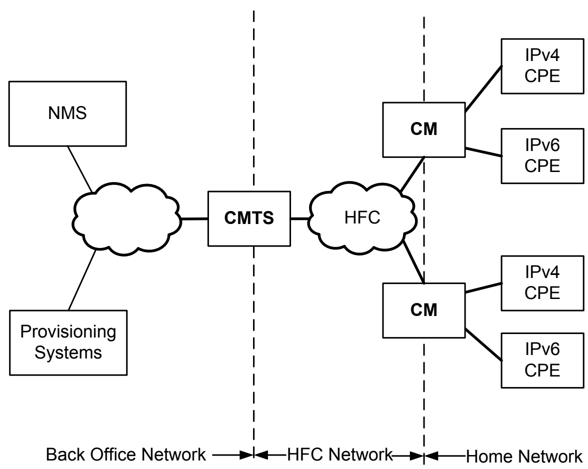
DOCSIS Cable Modem PHY

This lecture describes the most commonly used parts of the DOCSIS cable modem PHY specification.
After this lecture you should be able to: distinguish between upstream and downstream links based on frequency, transmitting device (CM or CMTS), and direction of information flow (US or DS); list four factors that result in lower data rates and more complex processing on the upstream; compute the maximum correctable error burst length for a given value of t and block interleaver size; and compute the raw US and DS data rates for a particular combination of modulation and symbol rate;

Introduction

The DOCSIS (Data Over Cable Service Interface Specification) is a standard defined by CableLabs, an R&D and standards organization funded by the cable industry.

DOCSIS defines the interface between cable modems (CMs) at the subscriber's premises and a cable modem termination system (CMTS) at the head end as shown in this diagram from the DOCSIS 3.0 MAC spec:



The DOCSIS Network

EuroDOCSIS is a version of DOCSIS for the 8 MHz channels used in Europe.

A CMTS is typically a rack-mounted router with plug-in cards supporting multiple upstream and downstream RF channels such as the following Cisco uBR10012 Universal Broadband Router (CMTS):

A CM is typically a small desktop device that connects to the cable TV co-ax cable and an Ethernet port such as the following Motorola SB5100 Cable Modem (CM):

DOCSIS systems make use of the bidirectional HFC access plan with upstream transmission at frequencies from 5 to 42 MHz (sometimes higher) and upstream transmission from 50 to 860 MHz (often lower).

The following table shows the assumptions about the downstream channel as specified in DOCSIS version 1.0:

Table 2-1. Assumed Downstream RF Channel Transmission Characteristics

Parameter	Value
Frequency range	Cable system normal downstream operating range is from 50 MHz to as high as 860 MHz. However, the values in this table apply only at frequencies ≥ 88 MHz.
RF channel spacing (design bandwidth)	6 MHz
Transit delay from headend to most distant customer	≤ 0.800 msec (typically much less)
Carrier-to-noise ratio in a 6-MHz band (analog video level)	Not less than 35 dB (Note 4)
Carrier-to-interference ratio for total power (discrete and broadband ingress signals)	Not less than 35 dB within the design bandwidth
Composite triple beat distortion for analog modulated carriers	Not greater than -50 dBc within the design bandwidth
Composite second order distortion for analog modulated carriers	Not greater than -50 dBc within the design bandwidth
Cross-modulation level	Not greater than -40 dBc within the design bandwidth
Amplitude ripple	0.5 dB within the design bandwidth
Group delay ripple in the spectrum occupied by the CMTS	75 ns within the design bandwidth
Micro-reflections bound for dominant echo	-10 dBc @ ≤ 0.5 µsec, -15 dBc @ ≤ 1.0 µsec -20 dBc @ ≤ 1.5 µsec, -30 dBc @ > 1.5 µsec
Carrier hum modulation	Not greater than -26 dBc (5%)
Burst noise	Not longer than 25 µsec at a 10 Hz average rate
Seasonal and diurnal signal level variation	8 dB
Signal level slope, 50-750 MHz	16 dB
Maximum analog video carrier level at the CM input, inclusive of above signal level variation	17 dBmV
Lowest analog video carrier level at the CM input, inclusive of above signal level variation	-5 dBmV

Notes to Table 2-1

1. Transmission is from the headend combiner to the CM input at the customer location.
2. For measurements above the normal downstream operating frequency band (except hum), impairments are referenced to the highest-frequency NTSC carrier level.
3. For hum measurements above the normal downstream operating frequency band, a continuous-wave carrier is sent at the test frequency at the same level as the highest-frequency NTSC carrier.
4. This presumes that the digital carrier is operated at analog peak carrier level. When the digital carrier is operated below the analog peak carrier level, this C/N may be less.
5. Measurement methods defined in [NCTA] or [CableLabs2].

Exercise 1: What is the Shannon capacity of this channel? What is the maximum symbol rate if the symbol period is to be more than 10 times the group delay ripple? What is the maximum area (in km^2) that can be serviced by one DOCSIS CMTS assuming a velocity factor of 0.66?

The following table shows the corresponding assumptions about the upstream channel:

Table 2-2. Assumed Upstream RF Channel Transmission Characteristics

Parameter	Value
Frequency range	5 to 42 MHz edge to edge
Transit delay from the most distant CM to the nearest CM or CMTS	≤ 0.800 msec (typically much less)
Carrier-to-noise ratio	Not less than 25 dB
Carrier-to-ingress power (the sum of discrete and broadband ingress signals) ratio	Not less than 25 dB (Note 2)
Carrier-to-interference (the sum of noise, distortion, common-path distortion and cross-modulation) ratio	Not less than 25 dB
Carrier hum modulation	Not greater than -23 dBc (7.0%)
Burst noise	Not longer than 10 µsec at a 1 kHz average rate for most cases (Notes 3, 4 and 5)
Amplitude ripple	5-42 MHz: 0.5 dB/MHz
Group delay ripple	5-42 MHz: 200 ns/MHz
Micro-reflections -- single echo	-10 dBc @ ≤ 0.5 µsec -20 dBc @ ≤ 1.0 µsec -30 dBc @ > 1.0 µsec
Seasonal and diurnal signal level variation	Not greater than 8 dB min to max

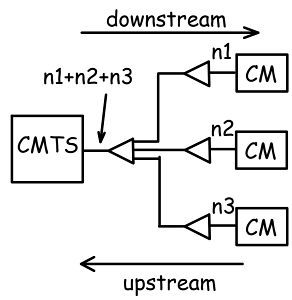
Notes to Table 2-2

1. Transmission is from the CM output at the customer location to the headend.
2. Ingress avoidance or tolerance techniques MAY be used to ensure operation in the presence of time-varying discrete ingress signals that could be as high as 0 dBc [CableLabs1].
3. Amplitude and frequency characteristics sufficiently strong to partially or wholly mask the data carrier.
4. CableLabs report containing distribution of return-path burst noise measurements and measurement method is forthcoming.
5. Impulse noise levels more prevalent at lower frequencies (< 15 MHz).

Exercise 2: Again compute the Shannon capacity based on the CNR and the maximum symbol rate based on a period equal to 10 times the group delay ripple.

Upstream data transmission in the HFC plant is significantly more difficult than downstream because:

- much less bandwidth is available (e.g. 37 MHz vs 810 MHz)
- CM cannot hear each other's transmissions so the CMTS must coordinate upstream transmissions to avoid collisions
- high-power HF transmitters operating at the upstream frequencies and can leak into ("ingress") the cable system
- noise and interference "funnels" towards the head end as shown below



Revisions to the DOCSIS spec since the first version in 1997 have therefore concentrated on improving upstream performance while remaining compatible with the large number of CMs already installed.

MAC Overview

The operation of the network is controlled by the CMTS which transmits continuously on one or more downstream (DS) channels. CMs receive from the CMTS and respond to CMTS commands by transmitting on one or more upstream (US) channels.

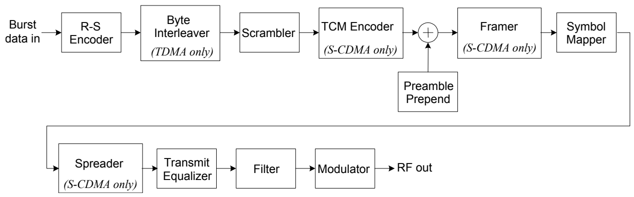
The CMTS periodically transmits a MAP ("Upstream Bandwidth Allocation Map") message allocating upstream "mini-slots" to the different CMs. The un-allocated time slots can be used by CMs on a contention basis.

The "mini-slot" durations are a power of 2 (1, 2, 4, ... 128) multiple of 6.25 μs.

In addition, the CMTS provides time and frequency synchronization and ranging (measurement of the distance to the CMTS) for CMs.

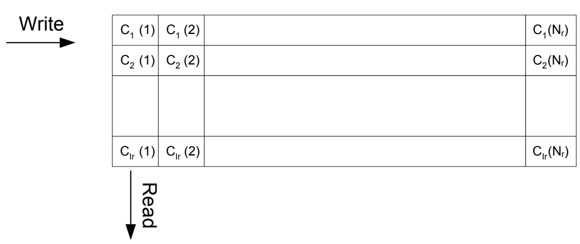
Upstream PHY

The following block diagram shows the sequence of operations performed on the US data before it is transmitted by a DOCSIS 3.0 CM:



A Reed-Solomon FEC block code is used. This code uses elements from GF(256) rather than GF(2). This means the code operates on bytes rather than bits. The number of parity bytes $(n-k)$ can be configured to be between 0 to 32 bytes per block (correctable errors, $t=0$ to 16) and the number of data bytes per block (k) can be configured to be between 16 and 253.

The purpose of the byte interleaver is to spread out noise bursts so that if the burst is short enough relative to the interleaver depth the number of errors per codeword will be sufficiently small that the FEC code can correct them. It operates as a block interleaver where the values are written row-wise and read out column-wise. The interleaver width is set to the RS codeword length $(n = k + 2t)$ and the depth is configurable with a maximum of 2048 bytes total memory.



Input sequence: $C_1(1),...C_1(N_r),C_2(1),....C_2(N_r),C_3(1).....C_{Ir}(N_r)$

Output sequence: $C_1(1),C_2(1)...C_{Ir}(1),C_1(2),....C_{Ir}(2),C_1(3).....C_{Ir}(N_r)$

Figure 6–5 - Byte Interleaver Operation

Exercise 3: Assuming 255 bytes per codeword, what is the maximum number of interleaver rows? If an error burst starts with the first byte, what is the longest error burst that will result in 2 or fewer errors per codeword? t or fewer errors per codeword? How many errors will appear at the output of the decoder for error burst of this length or shorter?

A 15-bit LFSR-based additive scrambler is used:

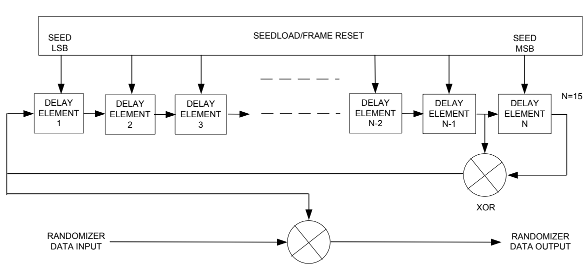


Figure 6–8 - Scrambler Structure

The modulation symbol rates are 160 to 5120 kHz with QPSK and 8- through 256-QAM modulation.

Exercise 4: What are the minimum and maximum bit rates for these symbol rates and modulation formats, not including FEC or other overhead?

The synchronous CDMA (S-CDMA) mode uses orthogonal spreading sequences to allow multiple users to transmit simultaneously on the upstream channel. We will not cover the S-CDMA mode. DOCSIS version 3.1 also has an upstream OFDM mode which we will also not cover.

Downstream

The downstream transmitter is based on ITU standard ITU-T J.83 for transmission of digital video over cable TV systems. The downstream parameters are as follows (from ITU-T J.83):

Table B.3 – Cable transmission format

Parameter	64-QAM format	256-QAM format
Modulation	64-QAM, rotationally invariant coding	256-QAM, rotationally invariant coding
Symbol size	3 bits for "I" and 3 bits for "Q" dimensions	4 bits for "I" and 4 bits for "Q" dimensions
Transmission band	54 to 860 MHz (Note)	54 to 860 MHz (Note)
Channel spacing	6 MHz (Note)	6 MHz (Note)
Symbol rate	5.056941 Msps ± 5 ppm (Note)	5.360537 Msps ± 5 ppm (Note)
Information bit rate	26.97035 Mbps ± 5 ppm (Note)	38.81070 Mbps ± 5 ppm (Note)
Frequency response	Square root raised cosine filter (Roll-off ≈ 0.18)	Square root raised cosine filter (Roll-off ≈ 0.12)
FEC framing	42-bit sync trailer following 60 RS blocks (see B.5.3)	40-bit sync trailer following 88 RS blocks (see B.5.3)
QAM constellation mapping	6 bits per symbol (see B.5.5)	8 bits per symbol (see B.5.5)
NOTE These values are specific to 6 MHz channel spacing. Additional sets of values for differing channel spacing are under study.		

The following diagram, also taken from the standard, shows the signal processing involved:

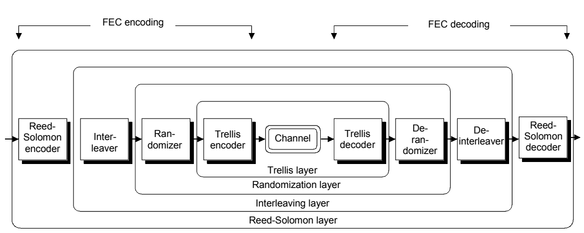


Figure B.7 – Layers of processing in the FEC

It supports 64- and 256-QAM modulation at symbol rates of approximately 5.05 and 5.36 (for 256-QAM). A concatenated Reed-Solomon (128,122) code over GF(128) (7-bit symbols) is used that can correct $t = 3$ errors per block.

A convolutional interleaver is used:

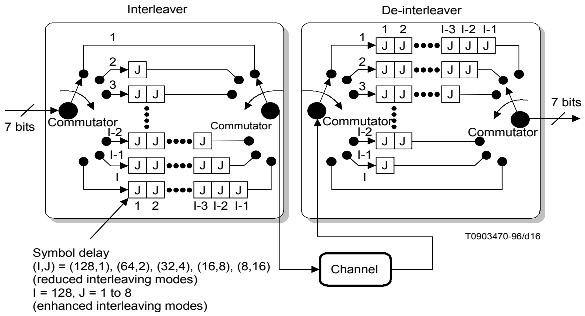


Figure B.8 – Interleaving functional block diagram

as well as a scrambler ("randomizer") based on LFSR operating on symbols from GF(128).

The modulator uses a technique called Trellis Coded Modulation (TCM) which uses a convolutional encoder to protect the bits in the constellation that are most likely to have errors.