An Overview of the DOCSIS Two Way Physical Layer

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Cable Modems and Cable Modem Termination Systems conforming to the Data Over Cable System Interface Specifications RF Specification provide system engineers with a new set of options that can be used to help ensure reliable data service delivery in cable plants.

A brief history of the decision process used in selecting which options to include is presented, but primarily, this paper describes the options available, in both the RF downstream and RF upstream directions, and helps clarify the criteria to be used when deciding how to apply those options when delivering digital data services.

INTRODUCTION

With the imminent advent of interoperable cable modems that conform to the Data Over Cable System Interface Specification (DOCSIS), cable operators will have many new, powerful options to help manage the delivery of two-way digital data services on their plant. This paper discusses some of the design decisions used to determine which options to include in DOCSIS systems.

Greater detail is provided on those options that can be optimized to suit the needs of a particular plant. Both the plant physical structure and the type of services to be delivered combine to dictate system settings. Options exist, in both the downstream and upstream physical layer, that enable DOCSIS systems to be customized in an optimum manner. The mechanisms employed are explained in enough detail to illuminate basic system operation.

Finally, a common side effect of normal operation of cable modems in general is discussed. This facilitates an understanding of the fact that optimum operation, of any cable modem system including those conforming to the DOCSIS specification, is a result of not just the cable modem system design, but also includes the basic cable plant design.

DESIGN PHILOSOPHY

Priority 1: Reliable Physical Layer Now

The highest priority used to decide what was in and what was left out of the DOCSIS RF specification was that the system must provide a reliable physical layer—NOW! The intention was to minimize the need to develop new techniques. These techniques, some being touted as “advanced” physical layers, are in the labs and in early trials, but would have added significant time to the front-end of any developments for compliant DOCSIS components.

The decision for DOCSIS was to use robust, tested techniques. If there existed a successful tool for delivering reliable data on a cable system, it was evaluated for inclusion into the specification. The best available implementations from the currently deployed field of cable modems were included in the specification

If there were any tried-and-true techniques that could be included, they were also investigated. For example, digital video is being delivered successfully—NOW! The same techniques can be used for delivering reliable digital data to cable modems too. Admittedly, some differences exist in the criteria needed for delivering digital video and those needed for delivering some forms of digital data services, but these are addressed in the specification.

Delivering reliable data was not enough. The specification needed to provide high-capacity in the digital data streams. The specification provides for two different kinds of downstream data channels with raw data rates of over 30 megabits per second (Mbps) or almost 43 Mbps. After removing the overhead for forward error correction (FEC), this still leaves information rates of approximately 27 Mbps or 39 Mbps respectively. Upstream data rates have many more possible formats which include a variety of raw data rates ranging from 320 kilobits per second (kbps) to 10.24 Mbps. These upstream channels are configurable to include a user-specified amount of FEC overhead, including none.

The specification also provides a growth path for cable operators delivering digital data services. Lower data rate, more robust channels can be deployed while plants are upgraded to provide a cleaner environment within which to deploy higher data rate channels when they are needed. Operators can also choose to deploy multiple upstream and multiple downstream channels to deliver a multiplicity of services to a multitude of subscribers.

DOWNSTREAM PHYSICAL LAYER

Downstream Physical Layer Design

The downstream physical layer is based on the International Telecommunication Union, ITU-T Recommendation J.83 (04/97), Digital Transmission of Television Signals, Annex B (ITU-T J.83B). This revision of ITU-T J.83B includes not only the original 64QAM modulation and a fixed depth interleaver used to deliver digital video, but also includes 256QAM for higher downstream channel data rates as well as a variable depth interleaver. DOCSIS compliant downstream channels may occupy any 6 MHz band between 88 MHz and 860 MHz.

64QAM versions of these downstream channels are beyond the test phases. They are deployed and successfully delivering digital video services to cable subscribers. 256QAM versions of these downstream channels have been proven in extensive rigorous tests. This technology is ready for use now.

The reliability of QAM modulated downstream channels is ensured because of the powerful concatenated FEC provided by the ITU-T J.83B specification. Multiple layers of error detection and error correction, coupled with variable depth interleaving to provide variable-length burst error resilience, deliver error rates ensuring customer satisfaction. The high data rates together with the low error rates provide a bandwidth efficient delivery mechanism for digital data delivery.

Downstream Error Protection

The target digital data delivery goal for these downstream channels is to have an error rate that yields less than one error in 15 minutes in a nominal cable system. Even with reduced noise margins, the downstream channels are designed to deliver 64QAM signals with a bit error rate (BER) of less than 10^{-8} at a carrier to noise (C/N) ratio of 23.5 dB. 256QAM channels can be expected to deliver a similar BER at 30 dB C/N. This translates to one error every 3 to 5 seconds. These downstream channels are shared between subscribers, so the error will naturally be distributed randomly to various subscribers. An additional benefit from the strength of this FEC is that it permits operation of the downstream digital data channels 10 dB lower than the nominal level of video carriers on the system. This helps minimize system loading while still delivering robust digital data services.

It is important to note that deploying 256QAM channels requires significantly higher C/N than when deploying 64QAM channels. This is one of the first choices to make when deploying DOCSIS modems: deciding which mode of operation to use for downstream channels. In a clean, new HFC plant that is currently delivering video signal to noise (SNR) of 49 dB or greater to the "big-screen tv" subscribers to successfully compete with the satellite delivery services, then the system may well support 256QAM downstream channels. On the other hand, if the plant consists of longer cascades working nearer to the FCC minimum system specifications while it is being upgraded to a HFC topology, consider deploying 64QAM channels instead.

One of the side effects of the interleaver is it adds latency in the downstream channels. The process of interleaving the outgoing symbols, shuffling the position of the symbols so that normally adjacent related symbols are now separated by unrelated symbols that would otherwise be transmitted later, delays the delivery time of related symbols. The benefit is that a burst of errors that damages adjacent symbols in transmission, damages only unrelated symbols. The FEC can then correct the damaged symbols once they are reshuffled back into their normal order as long as the burst damage did not span too many related symbols. There is an intrinsic relationship between the depth of the interleaving and the latency incurred by the interleaving. The deepest interleaving depth available in the DOCSIS RF specification provides 95 microsecond burst protection at the cost of 4 milliseconds of latency. Four milliseconds of latency is insignificant when watching digital video. If the only digital data services being provided are web browsing, e-mail and Internet access, then subscribers are spending seconds or more watching the message "Host contacted, waiting for reply" so 4 milliseconds is again insignificant. When deploying a near real-time constant bit rate service like IP telephony that requires an end-to-end latency of 20 milliseconds, it may be ill advised to squander 20 per cent of that budget on the downstream interleaver needlessly. The variable depth interleaver enables the system engineer to trade between how much burst error protection is required in the system and how much latency can be tolerated by the services being delivered. This is the next choice to be made when deploying DOCSIS modems: how much interleaving depth is required in this particular cable system.

UPSTREAM PHYSICAL LAYER

Flexible F/TDMA Design

DOCSIS compliant upstream channels provide for both frequency domain multiple access (FDMA) and time domain multiple access (TDMA). FDMA is provided by the ability to have multiple upstream channels simultaneously supporting multiple modems. This is the traditional realm of CATV low split systems wherein upstream channels reside in the spectrum between 5 MHz and 42 MHz. Downstream channels, as noted previously, utilize the spectrum between 88 MHz and 860 MHz.

TDMA is provided by the use of “slotting” on the upstream channels. Each upstream channel is divided into equal-time segments called “mini-slots”. The use of each and every mini-slot is controlled by the Cable Modem Termination System (CMTS) at the head end. The CMTS assigns contiguous intervals of mini-slots to individual cable modems, or makes them available for contention by groups of cable modems, or opens them up for contention by all modems. Additionally, the type of communication within the assigned interval is dictated by the CMTS. All DOCSIS compliant cable modems will time-coordinate all their upstream transmissions so that they only transmit within the appropriately allocated interval. This provides the mechanism for multiple access in the time domain.

Flexible Upstream Channel Parameters

In addition to the ability to have different upstream channels on different frequencies and have different mini-slot sizes on different channels, many other upstream channel parameters have options that need to be set to meet individual system needs. Each upstream channel has an assigned bandwidth associated with it. The occupied bandwidth is directly related to the channel’s data rate. DOCSIS compliant upstream channels occupy bandwidths of 200, 400, 800, 1600, or 3200 kHz. This corresponds to channel data rates of 160, 320, 640, 1280, or 2560 kilosymbols per second (ksym/sec). The specification provides for both QPSK and 16QAM transmissions upstream which allows us to have either 2 bits per symbol or 4 bits per symbol respectively. Channel data rates are available between 320 kbps (QPSK at 160 ksym/sec) and 10.24 Mbps (16QAM at 2560 ksym/sec). While the bandwidth is fixed for any upstream channel because the symbol rate is defined for that channel, the bit rate on the channel is variable because independent transmissions on that channel can be either QPSK modulated or 16QAM modulated.

Another powerful option available in DOCSIS compliant systems is the ability to flexibly define the amount of FEC protection included with certain types of upstream transmissions. Within an operational system, there are many kinds of packets being exchanged. There are relatively frequent housekeeping messages. The loss of one or more of these messages due to data errors is relatively insignificant because a virtually identical message will occur again in a relatively short time anyway. Other messages may be either time critical, like IP telephony packets, or will need to be retransmitted if lost, like TCP packets. If the packet is large, transmitting it again may consume more time than desirable.

The DOCSIS specified flexible FEC coding enables the system operator to set the size of the error protected data blocks and to set the number of correctable errors within each block. FEC changes can be done while the system is operating normally. In previous proprietary cable modem systems, when impairments in a data channel caused too many errors, the only solution was to abandon that frequency and hope to find a cleaner portion of the spectrum to place the channel. While DOCSIS compliant systems can do that too, the flexible FEC coding option enables the system operator to choose to stay on the same frequency by simply increasing the error protection on that channel. Even though the additional few bytes of error protection reduces the channel information rate a small amount, it makes the overall system capable of a much higher upstream spectral utilization.

The system operator now has the option to tailor each upstream channel to suit plant needs. Multiple modes of operation are available within one plant. Upstream feeds from portions of the plant which have more ingress or more homes passed, can have the upstream parameters set to provide more robust transmissions. The system operator could enable a more powerful FEC setting, lower symbol rates, and choose to use QPSK modulation. For newer nodes in the plant where ingress and noise are less of a problem, the upstream parameters could be tailored for more efficient transmissions. The system operator could reduce the FEC overhead, use higher symbol rates, and choose to use 16QAM modulation.

Table 1 itemizes the upstream physical layer features and the benefits they provide:

Feature	Benefit
Frequency agility	Ingress avoidance
Variable Reed-Solomon forward error correction	Adjustable amount of error correction
Variable Reed-Solomon block size	Individually tailor for large and small packet sizes
Multiple symbol rates	Fit channels into available spectrum
Wide channels with FEC	Ingress mitigation
Narrow channels	Intersymbol interference and reflection mitigation, ingress avoidance

Table 1. Features and benefits available in DOCSIS upstream channels

BURST PROFILES

The mechanism defined in the DOCSIS RF specification for managing the characteristics of upstream transmissions utilizes configurable "burst profile" parameters. Each upstream transmission is independent and is separated by an unoccupied guard time from other transmissions. An upstream transmission is also known as an upstream "burst". As previously noted, each burst must be exactly timed to occur within an allocated interval of mini-slots.

Burst profiles are defined in the CMTS on a per-upstream-channel basis and are passed to all cable modems using that upstream channel. All cable modems using the same upstream channel will therefore be using the same burst profiles. Cable modems on other upstream channels will use an independent set of burst profiles that may or may not be duplicated by burst profiles in use on any other upstream channel. This is the mechanism that allows a CMTS to set cable modems for most efficient transmissions based on the characteristics of that particular upstream channel.

Burst profiles are stored in the cable modem allowing rapid selection of optimum transmission modes for different types of bursts. Six active burst profiles are stored in each cable modem for the following types of bursts:

- Initial maintenance
- Periodic ranging
- Request
- Request with contention data
- Short data
- Long data

The first two burst types are used for initialization and routine maintenance. The middle two types of bursts are used by the cable modem to request an allocation of mini-slots. The last two are the burst types that carry most of the traffic in the system. A service like IP telephony will generate a steady stream of short packets, while a TCP/IP function like ftp will generate a sequence of short bursts of long packets. It makes sense to FEC encode these two types of packets differently to ensure reliable delivery with minimal overhead. There is no opportunity to retransmit the short packets because all are needed in near real-time. While retransmitting the long packets wastes system resources, it can be acceptable if needed only rarely. Items to consider for optimization include the modulation type, the FEC frame size, and the number of FEC correction bytes.

Table 2 details the burst profile parameters which must be defined for each burst profile. Most of these will be set to match the CMTS receiver needs, but as noted above, some of the parameters are used to optimize the system.

Parameter	Use or possible value
Modulation type	QPSK or 16QAM
Differential Encoding	On or Off
Preamble length	Set for receiver synchronization
Preamble starting point	Set for receiver synchronization
Scrambler seed	Set for receiver synchronization
Scrambler enable	On or Off
FEC correction bytes	Optimize: 0 to 10 bytes
FEC codeword length	Optimize: 16 to 253 bytes
Last codeword length	Normal or Shortened
Guard time	Dead time between bursts
Maximum burst length	Optimize for data services

Table 2. Burst profile parameters to be set in each DOCSIS upstream channel

User Unique Burst Parameters

In addition to the upstream channel parameters, mini-slot size, symbol rate, and frequency, and the burst profile parameters listed above, there is another set of parameters that are adjusted automatically by the CMTS and the cable modems. These parameters are unique for each cable modem in the system. Interesting side effects can occur if deliberate attention is not paid to these effects. Parameter settings unique to each cable modem include the upstream transmit power setting, minor frequency adjustments, and a timing or ranging offset.

Ranging Concepts

Each cable modem in the system is a unique distance from the CMTS. Each cable modem, therefore, will have unique timing and power requirements imposed upon it. The transmitter power required from the cable modem is determined by the home wiring environment, drop and cable lengths, and system components between the cable modem and the first return amplifier. The DOCSIS system design requires the CMTS and the cable modems iteratively communicate details about the power level received at the CMTS, using initial maintenance and periodic ranging intervals. The CMTS will read the incoming power level of a transmission from a cable modem, then determine whether the input level is too low, too high, or within the optimum range. The power level adjustment needed to center future incoming transmissions in the desired power window is transmitted to the cable modem. The cable modem adjusts its transmit power accordingly. This process is iteratively repeated until the optimum received power level of upstream transmissions is achieved by the cable modem. This process is performed during the initial maintenance interval when a cable modem first comes online and is repeated in each regularly scheduled periodic ranging interval. This ensures continued reliable communications between the CMTS and the cable modems.

As with power, there may be subtle differences between various cable modems due to normal component tolerances which cause the upstream transmit frequency to differ slightly from it nominal setting. To accommodate this difference, a frequency offset is also iteratively communicated until the optimum received frequency of upstream transmissions is achieved by the cable modem. The final frequency offset will be 10 Hz or less when ranging is successfully completed.

Finally, during the ranging process, the cable modem is assigned a timing offset that ensures its upstream transmissions arrive exactly within the allocated mini-slot. This is accomplished by the cable modem transmitting earlier than the assigned slot time so that delays caused by interleaving latency in the downstream, propagation in the system, and fixed processing overhead in both the CMTS and cable modem are negated. Ranging requires that the two-way round trip delay be negated because all upstream transmissions must align with the mini-slot timing as viewed by the CMTS. After a CMTS assigns the slot timing, it must then communicate that timing to the cable modem. The communication is delayed in the downstream direction, by latency, downstream propagation delay, and processing overhead. When the cable modem sends a transmission upstream, it is delayed by the upstream propagation delay and processing overhead. The sum of these delays is effectively removed by the ranging process.

Node Combining

The following is not solely a DOCSIS issue because cable modem systems in general have a ranging function that can result in this situation. It is, nevertheless, one of the more interesting side effects of the ranging process that occurs when combining nodes with different optical losses. At the head end, if these nodes are directly connected to a fixed loss combiner/splitter to route upstream signals to the CMTS, and possibly other digital data service devices, then the power level normalizing ranging process can create an undesirable situation.

The CMTS steers the cable modem transmit power to provide a constant RF level at the input of the CMTS. This translates to a constant RF level at the input to the combiner/splitter network that is the same point as the output of the upstream laser receiver. Because the upstream optical paths have different losses, the CMTS steers the cable modems to provide an uneven RF input to the return laser transmitter. While one of the nodes may have an optimum input RF level, all the other nodes will not.

Complications can occur at both ends of the variations. At the link with the most loss, there may not be enough cable modem transmit power available to transmit upstream through the in-home wiring, through a high-value tap, and up to the laser return transmitter. This can result in a lower than expected upstream received RF level even though the cable modem is transmitting at full upstream power. At the link with the least loss, the cable modems will be directed to lower their RF transmit power. This leaves the input to that node's laser transmitter with lower than desirable carrier to ingress ratios and the significant noise levels the input to the combiner/splitter network. The combination of the two ends yields a lower than desired carrier level together with a higher than desired noise level and ingress environment. The result can be an unreliable digital data delivery system.

The situation occurs because the cable modem system carrier level self adjustment has been combined with an unbalanced optical link and the overall system has become unbalanced. The remedy is to balance the optical loss of each laser return link by either adding optical attenuation or, more easily, the equivalent RF attenuation to the output of each return link. Once the return links are matched in loss, the system can be aligned so that not only not only is the input to the CMTS optimized by the ranging process, but with balanced return paths to each node, the system can optimize the input to each return laser link also. The result is a well-balanced system that can deliver reliable two-way digital data services.

GOING FORWARD

Going forward, there will soon be many new powerful physical layer options cable operators can use to help manage the delivery of two-way digital data services on their plant when deploying DOCSIS compliant systems. The options that exist in both the downstream and upstream physical layer enabling DOCSIS systems to be tailored in an optimum manner have, hopefully, been explained in enough detail to illuminate basic system operation. Ultimately, the quality of the delivered service will be perceived through the many facets of sales, installation, and support. With the new options available in these systems, reliability of the physical layer will not be perceived as the weak link in the chain.

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CableLabs is a research and development consortium of cable television system operators representing the continents of North America and South America. CableLabs plans and funds research and development projects that will help cable companies take advantage of future opportunities and meet future challenges in the cable television industry.