS master clock timing.

SYNCING CMTS AND CM

In order to keep the synchronism between CMTS and CM, the CMTS sends its 10.24MHz reference clock timing to the CM via the downstream QAM symbol clock and via timing information in downstream SYNC messages. The CM uses this information to replicate the clock locally.

4.2. MAC layer overview

As already mentioned, DOCSIS is a standard for layer 1 and 2 of the OSI model. This layer is responsible for sending data to the physical layer as well as receiving data from it. The specification for the MAC layer allow the operation of the MAC layer, for example, setting service flows, fault detection, setting channel bonding parameters, among others.

To keep this overview simple and small, only the generic MAC header format will be presented in this section. All the details of this layer can be read in the specification provided by cable labs (13).

THE GENERIC MAC FRAME

A MAC frame is the basic unit of information that is transferred between MAC sublayers at the CMTS and the CM. The same structure is used in both the upstream and downstream directions. The MAC frame has a variable length according to the request or indication that is being handled. The term frame is not to be misunderstood with framing, which indicates some fixed timing relationship.

Preceding a MAC frame is either a PMD sublayer overhead (upstream) or an MPEG transmission convergence header (downstream). The MAC frame is then divided in a MAC Header and a Data PDU. The latter is optional. Figure 10 illustrates the generic MAC frame and the contents of the MAC header.

In the case of upstream, the MAC layer only needs to know the overhead imposed by the physical layer, in order to meet the bandwidth requirements. The introduced FEC by the physical layer is completely transparent for the MAC layer. In figure 11 is given an example of the transportation of a MAC frame by the physical layer.

The format for the MAC header in figure 10 is to be used by the CM and CMTS. The header can have a maximum size of 247 bytes and a minimum size of 6 bytes. Table 3 contains the meaning of each field. This is a generic description of the header. There are several uses for it, for example, time header, request header, MAC management header, and so on.

In case of a data request from the upperlayer, the MAC header will feature a data payload with a maximum size of 1522 bytes. User data can use up to 1500 bytes, but in special case an extra 18 bytes can be used. It is also possible to send a data packet with no actual data. This is called a null packet and is needed in some cases, for example to set up dynamic services.

4.3. A summary on the key benefits of DOCSIS 3.0

While DOCSIS 3.0 revolutionizes the physical layer through the usage of channel bonding, most of the parameters brings with it two major features, channel bonding and enhanced multicast. Alongside, several features are updated, such as support for IPv6, security enhancements and network management.

Channel bonding and enhanced multicast are the key to provided new services demanded by the market. With channel bonding, operators are able to provide an increase in the physical layer throughput, reducing the latency introduced by this layer. With the use of an enhanced multicast service, these services can be provided while sparing a considerable amount of bandwidth. These services are defined as multicast streams and can be sent to devices as they request it. IPTV is an example of the new services enabled by DOCSIS 3.0.

With IPv4 being at its limit, the support of IPv6 is a must have addition to the DOCSIS environment, in order to keep every device connected to the Internet.

Security is also an important feature to upgrade, whether to prevent service theft or users' data theft. AES with 128 bits is used to keep the data private.

In the realm of network management, IP Data Record/Streaming Protocol (IPDR/SP) is used to acquire information from the devices in a more efficient way.

4.3.1 Channel Bonding

Up until DOCSIS 3.0, the data could only be sent over a 6MHz channel downstream (8MHz in Europe) and a 6,4MHz channel upstream. With this new specification, data is allowed to flow over ***m*** channels either downstream or upstream. This is known as **channel bonding** and is responsible for the speed boost of DOCSIS 3.0 compliant networks. As data can be sent over several channels, being 4 the minimum number of channels that a CM must support (downstream and upstream), this means an increment in the throughput of at least four times the previous one. This is valid either for the upstream and downstream signal. This process is highly dynamic as the CMTS may agree with the CM which channels to use. Note that if a device using DOCSIS 1.x or 2.0 is connected to the same CMTS, every device connected to it will fall back to the earliest version.

Consider a CM in a system that uses a 6MHz channel width and a modulation of 256 QAM, the maximum data rate that it can achieve is given by equation (5).

$$f_b = \log_2 256 * \frac{6 * 10^6}{1.12^1} = 42.85Mbps \, (5)$$

In a DOCSIS 3.0 environment this value is multiplied by four, meaning that the minimum throughput that is available to a CM is 42.85 *4 = 171.4 Mbps. The same thing can be done to the upstream channel, although the transmissions over that channel can be done using QPSK, 64QAM as modulation.

4.3.2 Enhanced multicast

Version 2.0 already featured a nice scheme for multicast, although it is again improved in this version supporting new versions of the IGMP and Multicast Listener Discovery (MLD) protocols. CMTS play an important role in dealing with multicast traffic, having more authority over the CMs, telling them which streams they should process. QoS services are also applied to multicast streams, dealing with them a service flow. This allows the CMTS to classify certain types of multicast streams and assign to them a level of QoS.

[1] For a downstream input into the CM, 1.2 is the roll-off factor to consider as stated in table 6-22 of Y for 256 QAM.

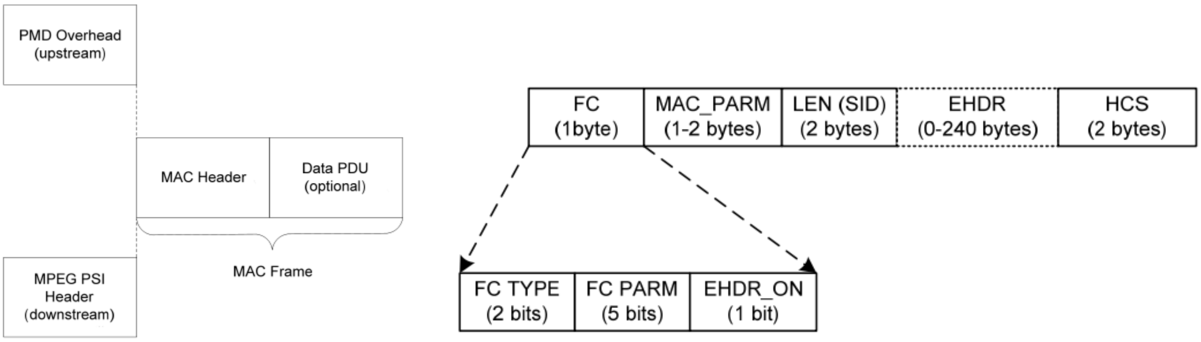

Figure 10-– MAC generic frame (left); MAC header format (13)

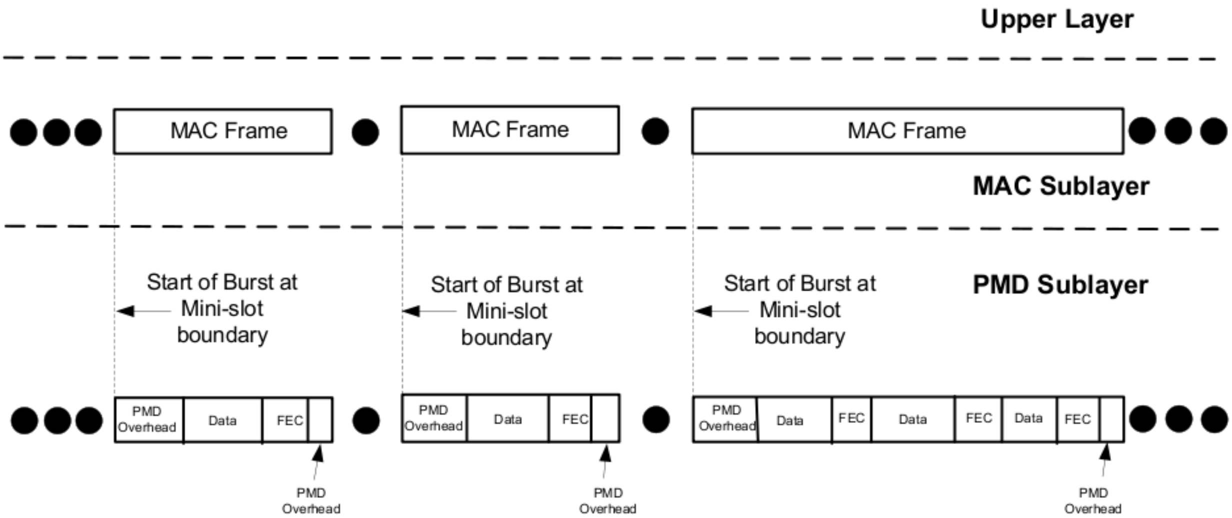

Figure 111 – Transport of a MAC frame by the physical layer (upstream) (13)

Table 3 – MAC header fields and usage (13)

Field	Usage
FC	Frame Control: Identifies type of MAC Header
FC TYPE	MAC Frame Control Type field: 00: Packet PDU MAC Header 01: ATM PDU MAC Header 10: Isolation Packet PDU MAC Header 11: MAC Specific Header
FC PARAM	Parameter bits, use dependent on FC_TYPE.
EHDR_ON	EHDR_ON When = 1, indicates that EHDR field is present (Length of EHDR (ELEN) determined by MAC_PARM field)
MAC PARAM	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 6–10) used for MAC frame count **else** (for Requests only) indicates the number of mini-slots requested
LEN (SID)	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).
EHDR	Extended MAC Header (where present; variable size).
HCS	Header checksum sequence

CONCLUSION

During the previous sections were discussed several topics in the area of cable networks.

The study started with a brief introduction to the cable networks and how they started to appear. The appearance of cable networks, or community cable television as it was known in that time, was mainly motivated by the strong will of several pioneers that went to the hills in search of a TV signal. Soon people realized the opportunity to turn this into a business and cable TV grew in popularity. With it, the network was also expanded.

With the revolution in the digital worlds and the appearance of computers, new services started appearing offering data services alongside a telephone. Soon, cable operators thought that they could also follow through in order to improve their earnings. Though, the network needed to be updated with a return path, which led to the introduction of fibre optic technology in the critical areas of the network. Even though, the equipment to provide users with a connection to the network was still very expensive and a standard was required to make every cable modem interoperable between operators.

Data Over Cable Service Interface Specifications appeared as a joint effort of the biggest cable operators to reduce the costs of the equipment. Throughout the years, DOCSIS evolved and 4 versions of the specifications were release. DOCSIS 1.0, the earliest version, provided a *best effort* service but allowed the reduction of cable modem's prices. DOCSIS 3.0, the latest version and currently being used by some operators, allows an extraordinary increase in throughput with channel bonding. With this new concept in the DOCSIS network, operators are able to increase their throughput up to the GB, as long as they sacrifice a few analogical TV channels to increase the number of bounded channels. Along with this, the newest version of DOCSIS provides better multicast support, better QoS and enhancements in security. All of this will allow the operators to provide new IP services, such as IPTV and keep up with the competitive marketplace.

Whenever a new iteration of DOCSIS was issued a considerable evolution was seen in every one. Version 1.1 is definitely the one that introduced more changes in the operation of DOCSIS, although this evolution never changed one thing, legacy support. Every DOCSIS device is compatible with any device independently of the DOCSIS version that it uses. Though, this may be an advantage to cable operators, as it eases the burden of transition between each version of DOCSIS. In the mean while, the presence of a legacy device in a DOCSIS path, leads every device to fall back to the DOCSIS version that is used by the earliest (oldest?) device. This means that many advantages of DOCSIS 3.0 may not be available because a DOCSIS 1.1 device is present between the costumer and the head end.

To sum up, DOCSIS 3.0 meets with its demands, to face the competition of the DSL market and provided new services. Cable operators will still be able to keep up with the competition as the consumer demand increase. In the end, if the trend of reducing the number of clients per node continues, cable operator will eventually have a fibre to home solution.

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