OPTIMIZING TRANSMISSION PARAMETERS IN DOCSIS 2.0 WITH A DIGITAL UPSTREAM CHANNEL ANALYZER (DUCA)

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Abstract

A new generation of data over cable service interface specification (DOCSIS) 2.0 cable modem and cable modem termination systems (CMTS) offer cable operators the promise of increased upstream capacity and greater robustness to common channel impairments such as ingress and impulse noise. It is already clear that the many tools in the new DOCSIS 2.0 standard that allow for efficient use of the upstream spectrum and mitigation of impairments also make the task of optimizing transmission parameters increasingly difficult. In fact, the performance of a DOCSIS 2.0 based CMTS will greatly depend on its ability to dynamically assess upstream channel conditions and set the transmission parameters accordingly.

In this paper we present digital upstream channel analyzer (DUCA) – a set of functions running on a DOCSIS 2.0 CMTS that implements algorithms for optimal channel allocation and selection of transmission parameters. DUCA analyzes the entire upstream spectrum, measures and records noise and impairment conditions, and sets the parameters of the various noise mitigating tools in DOCSIS 2.0 optimally for maximum upstream throughput.

We will show how proper selection of parameters, using DUCA, ensures that operators will benefit significantly from the new improved upstream PHY.

INTRODUCTION

After several years of ongoing debate, cable operators have selected advanced time division multiple access (A-TDMA) and synchronous code division multiple access (S-CDMA) as the upstream modulations in the new DOCSIS 2.0 specification. These technologies offer cable operators the opportunity to better utilize their cable infrastructure and to generate more revenue from increased use of the cable network upstream spectrum. DOCSIS 2.0 offers operators powerful tools to mitigate common channel impairments and spectrally efficient modulations to maximize the throughput in the bandwidth-limited upstream channel. However, the many tools in DOCSIS 2.0 make the selection of transmission parameters extremely difficult in comparison to DOCSIS 1.0, with the performance of DOCSIS 2.0 systems greatly depending on the choice of these parameters. In fact, DOCSIS 2.0 will only provide significant benefits to operators if and when CMTS systems make proper use of the many tools in this standard by implementing technology that dynamically sets transmission parameters for optimal performance. In this paper we will present such a technology – DUCA, which measures the impairments in the upstream channel and sets the transmission parameters for maximum throughput based on time-domain and frequency-domain analysis.

THE CABLE UPSTREAM CHANNEL

The cable network upstream channel has always been the weakest link in the cable network infrastructure. Given the tree-and-branch topology of the cable network, noise and interferences from the entire network are accumulated at the headend. Common upstream impairments include the following noise sources:

1) White noise generated by active components in the network.
2) Narrowband ingress noise, typically generated by other transmitters such as

amateur radio signals or resulting from Common Path Distortion [2].

3) High rate impulse noise originating from electric current. These impulses are short, typically less than one microsecond duration, and have a repetition rate of between several hundred to a few thousand occurrences per second.
4) Low rate wideband burst noise originating from several sources including electrical appliances in homes and laser clipping. These bursts could occur as frequently as every 10-20 seconds and could last as long as 10-50 microseconds.

In addition to the noise sources described above, the upstream signal is subject to multi-path reflections due to impedance mismatch of the plant's components and unterminated cables. For a more detailed description of cable upstream impairments see [1][2].

DOCSIS 2.0 BACKGROUND

In August 2001, cable operators decided that the new DOCSIS 2.0 upstream physical layer specification would include both A-TDMA, based on a proposal by Texas Instruments and Broadcom [1][3] and S-CDMA based on a proposal by Terayon. Both of these technologies were also included in the IEEE 802.14a specification, which was never finalized [4].

A-TDMA is essentially an evolution of DOCSIS 1.0. It extends the physical layer of DOCSIS 1.0/1.1 with the following enhancements:

1) Additional constellations: 8-QAM, 32-QAM and 64-QAM. This allows an increase in spectral efficiency by as much as 50 percent in good quality channels and provides more increments in spectral efficiency for finer matching of data rate with existing channel SNR.
2) Additional Symbol Rate 5.12 MB. This reduces the number of receivers required at the headend for a given plant by a factor or two and improves network efficiency due to statistical multiplexing of more users in an upstream channel.
3) Byte Interleaver to spread the effect of impulse and burst noise over time.
4) Improved error correction code. DOCSIS 2.0 extends the maximum error protection ability of DOCSIS 1.0's Reed-Solomon FEC from 10 byte errors to 16 byte errors, providing greater robustness to burst and impulse noise.
5) Improved Pre-Equalizer for mitigating multipath distortions.

S-CDMA adds to the above enhancements a spreader that provides greater immunity to severe cases of impulse noises, and Trellis Coded Modulation, which improves performance for white noise. When in S-CDMA mode, there is no byte interleaver as described above. Instead, an S-CDMA framer introduces time (as well as code) diversity. S-CDMA calls for much stricter timing requirements in order to maintain code diversity, allowing for the elimination of guard time between data packets. For more details on S-CDMA see [4].

SETTING TRANSMISSION PARAMETERS

DOCSIS 2.0 provides a new challenge in setting transmission parameters. While DOCSIS 1.0 provided operators with some limited flexibility in setting transmission parameters to match the varying channel conditions, in practice, parameters remained relatively static. Without the ability to track dynamic changes in the plant, operators had no choice but to set transmission parameters to the most robust mode (QPSK, Reed Solomon T=10) to accommodate worst-case scenarios. With penetration still low, such inefficient use of the upstream spectrum could be tolerated. Without ingress cancellation available to them, operators would typically set the frequency manually to ensure the transmission signals are within a region with little or no ingress. The more sophisticated CMTSs could automatically identify that ingress is interfering with the data signal and automatically shift modems to a different upstream frequency with no interference.

DOCSIS 2.0 requires a much more sophisticated setting mechanism. First, there are many more parameters to play with, such as modulation type (A-TDMA or S-CDMA), constellation, baud-rate, transmission power, preamble length and type, center frequency, error correction capability, interleaver parameters, spreader parameters and number of active codes in S-CDMA mode. Second, the premise of DOCSIS 2.0 is that the upstream traffic is significantly higher, with upstream channel throughput closer to capacity, leaving less room in the spectrum to avoid interferences, and making it crucial to efficiently utilize the channel spectrum.

FREQUENCY-DOMAIN ANALYSIS

The first step in setting optimal parameters is measuring channel conditions and detecting interferences. The most common tool in current CMTSs is upstream spectral analysis. Using wideband sampling and FFT, or alternatively using a frequency-sweeping filter, the upstream spectrum can be measured, identifying frequencies with ingress. This spectrum measurement is typically used to find ingress free regions for the data signals. However, with ingress cancellation technology, first introduced by Texas Instruments in the TNETC4521 INCA burst receiver (see also [5]), avoiding the ingresses is no longer necessary. While transmitting in an ingress free region is always desirable, a clean spectrum block, which is wide enough to accommodate the highest baud-rate, is not always available. In such cases a CMTS needs to make a decision on whether to reduce baud rate, allowing the signal to fit between other signals and interferences or to maintain the high baud rate and to cancel the interference with ingress cancellation technology. Given that ingress cancellation techniques allow for operation in negative C/I ratios (i.e. ingress that is stronger than the data signals), it is foreseeable that in many cases the parameter setting mechanism will determine that maintaining the higher baud rate while overlapping the ingress will result in higher throughput than if the baud rate were reduced and the ingress avoided. Ingress cancellation technology and the new modes of operation in DOCSIS 2.0 have transformed the traditional spectrum analysis of finding ingress free regions into a more complex optimization problem of setting baud rate, center frequency, constellation, coding and other parameters to maximize upstream throughput given the constraints of available spectrum, detected ingress and the performance of the ingress cancellation technology. Furthermore, as channel conditions change, these transmission parameters need to be adapted to the new environment. Tracking spectrum changes in an upstream channel densely occupied with data signals, and having to change in some cases the center frequency, baud rate and other transmission parameters of multiple upstream data signals concurrently in order to achieve higher throughput makes this ongoing optimization problem particularly challenging.

TIME-DOMAIN ANALYSIS

DOCSIS 2.0 provides new tools for mitigating impulse and burst noise: Byte Interleaver, stronger Reed Solomon error correction, S-CDMA spreading. In order to avoid unnecessary waste of bandwidth on a spectrally inefficient constellation or on coding overhead, the DOCSIS 2.0 CMTS needs to dynamically track impulse levels, and to optimally set the relevant parameters accordingly. Impulse strength, as well as impulse frequency and arrival statistics can be determined by employing various power detectors, which measure the signal level during quiet periods or in adjacent unoccupied frequencies. Finding quiet periods of time or unoccupied frequencies for measuring impulses may not be easy when operating close to channel capacity. In such cases the CMTS may have to regularly block time slots for impulse detection. To avoid wasting bandwidth on impulse detection, impulses can also be detected by analyzing decision errors, however this method is problematic since error measurements will be erroneous during impulse occurrences (because the error measurement relies on an incorrect decision). To overcome this problem, transmitted symbols and decision errors can be estimated by re-encoding corrected data bits after the Reed Solomon decoder. However, this results in a relatively complex algorithm.

A DOCSIS 2.0 CMTS has multiple tools for impulse mitigation. The spreading function of S-CDMA spreads the effect of the impulse over time and over the code space. This is a useful tool when impulse levels are limited, however if the impulse is very strong, spreading may actually decrease performance by causing multiple errors from every impulse (due to spreading) instead of taking the hit only once. In addition to spreading, Reed Solomon parameters are also the obvious candidates for adjusting based on measured impulse rates. Less intuitive, is the choice of baud-rate and constellation. Traditionally, the most common reaction to impulse noise in the channel is reducing baud-rate and reducing the constellation size, which indeed makes the signal more robust to moderate impulses. However, this comes at the expense of upstream throughput. A better approach may actually be to transmit at a high baud-rate using one of the larger constellations, thereby allowing more coding information, which will enable impulse mitigation with Reed Solomon coding. Various factors such as impulse power, impulse frequency and upstream channel utilization will affect the choice of these transmission parameters.

The tools for mitigating burst noise are the same ones used for impulse noise. Spreading provides good immunity to long bursts of noise. Reducing baud-rate can provide very strong immunity to very long burst noise even without spreading. However, given that long bursts (over 10 microsecond) are relatively rare, it may be better to transmit at high spectral efficiency with little coding overhead and sacrifice the occasional data packet instead of using a more robust mode with lower throughput. These are the types of trade-offs that the channel analysis function in a DOCSIS 2.0 CMTS needs to consider when setting transmission parameters.

MITIGATING OTHER IMPAIRMENTS

The most common impairment is the added white noise. Dealing with white noise is rather straightforward – setting the constellation size based on SNR measured with the upstream spectral analysis or by averaging the decision errors. Reed Solomon coding parameters also need to be set according to the measured SNR. When the SNR is low, a DOCSIS 2.0 CMTS may choose also to reduce the number of active codes in S-CDMA mode, or equivalently, to reduce the baud rate in A-TDMA mode and to allocate higher spectral density to the reduced baud-rate signal. In both of these cases, modems can operate at very low SNRs.

A MIX OF IMPAIRMENTS

A greater challenge for the DOCSIS 2.0 CMTS is when it is faced with the task of mitigating different types of noise simultaneously, especially when the optimal choice of parameters for each impairment are very different. For example, when ingress is combined with burst noise, the DOCSIS 2.0 needs to choose between a higher baud-rate that will improve the performance of the ingress cancellation, or a lower baud rate for greater immunity to long bursts. It needs to decide whether spreading will be used, providing greater immunity to bursts, but at the same time making ingress cancellation very difficult. Analyzing the mix of impairments, understanding the trade-offs and selecting the compromise set of parameters, which will provide optimal robustness to the measured impairment, while at the same time maximizing throughput, is essentially the role of the parameter decision function that a DOCSIS 2.0 CMTS needs to implement.

DUCA

We have presented the challenge that the cable industry faces in taking advantage of the new state-of-the-art DOSCIS 2.0 standard. It is likely to take several years before system vendors implement sophisticated detection and analysis tools, which make optimal use of the many tools provided by the new standard. Today, several years after the first DOCSIS 1.0 systems were certified, systems are still not realizing the full capability of this standard. DOCSIS 2.0 is likely to follow a similar path. To accelerate this process, Texas Instruments has introduced the concept of the DUCA, which is a functional block in a DOCSIS 2.0 CMTS dedicated to upstream channel measurement and analysis and optimal parameter selection. DUCA, which is best implemented using a dedicated Digital Signal Processor (DSP), performs time-domain and frequency-domain analysis as described in this paper, and dynamically sets the transmission parameters for optimal use of the upstream channel.

The following simulation is an example of upstream channel analysis performed by DUCA:

We simulated an upstream channel with multiple ingress as illustrated in Figure 1.

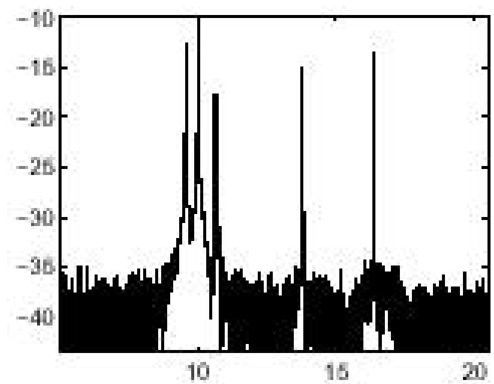

Figure 1: Upstream Channel Spectrum

In addition to ingress, this simulated channel is also corrupted by time-domain impairments, such as burst noise, which cannot be seen in the frequency-domain analysis.

Without DUCA capabilities in the CMTS, dynamic changes of the channel cannot be tracked, and therefore a robust mode, which can operate in worst-case scenarios, needs to be used. A typical choice of parameters for such a channel would include QPSK constellation, strong RS code and medium/low baud rate (2.56 Mbaud or even 1.28 Mbaud) to avoid in-band ingress noise. This results in upstream throughput of ~2.5-5 Mbit/sec, far below the optimum. Therefore, DUCA enables higher throughput in this channel. The DUCA algorithms identify and characterize the channel impairments (WGN, burst and impulse noises, ingress noise etc.), while taking into consideration ingress cancellation and other noise mitigation capabilities of the receiver. The impairment characterization is followed by an optimal channel allocation algorithm. Figure 2 shows the output of the DUCA channel allocation algorithm for one and two upstream channels. Note that for one upstream channel, the channel allocation algorithm determines that the highest throughput can be achieved by using the highest baud-rate and a 16-QAM constellation while overlapping two ingresses. The channel allocation algorithm determines that avoiding the ingress by reducing the baud-rate would not result in higher throughput even if a more spectrally efficient constellation can consequently be used. The transmission parameters selected result in upstream throughput of ~20Mbit/sec, a 4X-8X improvement compared to the over-robust transmission in the CMTS without DUCA.

SUMMARY

DOCSIS 2.0 gives cable operators a multitude of transmission parameters to define, such as modulation type (A-TDMA or S-CDMA), constellation, baud-rate, transmission power, preamble length and type, center frequency, error correction capability, interleaver parameters, spreader parameters and number of active codes in S-CDMA mode. Maximal channel throughput can only be achieved by using sophisticated mechanisms that optimally track and analyze the varying channel conditions and set the transmission parameters for optimal performance.

We have presented the concept of DUCA for optimal selection of those parameters in DOCSIS 2.0. We believe that channel analysis and parameter setting tools like DUCA will become more and more important as upstream data traffic increases, and over time more and more channel analysis algorithms will be developed and improved, enabling operators to realize the full potential of DOCSIS 2.0 and the cable upstream channel.

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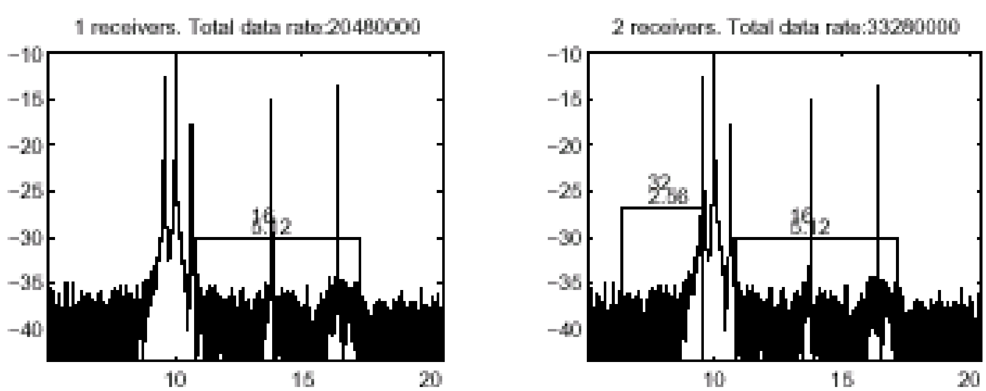

Figure 2: DUCA Channel Allocation Output