Now Possible: 100 Mbps Upstream Tiers in 5 - 42 MHz HFC Access Networks

A Technical Paper prepared for the Society of Cable Telecommunications Engineers

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Overview

DOCSIS® 3.1 Gigasphere technology, combined with advancements in upstream (U/S) link performance, will enable tier offerings previously thought to require expensive, lengthy, and disruptive electronic upgrades of the coaxial portions of HFC access networks. This paper will present and explain various potential DOCSIS® 3.1 and HFC access network operating configurations. Many of these configurations are likely to provide sufficient capacity for a highly-penetrated U/S tier offering of 100 Mbps, without the need for HFC access network spectrum split changes or wholesale cable modem (CM) change-outs.

DOCSIS® 3.1 Gigasphere technology is the primary enabler of this significant U/S speed improvement. The presented configurations will leverage four fundamental capabilities of DOCSIS® 3.1 not available in previous DOCSIS® versions:

- Much higher modulation orders for greater spectral efficiency, to 4096-QAM
- Advanced error correction coding and other enhancements to add robustness
- Multiple operating profiles to reduce the need for CNR headroom margin
- FaTDMA (frequency *and* time division multiple access) – to allow a new CM to use the entire spectrum for transmission bursts, even with legacy CMs present

A non-technical discussion of the relationship between U/S bit rate capacity, tier rate offering capability, and the associated service group traffic factors is included. An argument in favor of more aggressive tier offerings (as a portion of total capacity) is presented, including both initial and ongoing operational recommendations supporting this approach.

The U/S optical link, be it digital or linear analog, is well known as an HFC access network noise performance bottleneck. To open this bottleneck, U/S optical link technologies will be discussed that are capable of providing the critical dynamic range needed to achieve the full potential of DOCSIS® 3.1 Gigasphere technology.

HFC access networks come in many shapes and sizes. Presented here is a simple yet adaptable HFC U/S access network noise performance calculator that combines CM MER (modulation error ratio), optical link CNR, and coaxial network amplifier CNR. Access network CNR performance results will be discussed for a range of model variables to foster an understanding of the circumstances under which a 100 Mbps tier offering becomes possible. A copy of this MS Excel® model is embedded in this document to allow the reader to enter their own values and view the results at their leisure.

Coaxial network CNR limits use of high modulation orders in DOCSIS® 3.1. Example results from the noise performance calculator are utilized to model DOCSIS® 3.1 U/S network bit rate capacity for selected HFC access network configurations. This capacity model simulates DOCSIS® 3.1 operation across the 5-42 MHz U/S spectrum. The resulting potential tier rate offerings associated with predicted capacities are presented both as graphical model outputs and in tabular form.

A brief discussion of costs and a perspective on other operational factors is also provided.

It is assumed that the reader is familiar with the HFC access network architecture in common usage by North American cable operators, and the use of DOCSIS® technology to provide high speed internet service.

Perception and the New Reality

Since the advent of DOCSIS® 3.0 and U/S channel bonding, it has been generally regarded that the maximum possible U/S tier rate offering over 5-42 MHz sub-low reverse HFC access networks is limited to speeds on the order of less than 50 Mbps, for a tier that can be competitively priced and therefore widely subscribed to. Conventional wisdom is that, due mainly to the hostile nature of the HFC sub-low U/S spectrum, the maximum tier rate should be limited to one-third of the aggregate physical layer (PHY) bit rate of all bonded DOCSIS® carriers combined. This is generally regarded to result in a customer experience whereby during busy hour, 80 to 90% of consumer speed test attempts will produce the advertised or higher tier rate. Such policies have contributed to the excellent reputation and credibility that cable operators currently enjoy with respect to internet speeds offered.

For example, a common end-state channel plan with DOCSIS® 3.0 U/S bonding may consist of three each, 6.4 MHz-wide 64-QAM carriers (SC-QAM) plus a 3.2 MHz, 16-QAM carrier (for legacy CM connectivity). Such a combination yields an aggregate PHY layer rate on the order of 80 Mbps; when the one-third rule is applied, the current round of tier offerings of 25 to 30 Mbps makes sense. This tier rate also allows for a significant population of CMs to share the aggregate rate resource. That population is often limited by voice telephony penetration rates, since voice telephony traffic is a uninterruptible streaming service and consumes a known capacity per call. For instance, well-understood traffic statistics limit us to approximately 150 telephone customers or fewer per service group; if a given service group attains a 20% (of homes passed) telephony penetration, this means that the group size is limited to a ceiling of 750 homes passed. This serves to restrict the number of HFC U/S node connections that may be combined in the distribution hub. If two nodes pass 375 homes each, then only two nodes may be combined before reaching this practical telephony customer limit. In practice, typical service group sizes are lower (often much lower) than this limit due to the difficulty in exactly attaining the desired traffic levels when faced with fixed-size nodes where video traffic constrains node recombination in the D/S direction.

This telephony-based recombination limit has the serendipitous advantage of limiting the impact of noise and ingress interference on a given CMTS (now CCAP) U/S receive port.

Tiers vs. Capacity

Tiers are what our customers buy. Capacity is the number of bits we can pull into an U/S CCAP port per unit time (aka PHY rate).

The premise of this paper is that 100 Mbps tier rate offerings are possible. Only in the very most optimistic access network conditions, even with a 100% population of DOCSIS® 3.1 CMs, no legacy settops, etc. would PHY rate capacities in excess of 300 Mbps be possible in 5-42 MHz spectrum. Such performance levels would be unmaintainable in this still-hostile region. So how is it that we suggest that a 100 Mbps tier is attainable?

Let's take a look at D/S DOCSIS® offerings. In the D/S, bonded DOCSIS® 3.0 service today may span as many as 16 (6 MHz) channels; even higher bonded channel counts are on the way. A 16 channel offering, assuming a 37.5 Mbps per-channel PHY rate, should be good for a 300 Mbps D/S tier. The rule commonly applied to D/S service is tier rates can be as high as half of the PHY rate (2:1 rule), provided the number of CMs (therefore number of combined nodes on a CCAP port) is kept to a reasonable level. With higher numbers of CMs, the rule must be relaxed somewhat, but 2:1 is considered an upper limit for a competitively-priced and therefore highly penetrated top tier. The above mentioned speed test rule would also apply to the D/S as a gauge of success.

It should be understood that these rules are generalities based on experience and not hard mathematical limits. Speeds will vary; there are many factors that cause variations over both time and across locations. Tested service speeds can and will peak higher than the advertised tier rate. At non-busy times, this will be common. How much higher depends on numerous factors and controls.

A key assertion in this paper is that future useable *U/S* PHY:tier ratios will be similar to the *D/S* PHY:tier ratios in common use today, provided the top tier offerings are of similar speed. Our current experience with high speed U/S tier offerings is limited, and what experience we do have is based around top tier rates in the 10 Mbps to 25 Mbps class. In this paper we are proposing a top tier of 100 Mbps, which more closely resembles (in many cases exceeds) current D/S tier offerings. We also believe it is reasonable to expect that the traffic mix of a 100 Mbps tier, including applications used and the distribution statistics of packet sizes, will more closely resemble D/S usage patterns than do today's top U/S tiers.

Bottom line? A 100 Mbps tier will require a 200 Mbps PHY capacity. This assertion is used in this paper as a baseline requirement.

In order to maintain a high standard of customer experience, we recommend that when attempting such aggressive top tiers, continuing careful traffic monitoring and a planned traffic remediation response (service group segmentation) both are in place.

What is Needed: 100 Mbps Tier Enablers

With the case for an aggressive PHY to tier ratio behind us, what else do we need to enable a real 100 Mbps tier offering? Here is a short list:

DOCSIS® 3.1 – What It Does

The installed CCAP platform must have D 3.1 capability, and must be capable of both FaTDMA mode in software, and high modulation order reception in hardware; details on both coming up. Early D3.1 CCAP implementations may be missing one or the other of these prerequisites. This is a fixed cost, as it is needed in the entire market where the tier will be offered. The supplier community can provide guidance in this area.

The real beauty of this approach is that these much higher tier rates (even if less than 100 Mbps) can be offered upon the very first arrivals of D3.1 CMs. Unlike in certain D/S DOCSIS® 3.1 deployment scenarios, it is not necessary to attain a critical percentage penetration of new CMs. The very first CM in the field will operate at the desired tier rate, and when customers subscribe, we can deliver. This capability is by virtue of something called Frequency and Time Division Multiple Access (FaTDMA).

Higher modulation orders enable more bits per cycle (bits per second per Hertz), while FaTDMA mode allows D3.1 CMs to burst using the entire spectrum (on top of legacy DOCSIS® channel space) while the CCAP controls how legacy D2.0 and D3.0 CMs wait their turn to transmit. One suggested method to accomplish this is for the CCAP scheduling software to issue what have been referred to as "dummy grants." These dummy grants would in effect be transmit opportunities reserved for fictitious legacy CMs, when in fact the D3.1 CMs would instead be instructed to burst during these grant times. A graphic illustrating this mode is included - see Figure 1.

Besides FaTDMA and higher modulation orders, DOCSIS® 3.1 provides two other critical improvements over its predecessors: it is much more robust in the face of both noise and interference, and it is capable of being safely operated much closer to the CNR (MER) "crash point" by virtue of a feature called profiles.

The High CNR HFC Access Network – How It's Done

Note: In this paper, it is assumed that MER and CNR can be combined using power addition ($10*Log_{10}$). For our focus on AWGN as the primary impairment this assumption will serve our purposes.

We will spend a good amount of space and time on this issue here; it is not only critical to our goal, but often misunderstood. The main performance limiters are:

1) The optical link (or whatever facilities are used to backhaul bits from the outdoor node to the distribution hub)
2) The network of coaxial amplifiers
3) Spectral hostilities

The most important element among above limiters is a better node to hub connection, either in the form of high performance linear optics, or some type of baseband digital optics connection such as a Remote Physical Layer (R-PHY) node. For improvements in the coax network, since DOCSIS® 3.1 specifies a much higher CM transmit power requirement it may be possible to leverage that increase through careful access network alignment. This will improve both thermal CNR and signal to interference ratio at the same time.

Spectral hostilities are well known in the 5-42 MHz passband. We don't assume that DOCSIS® 3.1 alone will be sufficient to overcome this problem; it will be necessary to continue our already underway access network hardening efforts, including such activities as aggressive leakage repair and proactive maintenance of various sorts. This cleanup will not be a one-time activity, but will involve measured but sustained incremental operating cost. The side effect will be happier customers, as it is expected to produce reliability and availability benefits in the D/S as well making it a good investment. Most operators have already recognized this and have started down that road.

Service Group Size Controls

We acknowledge the critical nature of traffic engineering to our goal. Traffic engineering is an ongoing task, involving both monitoring and remediation. Our experience with traffic engineering is that when a new service is first deployed, there tends to be a flurry of activity while we sort things out; once this phase is over, traffic patterns will calm down and change only slowly. A benefit to the discipline of traffic-engineered segmentation is that when service groups are split, the number of connected amplifiers decreases, as does the amount of access network subject to interference. Both effects improve performance. It is our belief that if we are sufficiently aggressive with traffic engineering, performance will follow, not vice-versa.

A traffic-engineering approach to service group sizing will insure that capital spending is tied to the behavior of the customer base, rather that starting out as a fixed cost where investment may be stranded waiting for business that never shows up. Traffic engineered capacity allows greater per-unit spending, since overall spending is limited by demand. This has beneficial effects on both quality of service and maintainability (op-ex) by virtue of a continuing reduction of the average failure group size. In most cases where multiple optical links are being combined prior to connection to the CCAP input port, additional ports must be deployed to eliminate noise addition of multiple optical links. This investment is similar to and will provide most of the benefits that traffic-based service group size reductions provide.

Details of DOCSIS® 3.1 Operation

DOCSIS® 3.1 presents a valid opportunity to the self-help publishing community to think of training and tutorial production as a revenue stream. There are multiple places to get DOCSIS® 3.1 information at this confab, and I will not attempt to duplicate or replace these high quality resources. However, since the goal of this paper is so heavily dependent on the advancements of DOCSIS® 3.1, a fair amount of background material is appropriate and called for.

While DOCSIS® 3.1 builds on the foundation of DOCSIS® 3.0 in nearly every other way, the physical layer represents a radical departure. DOCSIS® 3.0 U/S uses two methods, S-CDMA which is sparsely deployed, and SC-QAM ATDMA, which is the basis of nearly all high speed internet service in North America. DOCSIS® 3.1 is backward-compatible, in that a CM must be capable of transmitting legacy SC-QAM channels by themselves, at the same time that other CMs transmit D3.1 channels, or even with bonding between the two types of channels in the same CM transmission.

OFDM, OFDMA, and TDMA

This legacy requirement somewhat obscures the fact that at its core, D3.1 is built on OFDM, a technology in wide use in the cellular telephone industry as well as many other places. OFDM stands for Orthogonal Frequency Division Multiplexing. In OFDM, payload data is “multiplexed” across multiple narrow subcarriers. D3.1 allows either 25 kHz or 50 kHz subcarrier spacing. The orthogonality of adjacent subcarriers serves to reduce intercarrier interference and facilitates tight packing. There are lots of subcarriers; for instance, 1480 25 kHz subcarriers or 740 50 kHz subcarriers could theoretically fit into the 5-42 MHz spectrum.

OFDMA stands for Orthogonal Frequency Division Multiple Access. This describes a system where multiple CMs are allowed to transmit at the same time using different groups of OFDM subcarriers (frequencies).

TDMA stands for Time Division Multiple Access, and describes a system where multiple CMs take turns transmitting using the same frequencies.

FaTDMA, as previously introduced, describes a system with aspects of both FDMA and TDMA system operation. DOCSIS® 3.1 enables and requires FaTDMA operation in the CM, although it does not mandate specific implementations on the CCAP side.

D 3.1 Channel Basics

A DOCSIS® 3.1 OFDMA U/S channel consists of a group of subcarriers, organized into minislots (see next section), with a settable bandwidth and spectrum location. CMs are required to implement two OFDMA channels capable of up to 96 MHz each. CMs are also required to implement DOCSIS® 3.0 SC-QAM channels; the combination of the OFDMA channels and SC-QAM channels is called the Transmit Channel Set (TCS). OFDMA channels are required to be agile from 5 MHz to 204 MHz, although CM implementation may be limited to a lower top band edge, as low as 85 MHz.

Channel widths are settable; with 25 kHz subcarriers, from 6.4 to 96 MHz; and with 50 kHz subcarriers, from 10 MHz to 96 MHz.

Any number of subcarriers may be excluded within an OFDMA channel between minislots but not within a minislot. This allows the system to reserve spectrum for legacy channels or narrowband interferers.

D 3.1 Minislot Basics

A minislot is a group (400 kHz worth) of subcarriers, transmitted for an OFDMA frame duration of (k) OFDM symbol times. (k) can take on a value in the range of 6 to 16 symbols. A minislot can be thought of as being rectangular in shape; in the vertical direction is the frequency axis, represented by a stack of subcarriers. In the horizontal direction is the time axis, represented by a number of symbol times that together constitute an OFDMA frame. During a frame, multiple CMs may be allowed to transmit, or the entire frame (or more) may be granted to a single CM.

A CCAP to CM grant is a transmit opportunity. A grant may be as small as a fractional minislot or may span many minislots in multiple consecutive frames.

Since minislots are uniform in bandwidth, they will contain either 16 ea. 25 kHz subcarriers or 8 ea. 50 kHz subcarriers.

Pilot subcarriers and complimentary pilot subcarriers are contained in each minislot. The quantity and locations of these pilots are selected by the CCAP from one of fourteen pilot structure patterns, somewhat dependent on the choice of subcarrier spacing. The purpose of using higher pilot densities is that is makes the transmission more robust against interference, but trades off efficiency to accomplish this.

Transmission Profiles

A profile can be thought of as an instruction set describing per-minislot bitloading and pilot patterns to be used in a transmission. Up to four profiles may be defined in each of the two OFDMA channels for a total of eight profiles. Profile descriptions are downloaded and stored in the CM. When a CCAP issues a grant it conveys the associated channel profile number; the CM then uses that profile to produce a transmission.

Each CCAP U/S port can have a unique set of eight profiles. A CM can change profiles on a per-grant basis if directed to do so. The construction of profiles may become automated based on subcarrier error rates and other parameters. This capability is potentially very powerful in that it allows transmissions to adapt to link conditions. If a particularly aggressive profile is used for a grant, and it is discovered that the FEC is working hard, the next grant may call for a less aggressive profile to be used. This allows a CM to transmit close to the crash point of the available link CNR.

In previous DOCSIS® versions, channel parameters were fixed; many dBs of noise safety margin were required to prevent errors as channel quality varied over time. In D3.1, profiles can be used for that purpose, allowing use of aggressive bitloading when the link is good, and fallback bitloading if it degrades. This capability has been referred to as the ability to "mine the margin."

Another interesting capability of profiles is the ability to set up profiles for specific passbands. For instance, if a node has a mix of 5-42 MHz and 5-40 MHz sections, specific profiles can address CMs in these sections, thus avoiding the need to abandon the uppermost 2 MHz because not all CMs can use it.

Bitloading Basics

Bitloading can be defined as applied subcarrier modulation order. Examples of modulation order are 16-QAM, 64-QAM, and 256-QAM. This is sometimes referred to as modulation density or QAM order. U/S bitloadings from BPSK to 4096-QAM are allowed in DOCSIS® 3.1 (BPSK is reserved for pilots only, and there are certain restrictions on orders below 64-QAM). The CM MUST support all bitloadings, while the CCAP MUST support bitloadings through 1024-QAM and SHOULD support bitloadings of 2048-QAM and 4096-QAM. 4096-QAM is ultra-efficient but is difficult to use as we shall see coming up.

Non-square lattice bitloadings are included in these requirements. Examples are 32-QAM, 128-QAM, and 512-QAM. This capability allows a profile to be more closely tailored to spectrum-location-specific link conditions, as it enables an approximate 3dB CNR granularity of adjustment to the link. 2048-QAM is particularly valuable as will be subsequently shown.

All subcarriers of the same type (data, pilot, complimentary pilot) in a minislot must use the same bitloading. A transmission profile may include minislots with a mix of different bitloadings, for instance to tailor robustness to specific spectrum locations. Since it is expected that DOCSIS® 3.1 transmissions will have uniform power spectral density across all minislots, relative level differences between channels are not usable to provide enhanced CNR to high bitloading cases. Since there are so many different bitloadings to choose from, this is inconsequential; instead of raising level, we lower bitloading when CNR is less than ideal.

FaTDMA Mode

When DOCSIS® 3.1 is first launched, the U/S spectrum will typically be filled with legacy DOCSIS® channels, in all the best spectrum locations. While DOCSIS® 3.1 minislots are narrow and can be sandwiched in between these channels, and D3.0 and D3.1 channels can be bonded together for a single CM transmission, there are several issues limiting the utility of this approach in 5-42 MHz access networks:

- DOCSIS® 3.1 requires a minimum of U/S spectrum to operate (6.4 MHz for 25 kHz subcarriers, 10 MHz for 50 kHz subcarriers), though this does not need to be contiguous
- Frequency guard bands must be established. OFDM requires good sidelobe transmission performance and does not tolerate high powered adjacent channels on top of sidelobes.
- The spectrum locations that remain after legacy channel allocations are less clean and will typically require use of lower bitloadings (e.g. below 15 MHz)
- Bonding between these limited spectrum additions and DOCSIS® 3.0 SC-QAM carriers will only marginally increase the overall PHY capacity. During the writing of the specification bonding was nearly made optional because of its limited usefulness.

FaTDMA mode is designed to address these limitations. In FaTDMA, the CCAP scheduling program will schedule legacy CM transmissions in a manner that provides one or more open OFDMA frames for exclusive D3.1 transmissions. During this exclusive frame time, one or more D3.1 CMs will transmit, using the entire spectrum (less, of course, any exclusions such as the settop return carrier and known narrow band interferers such as the CB radio band). Very high efficiencies are therefore possible, as D3.1 can take advantage of all of the advanced capabilities built into it. The CCAP can potentially be configured for very high burst rates from D3.1 CMs using this mode of operation. As populations of D3.1 CMs increase over time, FaTDMA also enables multiple CMs to transmit in the same frame, for highly efficient transmission of small grants.

Figure 1. illustrates how FaTDMA mode operates. In this example, legacy CMs transmit during T1, 3 & 5, while D3.1 CMs enjoy access to full-spectrum burst capability during T2, 4, and 6.

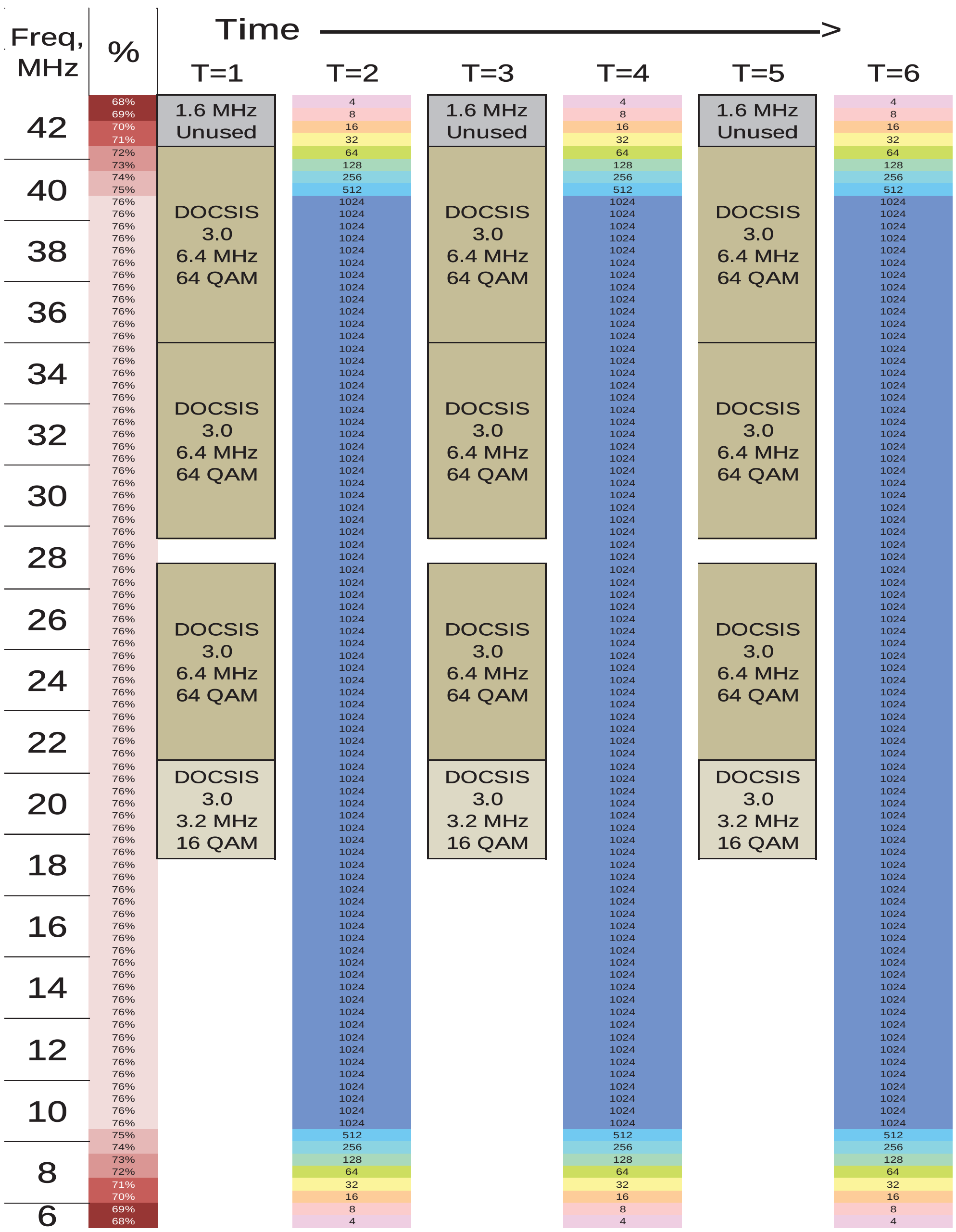
Figure 1:

FaTDMA Operation

Shown Using Capacity Model Format

Notes:

The horizontal axis shows time, while the vertical axis denotes frequency from 42 MHz to 5 MHz. Each highlighted cell represents a 400 kHz minislot. The number in the cell is the bitloading. The % column shows the approximate PHY efficiency of the minislot, comparing net PHY throughput to the raw theoretical bitrate for each particular bitloading. Efficiency is primarily a function of the selected pilot pattern and FEC overhead. In these figures, more robust pilot patterns are associated with lower bitloadings, although this is not a requirement and may not be the ideal configuration.



CCAP and CM Performance Requirements

CCAP receiver performance and bitloading are interrelated, as shown in Table 1 below. In the D3.1 specification, a CM MUST support all bitloadings in the table, while the CCAP MUST support BPSK through 1024-QAM, and MAY support 2048-QAM and 4096-QAM.

The CCAP is required to be capable of receiving a signal at the bitloading shown when the signal contains the level of noise listed, while producing a packet error ratio (PER) of 1 in 1*10^-6 or better.

The received signal is specified to include both the CM MER contribution and the link CNR contribution. If multiple CMs transmit during the same OFDMA frame, the received CNR will also contain out-of-band spurious noise contributions from multiple CMs

Modulation order (bitloading)	DOCSIS® 3.1-i02 required CNR
BPSK (pilots only)	8.0 dB
QPSK	11.0 dB
8 QAM	14.0 dB
16 QAM	17.0 dB
32 QAM	20.0 dB
64 QAM	23.0 dB
128 QAM	26.0 dB
256 QAM	29.0 dB
512 QAM	32.5 dB
1024 QAM	35.5 dB
2048 QAM (CCAP "should")	39.0 dB
4096 QAM (CCAP "should")	43.0 dB

Table 1. DOCSIS® 3.1 CCAP Required Performance vs. Bitloading

Taming the Hostile 5-42 MHz Spectrum - DOCSIS® 3.1 Tools

It is well known that the 5-42 MHz spectrum is fraught with issues and problems. For example, international shortwave with transmitting antennae sometimes close to our coax network, low cable losses that make it sensitive to return loss degradation causing reflections and echo, delay inequalities at both ends, impulse noise at very high power levels below 15 MHz, hum modulation much worse than at higher frequencies… the list goes on and on. D3.1 provides a great toolset to help with these difficulties.

Linear distortions out of scope
While D3.1 pre-equalization and cyclic prefixes are provided to counter linear distortion in the received signal similar to D3.0, those tools are considered out of scope in this paper. It is assumed that they do their jobs well, and that linear distortions such as echo, reflections, group delay, and channel tilt that are so severe that they cannot be fully compensated for will be promptly repaired. CableLabs offers an excellent software product developed by their proactive network maintenance group that is a great resource for tracking down the sources of these impairments.

LDPC coding
Perhaps the most significant improvement is in the use of LDPC (Low Density Parity Check) coding. By itself, this is considered good for an additional 4 dB of CNR performance; the addition of LDPC coding allows equivalent error rate reception of a given bitloading at a CNR 4 dB worse than with D3.0 coding.

Pilot subcarriers (no data) and complimentary pilot subcarriers (reduced rate data) maintain sync in hostile conditions, allowing the FEC to continue to operate. Pilots may also be boosted in level compared to data subcarriers in some configurations. Fourteen different pilot structures are provided, from sparse when channel conditions are excellent, to dense for the worst conditions. In this way efficiency can be traded off against robustness. Since pilot structure is called out in the transmission profile, it becomes part of the value proposition of profile assignment.

Time and frequency interleaving by the CM (and de-interleaving at the CCAP end) are combined in one operation. Time interleaving allows the FEC to clean up after brief, intermittent noise bursts, by spreading data out in time such that bit errors are more easily detected and corrected. Frequency interleaving works in a similar way in that narrowband interference events, even with longer durations, will impact only individual bits in a manner that allows easier FEC cleanup. Interleaving can operate across as many as 24 minislots (if the grant is large enough); if these are part of a full spectrum burst, they will span 9.6 MHz when minislots are contiguous, and even further if there are excluded subcarriers between minislots.

Power Spectral Density (CM output power) Leverage
This subject, besides (or perhaps because of) being near and dear to the author's (Brooks) heart, deserves a little more depth.

D3.1 requires that every CM be capable of a minimum of 65 dBmV total power when ODFMA channels are in use, although it is not required to output DOCSIS® 3.0 legacy carriers at levels above what the legacy spec calls out. The following Table 2 illustrates the value of this capability in a 5-42 MHz network.

Spec	Total Power	Carriers	Bandwidth	In 1.6 MHz
D3.0, 4x bonded	+57 dBmV	3x 6.4 MHz 1x 3.2 MHz	22.4 MHz	45.5 dBmV
D3.1, full grant	+65 dBmV	672 ea. 50 kHz	33.6 MHz	51.9 dBmV

Table 2: Power Spectral Density Compared to Legacy CM Requirements

In the above Table 2, the column labeled "In 1.6 MHz" depicts the amount of power per unit bandwidth; this is a measure of Power Spectral Density (PSD), sometimes referred to as "power per Hertz." As Table 2 shows, there is an approximate 6 dB PSD advantage available when CMs are limited to 5-42 MHz operation compared to DOCSIS® 3.0 CMs. This advantage is even greater when it is considered that the intended application, explicitly called out in the D3.1 specification, is to use what is referred to as the “gateway location.” The gateway location is defined as no more than a single 2-way splitter between the tap spigot and the CM. In theory, this combined advantage will directly translate (on a 1-for-1 basis) into both CNR improvement (by hitting coax amplifier inputs at higher levels) and perhaps even more significantly, INTERFERENCE ratio improvement (since interference is primarily ingress at a fixed level independent of CM output).

In practice, all of this leverage (and the additional 4 dB+ leverage attributable to gateway install location) will be somewhat tricky to take full advantage of. Since DOCSIS® 3.0 and earlier CMs will nearly always be present at the time DOCSIS® 3.1 is launched, any access network alignment set point adjustment that leverages this higher PSD will have an effect on those CMs as well. For instance, if the padding in front of the node laser (or node A/D converter) is increased by 6 dB, the operating point of the laser can be maintained during 6 dB hotter D3.1 full spectrum frame bursts, and 6 dB of padding can be removed in the hub such that the target receive level at the CCAP input remains constant. While this will provide instant CNR and interference improvements in the coax network, DOCSIS® 3.0 and earlier CMs may not be able to keep up. This is OK as long as they remain within the CCAP receiver input dynamic range window with sufficient CNR. High performance optics will help, since the NPR performance can easily be sufficient to allow legacy CMs a comfortable CNR when operated at 6 dB below D3.1 CM bursts.

This PSD leverage may also be limited by concerns about overdriving the return modules in the repeater amplifiers. There are countless different return module designs, and a proper analysis of their capabilities is beyond the scope of this paper. It is suspected that many can easily handle the additional power, while some may need to be upgraded to enjoy this leverage. This is a worthwhile subject for additional investigation and testing.

CM MER: A Big Squeeze for 4096-QAM

It was shown earlier that the D3.1 specification requires the CCAP to successfully receive 4096-QAM CM data when the signal contains noise at a 43 dB CNR. The D3.1 specification also stipulates that the CM may contain no higher than 44 dB MER in a full-spectrum grant burst. These numbers are only 1 dB apart! The following Table 3 illustrates the difficulty in utilizing 4096-QAM within these constraints.

QAM	CM MER	CCAP needs CNR	Network allowance
64	44	23	23.0
128	44	26	26.1
256	44	29	29.1
512	44	32.5	32.8
1024	44	35.5	36.2
2048	44	39	40.7
4096	44	43	49.9

Table 3: Access network CNR allowance for 4096-QAM operation; values in dB

Even with 50 dB optics, there is no real margin left for coax network operation. So what value does 4096-QAM offer? Profiles offer an answer. Real CM implementations may very well improve over time, and CCAP burst receivers may perform better than required. When these conditions are present, a transmission profile can be created to take advantage of them. This is also an example where R-PHY technology, with its complete elimination of the optical link contribution, offers an advantage.

Optics – Opening the Bottleneck

It is well known that the link between the node and the distribution hub is far and away the largest contributor to noise power in the received signal. This is true today whether linear optics or D/A conversion "digital return" is used in the link.

R-PHY (Remote Physical Layer Interface)

To address this bottleneck, a R-PHY (Remote Physical Layer) specification is being written that will build on the work done on DOCSIS® 3.1. R-PHY places the "business" end of the CCAP (the PHY layer) in the node, while most MAC (media access control) functions remain centralized in the core. R-PHY is not so much of an optical technology as it is an optics replacement technology; off the shelf digital baseband optics such as point-to-point optical Ethernet links are used for the node to hub link.

R-PHY completely eliminates the optical link CNR contribution, leaving the only the input gain blocks in the node itself as link CNR contributors. The R-PHY node demodulates the DOCSIS® signal, with baseband digital backhaul used between the node and the distribution hub. This results in very long distance capability (and lossless repeatability). This is in contrast to linear optics, which exhibit distance dependent performance. The long reach of R-PHY will make it a valuable tool for any operator with such links. R-PHY is considered again later in this paper.

Linear Optics

Ongoing advancements in linear optics are also capable of opening up the CNR backhaul restriction to a significant extent. Linear optics can offer extremely high CNR performance, particularly in medium to short links where EDFA repeaters are not required.

To put this assertion in perspective, a discussion of D/S optics is useful. D/S broadband linear optics forms the foundation of HFC, having been invented by Louis Williamson at TWC in the 1980's. There still exists no real replacement for this technology, though R-PHY promises to change that.

In modern D/S optics, a passband of 54-1002 MHz is typically carried, with CNR performance in the low 50dB range being common. Carriage of U/S signals over a D/S link should theoretically scale the CNR performance based on loading according to 10*Log math; every halving of bandwidth results in a 3 dB CNR improvement. Our common 950 MHz loaded D/S link producing a 50 dB CNR should therefore be capable of nearly 15 dB higher performance when operated with 35 MHz of loading, to an amazing 65 dB CNR! While this is not practical for a number of reasons, it serves to illustrate the value of reduced loading and the promise of improved optics.

At issue is the fact that these cooled DFB (distributed feedback) lasers are not inexpensive, and outdoor operation is a hostile environment.

Frequency (aka RF) Stacking

An answer to the cost issue is to carry more than one U/S link on the same laser. This idea has been around since the early 1990's and is commonly referred to as RF stacking, or just stacking. Stacking works by using RF up-conversion to mix incoming streams with a local oscillator, which allows them to be placed (stacked) higher in the passband. Placement is selected based on the oscillator frequency. A very real concern historically was with oscillator quality; stability, reliability, and phase noise. Suffice it to say that these issues have been solved in products offered by multiple OEMs, and present RF stacking platforms are enjoying a growing place in our networks as a result.

One interesting and beneficial side effect of stacking has to do with the spectrum locations chosen. Since the RF passband of linear DFB lasers is well up in the multi-gigahertz range, it is possible to leave large spectral gaps between the stacked signals. The gaps can be carefully selected such that second order distortion products fall in between the signals, allowing filters in the hub down-converter equipment to easily and effectively eliminate them.

Similar to non-stacked linear optics, RF stacking systems enjoy improved performance when operated with reduced loading. Loading can be reduced not only by carriage of a narrower passband, but also by reducing the number of stacked links. For instance, two links can be carried on a four-link capable laser.

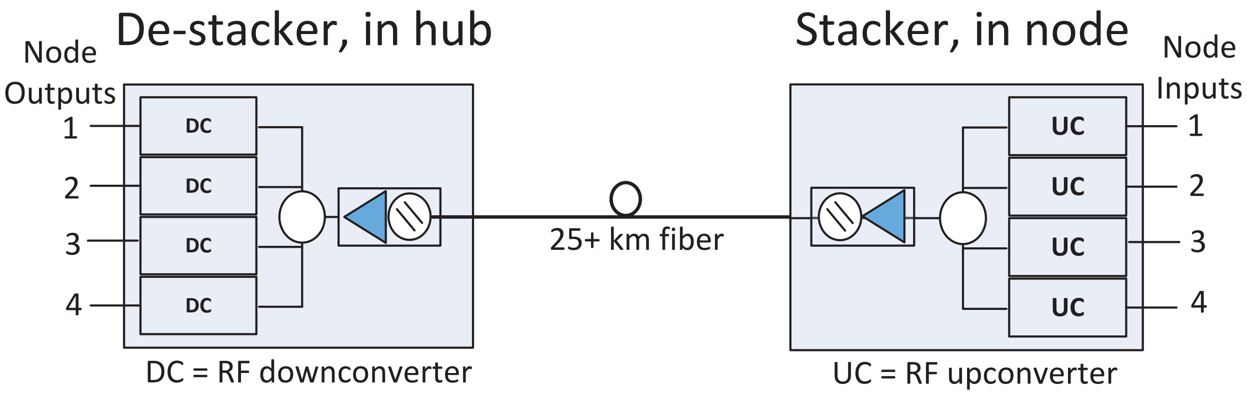


Figure 2: Stacking System Block Diagram, (Courtesy InnoTrans Communications)

Another interesting capability is made available when loading is reduced. A 5-42 MHz access network needs both very high CNR optics and the leverage the CM's increased power in order to achieve our desired 100 Mbps tier goal. These tools are less critical in 5-85 MHz or 5-204 MHz split operation. The DOCSIS® 3.1 CM transmit power specification requires 65 dBmV of output level INDEPENDENT of passband width. This means that the PSD advantage enjoyed at 5-42 MHz declines at 5-85 MHz, and further declines to a level similar to present DOCSIS® 3.0 5-42 MHz bonding under 5-204 MHz operation. Fortunately, the deficit in PSD is more than made up for by the additional DOCSIS® spectrum available, allowing very high tier rates to be easily achieved without resorting to the high order bitloadings that drive the need for high CM levels and high CNR optics. Therefore, the stacking system operated as a very high performance link in today's 5-42 MHz network will continue to serve valuable duty in a future 5-85 MHz or 5-204 MHz network at a somewhat lower CNR, and may even accommodate future service group segmentation where required via added links.

Figure 3 depicts measured data on a current stacked product when operated with 40 MHz of loading, with two of four links active. This product is capable of four links at 5-85 MHz and two links at 204 MHz. It is expected that 8 dB of usable dynamic range is achievable in real-world links such as this (9 dB shown).

ATN	NPR
0	41.8
1	45.9
2	49.6
3	51.9
4	53.8
5	54.1
6	53.8
7	53.4
8	52.4
9	51.8
10	50.8
11	50.0
12	49.3
13	48.7
14	48.0
15	47.1
16	46.5

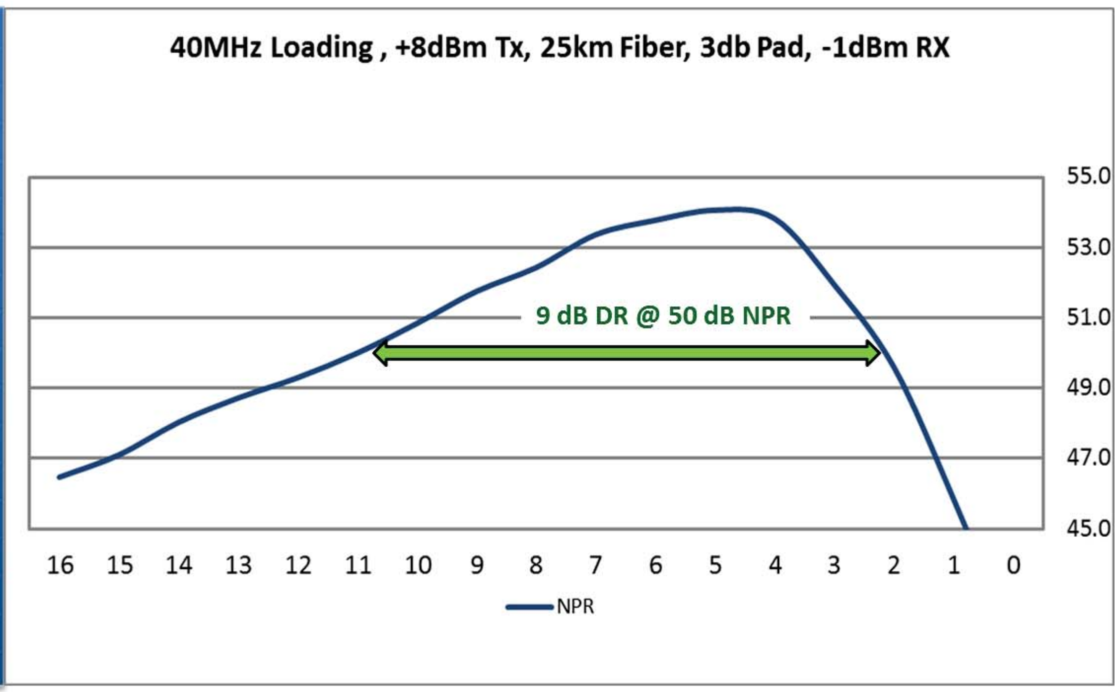


Figure 3: Frequency Stacked – NPR Curve. 25 km, 9dB Optical Link Loss (Courtesy InnoTrans Communications)

Case studies: Introducing the Upstream Coaxial Network Performance Calculator

The following group of figures show the results of noise addition in U/S coaxial networks. Since there are very few amplifiers in cascade, and those amplifiers exhibit very high intermodulation performance at 5-42 MHz spectrum loading, we have chosen to disregard nonlinear distortion in these models. We also make the assumption that the CM MER is primarily AWGN-like and does not contain appreciable phase noise, and as such can be directly added to CNR performance using ordinary power-based mathematics.

Calculator Basics

The last example (Figure 20) of this calculator is provided as an embedded MS-Excel® object, and may be freely copied or opened here for entry of parameters of the reader's choosing. Double-click on Figure 20.

A default CM MER is entered at the minimum required value of 44 dB; however this value is a variable (green cell and pie slice) and may be manipulated to show the impact of future CM performance improvements.

When zero is entered in the blue optical link field, the optical link is removed. This is useful to model the impact of R-PHY performance.

In unity-gain U/S operation, source noise sums when combined, assuming modern alignment practices are in use (align to fixed input levels). This is true of both coaxial repeater amplifiers and summation of optical receiver outputs in the distribution hub. This concept may be alien to engineers familiar with D/S noise math, where there is only one signal path, and amplifiers are cascaded after the optical link.

A useful way to consider noise summation of U/S amplifiers in a node is to think of them as being installed in a single long cascade. It then becomes obvious that the keys to good noise performance are input level, noise figure, and importantly, the total quantity of amplifiers. U/S noise performance is not a function of cascade depth. For example, a node plus 2 design with 8 total amplifiers will perform similarly to a node plus 8 design with 8 amplifiers with respect to U/S thermal noise addition, the dominant impairment.

Parameters Used in the Calculators

- 35 MHz of spectrum loading: 5-42 MHz less 2 MHz for a settop RDC carrier
- The coaxial portion of the access network must be set up to provide at least 6dB of excess CNR headroom (margin) to qualify for the next step (capacity modeling), although some examples are shown with less headroom for illustration purposes.
- The total reverse amplifier input power is entered as a default 24 dBmV. Here is the logic for that choice:
    - Start at the 65 dBmV required CM output power
    - Reserve 3dB for CM transmit power headroom (temperature variations, ranging, etc.)
    - Allow 4 dB for a house splitter, using the gateway location previously discussed
    - 2 dB is probably sufficient for the low drop and feeder cable losses at 42 MHz, given the assumption that the worst case is at the first tap out of an amplifier or node.
    - A tap value of 26 dB is assumed as the highest loss condition.

- 65-3-4-2-26=30 dBmV, still 6 dB higher than the 24 dBmV level we assume at the reverse amplifier input.

Additional Case Study Parameters:

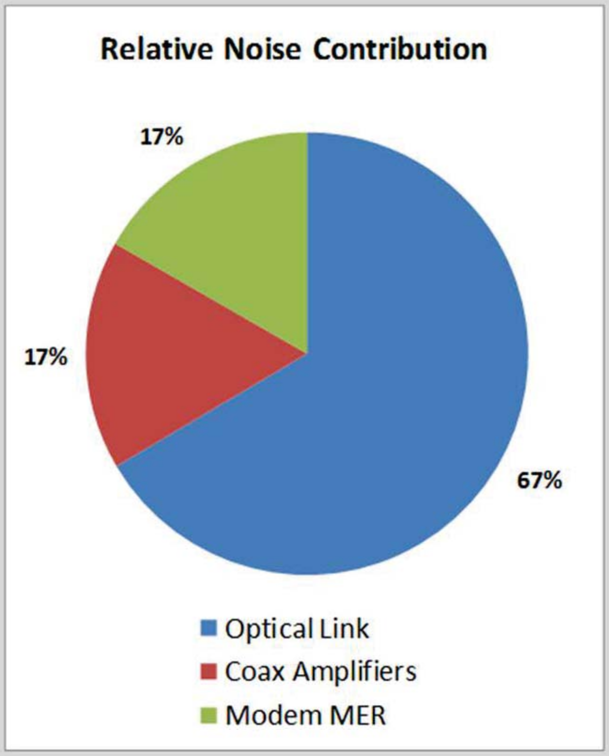
The following tables 4 and 5 list parameters used in the coax network performance calculators shown in figures 4 through 18.

Amplifier Count, Includes Node	Approximate Sizes in Homes Passed
1 (Node plus zero)	64
7	125
15	250
30	500
45	750
60	1000

Table 4: Example amplifier counts and associated node sizes

Optical Technology	CNRs Used in Model
Legacy Optics	38 dB
High CNR Linear Optics	50 dB
R-PHY (de-mod to baseband)	No contribution to CNR

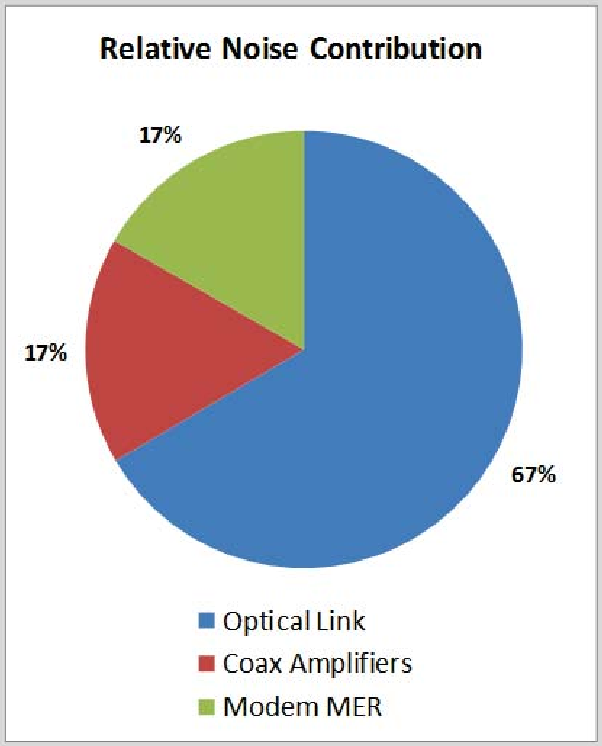
Table 5: CNR Contribution of optical links



Description	Value	Units
Number of amplifiers incl. node	60	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	43.98	dBc
Modem MER	44	dB
Required CNR of optical link	29.28	dBc
Desired Maximum Bitloading	256	QAM
Optical link CNR (R-PHY: set to 0)	38.0	dB
Coax plant noise margin	7.9	dB

Figure 4: 60 amplifiers with legacy optics, 256-QAM

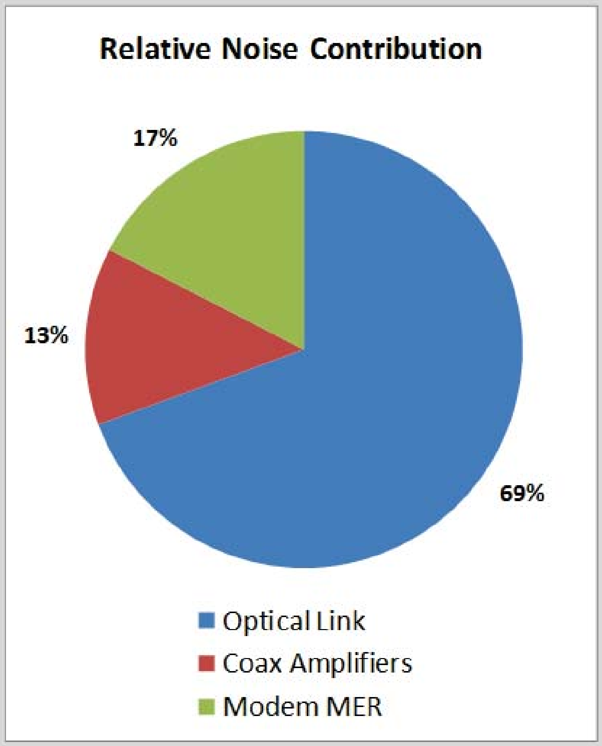
Note the 7.9 dB coax margin. Traffic would likely be the limiting factor in selection of a tier rate in such a large node, not coax CNR performance



Description	Value	Units
Number of amplifiers incl. node	60	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	43.98	dBc
Modem MER	44	dB
Required CNR of optical link	36.95	dBc
Desired Maximum Bitloading	1024	QAM
Optical link CNR (R-PHY: set to 0)	38.0	dB
Coax plant noise margin	0.9	dB

Figure 5: 60 amplifiers with legacy optics, 1024-QAM

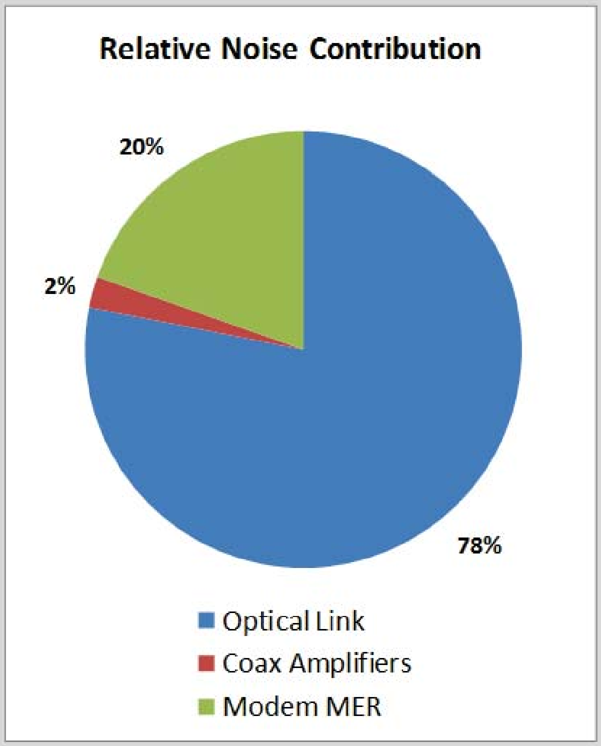
Note the how the former 7.9 dB coax margin has nearly disappeared when operation with 1024-QAM is attempted, showing the demanding requirements of raised bitloading



Description	Value	Units
Number of amplifiers incl. node	45	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	45.23	dBc
Modem MER	44	dB
Required CNR of optical link	36.74	dBc
Desired Maximum Bitloading	1024	QAM
Optical link CNR (R-PHY: set to 0)	38.0	dB
Coax plant noise margin	1.1	dB

Figure 6: 45 amplifiers with legacy optics, 1024-QAM

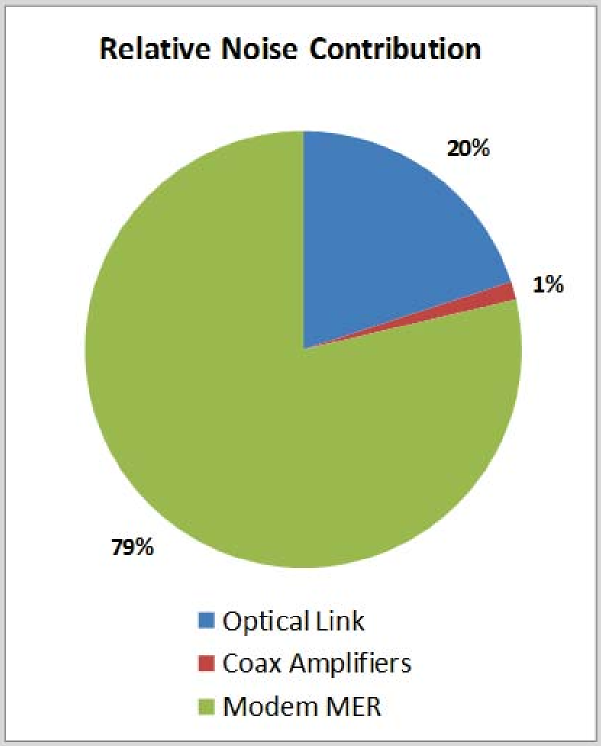
Note almost no margin improvement at 1024-QAM when the node size is reduced (from 60 to 45 amplifiers). Legacy optics continue to dominate as shown in the pie chart



Description	Value	Units
Number of amplifiers incl. node	7	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	53.31	dBc
Modem MER	44	dB
Required CNR of optical link	36.25	dBc
Desired Maximum Bitloading	1024	QAM
Optical link CNR (R-PHY: set to 0)	38.0	dB
Coax plant noise margin	1.7	dB

Figure 7: 7 amplifiers with legacy optics, 1024-QAM

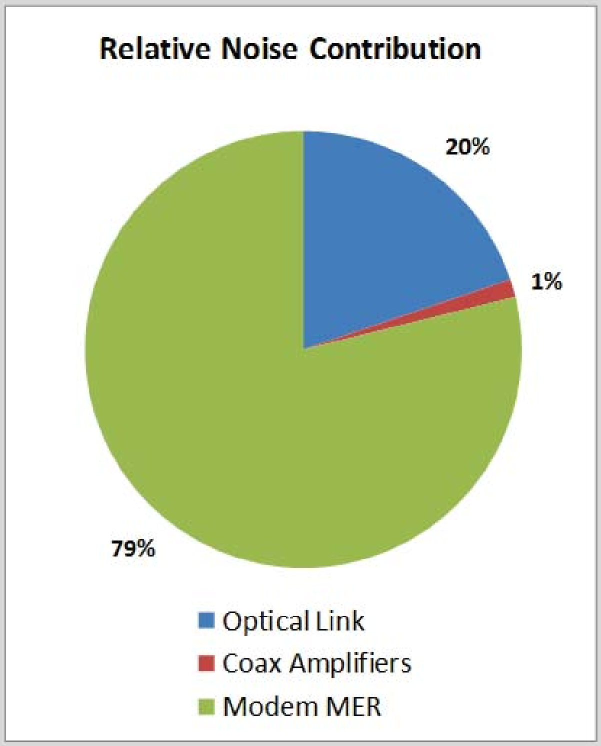
Even a very small node (7 amplifiers) does not allow safe operation with 1024-QAM. Again, legacy optics dominate.



Description	Value	Units
Number of amplifiers incl. node	1	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	61.76	dBc
Modem MER	44.05	dB
Required CNR of optical link	49.96	dBc
Desired Maximum Bitloading	4096	QAM
Optical link CNR (R-PHY: set to 0)	50.0	dB
Coax plant noise margin	0.0	dB

Figure 8: High CNR linear optics with Node+0, 4096-QAM

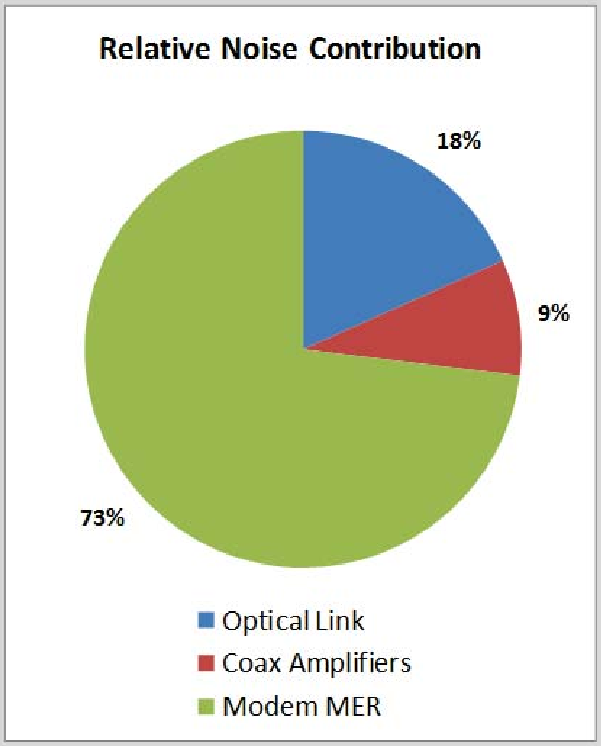
It was a near miss. It was necessary to nudge up the CM MER (by 0.05 dB) to prevent a “FAIL” state. Even with these stellar optics and node plus 0, 4096 QAM is essentially unusable. Note however the strong dominance of CM MER in the pie chart. A small improvement to the CM could put 4096-QAM on the map.



Description	Value	Units
Number of amplifiers incl. node	1	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	61.76	dBc
Modem MER	44	dB
Required CNR of optical link	40.68	dBc
Desired Maximum Bitloading	2048	QAM
Optical link CNR (R-PHY: set to 0)	50.0	dB
Coax plant noise margin	9.1	dB

Figure 9: High CNR linear optics with Node+0, 2048-QAM

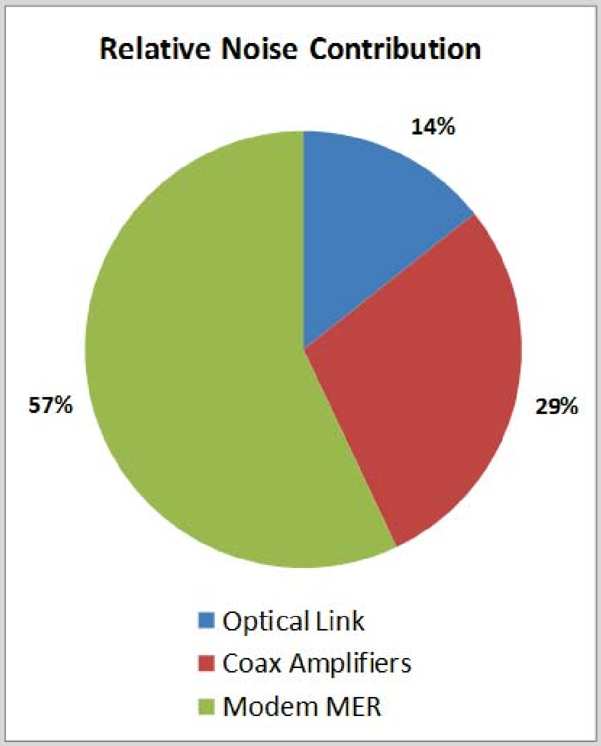
One step down in bitloading from the previous figure, and coax margin abounds. Note that CM MER still dominates the CNR budget.



Description	Value	Units
Number of amplifiers incl. node	7	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	53.31	dBc
Modem MER	44	dB
Required CNR of optical link	40.89	dBc
Desired Maximum Bitloading	2048	QAM
Optical link CNR (R-PHY: set to 0)	50.0	dB
Coax plant noise margin	7.7	dB

Figure 10: High CNR linear optics at 7 amplifiers, 2048-QAM

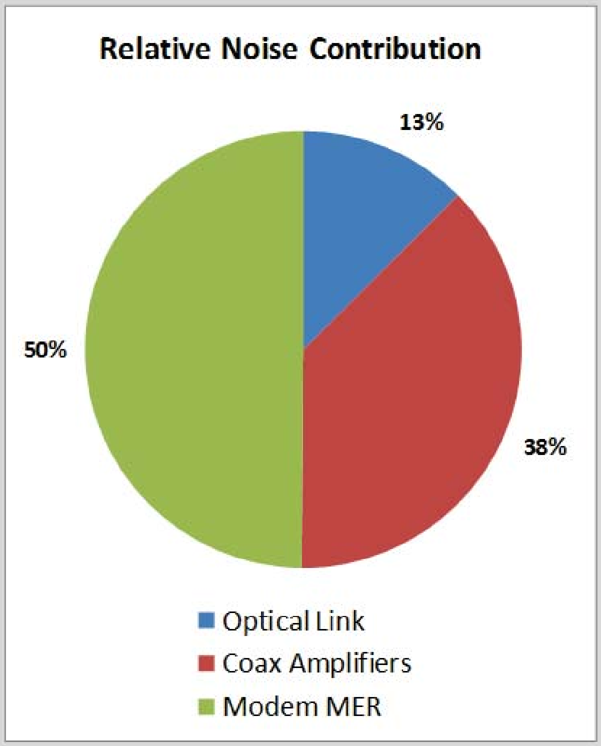
Adding amplifiers can be done while retaining margin, since CM MER still dominates.



Description	Value	Units
Number of amplifiers incl. node	30	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	46.99	dBc
Modem MER	44	dB
Required CNR of optical link	41.80	dBc
Desired Maximum Bitloading	2048	QAM
Optical link CNR (R-PHY: set to 0)	50.0	dB
Coax plant noise margin	4.6	dB

Figure 11: High CNR linear optics at 30 amplifiers, 2048-QAM

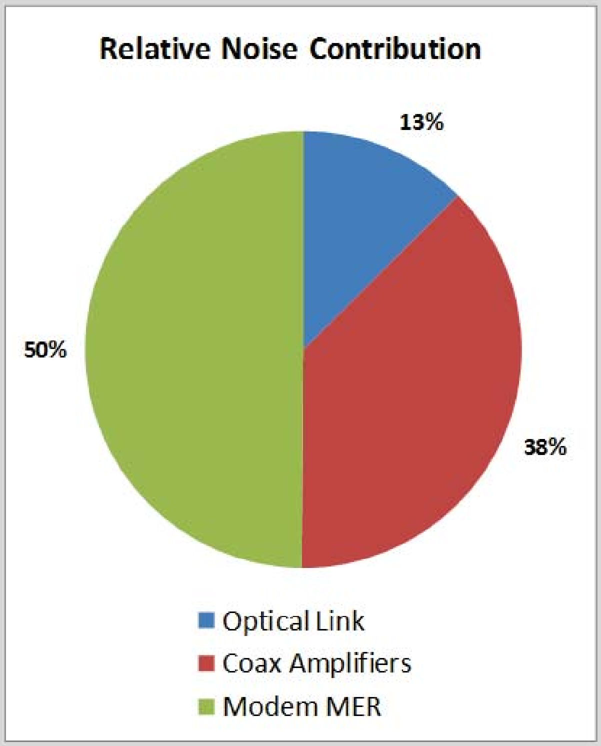
Adding amplifiers is still possible, but margin erosion is more evident. Note how CM MER is less in control. This example does not meet our 6dB coax margin criteria, though profiles may allow operation at 2048-QAM under the right conditions.



Description	Value	Units
Number of amplifiers incl. node	45	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	45.23	dBc
Modem MER	44	dB
Required CNR of optical link	42.51	dBc
Desired Maximum Bitloading	2048	QAM
Optical link CNR (R-PHY: set to 0)	50.0	dB
Coax plant noise margin	3.3	dB

Figure 12: High CNR linear optics at 45 amplifiers, 2048-QAM

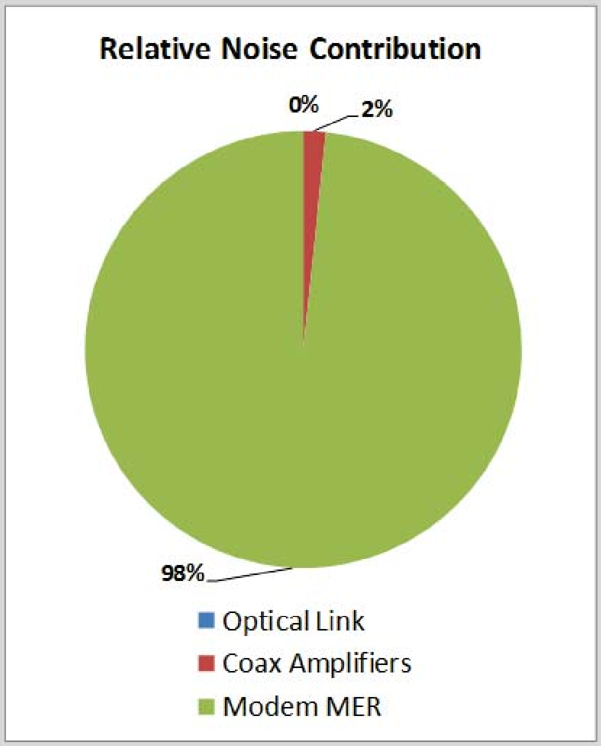
Even at 45 amplifiers, 2048-QAM operation is possible, though margin is thinning out. Note that CM MER is now only half of the budget. Again, this example does not meet our 6dB coax margin criteria, though profiles may allow operation at 2048-QAM under the right conditions.



Description	Value	Units
Number of amplifiers incl. node	45	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	45.23	dBc
Modem MER	44	dB
Required CNR of optical link	36.74	dBc
Desired Maximum Bitloading	1024	QAM
Optical link CNR (R-PHY: set to 0)	50.0	dB
Coax plant noise margin	7.8	dB

Figure 13: High CNR linear optics at 45 amplifiers, 1024-QAM

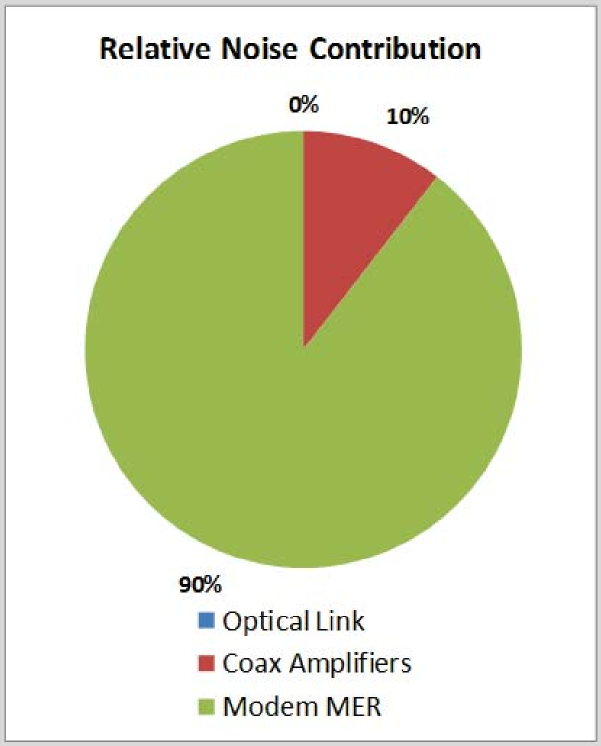
Dropping back one QAM step restores our required margin. The pie chart did not change from the previous figure, but operation at 1024-QAM relaxes the needed CNR performance even though the contributor shares are unchanged.



Description	Value	Units
Number of amplifiers incl. node	1	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	61.76	dBc
Modem MER	44	dB
Required CNR of optical link	50.16	dBc
Desired Maximum Bitloading	4096	QAM
Optical link CNR (R-PHY: set to 0)	0.0	dB
Coax plant noise margin	11.9	dB

Figure 14: R-PHY with node + 0 and 4096-QAM

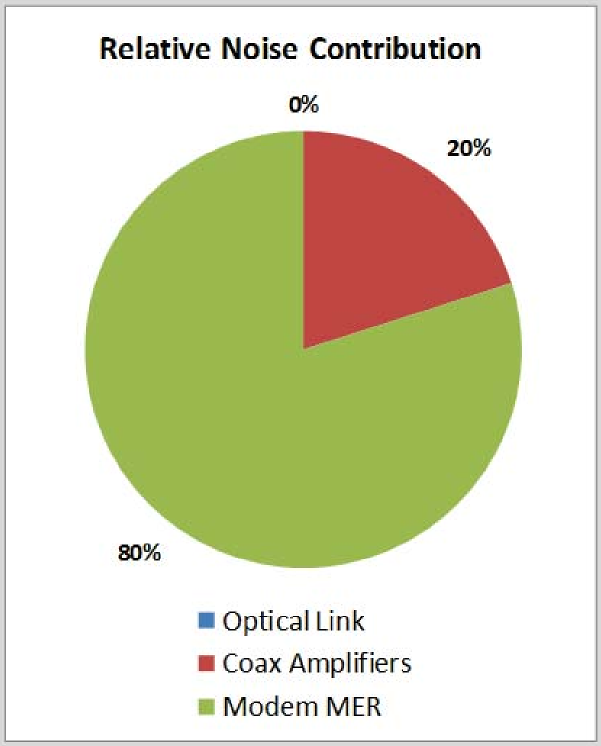
It doesn't get any better than this. Completely CM MER dominated.



Description	Value	Units
Number of amplifiers incl. node	7	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	53.31	dBc
Modem MER	44	dB
Required CNR of optical link	52.49	dBc
Desired Maximum Bitloading	4096	QAM
Optical link CNR (R-PHY: set to 0)	0.0	dB
Coax plant noise margin	3.4	dB

Figure 15: R-PHY with 7 amplifiers and 4096-QAM

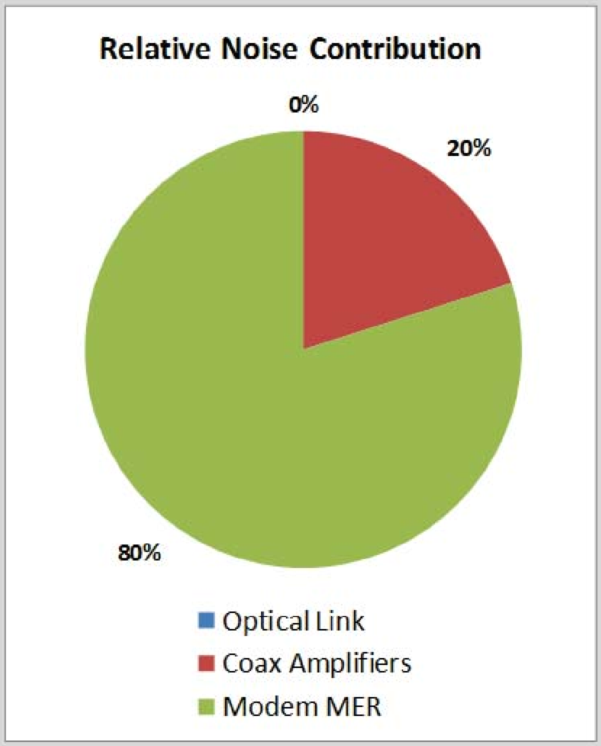
This shows the difficulty in using 4096-QAM. Even 7 amplifiers push coax margin below our 6dB criteria. CM MER dominates, and better CMs would directly translate into higher amplifier count 4096-QAM capable networks if they become available. 4096-QAM may still be useable under the right conditions via profiles.



Description	Value	Units
Number of amplifiers incl. node	15	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	50.00	dBc
Modem MER	44	dB
Required CNR of optical link	65.20	dBc
Desired Maximum Bitloading	4096	QAM
Optical link CNR (R-PHY: set to 0)	0.0	dB
Coax plant noise margin	0.1	dB

Figure 16: R-PHY with 15 amplifiers and 4096-QAM

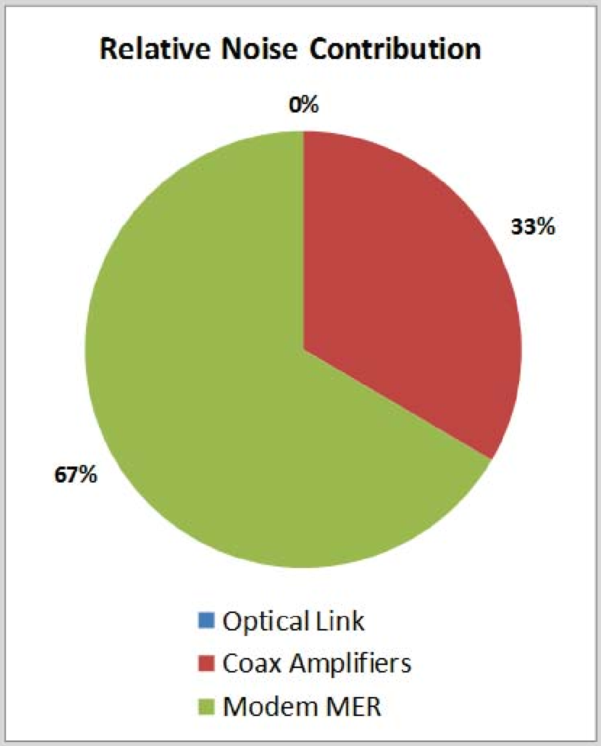
This further shows the difficulty in using 4096-QAM. At 15 amplifiers, the coax network margin has essentially vanished. CM MER continues to dominate, and better CMs would still translate into higher amplifier count 4096-QAM capable networks if they become available. 4096-QAM is unlikely to be useable under any conditions with so little margin.



Description	Value	Units
Number of amplifiers incl. node	15	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	50.00	dBc
Modem MER	44	dB
Required CNR of optical link	41.19	dBc
Desired Maximum Bitloading	2048	QAM
Optical link CNR (R-PHY: set to 0)	0.0	dB
Coax plant noise margin	9.3	dB

Figure 17: R-PHY with 15 amplifiers and 2048-QAM

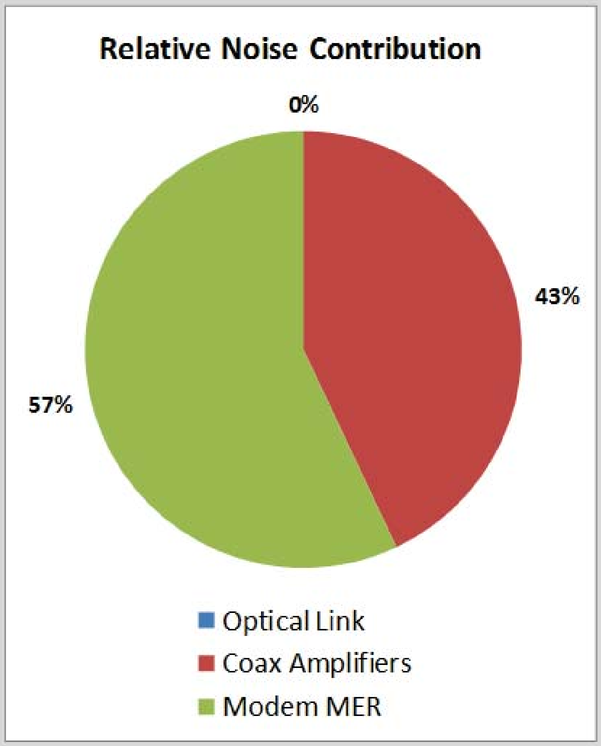
Dropping down to a less demanding 2048-QAM brings back plenty of margin.



Description	Value	Units
Number of amplifiers incl. node	30	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	46.99	dBc
Modem MER	44	dB
Required CNR of optical link	41.80	dBc
Desired Maximum Bitloading	2048	QAM
Optical link CNR (R-PHY: set to 0)	0.0	dB
Coax plant noise margin	6.3	dB

Figure 18: R-PHY with 30 amplifiers and 2048-QAM

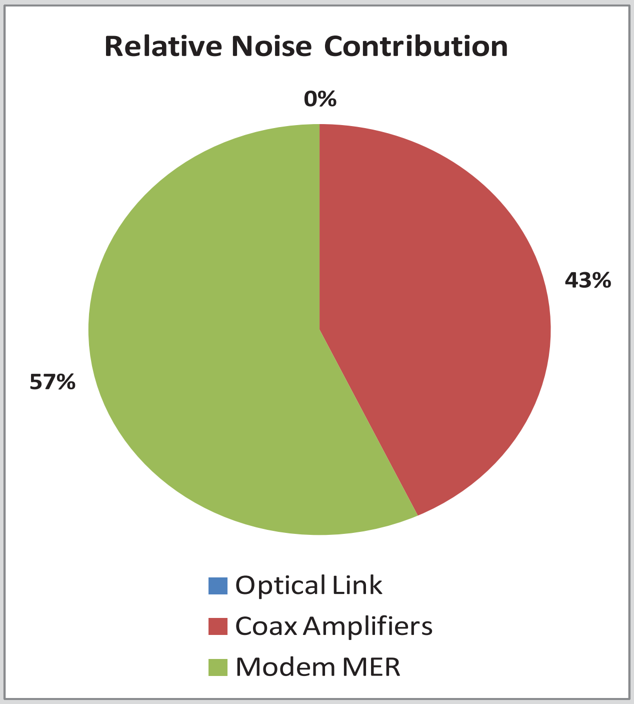
2048-QAM meets our criteria with R-PHY at 30 amplifiers. CM MER dominates



Description	Value	Units
Number of amplifiers incl. node	45	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	45.23	dBc
Modem MER	44	dB
Required CNR of optical link	42.51	dBc
Desired Maximum Bitloading	2048	QAM
Optical link CNR (R-PHY: set to 0)	0.0	dB
Coax plant noise margin	4.6	dB

Figure 19: R-PHY with 45 amplifiers and 2048-QAM

2048-QAM no longer meets our criteria with R-PHY at 45 amplifiers. CM MER is becoming an equal partner to coax network CNR. Compare to Figure 12, where a high CNR linear optical link provides a 2048-QAM coax margin of 3.3 dB, only 1.3 dB lower. According to our 6dB criteria, both networks would need to drop back to 1024 QAM at this node size.



Description	Value	Units
Number of amplifiers incl. node	45	ea.
Reverse amp input power, total	24	dBmV
Reverse amp noise figure	12	dB
Channel spacing, reference	6.4	MHz
DOCSIS 3.0 or 3.1?	3.1	3.0 or 3.1
Channel noise bandwidth	6.4	MHz
Noise in 6.4 MHz, 75Ω, 22°C	-57.14	dBmV
Lower band edge	5	MHz
Upper band edge	42	MHz
Excluded bandwidth	2	MHz
Occupied bandwidth	35	MHz
Equivalent channel count	5.5	ea.
Reverse amp in, 6.4 MHz channel	16.62	dBmV
Single Coax Amplifier CNR	61.76	dBc
Total Coax Amplifiers CNR	45.23	dBc
Modem MER	44	dB
Required CNR of optical link	36.74	dBc
Desired Maximum Bitloading	1024	QAM
Optical link CNR (R-PHY: set to 0)	0.0	dB
Coax plant noise margin	9.1	dB

Figure 20: Embedded MS-Excel® Model

This live model is configured to show R-PHY with 45 amplifiers. Double-click to open it. Modify white, green, or blue cells and watch what happens.

Note that there is a hidden worksheet area to the right with the DOCSIS® QAM requirements and other mechanics. Changing those cells will alter operation and not in a good way; proceed with caution.

Node size		Highest QAM bitloading possible with 6dB coax margin		
Amplifiers	Homes	R-PHY, No Optics	Linear Optics, 50 dB CNR	Legacy Optics, 38 dB CNR
N+0	65	4096	2048	256
7	125	2048	2048	256
15	250	2048	2048	256
30	500	2048	1024	256
45	750	1024	1024	256
60	1000	1024	1024	256

Table 6: Upstream Performance Calculator Results.
Red text bitloadings will be used in capacity case studies.

Capacity Case Studies

The U/S performance calculator results shown in table 6 will be considered the highest practical bitloadings possible in otherwise unimpaired HFC networks of the above dimensions. The 6 dB coaxial network margin criteria is provided to accommodate both variations in alignment over time and temperature, as well as reasonable maintenance allowances for technical operations similar to current practices. In many cases it is expected that higher bitloadings will be accessible, and intelligent use of profiles may permit speeds that are not possible with the margins shown here. Note that the margins provided here only apply to the coaxial portion of the network, not the optical link, CM MER, or CCAP receiver performance.

Capacity Case Study Parameters

An accommodation is made for a known narrowband interferer; CB radio in these examples. Either lower bitloading or subcarrier exclusions may be included based on profile construction. In practice, the sporadic and localized nature of narrowband interference may be taken advantage of if and when automated profile construction becomes available.

Bitloadings are reduced for minislots in the spectrum below 20 MHz and to a lesser extent at the very top of the passband.

FaTDMA is assumed as the default mode used by high-tier customers.

A 200 Mbps PHY rate is considered the gate for both 100 Mbps tier operation and for 2:1 PHY:tier ratio use. Lower PHY capacities are (somewhat arbitrarily) assigned a 3:1 PHY:tier ratio in line with current practices.

To simulate operation with an impaired network, all bitloadings were reduced by 2 bits per symbol, to simulate an overall 6 dB CNR reduction. Such an impairment may have multiple causes which are not explored here.

It is assumed that high-CNR linear optics can maintain a sufficiently wide dynamic range at 50 dB CNR. While this is narrower than ranges typically seen for DOCSIS® 3.0 and earlier service, profiles can now be used in cases where alignment drift occurs, alerting operators to the need to maintain the set point back to its original parameters. Prior to D3.1, such a proposal would have resulted in an access network outage until remediation was performed. Profiles can make such aggressive operations processes practical.

Notes:
The graphics in the following group of figures are produced by the same model presented earlier in the paper (to demonstrate FaTDMA operation). The notes from that section are repeated here for convenience.

The horizontal axis shows time, while the vertical axis denotes frequency from 42 MHz to 5 MHz. Each highlighted cell represents a 400 kHz minislot. The number in the cell is the bitloading. The % column shows the approximate PHY efficiency of the minislot, comparing net PHY throughput to the raw theoretical bitrate for each particular bitloading. Efficiency is primarily a function of the selected pilot pattern and FEC overhead. In these figures, more robust pilot patterns are associated with lower bitloadings, although this is not a requirement and may not necessarily be the optimum configuration.

These color key legends show Efficiency and Bitloading for fast visual identification. They apply to the subsequent sequence of Figures 23 through 31.

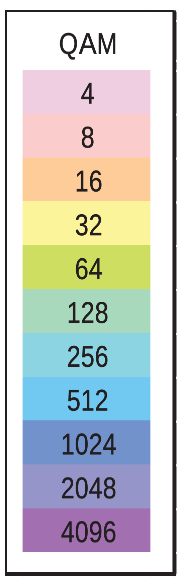


Figure 21:

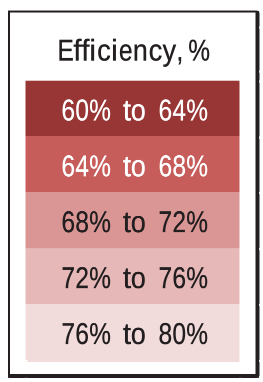


Figure 22:

Figure 23:

Perfect conditions

DOCSIS 3.1 Capacity	
Top Tier (2:1 rule):	**172 Mbit**
Top Tier (3:1 rule):	118 Mbit
DOCSIS 3.1 only:	344 Mbit
During 3.0 timeslot:	112 Mbit
Average, 2 time slots:	228 Mbit

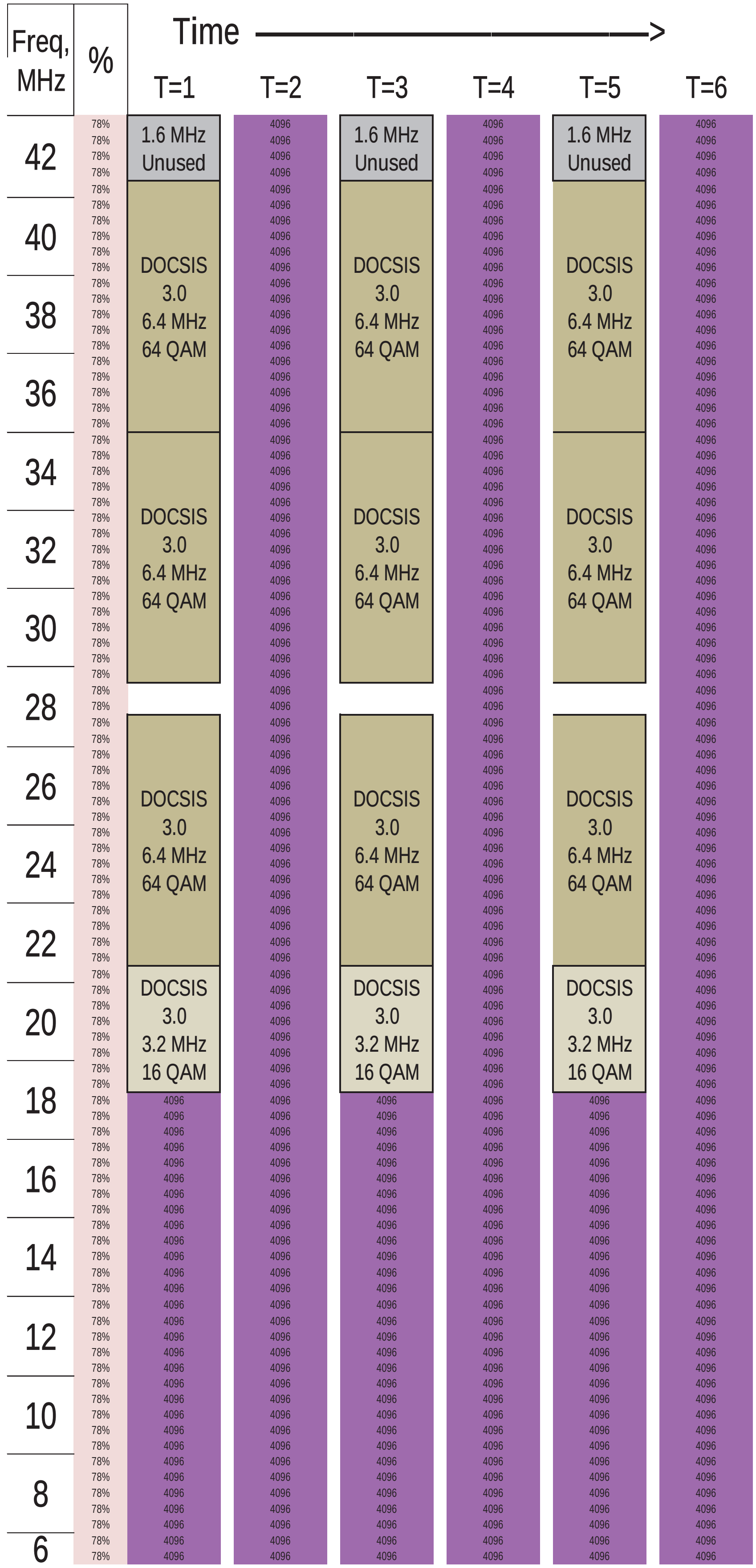


Figure 24:

R-PHY, node + 0

DOCSIS 3.1 Capacity	
Top Tier (2:1 rule):	127 Mbit
Top Tier (3:1 rule):	85 Mbit
DOCSIS 3.1 only:	254 Mbit
During 3.0 timeslot:	44 Mbit
Average, 2 time slots:	149 Mbit

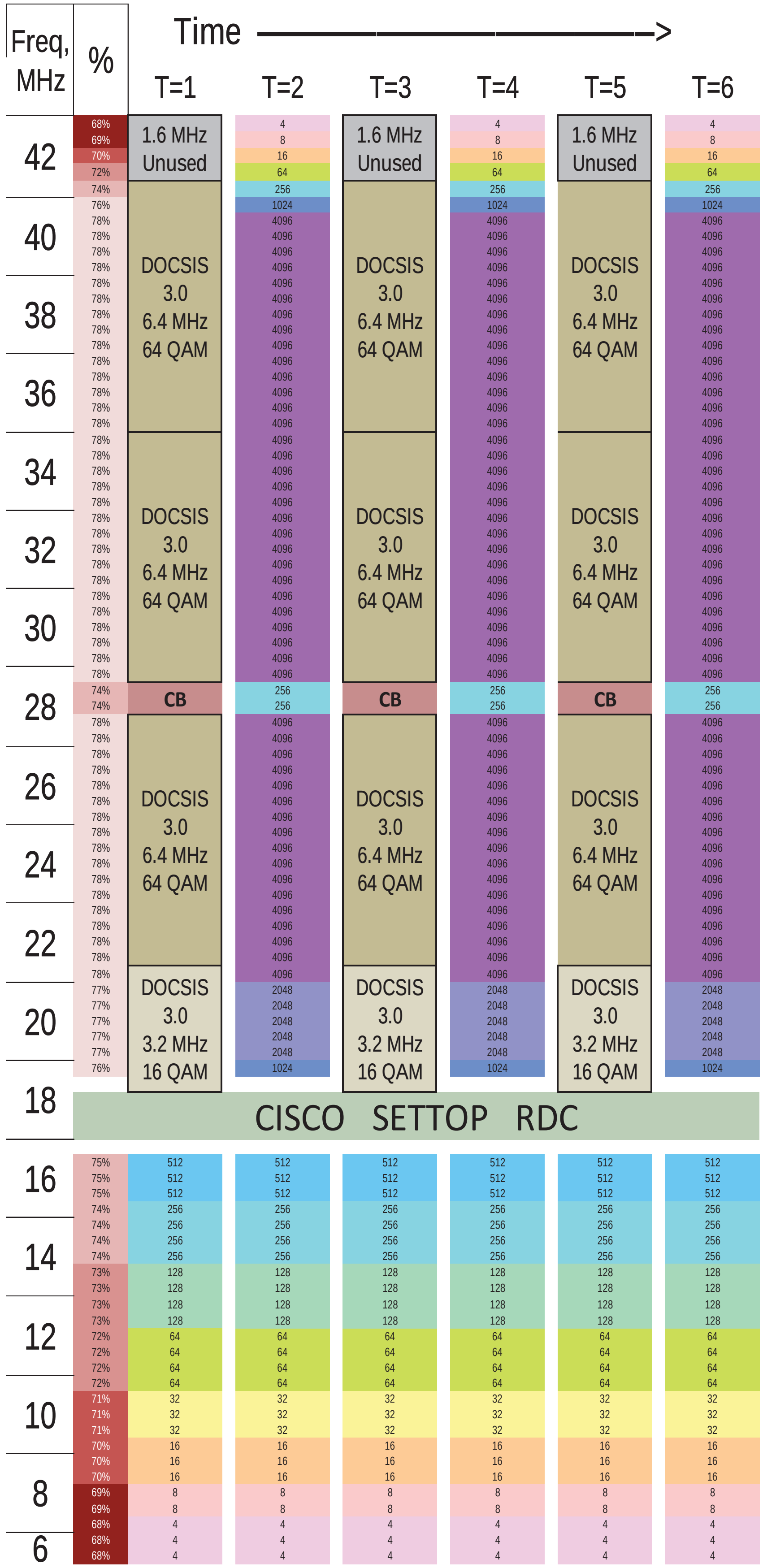


Figure 25:

Linear optics, 15 amplifiers

DOCSIS 3.1 Capacity	
Top Tier (2:1 rule):	**110 Mbit**
Top Tier (3:1 rule):	73 Mbit
DOCSIS 3.1 only:	220 Mbit
During 3.0 timeslot:	27 Mbit
Average, 2 time slots:	124 Mbit

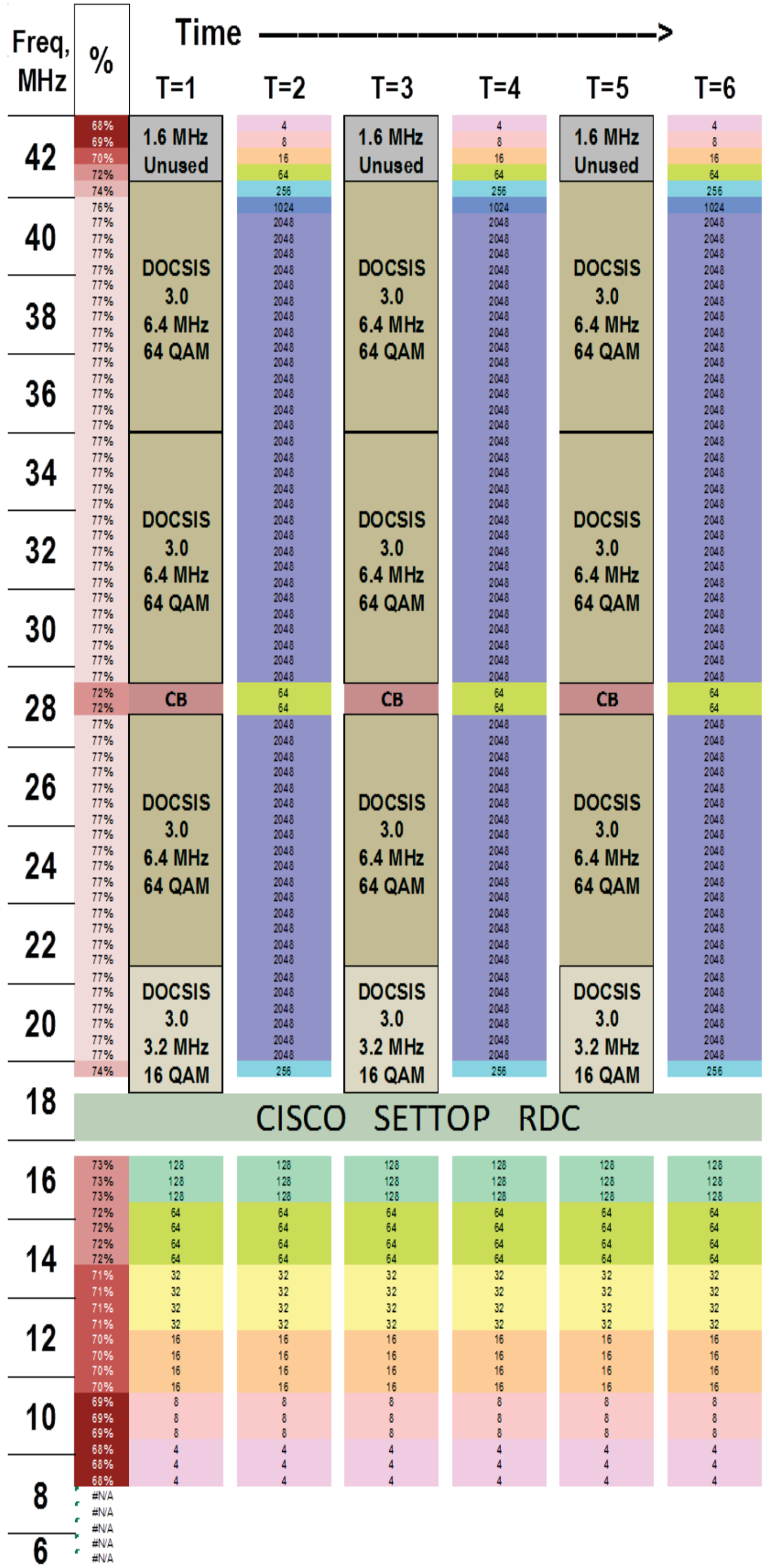


Figure 26:

Linear optics, 30 amplifiers

DOCSIS 3.1 Capacity	
Top Tier (2:1 rule):	**101 Mbit**
Top Tier (3:1 rule):	67 Mbit
DOCSIS 3.1 only:	202 Mbit
During 3.0 timeslot:	27 Mbit
Average, 2 time slots:	115 Mbit

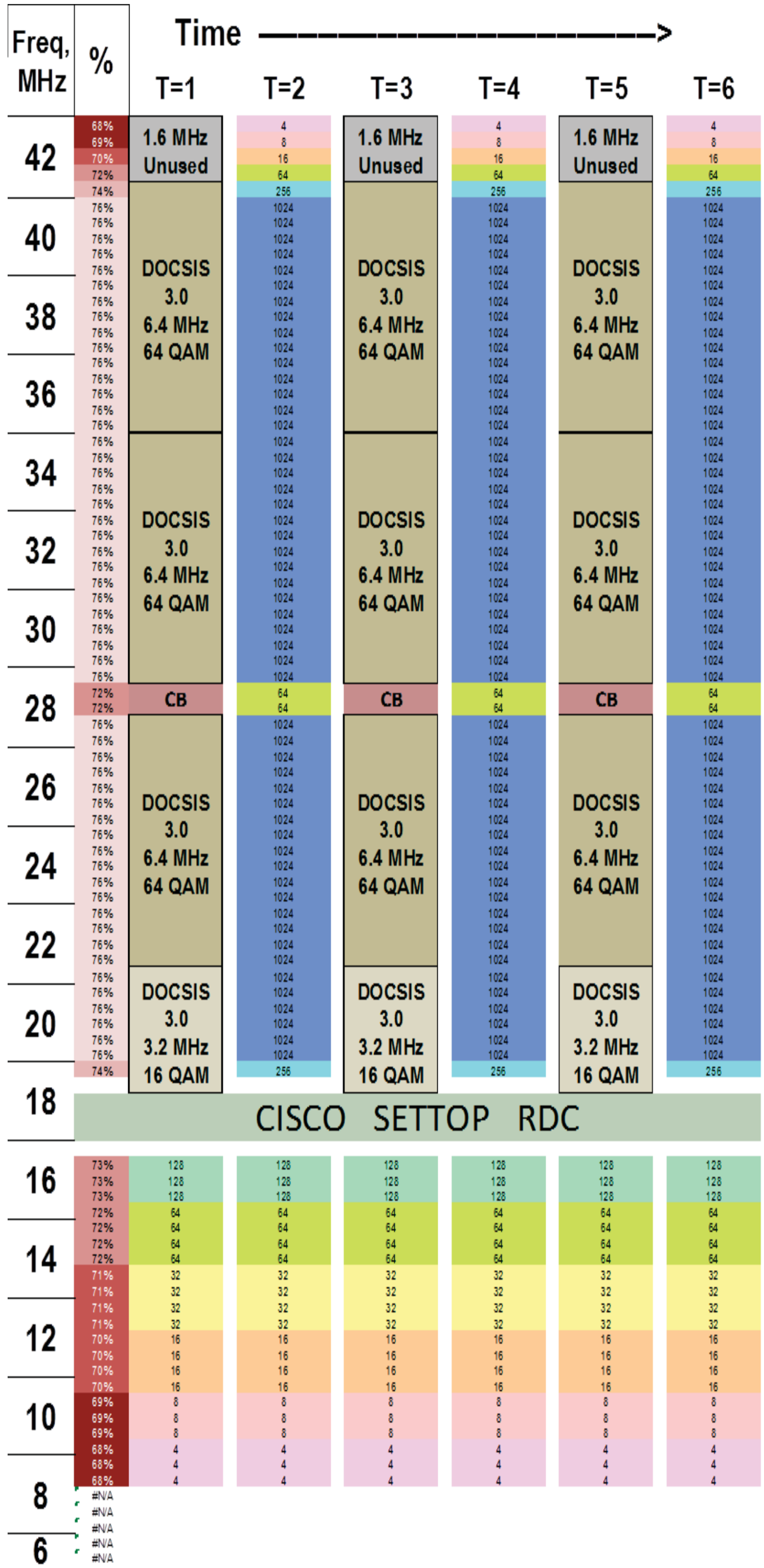


Figure 27:

Legacy optics, 45 amplifiers

DOCSIS 3.1 Capacity	
Top Tier (2:1 rule):	N/A
Top Tier (3:1 rule):	55 Mbit
DOCSIS 3.1 only:	165 Mbit
During 3.0 timeslot:	27 Mbit
Average, 2 time slots:	96 Mbit

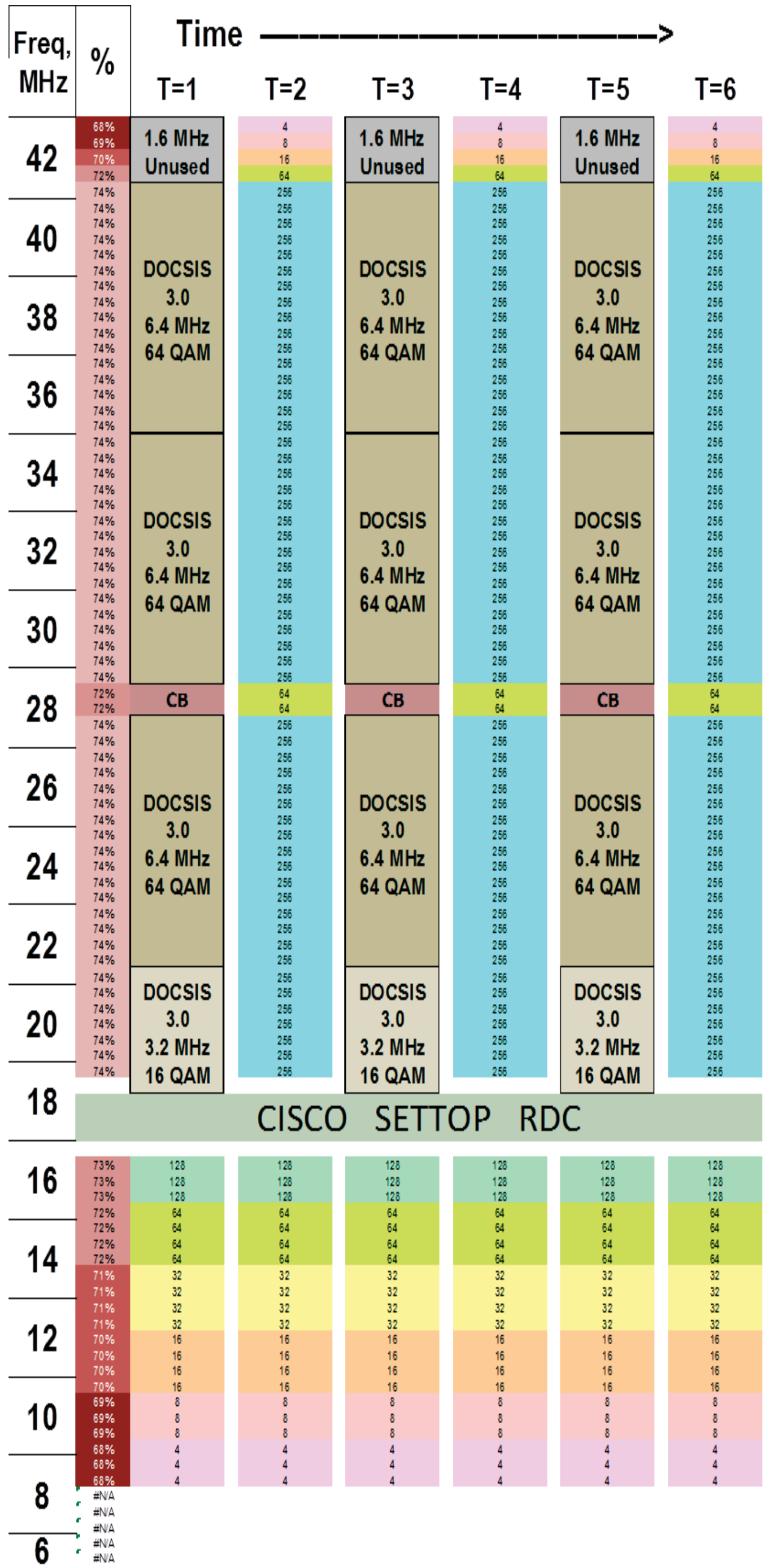


Figure 28:

Impaired: R-PHY, N+0, 6 dB

DOCSIS 3.1 Capacity	
Top Tier (2:1 rule):	**98 Mbit**
Top Tier (3:1 rule):	**65 Mbit**
DOCSIS 3.1 only:	195 Mbit
During 3.0 timeslot:	27 Mbit
Average, 2 time slots:	111 Mbit

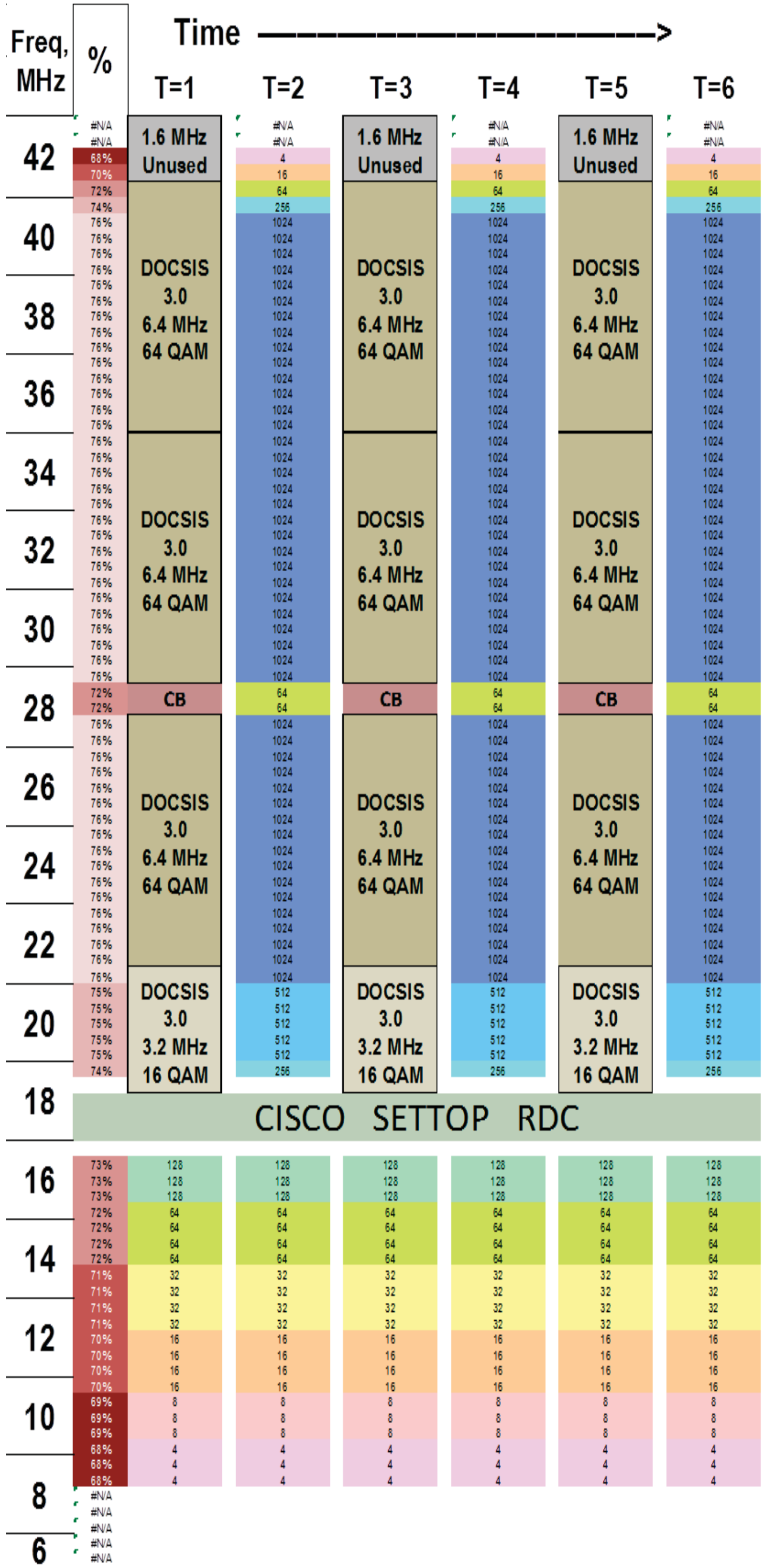


Figure 29:

Impaired: Linear, 15 amplifiers

DOCSIS 3.1 Capacity	
Top Tier (2:1 rule):	91 Mbit
Top Tier (3:1 rule):	**61 Mbit**
DOCSIS 3.1 only:	182 Mbit
During 3.0 timeslot:	14 Mbit
Average, 2 time slots:	98 Mbit

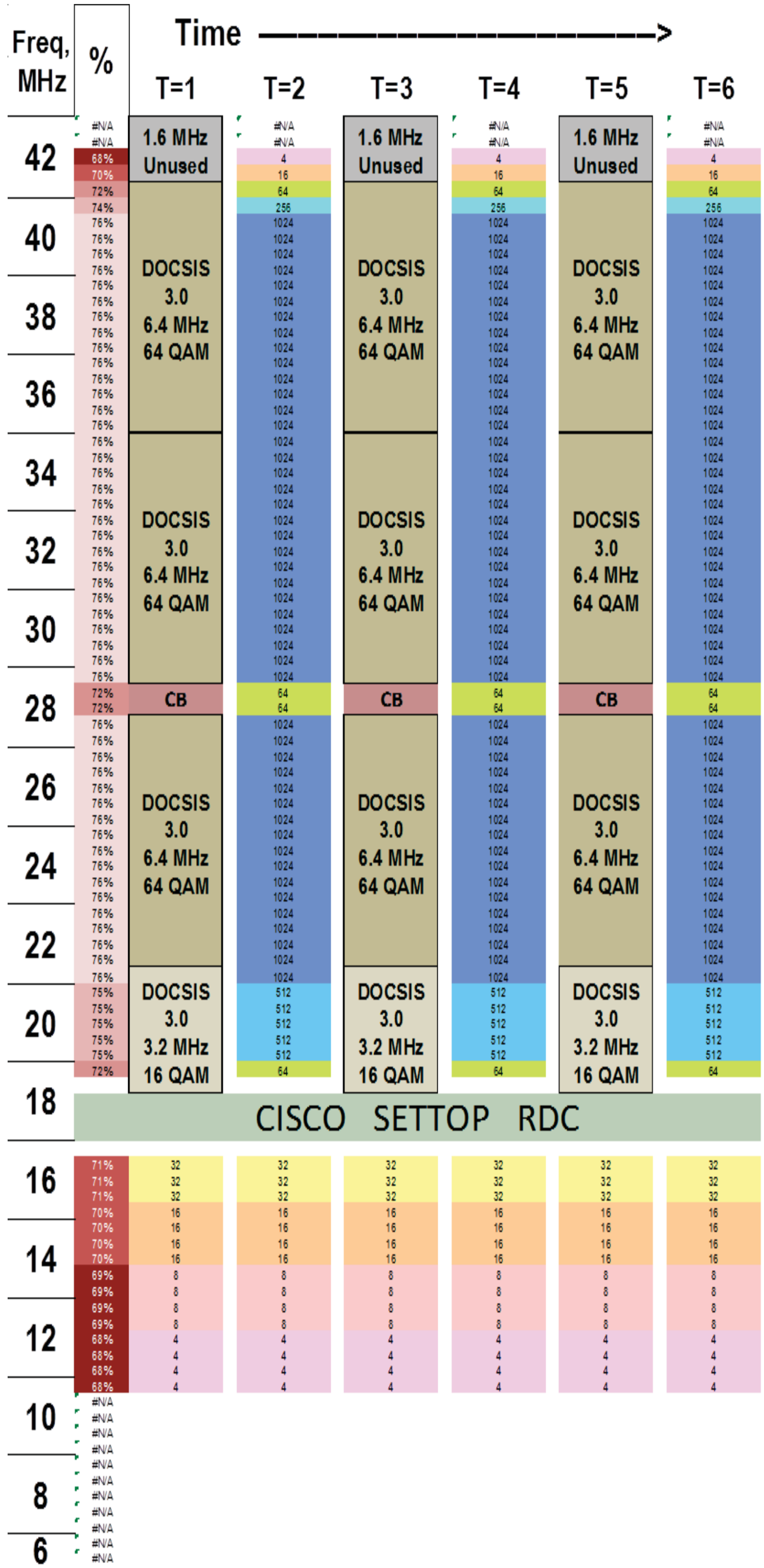


Figure 30:

Impaired: Linear, 30 amplifiers

DOCSIS 3.1 Capacity	
Top Tier (2:1 rule):	N/A
Top Tier (3:1 rule):	**49 Mbit**
DOCSIS 3.1 only:	148 Mbit
During 3.0 timeslot:	14 Mbit
Average, 2 time slots:	81 Mbit

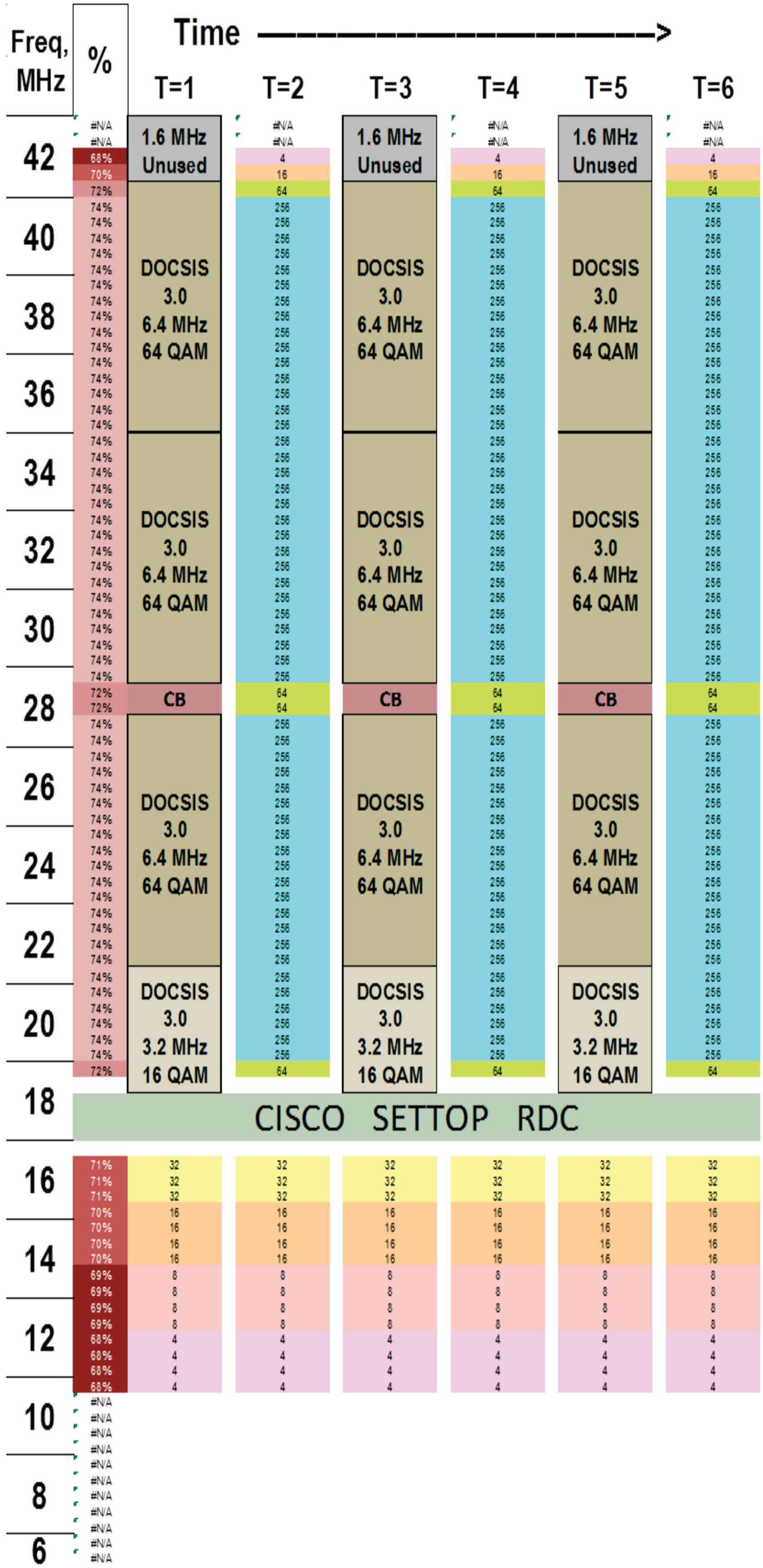
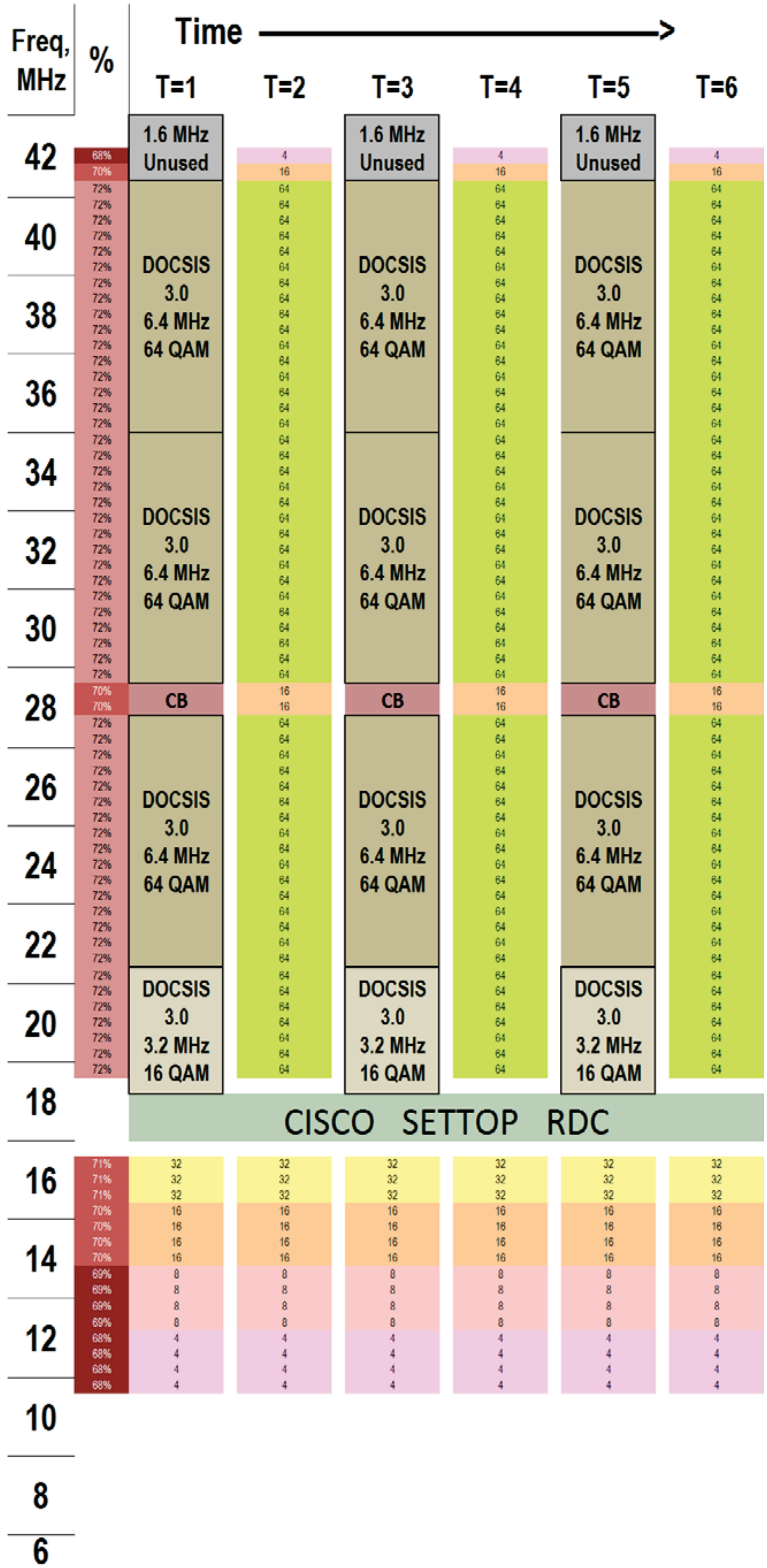


Figure 31:

Impaired: Legacy, 45 amplifiers

DOCSIS 3.1 Capacity	
Top Tier (2:1 rule):	N/A
Top Tier (3:1 rule):	**38 Mbit**
DOCSIS 3.1 only:	113 Mbit
During 3.0 timeslot:	14 Mbit
Average, 2 time slots:	64 Mbit



Summary of Model Results

Node size		Technology & QAM Bitloading	Tier, 6 dB coax margin		Tier, 6 dB impaired	
Amplifiers	Homes		PHY : Tier	Mbps	PHY : Tier	Mbps
N+0	65	R-PHY, 4096	2:1	**127**	3:1	**65**
15	250	Linear, 2048	2:1	**110**	3:1	**61**
45	500	Linear, 1024	2:1	**101**	3:1	**49**
60	750	Legacy, 256	3:1	**55**	3:1	**38**

Table 7: Estimated Tier Rate Capabilities
Four Example Network Cases, Normal and Impaired Operation

Note:
To simulate capacity in the impaired condition, all minislot bitrates from the normal operation condition were reduced by a full square lattice step (two bitloading steps down in the D3.1 specification). This is equivalent to an overall CNR reduction of 6 dB.

Observations Concerning Network Investments

The methods described in this paper carry obvious and not-so-obvious costs, both at deployment time and on an ongoing basis. Here is a short list:

Capital costs:
An unfortunate truth of launching a tier rate increase is that higher speeds require commensurate investment. On the capital side, the main components are optical or R-PHY equipment, hub de-combining with new CCAP ports, and field node splitting (also with new CCAP ports).

Expense-side costs:
On the expense side, the primary costs will be traffic monitoring and remediation after the initial installation, coax network hardening with associated ongoing maintenance, and U/S access network alignment (also with associated ongoing maintenance). Fortunately, much of this expense amounts to small increments to practices already in place.

Upstream and Downstream Spending Background and Realities

Cable Modem Capabilities
One of the authors (Brooks) was instrumental in the original selection of 5-85 MHz as the next common sense upper return system boundary if a new diplex split frequency were to be adopted. We were successful in establishing it as an option in the DOCSIS® 3.0 specification many years ago. Unfortunately, implementation of this option in the CM was not sufficiently low in cost (particularly where multiple diplex splits are implemented in the same CM), and as such, 5-85 capable CMs were never adopted in any significant quantity. Only one major operator internationally has deployed at 5-85 MHz to the best of our knowledge.

What was formerly optional has now changed to a requirement in the DOCSIS® 3.1 specification. All CMs MUST support 5-85 MHz operation, and the underlying silicon MUST support 5-204 MHz U/S operation.

Once sufficient quantities of these more capable CMs are in the homes of our customers, investment in a access network upgrade will yield immediate benefits. Until that time, the techniques described in this paper provide a way to enjoy the U/S capabilities of the DOCSIS® 3.1 system with success-based investments during the installation of the first few modems.

The Time Warner Cable Perspective
It has long been the belief at Time Warner Cable that the Achilles heel of modern HFC networks is not D/S capacity, but rather U/S capacity. In the D/S direction, leadership in switched digital video technology has allowed TWC to defer investment in digital to analog television adaptor technology until very recently. As TWC begins DTA deployments in earnest, it is quickly apparent that harvesting analog spectrum in a mix of 750, 870, and 1 GHz SDV-enabled access networks produces prodigious amounts of D/S spectrum. Upon population with high-channel-count D3.0 bonding groups, digital multicast can provide broadcast capacity dividends not unlike the SDV capacity dividends of the past decade. When first installed in unmodified networks, this DOCSIS capacity

will be modest. However, SDV-based experience in video traffic engineering has shown TWC the statistical power of service group traffic engineering and remediation, a skill that directly translates into the IPTV world. As previously observed in this paper, when a new technology is first installed, traffic will not match the platform assumptions. Only after time is spent adapting the network topology to the demand set will activity calm down to a manageable steady state level. Subsequent spending then becomes success-based, with all of the ensuing advantages. In this way, the D/S MPTS (multi-program transport stream) to IPTV video conversion process is likely to follow a path similar to what is being suggested for the U/S in this paper.

Distribution Hub Strategy
To make traffic engineering based remediation practical, it is necessary to have a network that is easily scaled where demand appears. Time Warner Cable is fortunate to have an HFC access access network architecture platform with well-positioned distribution hubs. Over 90% of the TWC customer base lives less than 20 km from a hub building. This short route distance makes practical the use of high performance optics, and is also key to future FTTx (fiber to the x) network overlays should they be required. Couple these short links with small nodes and abundant dark fiber (more than half of TWC networks carry 6 fibers per node), and traffic engineered demand remediation via segmentation becomes fast and efficient. While this short hub distance improves remediation ability for both U/S and D/S traffic, D/S is not subject to the network split based tier limits of U/S. In the D/S direction, SDV combined with multicast IPTV can offer the luxury of deferring further investment in the HFC access network, while allowing fast response to market requirements and competitive threats. This is only true if a matching U/S strategy is present. This paper hints at the possibility of such a strategy.

While TWC and other operators are well-positioned for D/S capacity, U/S capacity continues to be a concern shared with the entire industry. The capacity limit of DOSCIS 3.0 over the sub-low U/S of our current HFC networks is a risk factor in the face of market and competitive demands. While answering that risk that has been the focus of this paper, it is by no means the end of the story.

Comparison to a 5-85 MHz mid-split upgrade

As market demands and competitive threats continue to evolve, measured and timely responses will be called for. This paper presents an evolutionary step towards solving the immediate U/S capacity issue, while at the same time, potentially deferring investment for a technology choice we don't have to immediately make. As part of a potential access network technology evolution, there are four known future alternatives:

1. The subject of this paper: 100 Meg tiers over 5-42 MHz, retain the current D/S capacity
2. 5-85 MHz U/S mid-split with either 105-1002 or 105-1218 MHz D/S
3. 5-204 MHz U/S high-split with either 258-1002 or 258-1218 MHz D/S
4. Fiber to the home, either directly to EPON or combined with RFoG as a bridge technology to leverage legacy devices.

While a thorough analysis of these options is beyond the scope of this paper, a direct comparison between options 1 and 2 deserves at least an introduction. A comprehensive financial analysis was originally planned for inclusion in this paper, with a focus on costs and issues relative to a 5-85 MHz mid-split upgrade. Due to the complexity and scope that a reasonable treatment of that topic would require, we are saving it for subsequent publication. Our premise was and is that the techniques presented here make business sense both as an alternative to a 5-85 MHz upgrade, while at the same time, as an incremental investment towards a future split-change. Look for more from us in the future on this topic.

Here is a short list of some attributes of those two options:

100 Mbps over 5-42 MHz:

- Invest in D3.1 CCAP, optics, limited node splitting, and CMs
- No amplifier changes result in minimal customer disruption
- No legacy device protection filters; use of 85 MHz has been shown to cause interference
- No loss of fixed-tuned settop FDC carriage; therefore all legacy settops continue to function
- Faster completion for market or competitive responses
- Lower cost allows deferral of larger investment until needs become more clear
- Investment value carries forward to a future split change

~ 250 Mbps over 5-85 MHz mid-split

- Invest in D3.1 CCAP, optics, and CMs; upgrade 100% of node and electronics modules
- Yields 1002 MHz or greater additional D/S capacity as a by-product
- Node and amplifier modules are refreshed to address aging active electronics
- Optics performance is less critical than when only 5-42 MHz of spectrum is available, as the mid-split or high-split approaches require less aggressive bitloadings for high tier rates
- Access network maintenance is less demanding due to lower CNR requirements and bitloadings
- Service group size control is less critical due to the better statistics of larger shared capacity pools, both in the U/S and the D/S

Takeaways

We would like to leave you with a short list of important observations, understandings, and assertions that have been developed along the path of constructing this technical work:

- Total amplifier counts matter to U/S CNR performance; amplifier cascades do not.
- For U/S capacity, node size is important, while node plus zero has little relevance beyond the impact of forced, fixed-investment node size reduction
- HFC access network can support high U/S capacity at or near present node sizes with the right optical or backhaul solutions.
- Remote PHY is important for very long reach access networks, but is not required for and may not be competitive with linear optics for shorter 5-42 MHz links
- 4096-QAM is difficult to use, even with R-PHY, due to the dominance of CM MER. Improvements in CM MER may change that equation in the future.
- 100 Mbps tiers are possible in 5-42 MHz HFC access networks, and should be attempted once DOCSIS® 3.1 systems become available

Bibliography

Data-Over-Cable Service Interface Specification:

DOCSIS® 3.1
Physical Layer Specification
CM-SP-PHYv3.1-I02-140320

Credits

Alberto Campos, CableLabs
A very special thanks goes out to Alberto for his patience, detailed answers to my questions, and in particular for his monster of a DOCSIS 3.1 minislot dimensioning model, which gave me the confidence to at least make an approximation of physical layer efficiency of various bitloadings and pilot structures.

The following individuals also deserve mention for their editorial efforts, research work, and encouragement:

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Hermann Gysel, InnoTrans Communications
George Vasilakis, InnoTrans Communications
George Hart, Rogers Communications
Jack Moran, CableLabs
Belal Hamzeh, CableLabs

Abbreviations & Acronyms

DOCSIS®	Data Over Cable Service Interface Specification
DOCSIS® 2.0, 3.0	Data Over Cable Service Interface Specification, version 2.0 or 3.0
DOCSIS® 3.1	Data Over Cable Service Interface Specification, version 3.1
D2.0, D3.0	Data Over Cable Service Interface Specification, version 2.0 or 3.0
D3.1	Data Over Cable Service Interface Specification, version 3.1
CM	Cable Modem, Modem
CCAP	Converged Communications Access Platform (a physical device that includes and is often referred to interchangeably with CMTS)
CMTS	Cable Modem Termination System
HFC	Hybrid Fiber Coaxial (access network)
CNR	Carrier to Noise Ratio
MER	Modulation Error Ratio
PER	Packet Error Ratio
D/S	DownStream, aka forward; signal flow towards the customer
U/S	UpStream, aka return or reverse; signal flow towards the hub
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
TDMA	Time Division Multiple Access
FaTDMA	Frequency and Time Division Multiple Access
S-CDMA	Synchronous Code Division Multiple Access
A-TDMA	Advanced TDMA
PHY	PHYsical Layer
R-PHY	Remote PHYsical layer access platform
QAM	Quadrature Amplitude Modulation
SC-QAM	Single Carrier Quadrature Amplitude Modulation (in D3.0 & D2.0)
RF	Radio Frequency
BPSK	Bi-Phase Shift Keyed
QPSK	Quadrature Phase Shift Keyed
PSD	Power Spectral Density
UC	UpConverter
DC	DownConverter
Mbps	Bitrate, in million bits per second
5-42 MHz	HFC coaxial network U/S passband; FDMA with D/S and U/S crossover of 42 MHz to 54 MHz; aka sub-low or sub-low split
5-85 MHz	HFC coaxial network U/S passband; FDMA with D/S and U/S crossover of 85 MHz to105 or 108 MHz; aka mid-split
Gigasphere	CableLabs' consumer name for DOCSIS® 3.1 based technology
TCS	Transmit Channel Set
FEC	Forward Error Correction
MPTS	Multi-program transport stream (per MPEG specifications); the CATV industry transport standard for digital video over HFC
LDPC	Low Density Parity Check