DISTRIBUTED DIGITAL HFC ARCHITECTURE EXPANDS BI-DIRECTIONAL CAPACITY

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Abstract

This past year has brought about a re-kindling of interest in the concept of moving the boundary between digital content (both data and video) and the RF domain away from the headend and further into the HFC network, out to the fiber optic node. While few dispute certain operational benefits, such as the ability to change QAM allocations more easilty, or the ease of "set and forget" installations, there is still a great deal of debate around what functions should be moved, in what order, and in what combinations. This paper attempts to clarify some of the tradeoff decisions by presenting a careful analysis of the performance profiles of today's analog forward and reverse optical links, and contrasts them with the gains enabled by transitioning to digital links. This paper also quantifies the benefits, using digital re-designs of actual N+5 and N+0 HFC systems.

INTRODUCTION

Since the early 1990's, the cable industry has invested heavily in building the hybrid fiber coax (HFC) infrastructure that is unequaled today in its ability to deliver bandwidth-intensive services to hundreds of millions of subscribers worldwide. A perennial question that haunts the industry is whether the HFC architecture is a viable solution for the next twenty years of evolution in subscriber demands. The simple answer is an emphatic "Yes!"

The traditional HFC network (Figure 1) comprises five major elements contributing to the system impairments. Some networks have fewer elements. For example, Fiber Deep N+0 networks do not have RF amplifiers after the node, which is critical to enabling forward bandwidth expansion, and also reduces return path noise funneling. Similarly, RFoG networks move the fiber-to-coaxial cable interface to the home, and significantly lower CPE contribution to signal performance degradation by providing relatively high signal levels for in-house wiring and networking.

There are complementary layers of innovation at the cable headend to support increasing levels of spectral efficiency for any given signal level, and at the customer premises to control in-home signal degradation. The key to promoting the HFC architecture's resiliency, however, is in reclaiming the signal performance margin that is currently consumed by the outside plant in large part due to the complex art of propagating RF signals over fiber (a.k.a. "analog fiber").

Technology and subscriber demands have combined to create an industry-wide push to initiate a new phase of growth, significantly expanding forward and reverse capacity above current levels. It is therefore prudent to perform a thorough review of optical link options between headends and nodes.

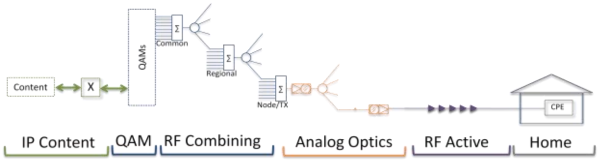

Figure 1: Five Major Elements of Traditional HFC Networks

EXISTING NETWORK ANALYSIS

Analog Forward Optical Links

Analog optical links (analog fiber) have served the cable telecommunications industry since late 1980's and have been crucial to the success of the broadband HFC telecommunications networks. They provided significant improvements in network reliability and service availability while maintaining optimal performance for signals carried on coax. They also significantly lowered operational costs and enabled network simplification by:

- Eliminating AML and FML links, which were used to serve remote pockets of subscribers but were burdened with regulatory and licensing compliance and subject to weather-related signal fading;
- Reducing RF amplifier cascades, which contribute significantly to noise and reliability issues, especially in the upstream path;
- Consolidating headends and hubs.

Analog optical links supported centralized signal processing at the time when the technology for distributed signal processing in the nodes was not practical without installation of secondary hubs and sizeable OTNs. With advances in silicon, especially in FPGA technology, distributed signal processing in the nodes is increasingly cost-competitive with and as reliable as traditional centralized processing. It is now possible to blur the functional boundaries between headend and node. As technology progresses, the choice of where to place the demarcation point is increasingly a question of operational organization rather than the feasibility of physical or functional capabilities in the node.

With the progress of the technology and the need for sizeable capacity gains in upstream and downstream, driven by demand and competition, it is important to understand the sources and causes of signal degradation in existing analog links, especially in relation to the content payload that is transmitted within the links.

OMI: Composite and Spectral Density

In a traditional, centralized architecture, signals are carried in their final RF format from headend through analog fibers and coaxial distribution network to CPEs. Hence, analog fiber OMI limits apply, and the performance of analog fiber is cascaded with the performance of all other network components from the RF signal source to the CPE.

In addition, the usable frequency bandwidth of fiber links in multi-octave HFC networks is constrained by the RF amplifier technology and cascades when carrying an RF signal load.

The original analog fiber transmitters were designed with sufficient OMI to support analog NTSC video in combination with 64- and 256-QAM signals over 450 MHz plant. As plant bandwidth expanded to 550 MHz, then 625 MHz, 750 MHz, and now 1 GHz, the composite OMI was distributed over increasingly wider bandwidth, leading to an increasingly lower OMI/Hz and OMI/channel. This trend is exacerbated by the discontinuation of analog NTSC video. In the presence of large numbers of analog NTSC channels, with their significantly higher CNR requirements, bandwidth expansion for QAM channel load added at levels 6 dB lower resulted in a very limited drop in OMI/Hz.

But in HFC networks with dominant QAM loading and even distribution of RF levels, the drop in OMI/Hz is noticeable. This results in per-channel degradation of analog fiber performance.

In HFC networks with RF amplifiers, the bandwidth capacity can be expanded by improving the end-to-end SNR, up to the capacity limit defined by Shannon's law:

$$C=B \log_2 (1+S/N)$$

With network CNR (SNR) of 33 dB (for 256-QAM signals), the theoretical capacity would reach approximately 11 bits/Hz and close to 9 Gbps in 154 6 MHz QAM channels. The real capacity with 154 256-QAM channels approximates 6.2 Gbps, remarkably close to the theoretical limits in the real network with all its operational margin requirements and changing operational conditions as well as equipment implementation losses. This is an endorsement for HFC networks, their design rules, and the operational practices developed by the cable industry and implemented by the network operators.

This capacity can be further increased approximately 15% to 20% (close to 7.5 Gbps after accounting for overhead losses) by increasing the FEC power . Further capacity expansion would require more efficient modulation/coding schemes. OFDM could increase the capacity by an additional 10% to 15% by limiting guardbands between RF digital carriers (increasing effective BW).

In the HFC network designed to carry 79 analog NTSC carriers (or equivalent analog load – minimum 50% of the operational bandwidth), some spectrum segments support better EOL performance (at least 10 dB better). These segments can carry digital RF carriers with higher modulation levels. Table 1 presents possible forward frequency allocation schemes for a 1 GHz HFC network and its related capacity. It also presents the increase in potential capacity for a traditional (not distributed) HFC N+5 network subject to a limited upgrade.

	Bandwidth (Channel Allocation)				
Bandwidth	Analog Channels	Priority Load Adv. PHY Digital RF Channels (BW)	Advanced PHY Digital RF Channels (BW)	Legacy Digital RF Channels	Approximate Total Data Capacity
54 to 1002 MHz	64	0	0	90	3.6 Gbps
	64	0	192 MHz	58	4.1 Gbps
	32	192 MHz	192 MHz	58	6.1 Gbps
	32	192 MHz	384 MHz	24	6.3 Gbps
	0	0	0	154	6.2 Gbps
	0	384 MHz	384 MHz	24	8.4 Gbps
282 to 1050 MHz	0	384 MHz	384 MHz	0	7.4 Gbps
282 to 1194 MHz	0	192 MHz	576 MHz	24	8.0 Gbps
	0	192 MHz	720 MHz	0	8.4 Gbps

Table 1: Enhanced Network Capacity (up to 1 GHz and above). Example for North America

As apparent from the table, in 1 GHz HFC networks designed to carry 79 analog NTSC channels and 75 RF digital channels, significant capacity gains can be realized by replacing analog channels and some existing RF digital channels (subject to the need to support legacy services) with RF digital channels with more robust FEC and OFDM coding.

This option exists for any network which has been designed to carry analog cable channels. However, in networks designed for a reduced upper operational frequency, the resultant increase in capacity would be lower. Moreover, in networks designed for QAM-only load, the capacity gains would be limited because there are no spectrum segments designed for higher performance; their design has been cost-optimized to reliably support services for 256-QAM signals as defined in ITU J-83, but some gains can be realized by replacing the existing QAM channels with RF digital channels with more robust FEC and OFDM coding which can be carried on the network with performance which supports the carriage of 256-QAM signals.

Further capacity gains would require either sizeable improvement of the EOL performance or bandwidth expansion, or both.

Operational Margins: The Reprieve Granted by VSB Modulation

The traditional North American HFC network loading contains 79 analog NTSC modulated carriers, which closely resembles the ratio of analog to QAM channels in other regions. In 1 GHz operational HFC networks, these analog channels are usually accompanied by 75 QAM modulated digital carriers. The 256-QAM signals are set usually 6 dB lower in RMS power relative to the equivalent RMS peak value of NTSC channels (or RMS values of CW carriers used during the testing). The analog carriers are considered "priority loading" due to their higher CNR requirements (relative to the CNR requirements for 256-QAM carriers as defined in ITU J-83).

The optical link OMI levels are optimized to allow for acceptable contribution of CTB and CSO and optical link noise (from all noise contributors) based on performance allocation among different HFC network elements (different for different operators and architectures) while still maintaining acceptable margin to QAM channel clipping. The commonly accepted clipping margin is set for 1 dB from BER values of 10E(-5) while a 1 GHz capable analog optical transmitter is tested with the nominal load of 79 CW carriers and 75 QAM carriers (either Annex B or C for 6 MHz wide channels or Annex A for 8 MHz wide channels).

In the operating environment, CW carriers are modulated with an average power 4 dB lower than their peak power (and with 79 channels, this lower power is realized). This margin is critical in an operational environment which is subject to test equipment errors, level setup errors and signal fluctuation, and ultimately results in quite reliable operation of analog optical links without clipping. It also changes the operating point of the laser transmitter. To maintain this reliable operation, it is recommended that this operational margin is maintained with the load that comprises exclusively RF modulated digital carriers or that the operational inaccuracies and variabilities are remedied at the analog fiber transmitter with composite power ALC to avoid clipping. Even in that case, 1 dB additional operating margin is recommended for reliable operation of the network with only an RF digital carrier load.

Table 2 compares the relative composite OMI change due to this modulation versus OMI with CW and QAM channel load. This table also presents the OMI/Hz change for different loads for two recommended operational margins.

Before we summarize the results of the analysis, the following assumptions and disclaimers should be noted :

1. The analysis presents only the results of relative OMI spectral density for fixed composite OMI values of the lasers and disregards RIN changes with frequency expansion.
2. It also assumes the same shot noise, receiver noise and IIN in the link as well as the same other impairment contribution in single- and multi-wavelength analog fiber links.
3. Consequently, it assumes that the analog fiber links were designed to provide adequate performance for the network carrying 79 NTSC analog channels and 75 256-QAM channels (or equivalent loads). For networks optimized to carry loads optimized for materially fewer analog NTSC channels or QAM-only load, the analog fiber links would have to be redesigned with:
   a. Transmitters with higher launch power (and the same OMI capabilities) assuming the launch power is not limited by other considerations;
   b. Transmitters with better RIN (especially if the receiver optical input levels are relatively high);
   c. Transmitters with higher OMI capabilities (it may affect other noise contributing mechanisms in analog fiber links);
   d. Receivers with much better performance, or
   e. A combination of the above remedies if they can be implemented.
4. If the analog fiber link transmitter was replaced, contribution from all other impairment sources and mechanisms must be reassessed.

Also, this analog fiber link performance improvement effort may be trumped by the BW expansion limitation of the RF coaxial section of the HFC system.

Traditional RF load		Digital RF carrier only load	
79 CW and 75 256-QAM signals	79 NTSC carriers and 75 256-QAM signals	Recommended with TX ALC	Recommended without TX ALC
[dB]	[dB]	[dB]	[dB]
-1	-3.9	-1	-3.9

Relative composite OMI referenced to maximal composite OMI for BER 10E(-5) of 256-QAM signals

	Existing Bandwidth 54 to 1002 MHz		
	154 256-QAM load	122 256-QAM & 192 MHz of priority load	90 256-QAM & 384 MHz of priority load
	[dB]	[dB]	[dB]
	924 MHz	732 & 192 MHz	540 & 384 MHz
TX with ALC	+3	+1/+7	0/+6
TX without ALC	+1	0/+4	0/+2.3

	Extended Bandwidth Analysis				
	186 256-QAM load	154 256-QAM & 192 MHz of priority load	186 256-QAM & 192 MHz of priority load	286 256-QAM load	314 256-QAM load
	[dB]	[dB]	[dB]	[dB]	[dB]
	1116 MHz	924 & 192 MHz	1308 MHz	1716 MHz	1884 MHz
TX w/ ALC	+2.6	+0.4/+6.4	0/+6	+0.4	-0.5
TX w/o ALC	+0.3	0/+1.7	NA	-1.5	-2

OMI per channel or Hz relative to the OMI per channel or Hz for 79 CW and 75 256-QAM load

Table 2: Relative OMI Analysis of Analog Fiber

The results of the analysis show that the replacement of analog channels with RF modulated digital channels within 1 GHz operating BW (54 to 1,002 MHz) in analog fiber links with ALC TXs enables approximately 3 dB increase in OMI per RF digital channel for all channels at the same level. Two other examples of loads result in a 6 dB higher OMI/Hz for a single priority load of 192 MHz BW segment and two priority loads of 192 MHz BW segment while maintaining the same or better OMI/channel for 256-QAM channels as exhibited in the link with 79 analog and 75 RF digital channel load. This approach preserves the performance of QAM-signals. In summary, the analysis supports the numbers presented in Table 1. It assumes that the source of the digital signal in the headend has sufficiently higher performance and the RF combining network is eliminated for the new signals (in fact, even if it remained, its impact is minimal).

The analysis also shows that the expansion of the optical fiber link bandwidth to 1.2 GHz and 1.4 GHz is also supported (assuming no degradation from RF amplifiers) with the addition of a single 192 MHz priority OMI segment. Further, the analysis shows that it is possible for analog fiber links to support in excess of 1.8 GHz of bandwidth with performance equivalent to the performance of 256-QAM signals.

Whether this expansion can be supported by the coaxial part of the HFC network will be analyzed further.

It is an operator’s choice to maintain, increase or lower the operating margin to clipping recommended by the authors. However, with OFDM signals and their higher PAPR, the clipping is more likely to occur. Even if the OFDM signals are more immune to clipping due to their characteristics as well as symbol rate and duration, in a hybrid load system all signals are clipped at the same time so 256-QAM signals supporting legacy services will be clipped much more often in a load with OFDM channels than in a purely QAM load. The operational margin is even more critical unless PAPR reduction methods are applied to the OFDM signals.

One last note: improvements in performance in high-performance optical links have a lower impact on EOL performance because the HFC network design is cost-optimized to take advantage of higher link performance. HFC networks deliver performance at the customer outlet: 47 to 49 dB CNR in frequency ranges carrying analog TV channels and 37 to 39 dB CNR and MER in frequency ranges carrying 256-QAM signals. This fact limits bandwidth expansion options that could be realized by incremental improvements in performance of the analog fiber link (if possible) without significant upgrades in the coaxial part of the HFC network. It is in this case where a step performance improvement can be realized with the replacement of the analog fiber link facilitating bandwidth expansion with just limited upgrades in the coaxial section of the HFC plant.

Analog Reverse Links

The reverse link analysis will start with an explanation of the operating requirements of the network.

Dynamic range

The dynamic range of the reverse optical link is defined as the range of the input power from the level where the link provides sufficient performance (CNR) to support end-to-end transport of the signals to the level where the reverse transmitter introduces clipping resulting in 10E(-6) BER. The CNR requirements for the reverse optical link will depend on the network configuration (how many CPEs and RF amplifiers are funneled into a single transmitter), the required combining levels and the CNR contribution of the RF splitting network and RF signal receivers (e.g., CMTSs) in the headend.

Dynamic range depends on several factors:

- Long loop AGC level range (hysteresis) and the operating point of the CMs within their output level range,
- Optical level stability of the transmitter,
- Gain/loss stability of the headend RF splitting/amplification network,
- Funneling of ingress and other impairments.

The long loop AGC hysteresis depends on implementation and could be as wide as ±3 dB (the wider window is beneficial for some considerations but is detrimental to reverse transmitter load fluctuations). In this analysis, it is assumed that the CM operates within its range of output levels so it is capable of reducing power when directed by long loop AGC. The analog optical transmitter power changes can be quite dramatic but well designed transmitters stay within ±1 dB (for the best designs sometimes lower). This is equivalent to a ±2 dB RF level change on the optical transmitter input enforced by long loop AGC. The RF splitting network, barring some unintended human error, should be reasonably stable but it is prudent to assume ±0.5 dB change. These three elements add to a 5.5 dB dynamic range requirement (level swing above the nominal link setting point). The additional contributors (ingress and noise funneling) depend on the network configuration and can be as high as 4-6 dB for N+5 HFC network, 2-4 dB for FD network and very little for RFoG networks (a subject for a separate discussion).

This results in a requirement of approximately 10 dB dynamic range for the analog reverse fiber link. Under simplified assumptions such as similar quality receiver and others, this translates to 10 dB better link performance requirements for the same distance, signal performance requirements and the same BW as in the forward if the RF amplifier funneling noise is disregarded and reverse receivers are not combined or the same and lower link performance requirements from lowering load BW, signal performance requirements and/or reach (The latter should match the forward reach unless E-O-E regeneration is implemented.)

Broadband Digital Links

Digital links have several advantages over the analog fiber links. The most important are:

- Link performance does not change with distance within the specified range.
- The link is extremely thermally stable and hence its dynamic range requirements can be lowered by 2 dB. (The input level operating point can be raised by 2 dB thus improving link CNR by 2 dB).
- The link performance does not change with the design BW as long as the same number of coding bits is used and the ratio of the sampling frequency to the upper operational frequency is the same.

Of course, as with an analog link, the link performance depends on the ratio of the real BW load to the maximum designed BW load because for lower real BW load the spectral density of the input signal can be increased within the limits of the maximum composite input power for the defined dynamic range.

Hence, for digital reverse links (and forward too), the considerations are related to and the decision is based on the cost of the link and the status of the technology. To their advantage, digital links provide all the benefits of analog links, with one notable exception, and bring additional benefits while avoiding all their shortcomings. If cost is not an issue, digital links can be made arbitrarily transparent to any signal requirements.

RF Headend and Hub Combining Network

The headend combining network is a negligible contributor to the system performance today but with a higher performance requirement for higher modulation signals, it cannot be neglected going forward. The main degradation is caused by crosstalk between narrowcast signals through the broadcast combining network which was built for analog fiber links with full spectrum transmitters (this degradation is eliminated in BC/NC overlay systems).

RF Amplifiers

RF amplifiers are a necessary evil in HFC networks when an optical node serves a large area through long coaxial cable runs. They compensate for coaxial cable loss which increases drastically with frequency, and for RF passive loss (reasonably flat in the most recent designs for up to 2 GHz and beyond). RF amplifier technology has progressed over the years. Most recently, after the first deployment of HFC networks, the operational BW of RF amplifiers increased from 450 MHz to 1002 MHz and their composite power output capability by 8 to 10 dB with the introduction of the first power doubling hybrids. This means that for a cable span of 18 dB loss, progress in RF amplifier silicon compensated for the increase in cable loss from 450 MHz to 1002 MHz. However, for longer cable spans, the RF amplifier network would have to be re-designed (re-spaced) or other network elements contributing to the signal impairments materially improved or eliminated. Alternatively, the signals placed above 450 MHz would be more immune to cable impairments and hence require lower levels thus increasing the “equivalent” level of the amplifier output power. Typically, QAM signals above 550 MHz and now above 450 MHz are at a 6 dB lower level relative to the equivalent analog channel level. This allowed for significant slope increase to compensate for the cable loss not compensated for by a simple linear extension of the existing slope.

The most recent introduction of GaN hybrids with increased output power capability enables linear extension of the slope from 1 to 1.2 GHz if RF actives with GaAs hybrids are replaced with the new actives. Table 3 presents the results of analysis for possible level/slop increases while maintaining the levels with 1 GHz within ±1 dB of the current levels under the assumption that the output power capability of GaN hybrids is approximately 2 dB higher than that of GaAs hybrids for the same level of performance. For RF actives with older hybrid generations, the output power capability increase was larger so when analyzing the network for BW upgrades, the generation of the RF active hybrids should be determined and considered.

		Levels at						
	Slope	54 MHz	551 MHz	999 MHz	1191 MHz	Load	Composite Power	Technology
Bandwidth	[dB]	[dBmV]	[dBmV]	[dBmV]	[dBmV]		[dBm]	
54 to 1002 MHz	14.0	37.1	44.4	45.0	NA	79CW + 75QAM(-6 dB)	14.9	GaAs
54 to 1002 MHz	14.0	37.1	44.4	45.0	NA	79A + 75QAM(-6 dB)	13.4	GaAs
54 to 1002 MHz	14.0	31.1	38.4	45.0	NA	154QAM	13.0	GaAs
54 to 1002 MHz	14.0	37.1	38.4	45.0	NA	384 MHzP (<500 MHz) + 90QAM(-6 dB)	14.5	GaAs
54 to 1194 MHz	17.0	31.1	38.4	45.0	48	192 MHz + 154QAM	16.0	GaN
54 to 1194 MHz	17.0	31.1	38.4	45.0	48	384 MHzP (<500 MHz) + 122QAM(-6 dB)	16.8	GaN
54 to 1002 MHz	18.0	39.6	48.9	51.5	NA	79CW + 75QAM(-6 dB)	19.9	GaAs
54 to 1002 MHz	18.0	39.6	48.9	51.5	NA	79A + 75QAM(-6 dB)	18.8	GaAs
54 to 1002 MHz	18.0	33.6	42.9	51.5	NA	154QAM	18.5	GaAs
54 to 1002 MHz	18.0	39.6	42.9	51.5	NA	384 MHzP (<500 MHz) + 90QAM(-6 dB)	19.6	GaAs
54 to 1194 MHz	21.5	33.6	42.8	54.8	48	192 MHz + 154QAM	22.0	GaN
54 to 1194 MHz	21.5	39.1	42.3	54.3	48	384 MHzP (<500 MHz) + 122QAM(-6 dB)	22.0	GaN

Table 3: Slopes and Levels in RF Actives of the HFC Plant: GaAs versus GaN

In House Wiring and CPE

The last section of the HFC network, in-house wiring, is out of the control of the network operator. It introduces the largest variability of performance due to several factors:

- Where in the cascade of RF amplifiers the CPE is located (some CPEs may be connected to the first line extended off the node, the others at the end of the cascade);
- Drop length variability to the house entrance;
- The in-house wiring splitting ratio and length of in-house wiring;
- The quality of the in-house wiring components.

The data presented during the standardization effort of advanced PHY for HFC access technologies support the high performance variability picture in both the downstream and upstream. In the downstream, the median SNR levels are close to a 36 dB value ±1 dB. There are however some CPEs with performance lower than 33 dB SNR. This number is bound to increase with an extension in the forward bandwidth unless the operators make an effort to lower the variability and improve the performance.

This variability should be lower in FD (passive coax) HFC networks as the cascade origination point difference disappears in this architecture.

Drop length variability will always be there but except for extreme cases it can be accounted for in the design rules.

The two last items are the most difficult to address but with integration/consolidation of CPE devices, gradual elimination of analog cable TV channels and improvements in home networking technologies, the needs for many CPE devices connected directly to the HFC network via extensive splitting to serve a number of rooms with different services, currently requiring separate CPEs, will gradually diminish.

In the extreme cases of high in-house wiring loss, the operator has an option to deploy drop amplifiers, uni- or bidirectional, depending on needs.

The ultimate solution would be deployment of residential gateways with the signal terminating there. This would allow for elimination of 10 dB loss of in-house wiring.

This, however, becomes critical for significant bandwidth expansion networks. For the incremental capacity expansion summarized in Table 1, the existing CPE configuration will cause only limited problem in the networks that were optimized for QAM-only load. In the networks with large numbers of analog channels, operating today reliably for both analog and digital services, the levels received by analog and digital CPEs and consumer electronic devices allow for the bandwidth expansion presented in Table 1 if they can be supported by other segments of the network.

Recap of the Existing 1 GHz Network Capacity Limits

The results presented in Table 1 show that the existing network capacity can be increased incrementally but the expansion of the capacity depends on how the network was designed.

If all positives align:

- All analog channels can be eliminated in the network designed to carry them reliably and replaced in large part by a priority load of RF digital channels;
- The expansion of bandwidth in analog fiber links is possible;
- The RF actives in N+x (x>3) use technology pre-dating GaN hybrids;

- All legacy digital channels can be replaced by Advanced PHY channels;
- The existing frequency split between downstream and upstream is not changed;
- The in-house wiring supports reliably services carried on the existing analog and digital channels;

then the network capacity can be increased from the reference number of 6.2 Gbps to above 10 Gbps.

Some of the conditions listed above are related to the transition from the existing services to the digital services on Advanced PHY (analog channel reclamation, replacement of legacy digital channels with Advanced PHY digital channels) and some on the technology capability. The analog fiber links are one of the major contributors to the technology related condition. Their elimination would enable remedying the remaining technology obstacles to capacity expansion. Indeed, it would allow for significantly larger bandwidth expansion than the maximum possible in the existing HFC network (without a distributed forward architecture) even if all the conditions for this expansion are met. This would allow for significant capacity expansion without the need to replace the existing legacy-signal based services.

DISTRIBUTED ARCHITECTURES

Telecommunication Networks

In data networking systems, distributed architectures are ubiquitous. Examples include the Internet, cellular voice networks, and aircraft control systems. Benefits of the distributed architecture include greater reliability (no single point of system failure), better cost-efficiency (small clusters of functionality rather than an expensive monolithic system), and easier scalability and manageability.

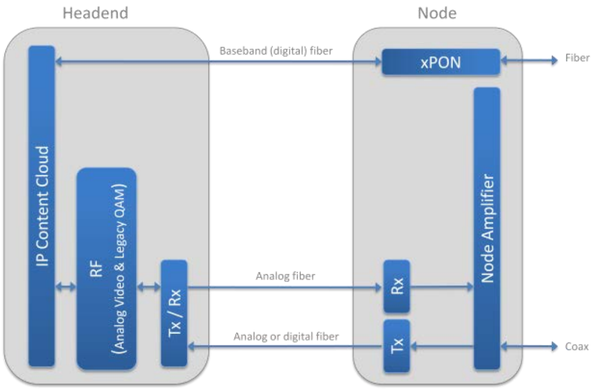

Figure 2: Headend-to-Node Block Diagram

Distributed Architecture Trends in HFC Networks

Until recently, the computational power required to process data and digital video and convert it to RF signals was so power- and space-intensive that it could only be done at the headend. A new generation of processors, computer memory, and FPGAs make it feasible now to migrate many functions further into the HFC network. The Distributed Broadband Access Architecture, in which downstream RF signals are generated (and upstream RF signals are terminated) remotely in the node, is an elegant concept that has long been discussed in theory, but data networking costs and harsh conditions in the node have made it impossible to implement until now. Space and power in the node are limited, and operating temperatures can easily exceed 70º C, but advances in silicon processes and capabilities, as well as data networking, make it possible now to implement certain RF-related functional blocks in a compact, low-power, temperature-hardened footprint. The most difficult and expensive functionalities to implement compactly are software-related—packet processing, filtering, and switching—or buffer and storage-related, but since these functionalities are well-suited to headend-based aggregation, leaving them at the cable headend for now not only simplifies implementation but also causes the least amount of operational change, and is also desirable from a software stability and maintenance perspective. Nonetheless, a few more generations of silicon will frame the option of an all-Ethernet HFC as merely a matter of preference, rather than a technological difficulty.

Happily, due to both the modular nature of modern fiber optic nodes, and also the frequency-based service channelization (a.k.a. frequency division duplex, or FDD), distributed digital functionality can be deployed as a simulcast or top-band frequency addition, in parallel with existing services. In addition, since downstream and upstream services are deployed on separate wavelengths, node-based modulation and demodulation can be introduced independently (see Figure 3).

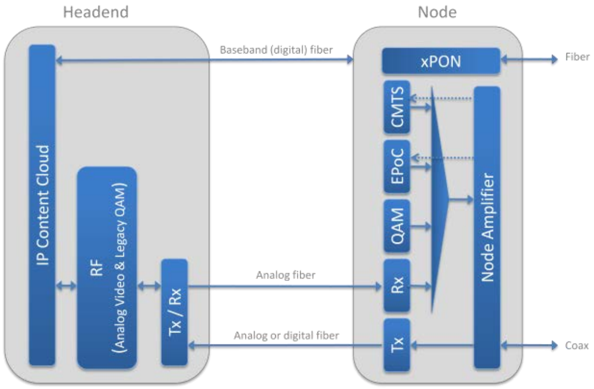

Figure 3: Migration of Services to the Node

As the analysis in the next section shows, the biggest benefit accrues from moving downstream RF generation from the headend to the node. Using today’s chips and components, it is possible to fill the entire forward band, from 54 MHz all the way to 1,000+ MHz, with universal (broadband, narrowcast, and data) QAM-RF channels generated in the node. It is also possible with today’s technology to place node-generated QAM channels all the way up to 1,800+ MHz. Future RF modulation standards and networking protocols can be added modularly (both physically in the node, and spectrally) as price-benefit tradeoffs dictate. For example, a Node QAM solution could be used to deliver legacy broadcast and narrowcast services in the 54 MHz – 1 GHz range, paired with a next-generation Ethernet-over-Coax solution above 1 GHz to deliver newer IP-based services. In certain cases, it may even be possible to directly convert Node QAM resources to other modulation protocols, although dense implementation of some of the more complex protocols currently under development will certainly require new silicon in order to meet power, space, and price constraints.

On a side note, the seemingly trivial question of what format to use for the digital transmission of bits between headend and node actually has cost and security implications. Options range from implementing a full multi-service TCP/IP router, to a Layer 3 or Layer 2 Ethernet switch, all the way down to a simple interleaved serial protocol. These solutions have a sliding scale of software complexity, introduce corresponding levels of delay and jitter, and require proportionate amounts of de-jittering buffer (which also consume space and power). Ultimately, the ability to connect the HFC plant directly to the headend IP network, or even the Internet, will be irresistible (see Figure 4). There will be certain costs, but many of those costs will become moot within a few generations of silicon, although vendors and operators should be mindful that the benefits of open Internet networking standards are paired with the responsibility to protect content from network-based theft, and the network itself from malicious intruders.

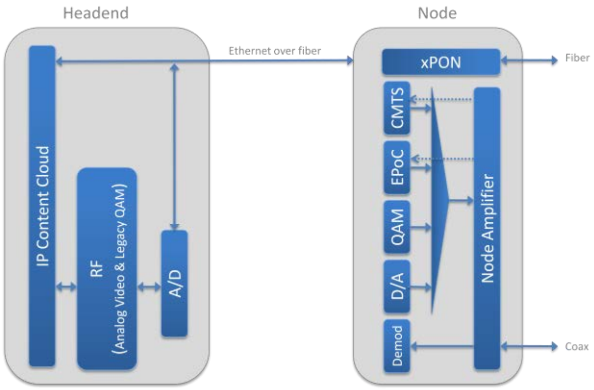

Figure 4: All-digital Broadband Access Architecture

In the upstream direction, some of the benefits of the Distributed Broadband Access Architecture can be realized simply by using digital return technology, already widely available from the top Optical Access Equipment vendors, and deployed in many hundreds of thousands of nodes. However, implementing upstream demodulators in the node have other benefits. For example, using a burst-receiver in the node to terminate the DOCSIS® return path not only reduces the noise funneling problem, but also simplifies the DOCSIS timing requirements and eliminates the need to keep cable modems within 100 miles of the headend. This approach meshes well with the goal of an all-Ethernet transport between headend and node.

Node Real-Estate

The Distributed Broadband Access Architecture is enabled through the precious real-estate owned by HFC operators: optical nodes. These robust and environmentally hardened enclosures with full remote monitoring and control provide significant advantage over CO/OTN-based topologies. They are much more robust and much closer to the final user and evolved into sophisticated yet reliable enclosures that are capable of supporting a multitude of Distributed Broadband Access Architectures in so called Virtual Hub configurations. Every optical node can be converted to a center of signal processing with all benefits of Distributed Broadband Access Architectures. The operational and technical and purely capacity expansion capability of this approach is unparalleled in any other telecommunications industry. Wi-Fi networks provide a similar approach but without the broad range of possible applications. Indeed, Wi-Fi networks can also benefit from and be supported by the optical node-based architecture.

CAPACITY EXPANSION WITH DISTRBUTED ARCHITECTURE

Bandwidth Expansion

Capacity expansions presented in Table 1 are mostly related to replacement of the existing legacy signals (analog and digital) with the Advanced PHY signals with their higher efficiency of bits/Hz. If there is a need to keep the legacy signals (and there will be for a while), the only viable solution to significantly increase the capacity is bandwidth expansion.

Bandwidth Efficiency

In any bandwidth, the material increase in capacity depends on improvement in network performance. As presented, the existing HFC networks for the performance they are designed achieve high efficiency already. This efficiency can be incrementally increased without improving the network performance by 20% to 30% with the introduction of Advanced PHY. However, the sizeable improvement in bandwidth efficiency will be gated by the capability of improving the network performance.

Both capacity expansion options are greatly advanced with distributed architectures.

DISTRIBUTED ARCHITECTURE IMPLEMENTATION CASES

Analysis Case Examples: Characteristics

Several examples of operating systems were selected for analysis. Characteristics of a few representative samples are collected in Table 4. These systems were re-designed with a distributed architecture for expanded bandwidth and their performance was modeled based on the design data. The list of the re-design cases analyzed is presented in Table 5.

Cascade	Existing High Fwd Freq [MHz]	MSO	System	Node	Plant Miles	HP	Density
							HP/MI
N + 5	750	A	Moscow	A149	11.91	758	64
				A168	10.55	955	91
				Total	22.46	1713	76
N + 5	860	B	Stalingrad	B15	7.94	556	70
				B52	6.81	628	92
				Total	14.75	1184	80
Fiber Deep (N + 0)	860	C	Kaliningrad	C004	1.10	92	84
				C005	1.26	116	92
				C006	0.95	50	53
				C007	1.02	123	121
				C008	0.90	64	71
				C009	0.89	77	87
				C010	0.92	64	70
				C011	1.24	120	97
				C012	1.01	111	110
				Total	9.29	817	88
Fiber Deep (N + 0)	1 GHz	D	Leningrad	D01	0.83	68	82
				D02	1.02	133	130
				D03	0.57	41	73
				D04	0.48	33	68
				D05	0.64	43	68
				D06	0.55	18	33
				D07	0.46	27	58
				D08	0.37	23	62
				D09	0.65	31	48
				D10	0.58	97	169
				D11	0.41	117	283
				D12	0.66	26	40
				D13	0.60	41	69
				D14	0.57	9	16
				D15	0.71	54	76
				D16	0.56	27	49
				Total	9.63	788	82

Table 4: Examples of Networks Analyzed and Re-Designed with Distributed Architecture

Original Design Freq & Type	C – New designs option 1 - with original house wiring								Number of Cases
	860	1002	1100	1200	1300	1400	1600	1800	
750 N+5	2	2							4
860 N+5		2	2	2					6
860 FD		9	9	9					27
1GHz FD				16	16	16			48
CPE	**Total number of test cases for individual network**								**85**
Original design Freq & Type	**G – New designs option 2 – without in-house wiring (with the gateway)**								
	860	1002	1100	1200	1300	1400	1600	1800	
750 N+x			2	2					4
860 N+x					2	2			4
860 FD					9	9	9		27
1GHz FD						16	16	16	48
Gateway	**Total number of test cases for individual network**								**83**
Grand-total number of test cases for individual network with different project specs									**168**

Table 5: Examples of Networks Analyzed and Re-Designed with Distributed Architecture

Downstream Performance of the RF Cascades

For apparent reasons, the RF cascade performance modeling for all extended bandwidth designs are presented for cases of the original 750 MHz N+5 and 860 MHz N+5 designs only.

The designs were performed with "Lode Data" design software under the following assumptions:

- No re-spacing of RF amplifiers;
- RF amplifiers with higher output level capability:
- 3 dB higher at the highest frequency for added bandwidth up to 1.2 GHz (assumes replacement of or modulation related de-loading from analog channels),
- 2 dB higher for bandwidth extension above 1.2 GHz (the analog channels are a smaller part of the total load and their removal or modulation effect is minimized),
- The amplifier gain is increased to support higher output levels at lower input levels defined by the design,
- This assumption may be too conservative for 750 MHz systems and for some 860 MHz systems with RF amplifiers dating back pre-GaAs period;
- Noise factor of RF amplifiers of any bandwidth is the same at the highest frequency as for 1 GHz amplifiers at the highest frequency;
- Passive loss above 1 GHz is the same as at 1 GHz. (The advanced passives designed for 2 GHz and above have usually lower losses above 1 GHz than the 1-GHz traditional passive loss at 1 GHz);
- Above 1.2 GHz, some traditional passives would exhibit excessive loss or suck-outs,
- The plate replacement is anticipated for the passives that do not meet the assumption;
- The input level is padded only if it exceeds the maximum required input level to the first hybrid and the remaining padding/gain alignment is performed interstage.

Table 6 summarizes the CNR modeling results for the cascades of RF amplifiers for the designs completed under these assumptions.

Design Scenario	Original Design Upper Frequency	Worst/Best Case CNR for Longest Cascade		Potential Capacity Increase (Legacy Signals/Adv. PHY – non-priority load)
		New Upper Frequency	Original Upper Frequency	
	[MHz]	[dB]	[dB]	[Gbps]
750 MHz N+5 “Moscow” system	750	49.8/52.2	49.8/52.2	0 (max original capacity: 6 Gbps with 384 Adv. PHY priority load)
	860	49.0/53.0	50.7/53.0	0.8/1.1
	1002	47.9/51.3	48.8/51.3	1.7/2.2
	1100	44.2/48.7	46.9/49.6	2.3/3.1
	1200	43.1/47.7	46.3/48.8	3.0/4.1
860 MHz N+5 “Stalingrad” System	860	56.0/56.2	56.0/56.2	0 (max original capacity: 6.8 Gbps with 384 Adv. PHY priority load)
	1002	55.9/56.1	56.6/56.9	0.9/1.2
	1100	55.2/55.7	55.3/55.9	1.5/2.0
	1200	54.1/54/1	54.5/54.6	2.2/2.9
	1300	52.5/53.0	54.2/54.6	2.9/3.8
	1400	51.8/51.9	53.5/53.6	3.5/4.6

Table 6: CNR Performance of Expanded Bandwidth RF Amplifier Cascades in Analyzed Networks

The results of the design and modeling show reasonable degradation in performance if the bandwidth extension is relatively low (up to 25% and 30% and increases at accelerated rate above these ranges). The impact of the decrease in performance will be modeled at EOL performance modeling.

<u>Drop Performance Modeling</u>

Table 7 summarizes the design and modeling results for the drop section of the HFC plant. The drop was assumed to be 150 feet of RG6 cable (close to the median value of the drop length based on analysis presented during Advanced PHY standardization activities) with a single coupler following the drop to the house and 50 feet of RG59 cable wiring inside the house.

Table 7 presents median input level designs. Based on the authors’ experience, and industry studies, the median input levels to CPE devices in the downstream direction are close to –3 dBmV for digital RF channels. The results of modeling, except for FD designs that take advantage of the absence of RF amplifier CNR contribution, closely match this number. The CNR performance was calculated based on the assumption of 10 dB NF for residential gateway and CPE devices.

Original design Freq & Type	New Design Frequency	Median CPE Input Levels at			CPE CNR at Median Input Levels at		
		Highest Freq./Original Design	New Design /Highest Original Frequency	Highest Frequency of New Design	Highest Freq./Original Design	New Design /Highest Original Frequency	Highest Frequency of New Design
	[MHz]	[dBmV]	[dBmV]	[dBmV]	[dB]	[dB]	[dB]
750 N+5	860	-3.02	-2.12	-2.63	44.22	45.12	44.61
	1,002	-3.02	-4.12	-5.15	44.22	43.12	42.09
860 N+5	1,002	-2.22	-1.42	-2.26	45.02	45.82	44.98
	1,100	-2.22	-2.62	-2.12	45.02	44.62	45.12
	1,200	-2.22	-4.42	-3.92	45.02	42.82	43.32
860 FD	1,002	-6.39	-6.09	-7.65	40.85	41.15	39.59
	1,100	-6.39	-7.59	-9.37	40.85	39.65	37.87
	1,200	-6.39	-9.59	-11.56	40.85	37.65	35.68
1GHz FD	1,200	-2.70	-3.71	-2.16	44.54	43.53	45.08
	1,300	-2.70	-5.24	-3.34	44.54	42.00	43.90
	1,400	-2.70	-7.18	-6.59	44.54	40.06	40.65
		Median RG Input Levels at			RG CNR at Median Input Levels at		
750 N+5	1,100	2.68	-0.23	-0.20	49.91	47.01	47.04
	1,200	2.68	-1.03	-1.50	49.91	46.21	45.74
860 N+5	1,300	4.04	1.14	1.39	51.28	48.38	48.63
	1,400	4.04	0.44	1.90	51.28	47.68	49.14
860 FD	1,300	-0.13	-4.23	-5.18	47.10	43.01	42.06
	1,400	-0.13	-5.52	-6.34	47.10	41.72	40.90
	1,600	-0.13	-6.43		47.10	40.81	
1GHz FD	1,400	4.42	-0.12	2.30	51.65	47.12	49.54
	1,600	4.42	-0.56	0.52	51.65	46.67	47.76
	1,800	4.42	-1.65	-1.14	51.65	45.59	46.10

Table 7: Drop Statistics and CNR Performance for Analyzed Cases.

		With Re-Designed Analog Fiber Link for Better Performance			Ditsributed Architecture Optimized for 1024-QAM with LDPC			Ditsributed Architecture Optimized for 4096-QAM with LDPC		
Original design Freq & Type	New Design Frequency	End-To-End Downstream Performance: CPE with In-House Wiring			End-To-End Downstream Performance: CPE with In-House Wiring			End-To-End Downstream Performance: CPE with In-House Wiring		
		Highest Freq./Original Design	New Design /Highest Original Frequency	Highest Frequency of New Design	Highest Freq./Original Design	New Design /Highest Original Frequency	Highest Frequency of New Design	Highest Freq./Original Design	New Design /Highest Original Frequency	Highest Frequency of New Design
	[MHz]	[dBmV]	[dBmV]	[dBmV]	[dBmV]	[dBmV]	[dBmV]	[dBmV]	[dBmV]	[dBmV]
750 N+5	860	36.81	37.00	36.83	40.07	40.49	40.12	42.16	42.85	42.23
	1,002	36.81	36.54	36.23	40.07	39.51	38.93	42.16	41.28	40.43
860 N+5	1,002	37.12	37.25	37.11	40.75	41.05	40.74	43.32	43.88	43.29
	1,100	37.12	37.04	37.12	40.75	40.58	40.76	43.32	43.00	43.34
	1,200	37.12	36.66	36.76	40.75	39.75	39.97	43.32	41.65	42.00
860 FD	1,002	36.18	36.28	35.71	38.78	38.97	37.96	40.23	40.49	39.12
	1,100	36.18	35.74	34.92	38.78	38.00	36.70	40.23	39.17	37.54
	1,200	36.18	34.81	33.67	38.78	36.54	34.94	40.23	37.34	35.48
1GHz FD	1,200	37.13	36.93	37.22	40.69	40.25	40.90	43.21	42.45	43.60
	1,300	37.13	36.55	37.01	40.69	39.46	40.42	43.21	41.21	42.73
	1,400	37.13	35.90	36.11	40.69	38.28	38.66	43.21	39.54	40.06
		End-To-End Downstream Performance: RG			End-To-End Downstream Performance: RG			End-To-End Downstream Performance: RG		
750 N+5	1,100	37.43	36.98	36.62	41.50	40.44	39.67	44.78	42.77	41.52
	1,200	37.43	36.83	36.25	41.50	40.11	38.96	44.78	42.22	40.49
860 N+5	1,300	37.69	37.48	37.46	42.21	41.65	41.58	46.47	45.10	44.96
	1,400	37.69	37.41	37.47	42.21	41.45	41.62	46.47	44.67	45.03
860 FD	1,300	37.50	36.81	36.56	41.57	39.99	39.49	44.94	42.03	41.26
	1,400	37.50	36.46	36.20	41.57	39.30	38.81	44.94	40.97	40.27
	1,600	37.50	36.17		41.57	38.76		44.94	40.20	
1GHz FD	1,400	37.82	37.50	37.71	42.44	41.58	42.13	47.12	44.95	46.25
	1,600	37.82	37.45	37.56	42.44	41.45	41.75	47.12	44.67	45.33
	1,800	37.82	37.30	37.37	42.44	41.10	41.27	47.12	43.96	44.30

Table 8: End-To-End Downstream Performance

Downstream End-To-End Performance

The results in Table 8 for the EOL (a.k.a. end-to-end) performance with analog fiber links show higher than expected results but this is mostly due to the many assumptions on the analog fiber link used during the analog fiber link capacity analysis presented in Table 1 (including the assumption that the links were designed to carry high numbers of analog channels). The test results also indicated that there is very little change in the performance from improving drop installation performance (moving CPE to RG). This indicates that the analog fiber link performance is the limiting factor and the critical component of the network. The assumptions used can be possibly met in a single wavelength 1310 nm analog links but very difficult to meet in multiwavelength applications.

On the other hand, a distributed architecture allows extended bandwidth with performance (median numbers) capable of supporting 4096-QAM at the highest frequencies to and in several cases beyond the limits analyzed even if the performance of the PHY output is at the level optimal for 256-QAM or 1024-QAM with LDPC (the implementations with guaranteed 43 dB SNR/MER and typically >44 dB SNR/MER).

Without relocation of the CPE devices into RG, 750 MHZ N+5 network bandwidth can be extended to 1002 MHz and entire bandwidth can support 4096-QAM (median). After relocation of the CPE devices into RG, the bandwidth can be extended to 1.2 GHz and the network could support 4096-QAM in the most part of that bandwidth. The analysis results also show that under the same two drop topologies, the 1GHz FD designs can be extended in BW to 1.4 GHz and 1.8 GHz respectively while supporting 4096-QAM with LDPC within most of those bandwidth ranges.

With the distributed architecture remote PHY optimized for higher performance (49 dB MER/SNR), these bandwidths can be easily extended or the network could provide high operational margins and support excessive loss drops

Note that in 1.8 GHz network, the downstream capacity (after replacing all legacy signals with Advanced PHY signals) can exceed 17 Gbps (starting from 168 MHz up to 1.8 GHz). The results show that the downstream bandwidth can be indeed extended to 2 GHz.

Upstream Network Capacity Analysis

Two different approaches are discussed for the upstream capacity expansion:

1. Moving downstream/upstream split band to upper frequencies (low split band),
2. Placing the new upstream bandwidth over the top frequency of the downstream bandwidth (over the top split band).

The pros and cons have been broadly discussed by the industry. The few (major) cons are listed below:

1. For split band relocation:
    a. Sizeable shift in upstream frequency would require remedies (also broadly discussed) up to and including legacy set top boxes with limited downstream OOB signaling agility;
    b. Alternative remedies range from placing simple frequency converters to complete OOB receivers attached to the set top boxes;
2. For over the top:
    a. High cable loss for the signal generated by CPEs, even if placed in residential gateways;
    b. Restriction to future downstream bandwidth expansion that would require a visit to the RF actives.

Both solutions could be implemented in TDD or FDD configurations. For over the top, TDD implementation addresses future forward capacity expansion (adding forward capacity by adding more or higher throughput TDD channels). The advantage of the FD architecture is that it can readily support both or either.

The advantages of the TDD approach will not be discussed in this paper. They are numerous and very well understood.

Unfortunately, today native HFC technologies do not support TDD. This is potentially a missed opportunity.

TDD technology, by implementing or maintaining some available capacity asymmetry, can be used over the top with upstream signals at much lower modulation levels and thus requiring lower power and lower performance. For example, using the same BW downstream and upstream but with 4096-QAM downstream and 64-QAM upstream would support asymmetric available capacity of 2-to-1 (if TDD is split equally between downstream and upstream but it is indeed flexible in how the capacity is used) but the upstream signal with the same FEC power strength as the FEC for the downstream signal could occupy an 18 dB lower SNR environment that can be implemented entirely or partially as lower level transmitting requirements in CPEs.

At lower frequencies with a traditional split band (high) approach, the lower part of the HFC bandwidth can be used for FDD and TDD (in FD networks). In this case, the lower loss would allow for fully symmetrical capacity availability in downstream and upstream without burdening CPE devices with extremely high output power requirements.

SUMMARY: BENEFITS OF DISTRIBUTED BROADBAND ARCHITECTURE

There are many operational and financial benefits to carrying only baseband digital signals in the fiber portion of the HFC network, rather than modulated RF signals. These include being able to leverage high-volume data networking equipment; reducing headend space and power consumption; increasing fiber reach; decoupling service group allocations from hard-wired RF combining networks; and eliminating the need for plant rebalancing, with “set and forget” channel power settings.

The most significant benefit, however, is that eliminating RF payload from the fiber unlocks as much as a three-fold improvement in the potential bandwidth capacity of the existing plant infrastructure. The plant modeling analysis above, using real design examples, shows that without re-spacing RF actives in a Fiber Deep and HFC network up to N+5 deployments, forward path capacity can reach nearly 20 Gpbs, given the aid of LDPC FEC encoding at the headend and more powerful GaN hybrid amplifiers in the node.

The source of this benefit is twofold. Firstly, by moving RF modulation and/or demodulation to the node, the entire “headend-quality” RF signal budget is available at the last mile, without incurring any of the traditional headend-side or optical transmission-related impairments. Secondly, there are system-wide benefits even during the transition period (while a node receives both digital optical signals and legacy analog optical signals) on top of bandwidth expansion. This is due to the fact that as video and data QAMs are migrated to the node, the decreased RF burden on headend optical transmitters enables increased OMI, which results in improved SNR at the node for legacy headend signals as well.

ABBREVIATIONS AND ACRONYMS

AGC	Automatic Gain Control
ALC	Automatic Level Control
AML	Amplitude Modulated Link
BC/NC	Broadcast/Narrowcast
BER	Bit Error Rate
BW	Bandwidth
CM	Cable Modem
CMTS	Cable Modem Termination System
CNR	Carrier-to-Noise Ratio
CO	Central Office
CPE	Customer Premises Equipment
CSO	Composite Second Order
CTB	Composite Triple Beat
dB	decibel
DOCSIS®	Data over Cable Service Interface Specification
E-O-E	Electrical-Optical-Electrical
EOL	End-of-Line
FD	Fiber Deep
FDD	Frequency Division Duplex
FEC	Forward Error Correction
FML	Frequency Modulated Link
FPGA	Field-Programmable Gate Array
GaAs	Gallium Arsenide
GaN	Gallium Nitride
Gbps	Gigabits per second
HFC	Hybrid Fiber Coaxial
IIN	Interferometric Intensity Noise
IP	Internet Protocol
LDPC	Low Density Parity Check
Mbps	Megabits per second
NA	North America
NF	Noise Factor
NTSC	National Television System Committee
OFDM	Orthogonal Frequency-Division Multiplexing
OMI	Optical Modulation Index
OOB	Out-of-Band
OTN	Optical Terminal Node
PAPR	Peak-to-Average Power Ratio
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
RFoG	Radio Frequency over Glass
RG	Residential Gateway
RIN	Relative Intensity Noise
RMS	Root-Mean-Square
SNR	Signal-to-Noise Ratio
TDD	Time Division Duplex
TX	Transmitter
VSB	Vestigial Sideband