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DOCSIS 3.1

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Introduction

DOCSIS Definition

- CableLabs developed DOCSIS technology to transfer data over coaxial cable that are deployed and used for cable TV connection.
- DOCSIS standards are adopted by the cable operators across the world so that internet data, voice and video services are provided using existing cable TV systems.

(contd...)

History

- DOCSIS 1.0
  - Released in March 1997.
  - Begin the transfer of data over cable system interface.
  - Support for high speed data over HFC had been defined.
- DOCSIS 1.1
  - Released in April 1999.
  - State of art QoS techniques had been added for priority services.

(contd...)

History

- DOCSIS 2.0
  - Released in December 2001
  - Increased modulation format for upstream to get more b/s/Hz.
  - For upstream Synchronous Code Division Multiple Access (SCDMA), new physical layer (PHY) had been added.
  - A state of art advanced Media Access Control layer (MAC) had been added.

(contd...)

History

    - Allocation of two dimensional upstream bandwidth and simultaneous transmission within the same channel had been enabled for QoS and QoE.
- DOCSIS 3.0
    - Released in August 2006.
    - Addition of IPV6 and multicast QoS.
    - Channel bonding.
    - Old modulation formats and FEC had been kept.

(contd...)

History

- DOCSIS 3.1
  - Released in October 2013.
  - Backward compatibility has enabled
    - Avoids tax on spectrum
    - DOCSIS MAC is leveraged across legacy single carrier PHY and new OFDM PHY
    - SC QAM and OFDM are enabled to share a bonding group

(contd...)

History

- Increase in capacity of data rate
  - Downstream capacity of 10+ Gbps has enabled
  - Upstream capacity of 1+ Gbps has enabled
  - The maximum is unbounded

(contd...)

History

DOCSIS Speed Comparison			
Version	Specification Released	Maximum Download Speed	Maximum Upload Speed
DOCSIS 1.X	1997	42.88 Mbps	10.24 Mbps
DOCSIS 2.0	2001	42.88 Mbps	30.72 Mbps
DOCSIS 3.0	2006	1372.16 Mbps	245.76 Mbps
DOCSIS 3.1	2013	10 Gbps	2 Gbps
Full duplex DOCSIS 3.0	2017	10 Gbps	10 Gbps

(contd...)

DOCSIS 3.1 Goals

- ❑ Increased spectral efficiency
- ❑ Increased data rates
- ❑ Different spectrum and plant conditions may be adapted easily
- ❑ Migration from old versions of DOCSIS easily
- ❑ Existing HFC systems are used for operation

(contd...)

DOCSIS 3.1 Specifications

- Modernization of PHY layer in order to increase bits per Hz
  - Legacy DOCSIS PHYs plus is supported
  - 16384 QAM / 4096 QAM downstream and upstream modulation formats
  - Addition of downstream OFDMA
  - Addition of upstream OFDMA
  - Addition of error correction technology

(contd...)

DOCSIS 3.1 Specifications

- ❑ BCH codes for outer FEC
- ❑ LDPC codes for inner FEC
- ❑ From DOCSIS to DOCSIS 3.1 FEC change may result in:
  - ❑ Increase in gain upto two modulation orders in the same SNR environment.
  - ❑ Gain could be close to a single order

(contd...)

DOCSIS 3.1 Specifications

- New cable spectrum band plan has been defined
  - Extension of upstream to 200 MHz
  - Extension of downstream to 1.2 GHz or 1.7 GHz

(contd...)

DOCSIS 3.1 Key Advantages

- The same last mile technology i.e., the coax cable, is used for supporting the higher gigabit speeds.
- It is a much more cost effective technology to implement for cable internet providers.
- A huge jump in download and upload internet speeds is offered.
- Backward compatibility.
- New certificate based security features are defined.
- The light sleep modes are supported during idle time.

(contd...)

Full Duplex DOCSIS

- Extension of DOCSIS 3.1 specifications
- Increased upstream capacity
- Symmetric multi-Gigabit services are enabled over existing HFC networks
- Doubles the efficiency of spectrum use

(contd...)

Full Duplex DOCSIS Key Features

- Symmetrical Up/Down Capabilities
- 10x the Upload Speeds Available Today

(contd...)

DOCSIS 3.1 Hurdles

- The large chunks of spectrum are cleared for OFDM carriers.
- Conversion to all digital carriers by eliminating analogs.
- New requirements for completely new standard.
- The testing and system monitoring tools are also new.
- Frequency extensions and Mid splits
- When downstream is extended to 1.2 GHz, there is MoCA interference.

(contd...)

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(contd...)

Fundamentals

Introduction

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Frequency Expansions

- Downstream Expansions
  - 1.2 GHz
    - Plant expansions of upto 1.2 GHz are supported by DOCSIS 3.1
    - 1.2 GHz must be supported by CM and CMTS of DOCSIS 3.1
  - 1.794 GHz
    - There is an optional support for 1.7 GHz by DOCSIS 3.1 CM and CMTS
    - It may be used in the later versions.

(contd...)

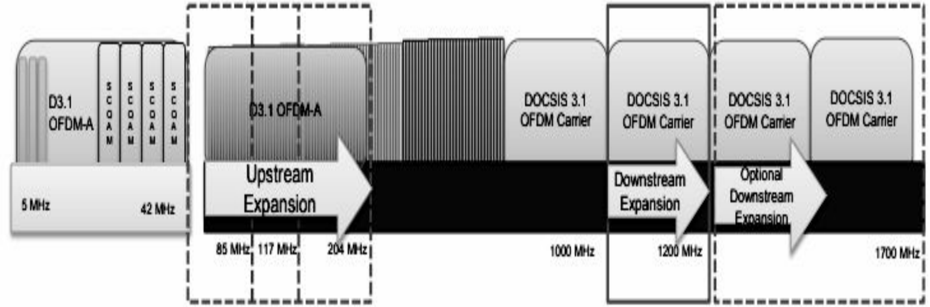
Frequency Expansions

- Upstream Expansions
  - 85 MHz QAM or OFDM
    - 85 MHz upstream is supported by DOCSIS 3.1 as by 3.0
  - 117 MHz OFDM
    - An additional support has been added by DOCSIS 3.1 for 117 MHz return
  - 204 MHz OFDM
    - An optional support has been added by DOCSIS 3.1 for 204 MHz return.

(contd...)

Frequency Expansions

- It is desirable to expand the frequency but not necessary.
- The width of downstream OFDM carriers is from 24 MHz to 192 MHz.
- The expansion of downstream is upto 1.7 GHz



Frequency Expansions

- The width of upstream OFDM carriers is from 6.4 MHz to 96 MHz.
- The expansion of downstream is upto 204 MHz.
- There is legacy carriers coexistence.
- Typically, less than 250 end devices are connected per node.

(contd...)

Some Issues in Mid Split to Ponder

- ❑ Upto 65 dBmV has been transmitted by DOCSIS 3.1 modems with isolation of home splitters.
- ❑ Tuner RF isolation has been deployed for TV IF from 41-47 MHz.
- ❑ Ingress of FM band in the return path.
- ❑ There is an egression of signal from the upstream carrier in the aeronautical band.
- ❑ OOB STB downstream carriers
- ❑ Tilt and equalization in upstream

(contd...)

Speeds and Frequencies

Downstream	DOCSIS 3.0		DOCSIS 3.1	
	Initial	Future	Initial	Future
DS Range (MHz)	54-1002	108-1002	252-1212	504-1700
DS QAM Level	256	256	256-4096	256-16384
# DS Channels	8	24	5x192 MHz	6x192 MHz
DS Capacity (bps)	300M	1G	8G	10G

(contd...)

Technologies in DOCSIS 3.1

- Advanced signal processing techniques are used by DOCSIS 3.1 to achieve higher throughput by fully utilizing the frequency spectrum and the available spectrum for data transfer in upstream and downstream can be increased.
- Higher order modulation for data transfer can be utilized by DOCSIS 3.1 by using the improvements in error correction technology.
- 4096 QAM has been supported by DOCSIS 3.1 that can be scaled upto 16384 QAM.

(contd...)

Technologies in DOCSIS 3.1

- Hence, data can be transmitted more efficiently.
- The use of Orthogonal Frequency Division Multiplexing (OFDM) is another improvement in DOCSIS 3.1
- A lot more data is allowed by OFDM to be packed in the same frequency spectrum than SC-QAM, used in DOCSIS 3.0.
- There is a splitting of a data stream into multiple streams in OFDM and then multiple frequency sub carriers are used to transmit them simultaneously.

(contd...)

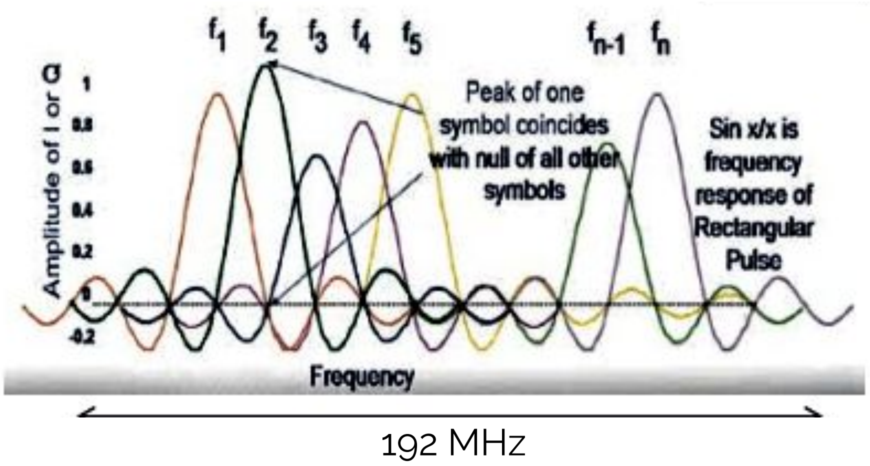
Technologies in DOCSIS 3.1

- Hence, more data has been transmitted on the same frequency band.
- Higher frequency spectrum for data transfers in upstream and downstream is allocated by DOCSIS 3.1 in addition to enhanced signal processing techniques like 4096 QAM and OFDM.
- Upstream frequency band from 5 MHz to 65 MHz and downstream from 85 MHz to 1002 MHz is used by DOCSIS 3.0 whereas upstream from 5 MHz to 204 MHz and downstream from 252 MHz to 1788 MHz is allocated by DOCSIS 3.1.

(contd...)

OFDM Carrier

- Stands for Orthogonal Frequency Division Multiplexing.
- Multi-Carrier Technology
- Individual narrowband subcarriers are used.
- FFT-Based Implementation



OFDM Technology

- In downstream, there is a spacing of subcarriers at either 25 or 50 kHz or within a downstream carrier of 192 MHz, there is a spacing of as many as 8000 sub-carriers at 25 kHz each.
- There is an overlapping of subcarriers in spectrum to get even greater spectral efficiency.
- When there are issues of interference or presence of legacy carriers, each subcarrier can be turned off.

(contd...)

OFDM Technology

- Each subcarrier has its own level of modulation.
- The bandwidth can be gained by eliminating guard band so that more bits per hertz can be transmitted.
- Due to orthogonality property of carriers, each of them are distinguishable and non interfering.
- The width of OFDM carriers in 6 MHz increment is from 24 to 192 MHz.
- There are upto five 192 MHz wide carriers.

(contd...)

OFDM Technology

- Symbol times are also longer.
- Spectrum efficiency is better due to deployment of carriers up to the edge of the channel without guard bands.
- Better utilization of spectrum through bit loading.
- Use of flexible modulation schemes.
- Different modulation schemes are used on the basis of performance of cable modem.
- On the basis of MER at the CPE, the level of modulation is evaluated.

(contd...)

Subcarrier Modulation

- Either a 25 kHz spacing or a 50 kHz spacing can be used to define subcarriers.
- This means that for a 192 MHz carrier, there are either
  - 4096 subcarriers, spacing of 50 kHz using 4k FFT
  - 8192 subcarriers, spacing of 25 kHz using 8k FFT
- Different order of QAM modulation has been used by each of these subcarriers.

(contd...)

Physical Layer Introduction

Introduction

- ❑ The ultimate goal of DOCSIS 3.1 is providing downstream at multi-gigabit per second and upstream at gigabit per second that resulted in the changes in the approach of PHY layer as compared to previous versions of DOCSIS.
- ❑ For downstream signal OFDM and for upstream signal OFDMA are used by DOCSIS 3.1, respectively, so that robust operation can be achieved and the spectrum can be used more efficiently than the previous versions.

(contd...)

Introduction

- A large number of subcarriers are composed in the downstream multicarrier system of the OFDM with spacing of either 25 kHz or 50 kHz.
- There is a grouping of these subcarriers into independently configurable OFDM channels and up to 192 MHz spectrum is occupying by each of them in the downstream having total of 7680 25 kHz subcarriers or 3840 50 kHz subcarriers out of which up to 190 MHz has been spanned by 7601 (25 kHz) or 3801 (50 kHz) active subcarriers.

(contd...)

Introduction

- Either 25 kHz or 50 kHz subcarriers are composed in the OFDMA upstream multicarrier system.
- There is a grouping of these subcarriers into independently configurable OFDMA channels and up to 96 MHz spectrum is occupying by each of them in the upstream having total of 3840 25 kHz subcarriers or 1920 50 kHz subcarriers.
- Low Density-parity Check (LDPC) FEC coding is used.

(contd...)

Introduction

- Efficiency has been optimized by defining the long FEC codeword types in upstream and downstream.
- The considerations for improvement and optimization of operation under special modes is included in the suite of specifications of DOCSIS 3.1.
- For minimization of CM power consumption, a light sleep mode is introduced.

(contd...)

Equipment Assumptions

- Frequency plan
- Compatibility with other services
- Fault isolation impact on other users
- Cable system terminal devices

(contd...)

RF Channel Assumptions

- Transmission Downstream

Parameter	Value
Frequency range	Cable system normal downstream operating range is from 54 MHz to 1002 MHz. Extended operating ranges include lower downstream edges of 108 MHz and 258 MHz and upper downstream edges of 1218 MHz and 1794 MHz.
RF channel spacing (design bandwidth)	24 to 192 MHz
One way transit delay from headend to most distant customer	≤ 0.800 ms (typically much less)
Signal to Composite Noise Ratio	≥ 35 dB
Carrier-to-Composite triple beat distortion ratio	Not less than 41 dB
Carrier-to-Composite second order distortion ratio	Not less than 41 dB
Carrier-to-Cross-modulation ratio	Not less than 41 dB
Carrier-to-any other discrete interference (ingress)	Not less than 41 dB
Maximum amplitude variation across the 6 MHz channel (digital channels)	≤ 1.74 dB pk-pk/6 MHz

RF Channel Assumptions

Parameter	Value
Group Delay Variation	≤113 ns over 24 MHz
Micro-reflections bound for dominant single echo	-20 dBc @ ≤ 0.5 µs -25 dBc @ ≤ 1.0 µs -30 dBc @ ≤ 1.5 µs -35 dBc @ > 2.0 µs -40 dBc @ > 3.0 µs -45 dBc @ > 4.5 µs -50 dBc @ > 5.0 µs
Carrier hum modulation	Not greater than -30 dBc (3%)
Maximum analog video carrier level at the CM input	17 dBmV
Maximum number of analog carriers	121

RF Channel Assumptions

- Transmission upstream

Parameter	Value
Frequency range	Cable system normal upstream operating range is from a lower band-edge of 5 MHz to upper band-edges to 42 MHz and 65 MHz. Extended operating ranges include upper upstream band-edges of 85 MHz, 117 MHz and 204 MHz.
One way transit delay from most distant customer to headend.	≤ 0.800 ms (typically much less)
Carrier-to-interference plus ingress (the sum of noise, distortion, common-path distortion and cross modulation and the sum of discrete and broadband ingress signals, impulse noise excluded) ratio	Not less than 25 dB
Carrier hum modulation	Not greater than -26 dBc (5.0%)
Maximum amplitude variation across the 6 MHz channel (digital channels)	≤ 2.78 dB pk-pk/6 MHz
Group Delay Variation	≤163 ns over 24 MHz
Micro-reflections bound for dominant single echo	-16 dBc @ ≤ 0.5 µs -22 dBc @ ≤ 1.0 µs -29 dBc @ ≤ 1.5 µs -35 dBc @ > 2.0 µs -42 dBc @ > 3.0 µs -51 dBc @ > 4.5 µs
Seasonal and diurnal reverse gain (loss) variation	Not greater than 14 dB min to max

Transmission levels

- The required margin above noise and interference can be achieved by lowering the nominal power level of the upstream.
- To set upstream signal levels, it is desired to follow uniform power loading per unit bandwidth with specific levels established by the cable network operator so that the required carrier-to-noise and carrier-to-interference ratios can be achieved.

(contd...)

Physical Sublayer for OFDM I

Upstream and Downstream Frequency Plan

- Downstream CM Spectrum
- Downstream CMTS Spectrum
- Upstream CM Spectrum
- Upstream CMTS Spectrum
- Downstream Exclusion Band Rules
- Upstream Exclusion Band Rules

(contd...)

Subcarrier Clocking

- A subcarrier clock frequency defines each OFDM symbol who is nominally 20 usec or 40 usec.
- During one period of the Subcarrier Clock, the CMTS generates the number of cycles of each subcarrier which must be an integer number.
- There must be a synchronization of the CMTS Subcarrier Clock with the 10.24 MHz Master Clock.
- Each OFDM symbol has a cyclic prefix which is an integer multiple of 1/64th, of the Subcarrier Clock period.

(contd...)

Subcarrier Clocking

- The sum of one Subcarrier Clock period and the cyclic prefix duration gives the duration of each OFDM symbol.
- The phase of each subcarrier within one OFDM symbol is the same.

(contd...)

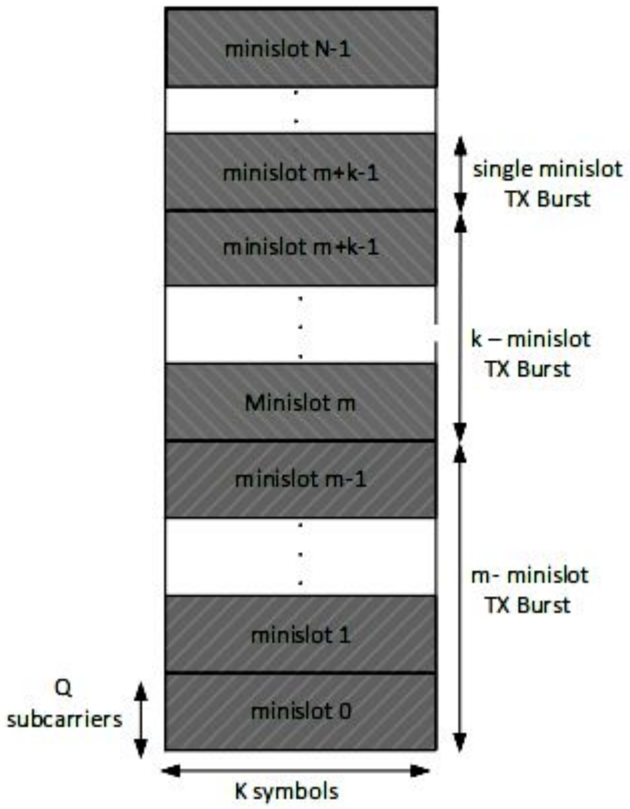
Upstream Transmit and Receive

- Signal processing and requirements
  - The OFDMA frames are used for upstream transmission.
  - A configurable number of OFDM symbols are comprised in each OFDMA frame.
  - The same OFDMA frame has been shared by several transmitters by transmitting data and pilots on the allocated sub-carriers of the OFDMA frame.

(contd...)

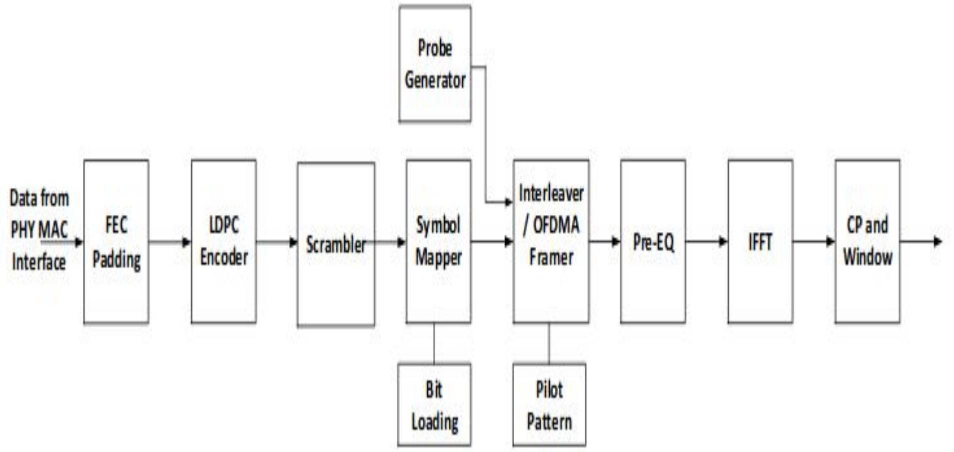
Upstream Transmit and Receive

- An OFDMA frame structure is shown in the figure.



Upstream Transmit and Receive

- The PHY receives and processes serial data signals from the PHY-MAC convergence layer as shown in the figure.



Upstream Transmit and Receive

- Time and Frequency Synchronization
  - CM upstream frequency and timing of transmissions can be obtained on the basis of downstream tracking and receiving and implementing timing adjustments from the CMTS.
  - It includes:
    - Channel Frequency Accuracy
    - Channel Timing Accuracy
    - Upstream Subcarrier Clock Frequency

(contd...)

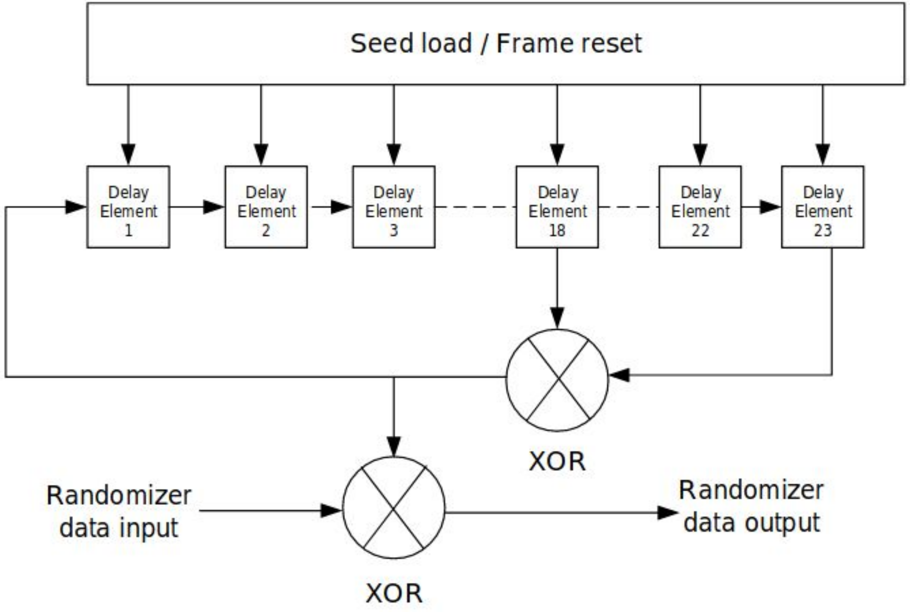
Upstream Transmit and Receive

- Forward Error Correction
- FEC Codeword Selection
- FEC Encoding
- Shortening of LDPC Codewords

(contd...)

Upstream Transmit and Receive

- Data randomization
  - A randomizer has been implemented in the upstream modulator as shown in the figure where the 23-bit seed value is programmable.



Upstream Transmit and Receive

- Time and Frequency Interleaving and De-interleaving
  - The burst noise affects the upstream transmissions, hence, the SNR of all the subcarriers of a few successive OFDMA symbols can be reduced.
  - Ingress may also impact the upstream transmission that can last for several symbol periods and hence, the SNR of a subset of subcarriers can be reduced over an entire frame of OFDMA.

(contd...)

Upstream Transmit and Receive

- The purpose of interleaver is the distribution over the affected subcarriers over a number of FEC blocks and enables the FEC to correct the corrupt data.

(contd...)

Upstream Transmit and Receive

- ❑ Mapping of Bits to Cell Words
  - ❑ Minislots grant the transmission opportunities to the CMs and are associated with subslots.
  - ❑ The modulation order of all subcarriers within a minislot is same.
  - ❑ The Profile associated with the minislot determines the modulation order to be used as different minislots may have different modulation orders.

(contd...)

Upstream Transmit and Receive

- The incoming serial binary bitstream from the data scrambler to constellation symbols can be modulated by the CM using the constellation mapping.
- The bit stream can be encoded by the CM such that the first bit is the least-significant bit of the constellation symbol when bits are mapped into constellation symbols.
- All constellations in the CM must have same nominal average power.

(contd...)

Physical Sublayer for OFDM II

Upstream Transmit and Receive

- Mapping and De-mapping Bits to or from QAM subcarriers
  - Minislots grant the transmission opportunities to the CMs and are associated with subslots.
  - Modulation formats
    - The zero valued subcarriers of upstream OFDMA channels must be supported by the CM modulator and CMTS demodulator.

(contd...)

Upstream Transmit and Receive

- BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM, 64-QAM, 128-QAM, 256-QAM, 512-QAM, 1024-QAM, 2048-QAM, and 4096-QAM must be supported by the CM modulator and CMTS demodulator for subcarriers of upstream OFDMA channels.

- Constellation mapping
  - The bit stream must be encoded by the CM such that the first bit is the least-significant bit of the first QAM subcarrier constellation m-tuple.

(contd...)

Upstream Transmit and Receive

- The interleaved m-tuples must be modulated by the CM onto subcarriers using QAM constellation mappings.
- It must be ensured by the CM that all QAM constellations subcarriers have the same nominal average power using the scaling factors.
- The incoming QAM constellation subcarriers of a minislot must be demodulated by the CMTS receiver according to the Profile associated with the minislot.

(contd...)

Upstream Transmit and Receive

- REQ messages
  - The short messages are called REQ messages used by the CM to request transmission opportunities from the CMTS.
  - The structure of these messages is different from the data message as they are always 56 bits long, use QPSK modulation, do not apply any FEC and are block interleaved.

(contd...)

Upstream Transmit and Receive

- IDFT
  - IDFT is used by the CM to transmit the upstream OFDMA signal.
- Cyclic Prefix and Windowing
  - The upstream transmission applies cyclic prefix and windowing.
  - The receiver is enabled to overcome the effects of inter-symbol interference (ISI) and inter-carrier interference caused by micro-reflections in the channel by adding the cyclic prefix.

(contd...)

Upstream Transmit and Receive

- The channel capacity has been maximized by applying windowing y sharpening the edges of the spectrum of the OFDMA signal.
- At the two ends of the spectrum of the symbol of the OFDM as well as at the ends of internal exclusion bands, there occurs spectral edges.

- Fidelity requirements
  - A CM’s Transmit Channel Set (TCS) is the combination of legacy channels that transmits the OFDMA channels.

(contd...)

Upstream Transmit and Receive

- Upto 8 channels of legacy DOCSIS plus up to 2 channel-blocks of OFDMA are generated by CM of DOCSIS 3.1.
- "Equivalent channel power" of a legacy DOCSIS channel refers to the power in 1.6 MHz of spectrum.
- The average power of the subcarriers of the OFDMA of the channel that has been normalized to 1.6 MHz bandwidth is called the "equivalent channel power" of an OFDMA channel.
- The reported power of TCS describes its each channel.

(contd...)

Upstream Transmit and Receive

- CMTS Receiver Input Power Requirements

Modulation	Minimum Set Point	Maximum Set Point	Range
QPSK	-4 dBmV	10 dBmV	-9 / +3
8-QAM	-4 dBmV	10 dBmV	-9 / +3
16-QAM	-4 dBmV	10 dBmV	-9 / +3
32-QAM	-4 dBmV	10 dBmV	-9 / +3
64-QAM	-4 dBmV	10 dBmV	-9 / +3

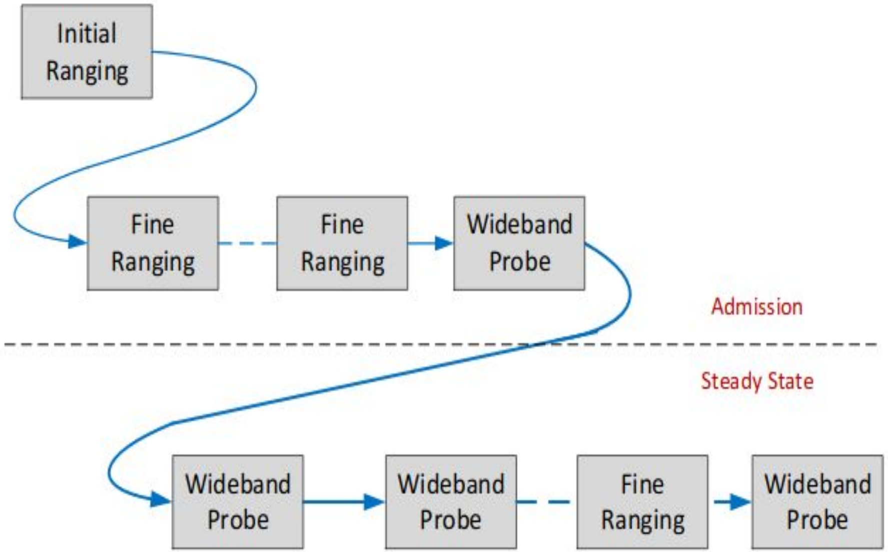
Upstream Transmit and Receive

- CMTS Receiver Input Power Requirements

Modulation	Minimum Set Point	Maximum Set Point	Range
128-QAM	0 dBmV	10 dBmV	-9 / +3
256-QAM	0 dBmV	10 dBmV	-9 / +3
512-QAM	0 dBmV	10 dBmV	-3 / +3
1024-QAM	0 dBmV	10 dBmV	-3 / +3
2048-QAM	7 dBmV	10 dBmV	-3 / +3
4096-QAM	10 dBmV	10 dBmV	-3 / +3

Upstream Transmit and Receive

- Ranging
  - Figure shows the three steps of ranging.



Upstream Transmit and Receive

- Upstream pre-equalization
  - A linear pre-equalizer must be implemented by the CM with a single complex coefficient per subcarrier.
  - A CM must be directed by the CMTS to pre-equalize its upstream transmission by using CMTS-assigned pre-equalization coefficients.
  - To update the pre-equalizer coefficient, the CM's probe signal is used by the CMTS.

(contd...)

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Physical Sublayer for OFDM III

Downstream Transmit and Receive

- Signal Processing
  - The PHY receives and processes the serial data signals received from the PHY-MAC Convergence Layer as shown in the figure.
  - The OFDM symbols are yielded by this process with 4096 subcarriers for the 4K FFT mode and 8192 subcarriers for the 8K FFT mode.
  - Each symbol consists of
    - Data subcarriers
    - Scattered pilots

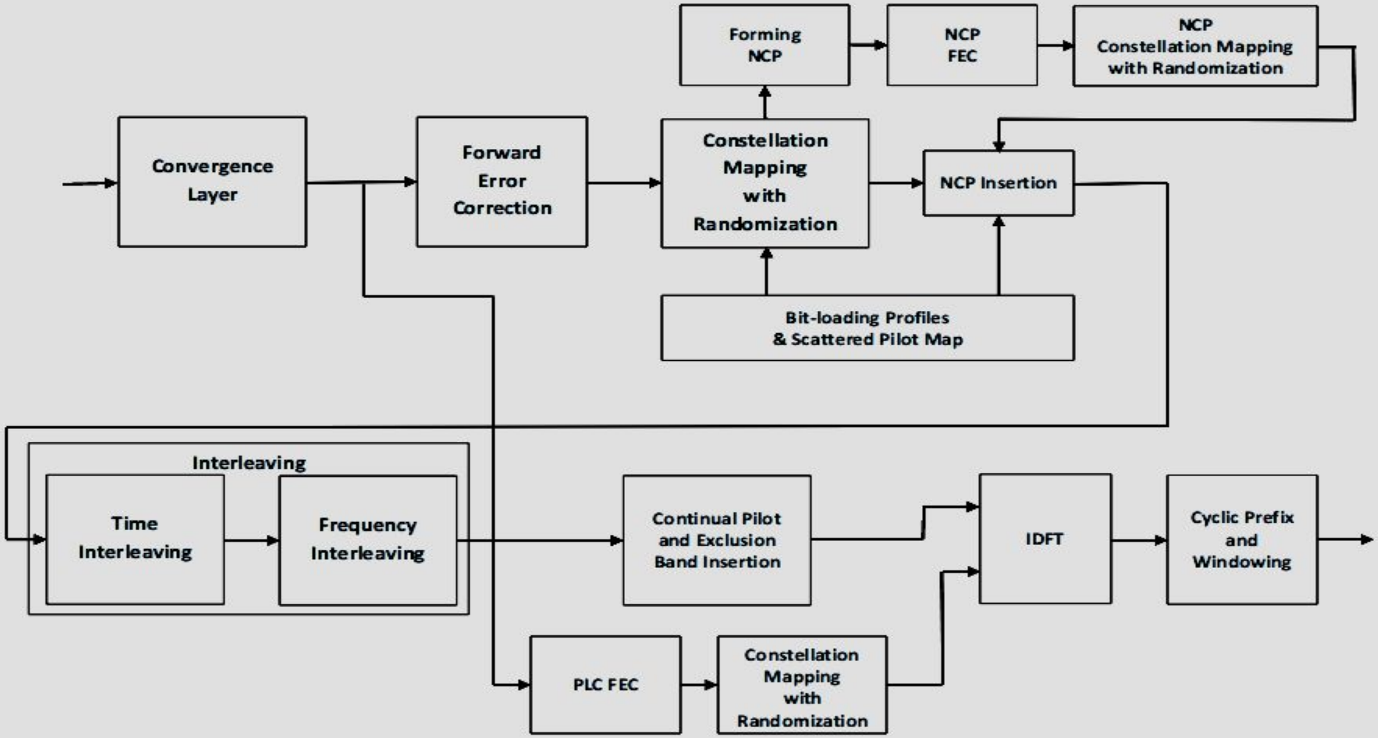
(contd...)

Downstream Transmit and Receive

- ❑ Continuous pilots
- ❑ PLC subcarriers
- ❑ Excluded subcarriers that are set to zero

(contd...)

Downstream Transmit and Receive



Downstream Transmit and Receive

- Time and Frequency Synchronization
  - Downstream sampling rate
  - OFDM RF Transmission Synchronization
  - Downstream OFDM Symbol Clock Jitter
  - Downstream Timing Acquisition Accuracy
  - Downstream Carrier Frequency Acquisition Accuracy
  - Downstream Acquisition Time

(contd...)

Downstream Transmit and Receive

- Downstream Forward Error Correction
  - The downstream forward error correction scheme, based on FEC Encoding, is used with the following modifications:
    - A codeword will be the size of the short FEC Frame.
    - The code rate 8/9 is used only.
    - Introduction to the support for non-square constellations
    - Introduction to the support for mixed modulation codewords
    - Introduction to the support for codeword shortening

(contd...)

Downstream Transmit and Receive

- Introduction of bit interleaving and demultiplexing for non-square constellations, mixed modulation mode constellations and for shortened codewords.
- No requirement for the support for QPSK modulation.

(contd...)

Downstream Transmit and Receive

- Mapping Bits to QAM Constellations
  - Addition of parameters for mapping bits onto non-square constellations
  - Addition of parameters for mapping bits of shortened codewords onto all constellation types
  - Addition of parameters for mapping bits of mixed-modulation codewords onto all constellation types

(contd...)

Physical Sublayer for OFDM IV

Downstream Transmit and Receive

- Interleaving and de-interleaving
  - The impacts of burst noise and ingress on the DOCSIS signal can be minimized by applying time interleaving and then frequency interleaving.
  - The time interleaver which is a convolutional interleaver and operates in the time dimension on individual subcarriers of a sequence of OFDM symbols.

(contd...)

Downstream Transmit and Receive

- The frequency location of any OFDM subcarrier is not changed by the time interleaver.
- The frequency interleaver works along the frequency dimension.
- The frequency locations of individual OFDM subcarriers are changed by the frequency interleaver.
- Dispersion of ingress is the aim of frequency interleaving.
- The burst affected subcarriers are distributed by using frequency interleaving over a number of LDPC codewords.

(contd...)

Downstream Transmit and Receive

- IDFT
  - Downstream Transmitter Inverse Discrete Fourier Transform
  - Subcarrier Referencing

(contd...)

Downstream Transmit and Receive

- Cyclic Prefix and Windowing
  - The effects of inter-symbol-interference and inter-carrier-interference caused by micro-reflections in the channel is overcome by using the cyclic prefix at the receiver.
  - The channel capacity has been maximized by using windowing in which the edges of the spectrum of the OFDM signal can be sharpened.

(contd...)

Downstream Transmit and Receive

- Fidelity requirements
  - For an OFDM channel there is
    - The occupied bandwidth
    - The encompassed spectrum
    - The modulated spectrum
    - The number of equivalent legacy DOCSIS channels
  - CMTS Output Electrical Requirements

(contd...)

Downstream Transmit and Receive

- CMTS Transmitter Output Requirements
  - CMTS Output Electrical Requirements

(contd...)

Downstream Transmit and Receive

- Cable Modem Receiver Input Requirements
  - Any range of OFDM subcarriers must be accepted by the CM defined between Lower Frequency Boundary and Upper Frequency Boundary simultaneously.
  - OFDM configuration settings describe the active subcarrier frequencies, loading, and other OFDM characteristics and CM exclusion bands and profile definition.

(contd...)

Downstream Transmit and Receive

- Cable Modem Receiver Capabilities
  - CM Error Rate Performance in AWGN Channel
- Physical Layer Link Channel (PLC)
  - PLC Placement
  - PLC Structure
  - PLC Preamble Modulation
  - PHY Parameters Carried by the PLC

(contd...)

Downstream Transmit and Receive

- Downstream Pilot Patterns
  - The subcarriers modulated by the CMTS are the pilot channels with a defined modulation pattern that is known to all the CMs in the system to allow interoperability.
  - There are two types of pilots: continuous and scattered.
  - Continuous pilots occur at fixed frequencies in every symbol.
  - Scattered pilots occur at different frequency locations in different symbols.

(contd...)

PHY-MAC Convergence

Upstream Profiles

- Multiple minislots are comprised in upstream profiles and bit loading and pilot pattern characterized them.
- Bit loading and pilot patterns can vary between minislots with in the profile.
- There is a variation of bit loading and pilot pattern assignment of minislots between profiles.
- The portions of a single minislot may be used by the different FEC codeword sizes.

(contd...)

Upstream Profiles

- A long codeword is needed with 17 kb grant to cover the first 16200 bits and a 1 kb codeword to cover the rest of the bits.
- The first long codeword can land in the middle of a minislot.
- The minislot and frame boundaries are crossed by the FEC codewords.

(contd...)

Upstream Minislots

- A size in terms of the number of symbols and number of subcarriers defines the minislots.
- They include data carried on data subcarriers, pilots carried on pilot subcarriers and complementary pilots that can carry data but at a lower modulation order.
- They include:
  - Minislot parameters

(contd...)

Upstream Minislots

- Minislot Structure
- Modulation of Data Subcarriers
- Location of Pilots
- Modulation Order of Pilots
- Location of Complementary Pilots
- Modulation Order of Complementary Pilots
- Pilot Overhead

(contd...)

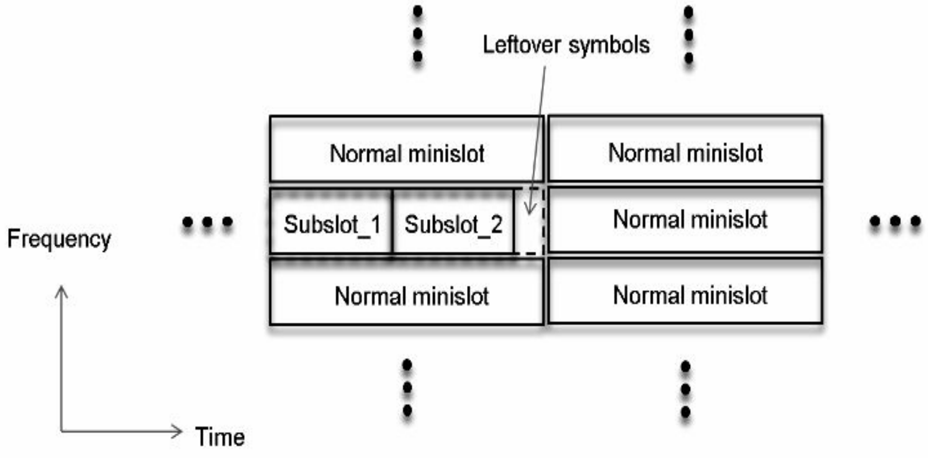
Upstream Minislots

- ❑ Mapping Minislots to Subcarriers
- ❑ Ordering of Data Bits within a Minislot
- ❑ Modulation Order Variability

(contd...)

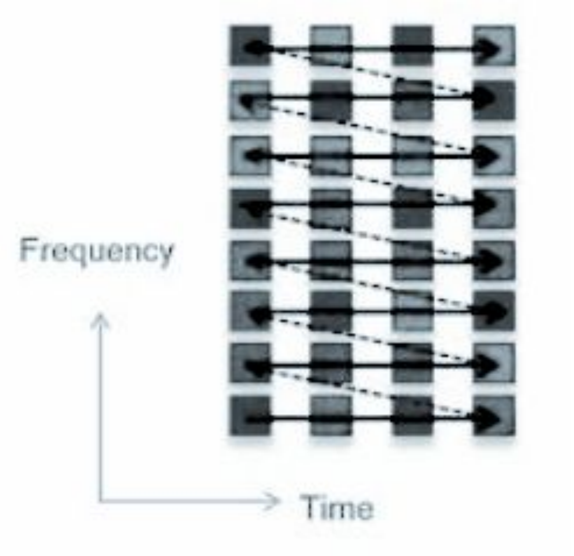
Upstream Subslots

- Subslot structure



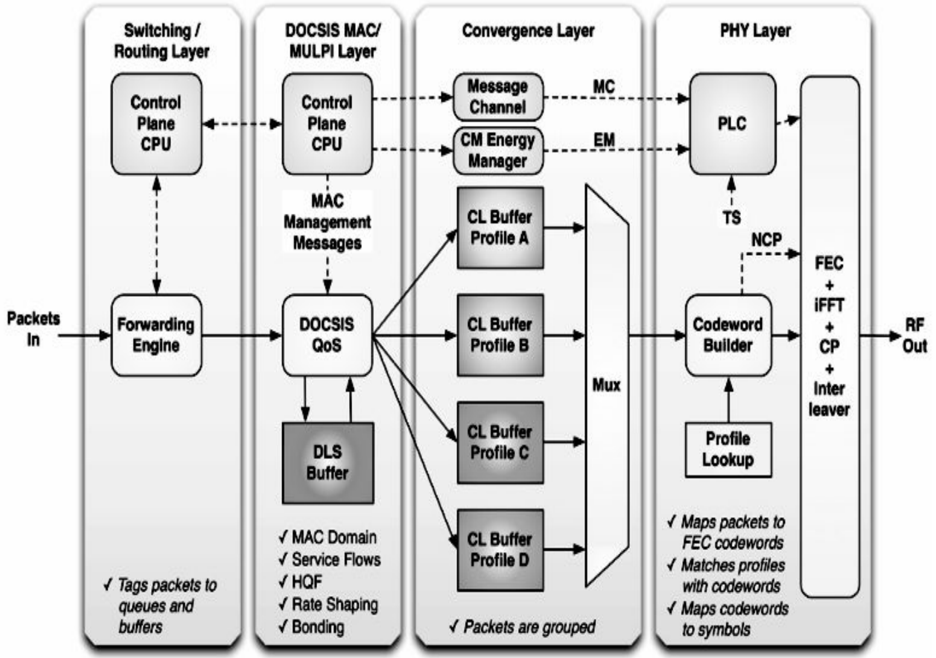
Upstream Subslots

- Data mapping among subslots



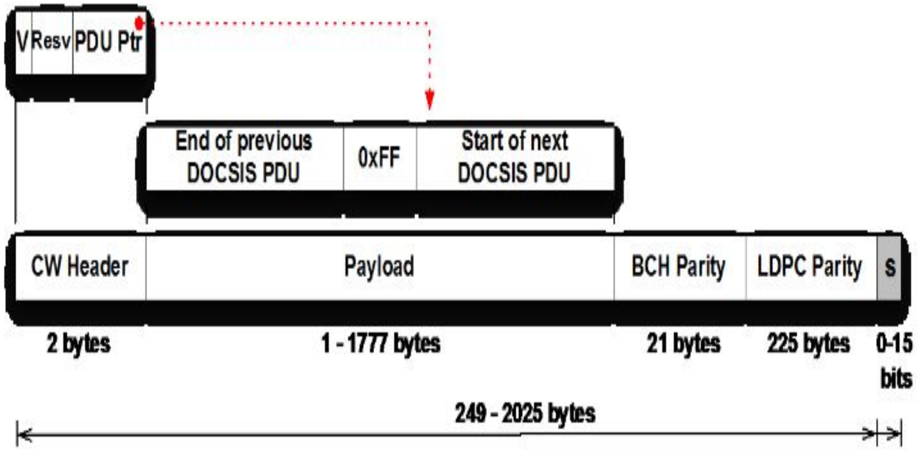
Downstream Operation

- Figure shows the block diagram of convergence layer in downstream.
- The operation of downstream can split into two planes:
  - The forwarding plane
  - The control plane



MAC Frame to Codewords

- Figure shows the downstream LDPC codeword.



Subcarrier Numbering Conventions

- Subcarriers are numbered from lower frequency to higher frequency within a FFT block.
- All subcarriers within the 204.8 MHz bandwidth are numbered, including the outside excluded subcarriers.
- Numbering starts at 0 and goes to 4095 for 4K FFT, and 0 to 8191 for 8K FFT.
- There is a mapping of data codewords to subcarriers from a lower number to a higher number.

(contd...)

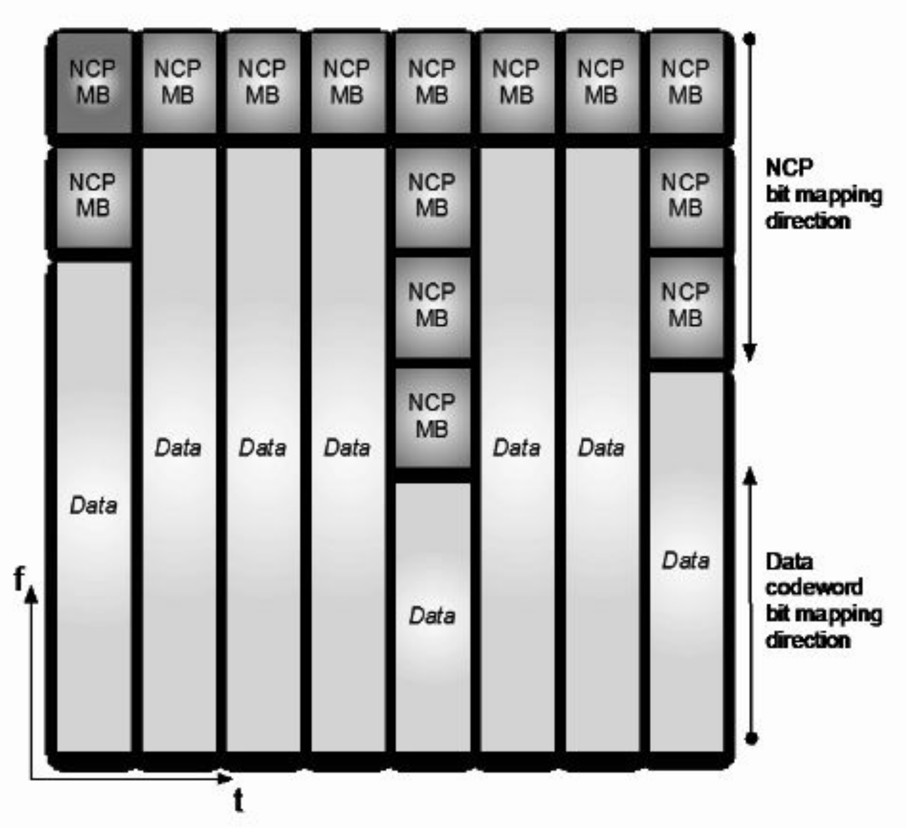
Next Codeword Pointer

- When there is a mapping of the data codewords on to the subcarriers within a symbol, a pointer is needed to identify the start of the data codeword.
- This is known as the Next Codeword Pointer (NCP).
- Each OFDM symbol has a variable number of NCP message blocks (MBs).
- To make sure that all subcarriers are used without reserving empty NCP MBs, the mapping of the NCP occurs in the opposite direction of the mapping for data.

(contd...)

Next Codeword Pointer

- Figure shows the relationship of NCP message blocks to the data channel.



OSSI

Key Features

Features	Management Functional Area	OSI layer	Description
OFDM downstream signals and OFDMA upstream signals	Configuration	PHY	Provisioning physical downstream and upstream interfaces that support OFDM/OFDMA receivers according to their capabilities.
Plant Topology	Configuration	PHY, MAC (Data Link)	Provisioning flexible arrangements of US/DS channels for channel bonding configuration to reflect HFC plant topology.
Enhanced Diagnostics	Fault	PHY, MAC, Network	Expanded metrics for Proactive Network Maintenance (PNM).
Enhanced Performance Data Collection	Performance	PHY, MAC, Network	Collection of large statistical data sets for DOCSIS 3.1 feature sets.
Enhanced Signal Quality Monitoring	Performance	PHY	To gather information on narrow band ingress and distortion affecting the quality of the RF signals.
Light Sleep Mode	Configuration	MAC	Energy efficiency mode for the Cable Modem to minimize power consumption.
Backup Primary Channels	Configuration	MAC	Retrieval of configuration status of backup downstream interfaces
Active Queue Management (AQM)	Configuration	MAC	Configuration of buffer management associated with service flows.

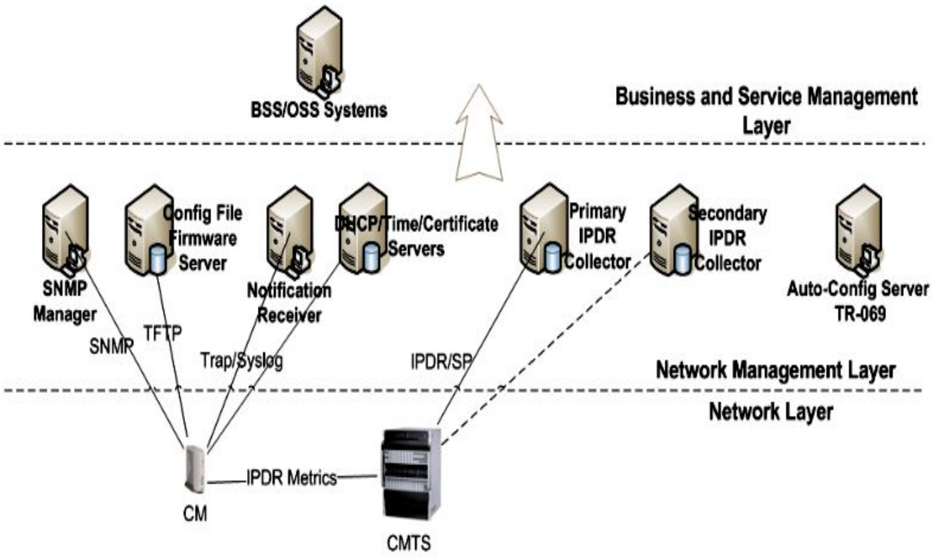
Key Features

- ❑ Fault Management Features
- ❑ Configuration Management Features
- ❑ Performance Management Features
- ❑ Security Management Features
- ❑ Accounting Management Features

(contd...)

Architectural Overview

- The CM management architecture is shown in the figure.



Architectural Overview

- Fault Management
  - The goals of fault management are providing failure detection, diagnosis, and performing or indicating necessary fault correction.
  - Fault identification relies on the ability of monitoring and detecting problems and on the ability of diagnosing and correcting problems.

(contd...)

Architectural Overview

- Configuration Management
  - Addition, initialization, maintenance and updation of network elements is included in the configuration management.
  - Configuration management controls the network by modifying operating parameters on network elements.
  - Both physical resources and and logical objects are included in the configuration parameters.

(contd...)

Architectural Overview

- The configuration state is monitored by the configuration management while the network is in operation and changes are made in response to commands by a management system.

(contd...)

Architectural Overview

- Accounting Management
  - Usage data collection and permitting the billing to the customer on the basis of the use of network resources by the subscriber are included in the accounting management.
  - The usage statistics for supporting billing are provided by the CMTS.

(contd...)

Architectural Overview

- Performance Management
  - The collection of statistics of parameters is included in the performance management functions.
  - These functions are used for determining the health of the network and check the QoS provided to the subscribers.

(contd...)

Architectural Overview

- Security Management
  - Both security of management information and management of the security information is performed by the security management.
  - By using this, the traffic is authenticated and secured on the HFC.
  - The end users are prevented from accessing and initiating configuration changes by using the security of the management interface.

Management Protocols

- The Simple Network Management Protocol (SNMP) versions 1, 2c and 3 are used by OSSI for defining the management information for a network element.
- There is a retrieval of data such as counter values and state information by the management system by using the polling based protocol, SNMP.
- The management systems are informed of fault conditions and security violations by using the events defined as a notification.

(contd...)

Information Models

- The requirements with use cases are defined by this approach for describing the interactions between the operations support systems and the network element.
- There is a representation of the management information in terms of objects along with their attributes and the interactions between these encapsulated objects.
- UML Class Diagram are developed for capturing these managed objects and their attributes.

(contd...)

Information Models

- The DOCSIS 3.1 Information Models are referred as the collection of UML Class Diagrams and Use Case Diagrams.
- There is a representation of the managed objects in a protocol specific form which are termed as a management data model.

(contd...)

MULPI

MULPI Key Features

- On the downstream:
  - Variable bit loading and multi-profile DS support
  - Downstream Convergence Layer
  - OFDM bonding on the downstream
  - OFDM + legacy bonding

(contd...)

MULPI Key Features

- On the upstream:
  - Variable bit loading and multi-profile US
  - Probing
  - OFDM bonding
  - OFDMA + legacy bonding and time share

(contd...)

MAC Features

- Energy Management
- HQoS
- AQM
- Enhanced Support for Timing Protocols

(contd...)

Removal of Legacy Features

- ❑ Many legacy features are removed from DOCSIS 3.1.
- ❑ Payload Header Suppression (PHS), use of the legacy request mechanism, use of many US Extended Headers, and the use of many messages such as UCI, UCC, TST-REQ are included in this.
- ❑ The use of the DCC message is also deprecated.

(contd...)

Legacy Features Used in D3.1

- ❑ Downstream Channel Bonding with Multiple Receive Channels
- ❑ Upstream Channel Bonding with Multiple Transmit Channels
- ❑ IPv6
- ❑ Source-Specific Multicast
- ❑ Multicast QoS

(contd...)

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Technical Overview

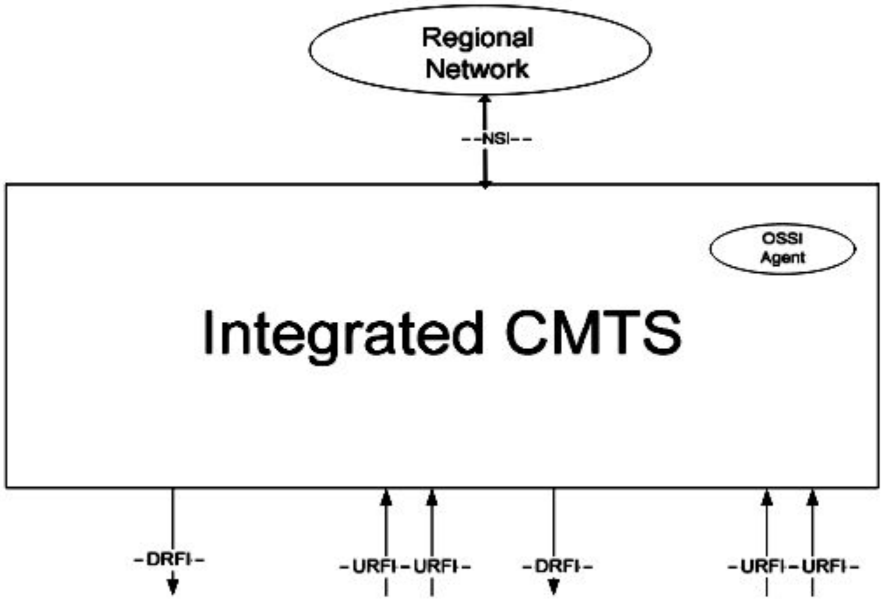
CMTS

- The packets between one or more Network Side Interface (NSI) ports and DOCSIS RF Interface (RFI) ports are forwarded by a CMTS which is a network element of DOCSIS.

(contd...)

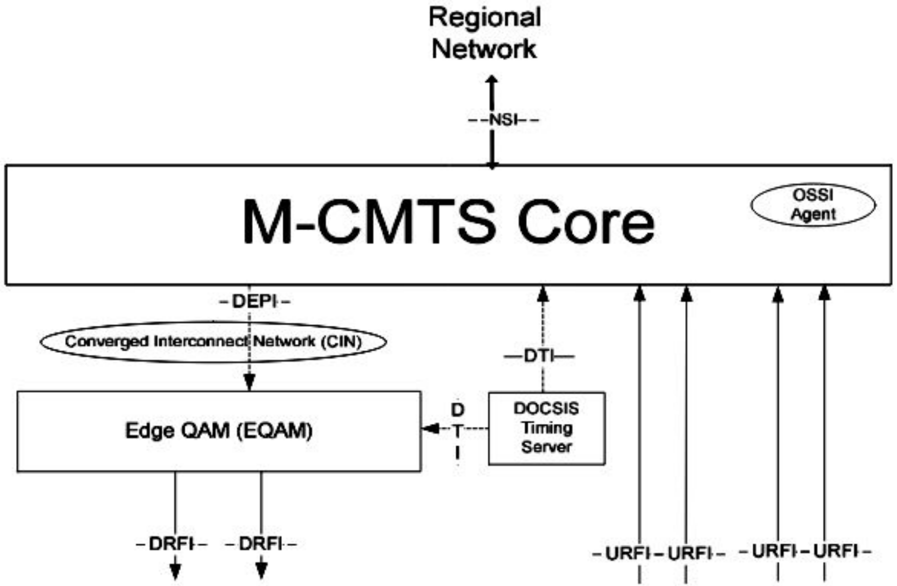
CMTS Types

- Integrated CMTS
  - A single OSSI entity is implemented by an Integrated CMTS for cable operator configuration.
  - The CMTS Downstream RF Interfaces (DRFIs) and Upstream RF Interfaces (URFIs) are managed by it.



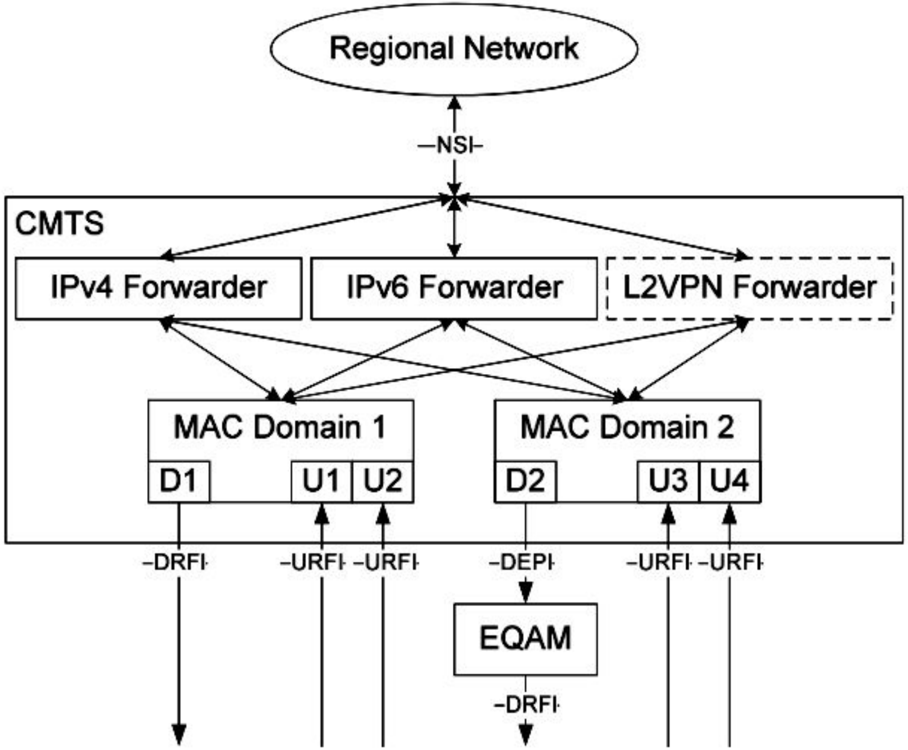
CMTS Types

- Modular CMTS
  - The network diagram of a Modular CMTS (M-CMTS) is shown in the figure.



CMTS Types

- CMTS Internal Forwarding Model
  - The logical operational model of internal packet forwarding within a CMTS is shown in the figure.



Downstream Convergence Layer

- Control Channel
  - PLC
    - A narrowband signalling channel known as the PHY link channel whose location is within the downstream OFDM channel.
    - The "blind" channel acquisition is enabled by the PLC so that downstream timing reference and scattered pilot pattern synchronization has been provided.

(contd...)

Downstream Convergence Layer

- In the first step of acquiring an OFDM channel, a CM acquires the PLC.
- The complete OFDM channel is acquired by the CM in the second step on the basis of the channel parameters obtained from the PLC.
- There is a fixed frame structure of PLC that consists of 128 symbols and 8 or 16 subcarriers depending on the size of FFT.

(contd...)

Downstream Convergence Layer

- a preamble of 8 symbols and 120 data symbols is included in the frame structure of PLC.
- The preamble of PLC is BPSK modulated and a well-known data pattern is contained in it.
- 16 QAM is used to modulate the data symbols of the PLC.
- Self-contained Message Blocks (MBs) are consisted in the data portion of the PLC.

(contd...)

Downstream Convergence Layer

- NCP
  - The information about the mapping of FEC codewords to subcarriers within a symbol is carried by the Next Codeword Pointer (NCP).

(contd...)

OFDMA Upstream

- DOCSIS 3.1 uses a new type of channel for upstream known as OFDMA.
- They can span more spectrum than any other upstream channels.
- LDPC is used for forward error correction.
- A framing structure is utilised that consists of a number of symbols in time and a number of subcarriers in frequency.
- There are fixed LDPC codeword sizes.
- There are 7 data profiles and each of them describes the modulation rate and pilot pattern.

(contd...)

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(contd...)

QoS

- Requirements of QoS
  - Pre-configuring by configuration and registration function for per-CM QoS Service Flows and traffic parameters.
  - Establishment of QoS-enabled Service Flows and traffic parameters by a signalling function.
  - The Service Flow QoS parameters are used to provide CMTS MAC scheduling of service flows of downstream and upstream.

(contd...)

QoS

- The Service Flow QoS parameters are used to provide CM and CMTS traffic-shaping, traffic-policing, and traffic-prioritization.
- Classification of packets arriving from the upper layer service interface to a specific active Service Flow.
- Grouping of Service Flow properties into named Service Classes.
- Assignment of Service Flows to particular upstream or downstream channels.

(contd...)

QoS

- Individual and Group Service Flow
  - Individual Service Flows are defined as Service Flows created by the Registration process of a single CM or a Dynamic Service Addition process to a single CM.
  - Group Service Flows are created by the CMTS and may or may not be communicated to the CM.
  - The packets forwarded by an individual CM to an Individual Service Flow are classified by the CMTS.

(contd...)

QoS

- Hierarchical QoS
  - An optional, intermediate level is provided by HQoS in the scheduling hierarchy between Service Flows and channels and aggregate QoS treatment is introduced.
  - HQoS either aggregates the unicast Service Flows associated with a single CM or the Service Flows associated with multiple CMs.

(contd...)

QoS

- AQM
  - All upstream Best Effort and Non-Real-Time Polling Service Flows and all downstream Service Flows are provided with Active Queue Management by default.
  - The buffering latency in the CM (for upstream) and CMTS (for downstream) during heavy traffic loads has been reduced by AQM without significantly impacting throughput.

(contd...)

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Technical Overview

Channel Bonding

- Downstream Channel Bonding
  - It means distributing the packets from the same service flow over different downstream channels.
  - The group of Downstream Channels over which there is a distribution of the packets of a downstream service flow is called a Downstream Bonding Group (DBG).

(contd...)

Channel Bonding

- An identified set of one or more channels over which there is a scheduling of the packets of a service flow is called Downstream Channel Set (DCS).CMTS assigns a 16-bit Downstream Channel Set ID (DCS ID) to each DCS.
- A 20-bit Downstream Service ID (DSID) identifies a downstream sequence of packets at CMTS and CM.
- The set of downstream channels assigned to an individual CM is called its Receive Channel Set.

(contd...)

Channel Bonding

- Upstream Channel Bonding
  - The higher upstream bandwidth per user has been provided by the cable operators so that they can compete with FTTx offerings and services has been provided to small businesses.
  - An increased upstream throughput has been provided by cable from a single user or group of users by transmitting simultaneously on the multiple upstream channels.

(contd...)

Channel Bonding

- This concept is called upstream channel bonding i.e. a larger bandwidth pipe is created by combining the smaller bandwidth upstream channels together.
- The CMTS controls the actual bonding process via grants.
- The request for bandwidth for given service flow has been made by the CM on one of the service flow's associated upstream channels.
- The CMTS then chooses whether to grant the request on one or more of the channels associated with that service flow.

(contd...)

Channel Bonding

- It is the responsibility of the CMTS to allocate the bandwidth across the individual upstream channels.
- The CM divides its transmission according to the transmit time for each grant and the size of each grant after receiving the grants over multiple channels.
- An incrementing sequence number is placed in the traffic transmitted in each grant by the CM.

(contd...)

Channel Bonding

- The original data stream is reconstructed by the CMTS by using the sequence number in the traffic.
- The synchronization between the upstream channels and a master clock is required by this mechanism for upstream channel bonding.
- The CMs clock domains and timing recovery has been simplified.

(contd...)

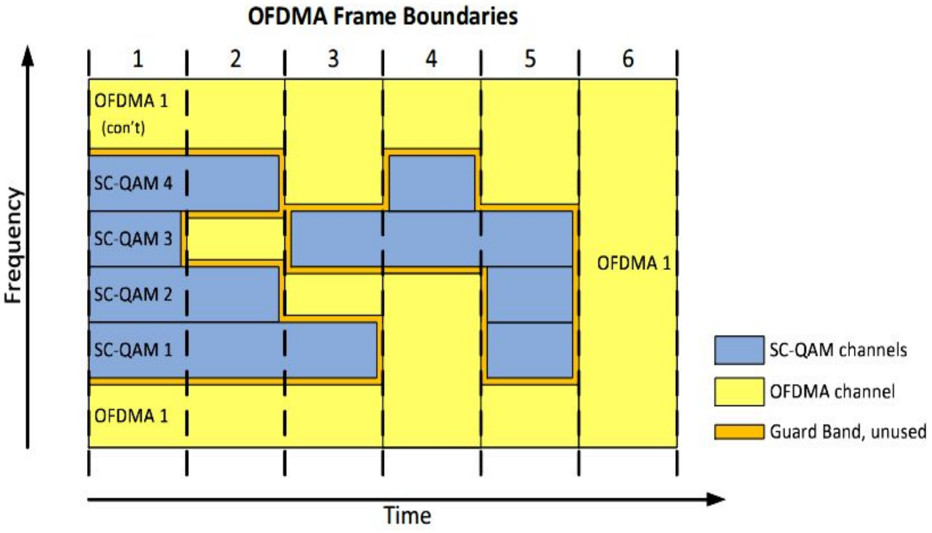
Upstream Time and Frequency Multiplexing

- Simultaneous Time and Frequency Division Multiplexing (TaFDM) between SC-QAM and OFDMA channels has been supported by DOCSIS 3.1 along with upstream channel bonding.
- This means that both
  - OFDMA and SC-QAM can simultaneously operate on separate frequencies
  - OFDMA and SC-QAM can also operate on the same frequencies, divided in time

(contd...)

Upstream Time and Frequency Multiplexing

- Upstream time and frequency multiplexing is shown in the figure.



Autonomous Load Balancing

- Autonomous load balancing of CMs is supported by DOCSIS 3.1.
- The load balancing operations of DOCSIS 2.0 CMTSs differ than that of DOCSIS 3.0 and DOCSIS 3.1 CMTSs in two ways:
  - Balancing of pre-3.0 DOCSIS CMs
  - Balancing of DOCSIS 3.0 CMs
  - Balancing of DOCSIS 3.1 CMs

(contd...)

Multicast Operation

- IP Multicast has been supported by DOCSIS with features such as Source Specific Multicast, IPv6 multicast, and bonded multicast.
- No additional multicast features were added with DOCSIS 3.1.
- The existing multicast features can now operate with both 3.0 channels and DOCSIS 3.1 OFDM channels.

(contd...)

Network and Higher Layer Protocols

- For operation and management of the CM and CMTS, the following Higher Layer Protocols are used by DOCSIS:
  - Simple Network Management Protocol (SNMP).
  - Trivial File Transfer Protocol (TFTP)
  - Dynamic Host Configuration Protocol (DHCP) v4 and v6

(contd...)

Initialization, Provisioning and Management of CMs

- The CM goes through a number of steps during initialization before becoming fully operational on the DOCSIS network.
- There are four fundamental stages of the full initialization sequence:
  - topology resolution and physical layer initialization
  - authentication and encryption initialization
  - IP initialization
  - registration (MAC layer initialization)

(contd...)

Initialization, Provisioning and Management of CPEs

- DHCP is used by DOCSIS for the provisioning of CPE devices.
- A DHCP relay agent has been supported by CMTS and a CPE IP Address request is associated with the subscriber Cable Modem MAC Address by the operator.

(contd...)

Enhanced Support for Timing Protocol

- A set of techniques coupled with extensions to the DOCSIS signalling messages is called the DOCSIS Time Protocol (DTP) in which the timing and frequency system of DOCSIS is allowed to be interfaced to external timing protocols with high accuracy.
- The primary application of DTP is to provide precise frequency and time to an external system that is connected to the network port of a DOCSIS CM.

(contd...)

Enhanced Support for Timing Protocol

- DTP allows the source to be accurately replicated at the egress port of the CM when the CMTS has a legitimate frequency and time source.
- A set of native DOCSIS protocols are combined to accomplish this.
- DTP relies on the DOCSIS 3.1 Extended Timestamp such as higher accuracy and a notion of absolute time has been provided.

(contd...)

Energy Management

- A new energy management feature has been introduced in DOCSIS 3.1 that is applicable to CMs whose primary downstream is an OFDM channel.
- The reduced power consumption is achieved at the CM in DOCSIS Light Sleep (DLS) mode by periodically shutting down the receiver circuitry during sleep.
- The sleep time can range up to 200 msec.

(contd...)

MAC Specifications

Definitions

- MAC-Sublayer Domain
  - A MAC-sublayer domain is a collection of upstream and downstream channels for which a single MAC Allocation and Management protocol operates.
  - One CMTS and some number of CMs are included in its attachments.
  - All of the upstream and downstream channels are serviced by the CMTS.

(contd...)

Definitions

- One or more logical upstream channels and one or more downstream channels are accessed by each CM.
- Any packets received shall be discarded by the CMTS that have a source MAC address that is not a unicast MAC address.

- MAC Service Access Point
  - A MAC Service Access Point (MSAP) is an attachment to a MAC-sublayer domain.

(contd...)

Definitions

- Service Flows
  - A mechanism is provided by Service Flows for upstream and downstream Quality of Service management.
  - Service Flows are integral to allocation of bandwidth.
  - A particular unidirectional mapping is defined between a CM and the CMTS by a Service Flow ID.
  - Associated Service IDs or SIDs are comprised in the active Upstream Service Flow IDs.

(contd...)

Definitions

- Upstream bandwidth is allocated to SIDs, and hence to CMs, by the CMTS.
- The mechanism is provided by Service IDs which is used to implement upstream Quality of Service.

(contd...)

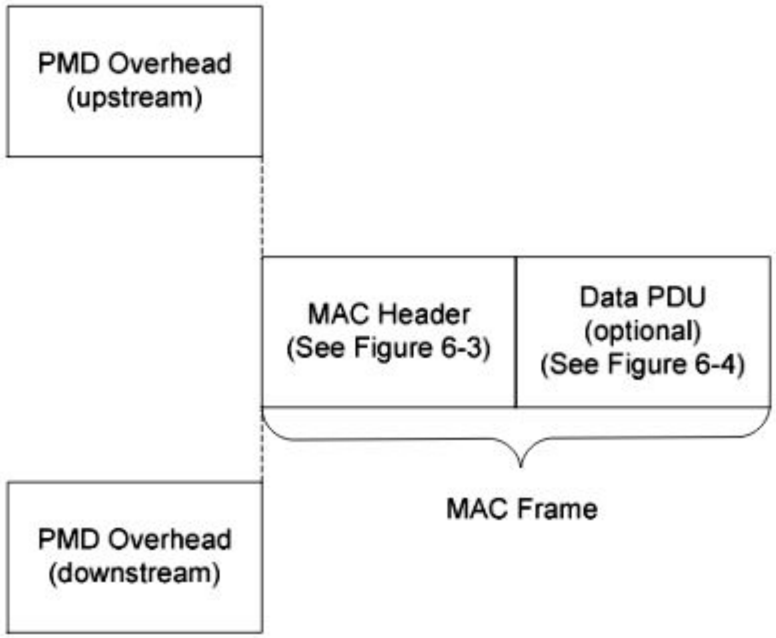
Logical Upstream Channels

- The MAC layer deals with logical upstreams.
- There is an identification of a logical upstream with an upstream channel ID which is unique within the MSAP.
- A contiguous stream of minislots is consisted in a logical upstream.
- A CM operating with Multiple Transmit Channel Mode disabled can only register to operate on a single logical upstream channel.
- A CM in Multiple Transmit Channel Mode of operation can register to operate on one or more logical upstream channels.

(contd...)

MAC Frame Format

- Generic MAC frame format is shown in the figure.



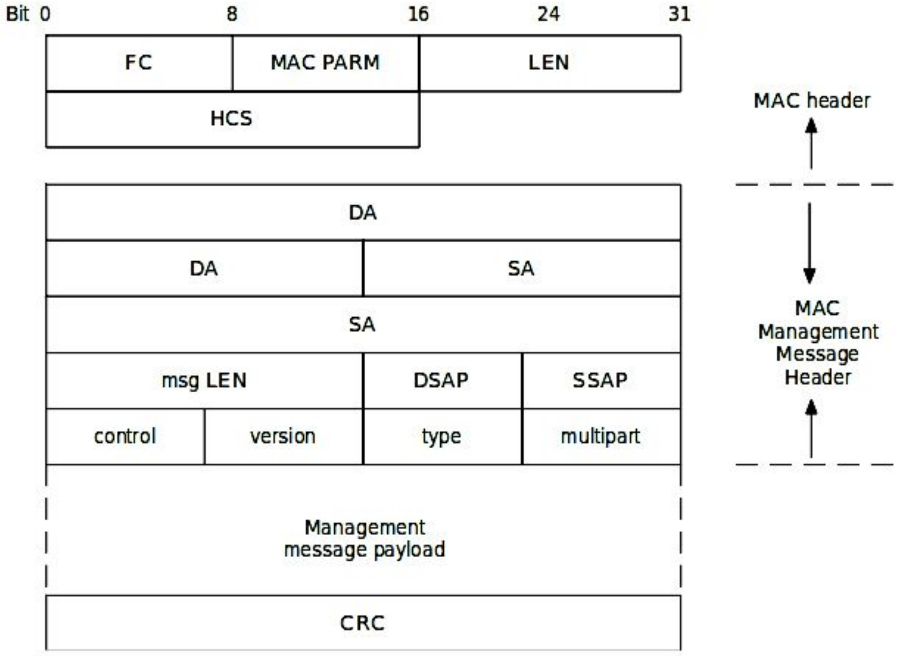
Segment Header Format

- A Segment Header shall be used by the CM when packets are transmitted in Multiple Transmit Channel Mode for service flows where there is enabling of the use of service header.
- Segment header format is shown in figure.

PFI (1 bit)	R (1 bit)	Pointer Field (14 bits)	Sequence # (13 bits)	SC (3 bits)	Request (2 Bytes)	HCS (2 Bytes)

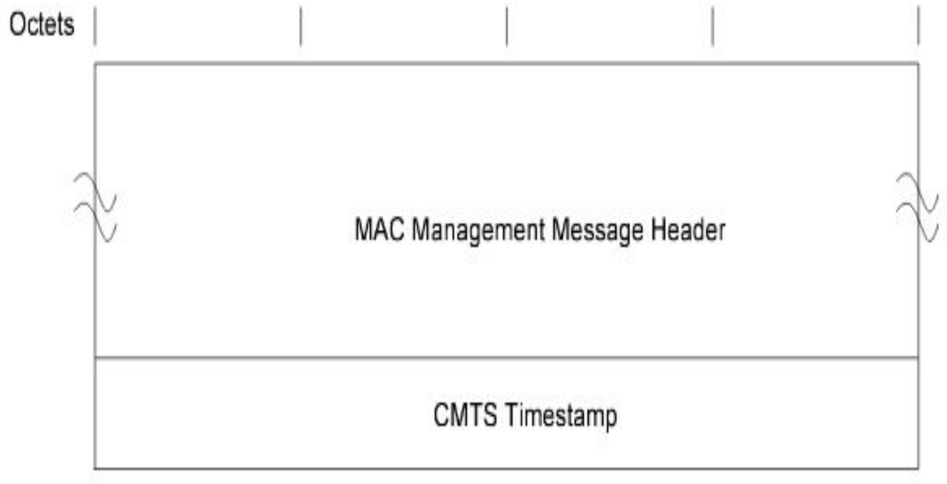
MAC Management Messages

- MAC Management Messages are encapsulated in an LLC unnumbered information frame bt the CM or CMTS which in turn is encapsulated within the cable network MAC framing as shown in the figure.



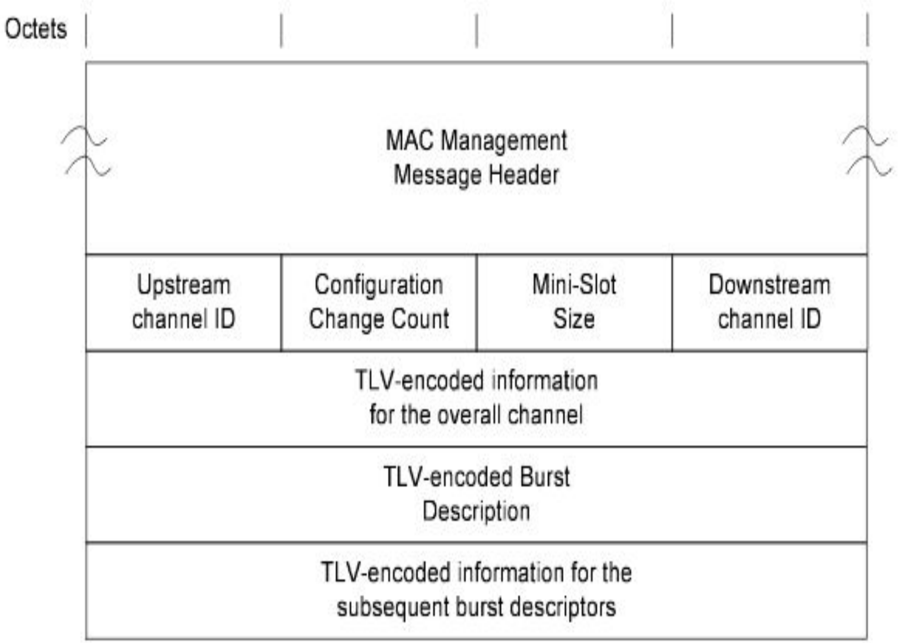
MAC Management Messages

- CMTS transmits time synchronization (SYNC) at a periodic interval so that MAC sublayer timing can be established.
- SYNCs are transmitted by the CMTS on Primary-Capable DS Channels.
- SYNCs are not transmitted on non-Primary Capable DS Channels.
- Figure shows the SYNC format.



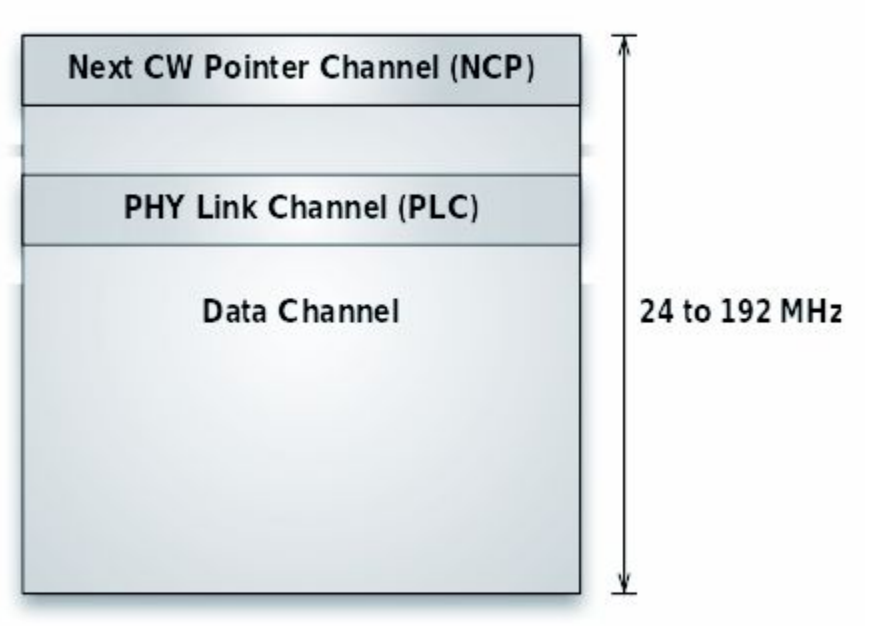
MAC Management Messages

- The CMTS transmits the UCD at a periodic interval to define the characteristics of a logical upstream channel as shown in the figure.
- The CMTS transmits a separate message for each logical upstream that is in use.



PHY Link Channel

- Figure shows the PHY Link Channel (PLC) relative to the OFDM channel.
- Several tasks are performed by using it:
  - Timestamp
  - Energy management
  - Message channel for bringing new CMs on line.
  - Trigger message for synchronizing an event between the CMTS and CM.



PHY Link Channel

- Figure shows the structure of the PLC frame.