HI PHY LITE – A PRAGMATIC APROACH TO ADVANCED PHY

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Abstract

This paper presents a new generation of Cable Modem and Cable Modem Termination Systems (CMTS) which utilize an advanced upstream Physical Layer technology known as 'HI PHY Lite' or 'Advanced TDMA', which increases the upstream capacity and improves robustness to common channel impairments while maintaining full backward compatibility to DOCSIS 1.1 systems.

In this paper we will provide an overview on the HI PHY Lite Modulation scheme, and will present data on the performance of the HI PHY Lite system in various channel. We will demonstrate how HI PHY Lite systems provide MSOs an evolutionary path to increasing the capacity of the CATV reverse channel, thereby allowing operators to offer their subscribers greater upstream bandwidth for various services such as video conferencing and telephony.

INTRODUCTION

Cable operators have been remarkably successful in establishing DOCSIS as the standard for data over cable service in North America. Today, dozens of cable modem vendors offer interoperable, DOCSIS standard-based cable modems, using chip-sets from multiple silicon vendors. The vast majority of cable modems deployed today in North America are DOCSIS based, and DOCSIS and its derivative Euro-DOCSIS are also being widely deployed in Europe and the rest of the world.

What contributed to the rapid turn around from conception to deployment of DOCSIS systems was the fact that when designing the DOCSIS specification operators preferred mature and proven technologies over state-of-the-art. Faced with competition from DSL service providers, cable MSOs focused on getting a solid solution as fast-to-market as possible, with improvement to be considered for future generations.

Having successfully completed the first phase of establishing a cable modem standard, operators can now focus on improvements. One area for improvement is the transmission scheme used for the upstream channel. Current DOCSIS systems do not efficiently use the scarce bandwidth available to operators in many of the upstream channels. This inefficiency does not degrade service today given that penetration of cable data service is relatively low and common cable data service usage is asymmetric in its consumption of bandwidth. The most common use of cable data service, Internet browsing, is highly asymmetric in nature, requiring very little data to be transmitted in the upstream in comparison to the amount of data transmitted in the downstream. However, as cable modem penetration increases and as more symmetric services and applications such as voice over IP, video conferencing and peer-to-peer networking gain popularity, the inefficient use of the upstream channel could potentially limit operators in expanding their services. Furthermore, the shortage of bandwidth in the upstream is exacerbated by the fact that the upstream channel is plagued with various interferences, which further limit the use of the already limited upstream channel.

To address the problem of the upstream channel the Society of Cable Telecommunications Engineers (SCTE) requested from the IEEE to evaluate new technologies for possible enhancement of the current upstream Physical Layer (PHY) specification. IEEE 802.14a working group was set to up to do this work, and to design a new PHY specification which would provide higher capacity in the upstream while at the same time providing greater immunity to common channel impairments. Although this effort, which will be described in greater detail in this paper, did not result in a completed specification, it did lead to draft specification, a derivative of which is the *HI PHY Lite* (a.k.a *Advanced TDMA*) proposal which is the subject of this paper.

THE CATV UPSTREAM CHANNEL

The upstream channel in the cable TV network covers the 5-42MHz frequency band. Due to the 'tree and branch' topology of the CATV network, the upstream is characterized by noise which is the accumulation of noise generated throughout the network. This includes the following noise sources:

1) White noise generated by active components on the network
2) Narrowband Ingress, typically originating from other transmitters such as amateur AM radio.
3) High rate impulse noise originating from electric current, consisting of short, typically one microsecond or shorter, noise impulses at a repetition rate varying form a few hundred occurrences per second to several thousands per second.
4) Low rate, but long duration, wideband bursts which could occur as frequently as every 10-20 seconds and could last 10-50 microsecond.

On top of these noise sources, the upstream signal is subject to multi-path reflections due to impedance mismatch of the plant's components and unterminated cables

PROPOSED SOLUTIONS FOR THE UPSTREAM CHANNEL AND IEEE 802.14 ACTIVITY

Three proposals were submitted to the IEEE 802.14 for consideration as next generation CATV upstream PHY (a.k.a HI PHY). The proposals included Frequency Agile TDMA (FA-TDMA), Variable Constellation Multi-tone (VCMT) and Synchronous CDMA (S-CDMA). IEEE 802.14a HI PHY working group adopted a combination of the advanced TDMA and S-CDMA (as an optional mode) proposals as the basis for its specification. For a more detailed description of the proposals and the debate in IEEE 802.14 see [1].

After a long process which spanned over a year, IEEE 801.14a, HI PHY working group was unable to reach an agreed upon specification and was ultimately disband without completing its goal.

HI PHY LITE

The *HI PHY Lite* modulation scheme was jointly developed by Texas Instruments and Broadcom Corporation [2]. It was derived from the more complicated modulation scheme proposed by the IEEE802.14a work group. However, *HI PHY Lite* excludes many of the IEEE802.14a modulation tools, such as TCM and BICM line codes, inner interleaving, non-linear precoding, CDMA modulations, and synchronous modulations, hence the use of the term 'Lite'. In our opinion, all those tools provide a relatively marginal performance gain, which does not justify the significant increase in cost, complexity and in the time it would take to the industry to reach fully tested and interoperable and multi vendor products.

HI PHY Lite modulation scheme extends the Physical layer of DOCSIS 1.0 in the following manner:

8, 32, and 64 QAM constellations

This allows increasing the spectral efficiency by up to 50% in cable plants that have good SNR, compared to DOCSIS 1.0 or 1.1 whose highest constellation is 16QAM. Such cable plants are expected to become more and more common as operators improve their plants and pull fiber deeper into the HFC.

By adding 8-QAM and 32-QAM constellations, the *HI PHY Lite* modulation scheme enables finer matching the data rate in the channel to the SNR conditions in the plant.

Symbol rate of 5.12 MHz

This allows reducing the number of headend receivers per CMTS by a factor of two, and thus offering smaller CMTS equipment, in comparison to DOCSIS 1.0/1.1, where the highest symbol rate is 2.56 MHz. It also allows improving the network efficiency of the upstream plant, as the bandwidth demand of the cable plant can be shared across a smaller number of channels.

Improved Error Correction Code

The *HI PHY Lite* Forward Error Correction (FEC) scheme includes dynamic interleaving and extends the maximum error protection ability of DOCSIS 1.0's Reed-Solomon FEC from 10 byte errors to 16 byte errors. This allows significantly higher robustness to burst noise and impulse noise.

HI PHY LITE PERFORMANCE

In this paragraph we describe the performance of a *HI PHY Lite* system which uses the new generation of Texas Instruments Headend Burst Receiver IC (TCNET4522) and HI PHY Lite DOCSIS CM IC (TCNET4042) which implement Hi PHY Lite, and utilize Texas Instruments' INCA™ technology for ingress cancellation and capacity increase

Performance in White Noise

Table 2 shows white noise performance that can be achieved by the TCNET4522 and TCNET4042[1]

Table 1: HI-PHY Lite Throughput

Constellation	Throughput [bits/symbol]	SNR @ post FEC BER=10^{-8}
QPSK	1.75	8.5 dB
8QAM	2.73	13.1 dB
16QAM	3.64	16.0 dB
32QAM	4.55	19.3 dB
64QAM	5.45	22.2 dB

The performance in QPSK and 16QAM modulation is very similar to the attainable performance when using the DOCSIS scheme, beside a fraction of dB improvement which can be obtained by using the maximal T=16 error protection capability of the Reed-Solomon FEC. We observe that the 64QAM modulation, which allows 50% throughput increase compared to DOCSIS, is feasible when the SNR is 22 dB or higher. We believe that such SNR levels are becoming more and more common as cable operators increase the fiber portion of HFC plants, and clean the upstream plants. On the other hand, some of the cable plants are still not "clean" yet, and there is also a need to operate at very low SNR levels. Figure 1 depicts the ability of the TCNET4522 and TCNET4042 to operate at very low SNR levels[2]. As we can see, one needs to sacrifice data rate in order to operate at low SNR levels, however, operation is

[1] When calculating SNR, the noise power is measured over the bandwidth of the signal (1.25 times the symbol rate)
[2] The noise power is measured over the bandwidth of a 5.12 Mega-symbols per second

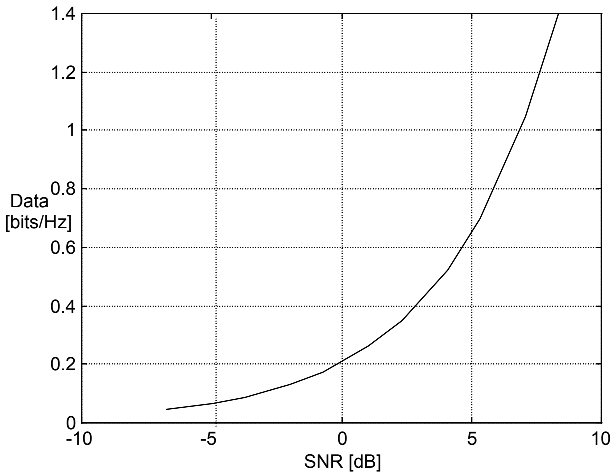


Figure 1: Operation at the Low SNR

feasible even at SNR levels of –7 dB (that is the noise power is higher by 7 dB than the signal power). Operation in these low SNR levels is achieved by retreating to the low symbol rates of DOCSIS, while the CM still maintains the high power level of a full-band 5.12 Mega-symbols-per-second HI PHY Lite signal.

Ingress Noise Performance

Perhaps the biggest advantage of the TCNET4522 burst receiver is its robustness to narrowband ingress, using the INCA[3] algorithms. Table 3 shows Carrier to Interference (C/I) that can be tolerated by the 4522 when the noise is a sine wave (CW) signal, with a BER of 10^{-8}.

Table 2: CW Ingress Noise Performance

Constellation	C/I with 4522	C/I with conventional receivers
QPSK	0 dB	9 dB
16-QAM	3 dB	16 dB
64-QAM	6 dB	22 dB

As one can see, the INCA algorithms allow improvements of 9-16 dB in the robustness to ingress noise.

The TCNET4522 and TCNET4042 were also tested with ingress noise signals recorded in noisy cable plants. Figure 2 shows the noise spectrum of a plant with heavy ingress noise. It also shows the spectrum of the signal plus noise in the case where the system operated in 16 QAM. The signal level that was required for proper operation was 15.5 dB above the power level of the noise, which is 4-5 dB better than the power level required by conventional burst receivers. We note that this figure shows the time-average of the noise spectrum, but actually the noise spectrum was dynamically time varying.

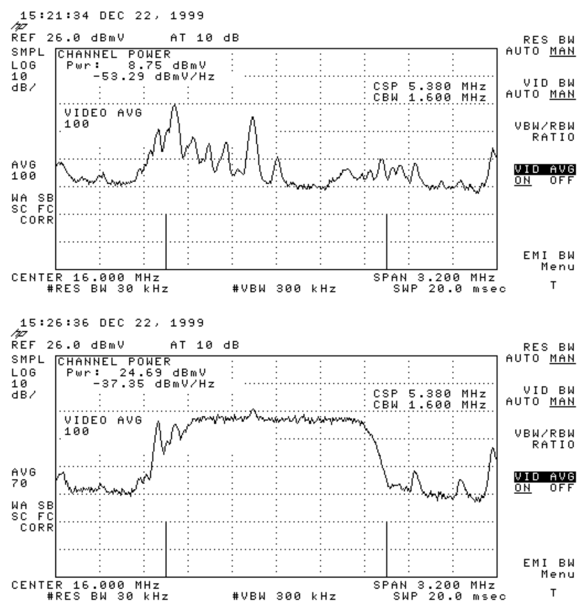


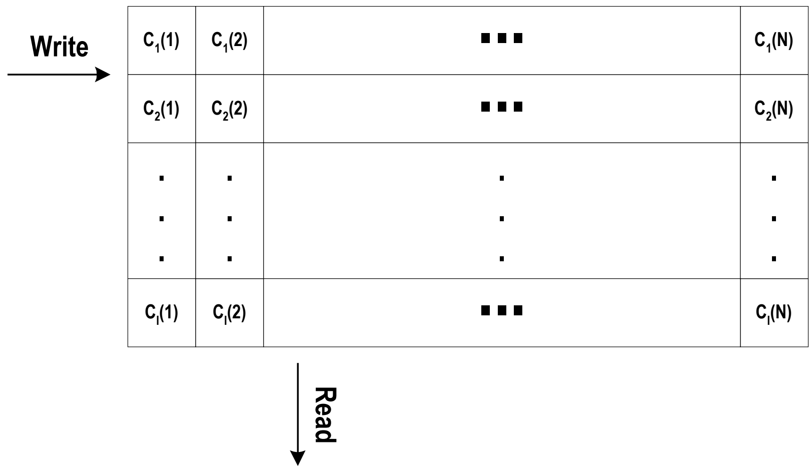
Figure 2

Burst Noise Performance

The DOCSIS 1.0 Upstream PHY combats burst noise by using Reed-Solomon error correction codes. These codes can correct up to T byte errors, where T=0…10. The maximal burst length that can be corrected by a DOCSIS 1.0 system is:

$$T_{BURST} = T/R_{byte}$$

Figure 3: The HI PHY Lite Interleaver



Where T is the correction factor of the code, and R_{byte} is the byte rate of the channel. Thus, for example, when the channel operates at its maximum byte rate, R_{byte}=1.28 10^6 bytes per second, and its maximum error protection capability, T=10, the maximal burst length that can be tolerated is 7-8 microseconds.

The *HI-PHY Lite* scheme employs a 2048 bytes block byte interleaver that allows a significantly improving burst correction capability. The byte interleaver is shown in Figure 3. It is a two-dimensional memory structure with *N* columns and *I* rows, where *N* is the Reed-Solomon code-word length. The interleaver performs permutations on a block of $N \times I$ data bytes in the following way: The bytes are written into the interleaver row by row, and read from the interleaver column by column (see Figure 3). The CM and CMTS dynamically program the interleaver's parameters in order to optimize them to the size of each data packet.

When a byte interleaver is used, the maximum burst length that can be corrected by a *HI-PHY Lite* system is multiplied by the interleaver depth (*I*), that is:

$$T_{BURST} = I \text{ x } T/R_{byte}$$

When the SNR in the channel is high, higher constellations can be used in conjunction with low code-rate Reed-Solomon code and byte interleaving to further increase burst noise robustness.

Figure 4 shows the attainable throughput of a *HI-PHY Lite* system as a function of the burst

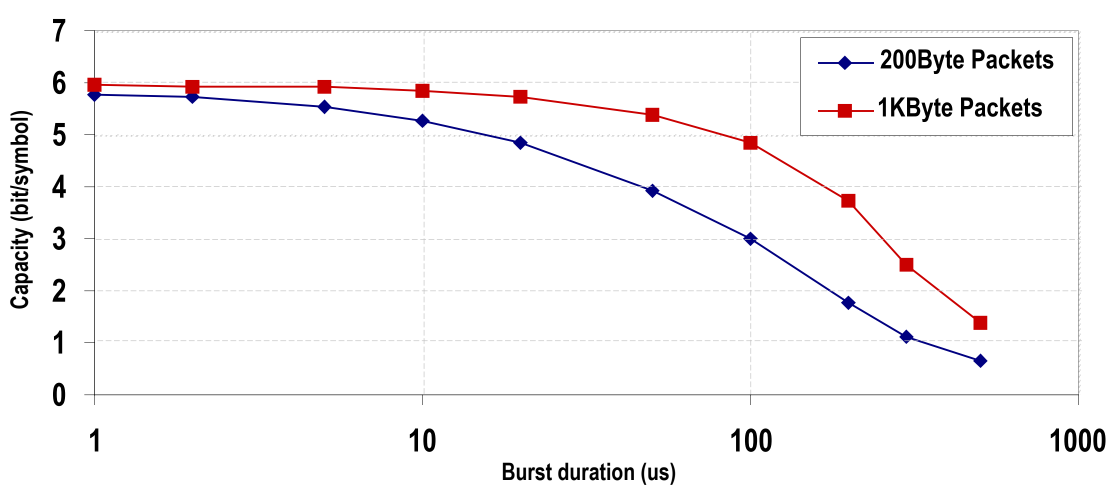


Figure 4. HI PHY Lite Burst Tolerance (Rs=1.28Mbaud)

length that the system can tolerate.
Performance is analyzed for 200 byte packets and 1Kbytes packets. In this test we have used error correction factor T=10. An improvement by up to a factor of 1.6 in burst duration can be obtained by using the maximum error correction factor of *HI PHY Lite* FEC, T=16.

For the 200 byte packets, interleaving is limited, thus burst tolerance performance is degraded. In comparison, DOCSIS 1.0 frames, which do not have any interleaving, can tolerate bursts that are shorter than 30us and 13us for QPSK and 16-QAM respectively. The longest burst that could be tolerated in 64-QAM without interleaving is 7u.

Note that when extremely large noise bursts are present, they can be tolerated by reducing the baud rate (burst tolerance, $T_{BURST,}$ is increased by the factor of baud rate decrease through the decrease in R_{byte}).

We observe that the *HI-PHY Lite* system can easily tolerate bursts of up to 10 microseconds, which covers the vast majority of the noise bursts in the system. By gradually trading throughput for burst noise robustness, the system can tolerate bursts of up to 500 microseconds, which are considered to be very rare.

It is important to note that the burst robustness is proportional to the symbol rate, and it can be further improved by up to a factor of 8 by using the lower symbol rates of DOCSIS. This increases the number of upstream channels and may sacrifice MAC layer efficiency, but it provides a pragmatic solution for the rare cases of frequent occurrence of very long noise bursts (more than 100 microseconds).

Finally, we note that the TCNET4522 employs signal processing algorithms that detects noise bursts and allows improvement of the maximum burst length protection by up to a factor of two. In this case:

$$T_{BURST} = k_{BURST} \text{ x } I \text{ x } T/R_{byte}$$

Where k_{BURST} is in the range of [1,2], depending on the characteristics of the signal (e.g. its constellation) and the noise burst (e.g. its power level).

We conclude that by using *HI-PHY Lite*, the cable operator can achieve extremely high robustness to long noise bursts by using low symbol rates and/or slightly lower throughput.

Impulse Noise Performance

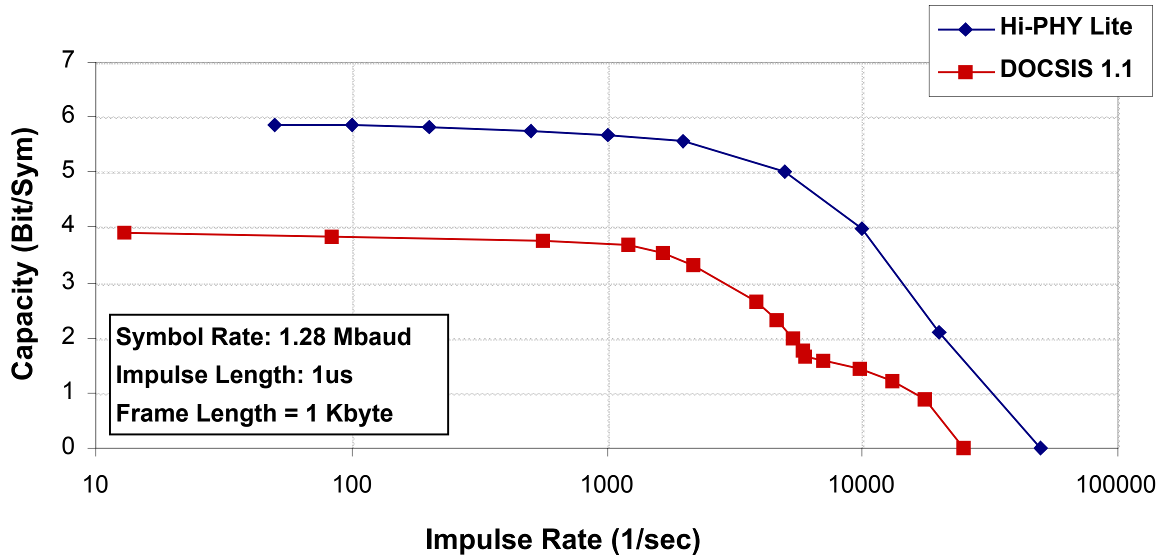
Figure 5 shows the attainable throughput of the DOCSIS 1.0 and *HI-PHY Lite* in a 1.28M symbols per second channel with 1000 bytes data packets. The noise impulses are 1 microsecond each, and the SNR is –5dB within the impulses and 25dB otherwise. The impulses appear randomly in time (Poisson distribution) and the horizontal axis of the figure is the average number of impulses per second. In this tests we have only used FEC error protection factors of T=0...10, and some improvement in performance can further be gained by using T=11…16.

We observe that the HI-PHY Lite modulation scheme can easily tolerate 1000 impulses per second and by trading data rate it can tolerate up to 25000 impulses per second. The DOCSIS 1.0 modulation scheme is inferior to HI-PHY Lite mainly due to lacking higher constellations. However, both HI-PHY Lite and DOCSIS 1.0 are capable of operating in scenarios of 1000-10000 impulses per second which are believed to represent the toughest upstream channels.

Inter-symbol-Interference

As in DOCSIS 1.1, the CM and CMTS support a T-spaced linear pre-equalizer in order to address reflection in the upstream

Figure 5: Hi-Phy Lite - Capacity vs. Impulse Rate



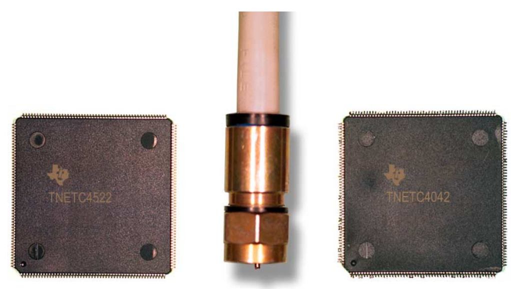
channel. While in DOCSIS 1.1 the pre-equalizer has 8 taps, in the new *HI PHY Lite* modulation scheme, the pre-equalizer was extended to 24 taps to support the larger symbol rate and the higher constellations.

SILICON IMPLEMENTATION

Figure 6 shows a picture of the TCNET4522 and the TCNET4042 chips. The TNETC4522 is a dual burst receiver that supports *two HI PHY Lite* upstream channels of up to 30 Mbps each. Its total throughput of reaches up to 60 Mbps, which translates to a significant improvement in the throughput per board area, compared to previous solutions that supported a single DOCSIS channel at up to 10 Mbps. The TNETC4522 directly samples the whole IF spectrum and the required upstream frequencies are digitally demodulated. This scheme eliminates the necessity for a tuner.

The TNETC4042 is an integrated cable modem chip, which fully supports *the HI PHY Lite* modulation scheme. The chip is backward compatible with the DOCSIS 1.0 and DOCSIS 1.1 standards, and a modem built around TNETC4042 has gained CableLabs DOCSIS1.0 certification.

Figure 6



SUMMARY

We have presented a new generation of CM and CMTS IC's which implement HI PHY Lite modulation scheme and incorporate INCA™ technology. The attainable performance of these IC's was demonstrated in this paper.

The *HI PHY Lite* specification emphasizes simplicity, multi-vendor interoperability and backward compatibility. While communication technology does offer building blocks such as TCM, Precoding etc, which could possibly enhance the performance of the system, it is our opinion that the performance gained by these enhancements would be marginal, not justifying the added complexity which would ultimately impact multi-vendor interoperability and cost.

This new technology enables significant improvement to upstream throughput allowing operators to offer subscribers services which demand greater bandwidth in the upstream such as VoIP and Video conferencing.

REFERENCES

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