Extracting Additional DOCSIS Upstream Capacity Without HFC Network Upgrades

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1. Introduction

Getting additional capacity out of a Data-Over-Cable Service Interface Specifications (DOCSIS®) system without upgrading the Hybrid Fiber Coax (HFC) plant is a constant job for network engineers. With operators deploying larger amounts of upstream (US) spectrum, it's even more important to extract the maximum capacity from this spectrum.

In this paper we will look at an often-overlooked method to add US capacity via optimally setting and dynamically adjusting the return levels of a DOCSIS system. The return level set point (RLSP) is an indirect method of controlling the modem transmitter (TX). DOCSIS systems have been historically set statically to achieve a flat radio frequency (RF) level at the input of the receiver, whether this is in a Remote PHY architecture or an Integrated-CCAP architecture. This results in the TX being adjusted by the CMTS via DOCSIS ranging[1] until its RLSP is achieved. In addition, operators have not dynamically adjusted the RLSP and have set this uniformly across all US Ports based on plant design.

This paper will explore why flipping the paradigm by having the modem TX at or near its maximum power by letting the CMTS vary the RLSP dynamically, can provide capacity benefits. All of this can be done without any work being done on the HFC plant.

We will provide a conceptual overview of why and how this approach can lead to greater capacity of the US channels by using an example to illustrate these gains on some representative HFC networks. Although our discussion and example will use a Remote PHY (R-PHY) architecture with Full Duplex (FDX) US channels, the principles can be applied to other architectures and DOCSIS 3.1 since they support higher modulation orders to fully exploit signal-to-noise gains.

2. Conceptual Overview and Plant Physics

In this section, we will first discuss the current operator practice of setting the RLSP and conceptually discuss why changing this value provides capacity improvement. A note regarding the term RLSP, as mentioned above, RSLP is an indirect method of controlling the modem's US TX power. In this paper, we will use the term RLSP and setting or controlling the modem TX power per channel to generally mean the same thing and be used interchangeably unless stated otherwise.

2.1. Current RLSP Approach

Operators today design the HFC plant, whether it is a passive plant (N+0) or with a cascade of amplifiers (N+x) to extend the reach of the RF portion of the HFC plant. By reach, we mean that the plant design has a path loss that results in nominal values at cable modems RX power of around -3 dBmV and TX power around 48 dBmV/6.4MHz for an FDX customer. This allows enough margin in the RX and TX of the modem to account for variations in drop lengths of coax cable from the tap as well as variations in home wiring. Based on these design rules (path loss), operators will set the RX level at the CMTS's burst receiver for all US Node Ports. For example, a typical value for a Fiber Deep passive architecture is 8 dBmV/6.4 MHz RLSP at the Fiber Node[2]. This value is statically configured for each US port of all the Nodes of this plant type. This results in a simple but least common denominator (LCD) approach to network configuration.

While this static one-size-fits-all RLSP setting works, it results in several inefficiencies. For example:

- TX power of modem not optimally controlled due to statically setting the RLSP for the group rather than tailored to the as-built capability of the link of each Node or Node port

- Modem TX power that is not effectively distributed on the channels that can provide more capacity
- Not accounting for modem TX power from unused (admin down) channels such that the unused total composite power (TCP) is spread to the active channels
- Plant changes over time due to environmental effects

A Fiber Node typically has 4 ports (legs) that travel in different geographical directions (North/South/East/West) to serve different streets and/or neighborhoods. It is unlikely that all the legs have equal path loss due to the variety of physical streets or even different type of neighborhoods within the serving area of the Node, e.g., Multi Dwelling Unit (MDU) versus Single Family Unit (SFU). Even in the cases where Nodes or Node legs feed the same plant type in a region of country, the path loss is not uniformly controlled. In cases where a single Node serves different plant types from each, operators still configure based on the predominant plant type of the Node and statically set the RLSP accordingly. In short, whether its path loss variance within a leg or across legs or across Node, a least common denominator setting of RLSP by operators provides room for optimization. See Figure 1, Simplified Node and HFC Block Diagram, for internal functional view of the Node.

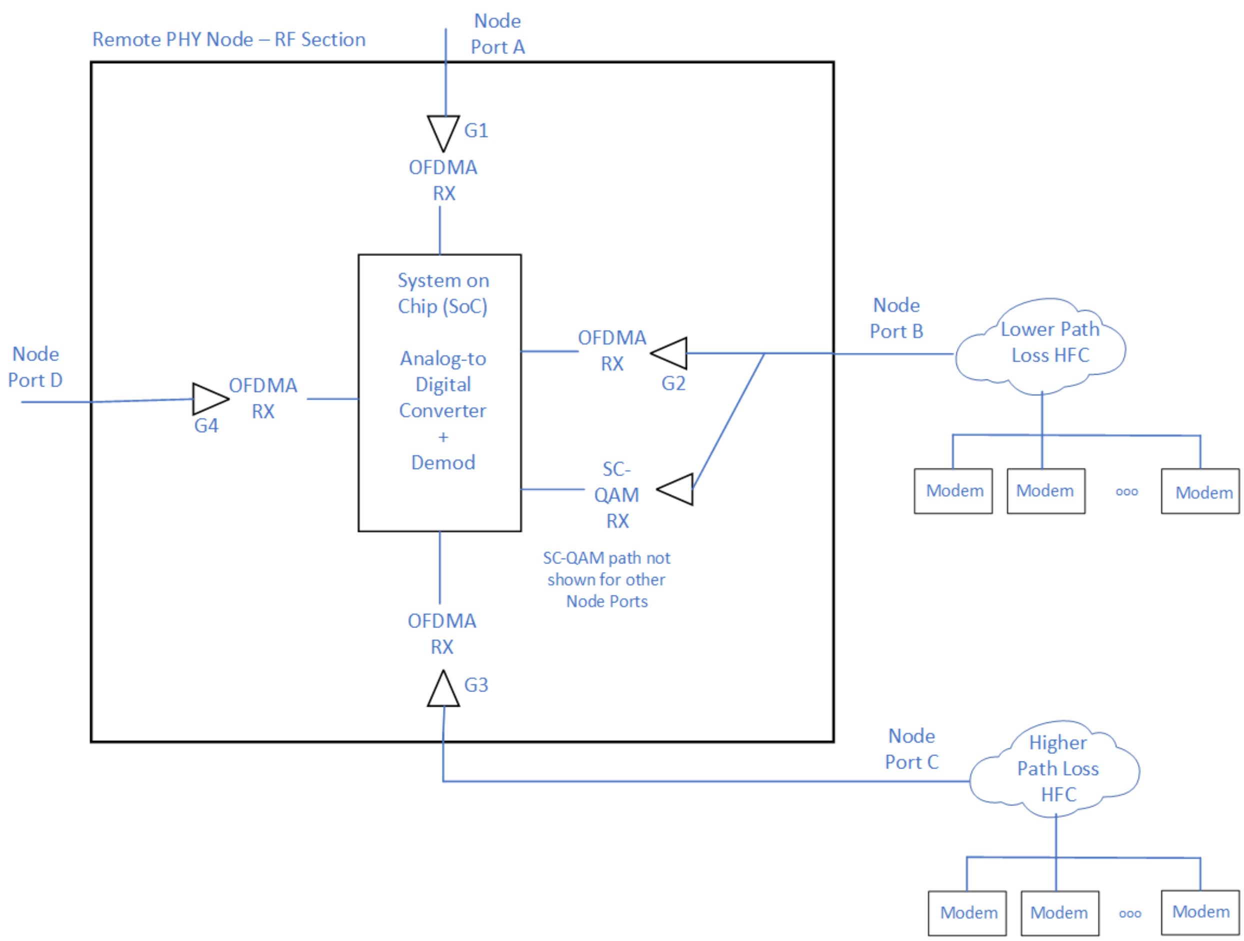

Figure 1 – Simplified Node and HFC Diagram

As an aside, in Integrated-CMTS deployments of the past, the RLSP static value of 0 dBmV in the CMTS configuration was set for all plant types. This was common practice so much so that any other value was thought to be a misconfiguration. Even today with Remote PHY deployment with the RF terminating at the Node, the value of "0 dBmV" has had to be preserved for operational practice. To preserve this operational ingrained magic value, a delta receive (RX) power (the difference between the RLSP and actual level) is used in addition to the absolute level. In addition, the range around the RLSP over which past Cable Modem Termination System (CMTS's) kept a modem ranged to keep the channel operational was +/- 6dB. This also has been operationally institutionalized, and we will discuss below how these values can and should be changed to extract capacity.

2.2. More Optimal RLSP Approach

In simple terms, we want to increase the signal-to-noise ratio (SNR) at the CMTS receiver (Node) by getting modems to transmit higher than they would by using a static flat RLSP across all the US channels. The higher the "S" in the SNR equation the higher the modulation order and the higher the capacity. This is the crux of what this paper recommends, and the remaining discussion is how to achieve this.

Using telemetry to compute the as-built path loss from each Node Port for each modem's TX channel allows us to determine how much each channel TX can be increased. This would be done algorithmically such that most of the modem's channels are transmitting near their maximum capability with adjustments made periodically to keep them at their optimal level. Looking back at Figure 1, whereas the gains G1 to G4 on the Node is based on same RLSP configured value, having a per Node Port RLSP will change the operating point gains G1 to G4 to keep the signal from that Node Port optimally within its dynamic range of the Analog-to-Digital (A/D) converter and demodulator. The G1 to G4 gains will vary due to the different path loss from the modem to the Node Port. The details of how much gain is needed from the analog side or from the digital side inside the System-on-a-Chip (SoC) or a combination of the two is handled by the SoC vendor based on the configured valued to the Node and the signal level.

Although the goal is to get all modems channels to their max transmit, this is usually not possible due to the TCP limits of the modem's transmitters. In an FDX DOCSIS system, there are two independent transmission channel sets: one for the legacy upstream channels (<85 MHz), and one for the FDX upstream channels (108-684 MHz). DOCSIS specifications defines a TCP for the FDX orthogonal frequency division multiple access (OFDMA) channels that are separate from the TCP limits of channels in the legacy band (<85 MHz). The RLSP can be set to per each type to stay with the modem's TCP limits. For example, for a FDX modem, the TCP limit is 64.5 dBmV for all FDX US channels and 55 dBmV for channels in the legacy band.

The question then arises how should the TX power (TCP) be distributed across each set of TCP limits to maximize the total capacity of the link? We can intuitively guess putting more power towards the channels with lower path loss (resistance) allows for more power to reach the receiver rather than burning up as heat.

Analytically this question has been studied in information theory literature and indeed confirms our hunch.[3] [4]. Path loss can be commuted for each channel by measuring each TX level at the modem versus the RX level at the DOCSIS receiver. This data is generally already collected today by Operational Support Systems (OSS) to help with debugging of partial service conditions.

Using the water-filling approach results in the plot like what is shown below in Figure 2, System Performance Metrics. Refer to paper by our colleague Dr. Richard Prodan for details on analytical approach to solve for each channel's TX power in cable systems.[5]

From this we see that the Node RLSP and RX level is down tilted as opposed to flat to cause the modem's channels US TX to be down tilted also, e.g., higher modem TX for the lower frequency channels. Each red step is due to the 6 OFDMA channels TX power being controlled via RLSP.

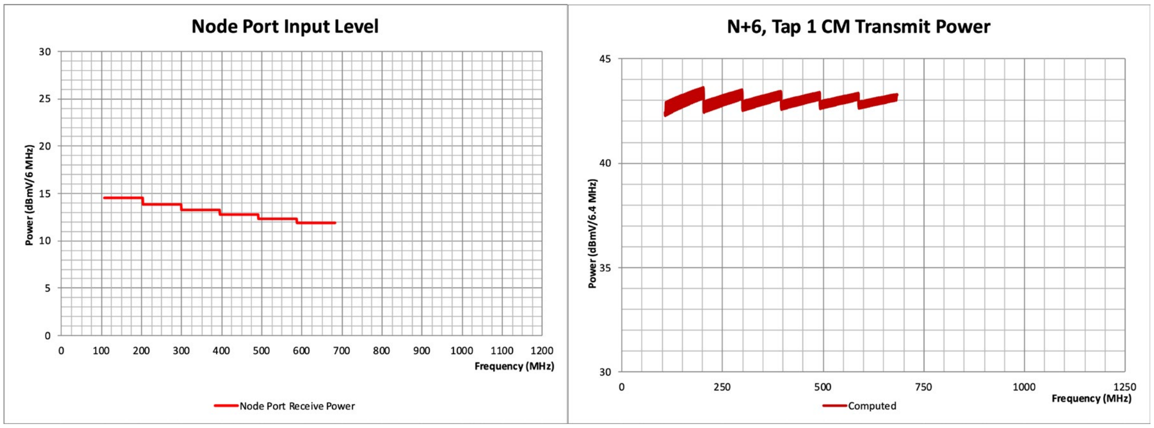

Figure 2 – Node RLSP and Modem TX Power via Water-filling

As mentioned, the modem TX control should be done dynamically in two ways: 1) as part of DOCSIS ranging 2) as part of RLSP settings to increase the SNR beyond the ranging power target. Such a closed loop system will need to continuously evaluate several metrics to make decisions on how to vary the modem TX. A typical system would collect the modems TX power per channel, the actual RX level at the CMTS receiver, SNR per channel per modem at the Node, and modem to Node leg mapping. See below for details.

The benefits of higher SNR resulting in higher capacity can be realized in DOCSIS 3.0/3.1 networks, however, in DOCSIS 4.0 networks that have a much higher amount of US spectrum and modulation orders, the multiplicative effect on capacity will be much greater. DOCSIS 3.0 with single carrier quadrature amplitude modulation (SC-QAM) only channels with limited modulation orders (64-QAM max) and sub-split architectures (US limited to ~42 MHz) will have the least benefit from the methods advocated in this paper and unlikely to justify the complexity of doing the things noted in this paper.

2.3. Elements of A Closed Loop System to Optimize Capacity

Figure 3, Closed Loop Optimized TX System describes the basic elements of a system that can be used to increase capacity by optimizing the modem TX power. Starting from the left side of the diagram going clockwise, several stats are leveraged that have been collected from modems and the CMTS receiver (Node). These are stats that operators typically already collect and store for use by other Back Office applications. The CMTS Core and Node perform all DOCSIS functions, with the Node terminating the RF US signals in a Remote PHY architecture. Next are two paths from the Node out towards the customer. One path has higher path loss than the other. Note the CMTS receiver is part of the Node in an architecture and terminates the RF US signal.

Once the TX Analysis functional block computes the new RLSP and modem TX setting, it passes the values to the Profile Management Application (PMA) block. This block then applies the setting to CMTS Core/Node. Once the new settings are running, the PMA triggers a new Receive Modulation Error Ratio (RxMER) measurement via a Probe frame and computes the new bit-loading (modulation order per OFDMA subcarrier) based on the updated RxMER values from the DOCSIS receive power at the node. RxMER is an equivalent to SNR in a digital system. The PMA system already does the functions of collecting RxMER values and setting bit loading but now factors in RxMER improvements from the change in modem's transmit power. See the PMA Technical Report[6] for details on how it works to increase capacity by continuously optimizing the bit loading.

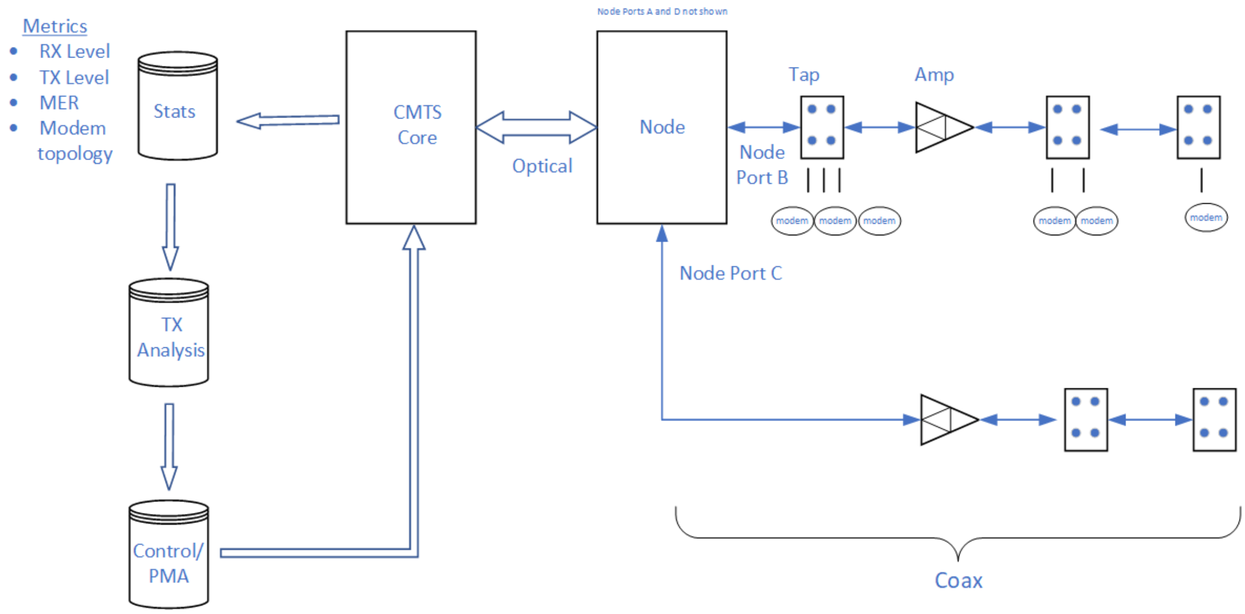

Figure 3 – Closed Loop Optimized Modem TX System

At a high level, the TX Analysis function computes the new RLSP, and modem TX setting based on the following procedure:

- Get the list of all the modems connected to each Node Port as the optimization is done per Port
- Get each modem's TX and RX power per channel to compute the as-built loss and not the design guideline
- Determine the optimal RLSP for each RF channel based on the Node Port modem group path loss to allow Node to adjust RF gains per Port, e.g., the gains G1 to G4 shown in Figure 1, Simplified Node and HFC Diagram
- Compute per modem the optimal allocation of it's transmit TCP to be distributed to the active channels that will increase capacity per water-fill algorithm
- Pass settings for the RLSP and the modem TX power to the Control/PMA block

The group path loss can be determined with simple arithmetic averages or weighted averages that push the mean higher. This is used to get each modem to transmit at its maximum by setting the RLSP as high as possible. Note that by design some percentage of modems will be below the target RLSP and leverage the dynamic range of the CMTS RX (Node) to keep the channel working. We will discuss the need to expand the DOCSIS ranging window to keep these modems working.

3. Example System and Future

In this section, we will describe how the above system works with a hypothetical example with numbers from lab results and simulations. This will hopefully better illustrate the concepts presented in this paper to achieve US capacity gains. We also discuss how to mitigate some potential issues when modems lack the transmit power to fully hit the Node Receiver at the RLSP.

3.1. Example System and Lab Results

The performance improvement that can be gained by using non-uniform RLSP set points is illustrated with an example using a Node Port pair of an FDX D4.0 node.

In this example, the FDX US is activated over the 108-684 MHz band, with six 96MHz OFDMA channels occupying the 576 MHz of FDX spectrum. On this node, Port C is experiencing a network loss that is 8 dB higher than Port B being driven by the node. In this example, both ports were experiencing the same level of echo, resulting in the same total echo power at the FDX receiver. The only difference between the two Node Ports is the higher path loss that a modem would experience if connected through Node Port C.

Port C, with its higher path loss, has the port RLSP configured for –7dBmV/1.6 MHz. The path loss experienced by the modem that is connected through Node Port C has resulted in a modem FDX band TCP of +62.3dBmV, close to the maximum RLSP you would want to provision for this port. The resulting wideband probe RxMER result for an FDX modem connected through Node Port C is shown in Figure 4.

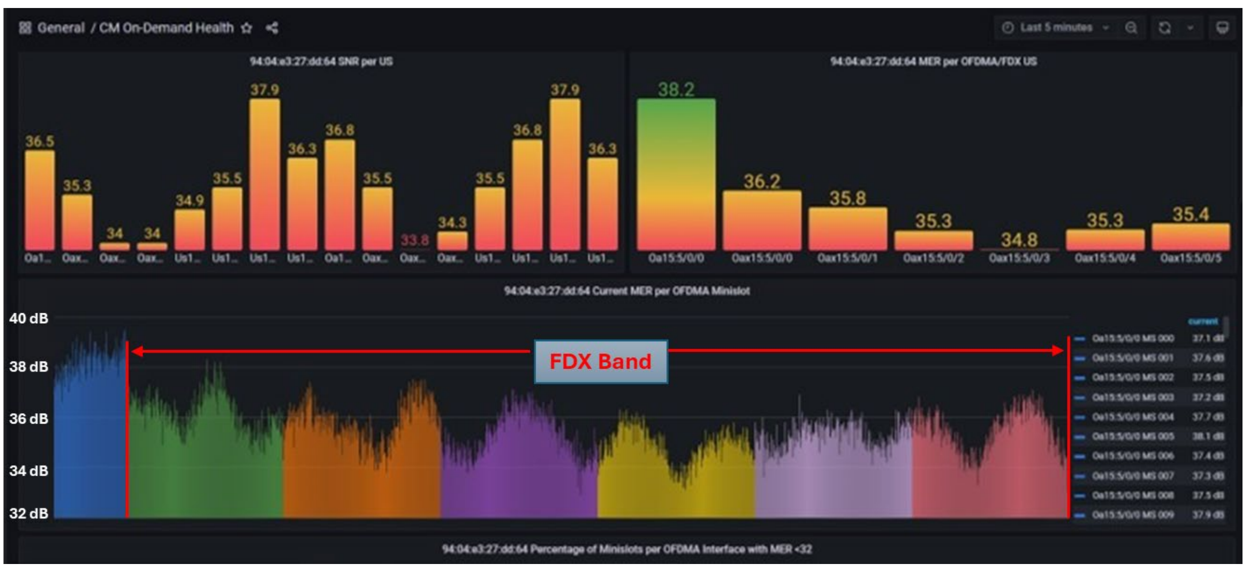

Figure 4 – Port C Wideband OFDMA MER with Uniform RLSP Configuration

The above plot shows that the wideband probe RxMER supports uniform 1KQAM bit loading across the entire FDX band for modem connection through Node Port C. Note the top graph is RxMER per channel while the bottom graph is RxMER per mini-slot. If uniform-RLSP set points were employed, then modems connected through Node Port B would also be operating at a RLSP of –7dBmV/1.6 MHz, even though the lower path loss on Port B could support connecting modems with a higher port RLSP setting. This lowest common denominator approach to RLSP configuration would result in 1KQAM bit loading on node Port B as well, due to the FDX band OFDMA mini-slot RxMER ranging from 34-36 dB.

Using a non-uniform RLSP approach, Node Port B was then reconfigured to +2dBmV/1.6 MHz. Since the path loss on this port is significantly lower, the modem connected through this port was able to bond the FDX band OFDMAs with a transmit TCP of +62.4 dBmV. Note that the RX power at Node Port B is 9 dB higher than Port C as would have been the case if a uniform RLSP approach was used.

The resulting wideband probe RxMER for an FDX modem connected through Node Port B is shown in Figure 5. The RxMER values have measurably improved to a range of 41-43dB. At this RxMER range, uniform bit loading at 2KQAM is easily supported when connecting through Node Port 2. Due to employing a non-uniform RLSP approach, the ratio of echo power to US burst power was reduced on Port B, increasing the US SNR on this port, and leading to greater throughput capacity on Port B.

Figure 5 – Port B Wideband OFDMA MER with Non-uniform RLSP Configuration

3.1. System Issues and Mitigation Methods

While we have been discussing the method of adjusting the modem transmit power level to its maximum, there could be some percentage of devices that cannot meet the RLSP by such a wide margin that the channel becomes inoperable, i.e. goes into partial service. To address this concern, widening the range over which modems can stay ranged and registered with CMTS Core is needed.

As noted earlier, historically CMTS have had a +/- 6dB window around the RLSP before the CMTS stops providing ranging opportunities. This magic value was likely due to early DOCSIS specifications and implementations of the past. In our experience from lab and field testing, channels can work well below the typical –6dB below RLSP to –9dB or lower. This is due to a couple of factors. First, the R-PHY architecture has an input level much higher than 0 dBmV levels. Second, the current Node receiver's dynamic range and improved fidelity to maintain high modulation orders of 512-QAM or better even at such low levels below the RLSP.

3.2. Future Software Changes to CMTS Core and Back Office Systems

Software Changes to the CMTS and Node will be required to implement some of the methods discussed in this paper.

- Per leg RLSP configuration controls are typically not available today in the CMTS and Node
- Direct TX control per modem (or group of modems) per channel in the CMTS is not available today - this does not rely on the RLSP, but the modem directly told to offset its power via DOCSIS range response messages

To restate the above points, while in this paper we have noted that modem TX is indirectly controlled by setting RLSP, direct modem TX control is also needed to fully uncover all the latent capacity. The CMTS controls the modem TX today to get the actual RX difference to RLSP to zero. But the RLSP can be changed to get the modem's TX channel power higher when the modem TX is at or below the TCP limit. Both methods, indirect and direct methods work together to optimize capacity. The indirect RLSP control to the Node is to internally adjust its dynamic range and front-end gain settings. The direct RLSP control method is to down tilt the individual modem TX power as governed by the water-filling algorithm.

In addition, although PMA implementation exists, they currently do not control and factor in modem TX adjustments as has been discussed in this paper. Augmentation of PMA functionality, along with the development of TX Analytic engine, will be needed to fully realize the capacity gains discussed in this paper.

4. Conclusion

Today Cable Operators set DOCSIS CMTS systems to equalize the RF signal at the upstream receiver and let the modem transmit power level vary as needed to achieve this. In this paper, we provided a conceptual understanding of why using a flat static value for Node receive power level (RLSP) to control the cable modem transmit power level leaves room for optimization. Boosting the "S"(signal) in the SNR equation from each modem allows higher bit loading and hence more capacity. This paper provides an intuitive explanation of why a cable modem's finite TCP is best used by allocating more power to the less attenuated channels. We explored a couple of different methods to achieve this. We discussed the need for future work on the exact algorithm for setting modem TX power optimally and how often the tuning parameters need to adapt in a future PMA 2.0 system. All these changes do not require any work on the HFC plant.

Abbreviations

A/D	analog-to-digital
CMTS	cable modem termination system
dBmV	decibel millivolt
DOCSIS	data over cable service interface specifications
FDX	full duplex
HFC	hybrid fiber coax
Hz	hertz
LCD	least common denominator
MDU	multi dwelling unit
MER	modulation error ratio
MHz	megahertz
OFDMA	orthogonal frequency division multiple access
OSS	operational support systems
PMA	profile management application
RF	radio frequency
RLSP	return level set point
R-PHY	remote physical
RX	receive
SCTE	Society of Cable Telecommunications Engineers
SC-QAM	single carrier quadrature amplitude modulation
SFU	single family unit
SoC	system-on-a-chip
TCP	total composite power
TX	transmit
US	upstream

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