Layer 1 Considerations for Extended Spectrum Utilization in Hybrid Fiber Coax & Distributed Access Architecture Networks

A Technical Paper prepared for SCTE•ISBE by

Ron Wolfe
Sr. Director, Engineering
Charter Communications, Inc.
14810 Grasslands Drive
Englewood, CO 80112
+1 (720) 518-2307
Ron.Wolfe@Charter.com

Table of Contents

List of Figures

List of Tables

Introduction

Traffic needs in service provider networks continues to grow rapidly. Although the cumulative average growth rate for per subscriber data consumption has somewhat abated, the competitive pressure has not, and there is a growing consensus among service providers that capacity planning for the future needs to begin now.

There are numerous drivers to current and future growth and among them are the rapid growth of IP delivered video services, backhaul of wireless services and the emergence of cloud connected devices such as surveillance cameras, machine to machine communication, health and wellness monitors and inter-autonomous vehicle communications. The exponential growth of these internet of things (IoT) types of devices, though each is a relatively small consumer of resources, will begin to emerge from the "noise floor" of network traffic consumers. As service providers look at their networks today, there is little argument that further increases in capacity are necessary in the near future.

Fortunately, there are pathways to additional capacity. Fiber to the premise solutions remain a viable and highly effective option, particularly so in green field environments, but our industry's strategic asset has always been its existing coaxial infrastructure, and that remains our most readily accessible and cost-effective path to higher capacity. Our hybrid fiber coaxial (HFC) networks have grown in capacity over the years through an ongoing succession of bandwidth expansion, digital compression, serving group splits and multicast solutions. The roadmap to capacity expansion for HFC networks beyond 1,218 MHz is a multi-faceted challenge, but there are numerous companies in both the supplier and service provider communities who are collaborating to identify the challenges and develop solutions to address those challenges. This paper will explore the challenges without necessarily offering solutions for each. It is likely that SCTE-ISBE's EXPO 2020 will have numerous presentations proposing solutions that will lead to the realization of the Data Over Cable Service Interface Specifications (DOCSIS®) 4.0 technology and applications that take advantage of spectrum beyond the proposed DOCSIS specification extension to 1,794 MHz.

Scope of the Extended Spectrum Challenge

This paper is limited in scope to Layer 1 considerations, as stated in the title. Layer 1 of the outside plant (OSP) network consists of optical transmitters and receivers, coaxial cable, radio frequency (RF) amplifiers and passive devices such as directional couplers and taps, splitters and power inserters. For DOCSIS 4.0 technology or other extended spectrum services to be fully leveraged, all of these devices must exhibit satisfactory performance over the entire frequency range of 5 MHz to 1,794 MHz, with a future upgrade path to 3 GHz. It is premature to make exact predictions of performance and requirements for this area of the spectrum as the DOCSIS 4.0 specifications are only now beginning development. In the following sections we will explore each of these key elements of the layer 1 network.

Coaxial Cable

Coaxial cables have been in production for many years, and the materials and technologies used to manufacture coaxial cables has evolved over that time. Coaxial cables were not specified or measured to 1 GHz until the early 1990's, and cables older than this may have degraded due to environmental conditions. This doesn't necessarily mean the cable is not useable at frequencies beyond 1 GHz, regardless of age, but it does make it necessary to sample test older coaxial cables to determine the performance characteristics. It is a safe assumption that some cable spans will require replacement, and history tells us that an expectation of 10-15% of either replacement cable or newly added cable is realistic.

Attenuation in coaxial cables increases with frequency, so it will be necessary to account for this in the design process. As an approximate measure, the loss of coax increases by a factor of 1.4 each time the frequency doubles. Stated mathematically, the attenuation of coaxial cable increases proportionately to the square root of the frequency ratio. Table 1 provides loss data in dB for hardline cable and Table 2 provides loss data in dB for drop cable.

As can be seen from the rightmost columns, there is an increase in attenuation between 1,002 MHz and 1,794 MHz of roughly 40%. This will mean that long continuous runs of untapped coaxial cables such as trunk runs or "express" feeder runs will require careful attention as this means the gain requirement for the span goes up by 40% as well. Tapped runs tend to less problematic as the increases in through loss for taps is significantly less than 40% over the same frequency span.

It is important to note that while coaxial cable performance is predictable in the majority of cases there are some spectral areas where environmental and process variations could cause performance to differ from that predicted. It is also possible that there will be areas of the spectrum that will not be able to support the same modulation profile as those areas that are more true to predicted behavior. Sample testing is the most reliable means to determine whether this is the case.

Table 1 - Loss Table for Hardline Coaxial Cables (dB/100ft)

	5MHz	54MHz	204MHz	750MHz	860MHz	1,002MHz	1,218MHz	1,794MHz	3,000MHz
.500	0.16	0.54	1.09	2.16	2.34	2.52	2.81	3.54	4.77
.625	0.13	0.46	0.92	1.78	1.93	2.07	2.30	2.89	3.87
.750	0.11	0.37	0.74	1.48	1.61	1.74	1.94	2.45	3.34
.875	.09	0.33	0.66	1.29	1.41	1.53	1.68	2.13	2.89

Table 2 - Loss Table for Subscriber Drop Coaxial Cables (dB/100ft)

	5MHz	54MHz	204MHz	750MHz	860MHz	1,002MHz	1,218MHz	1,794MHz	3,000MHz
Series 6	0.58	1.60	3.05	5.65	6.10	6.55	7.04	8.49	10.68
RG11	0.38	0.96	1.90	3.65	3.98	4.35	4.80	6.11	8.37

Analog Optical Transport

Since the early 1990's analog optical transport has been the predominant means for signal distribution from hubs to neighborhoods served by optical nodes. Return path transport has been a combination of analog and digital transport. Analog transmitters are subject to clipping when the power of the input signal exceeds the dynamic range of the transmitter. Transmitters are typically designed to operate with a flat input spectrum. Increasing the channel load without making per channel drive level adjustments can cause clipping. The typical response to this is to lower the drive level such that the total composite power used to modulate the laser stays the same. That means that the optical modulation index (OMI) of the transmitter decreases on a per channel basis. This could have an adverse effect on the performance of the link.

In the case of digital transmitters used in the return path changes will also be required. Most extended spectrum planners anticipate a minimum extension of the return spectrum to 204 MHz, with frequencies as high as 492 MHz or even 684 MHz being discussed. Just as is true in the downstream transport, this higher power loading of the return transmitters could cause clipping without a reduction in per channel power resulting in an adverse impact on the performance of the upstream link and/or an increased risk of clipping.

Multi-wavelength analog optical links are complex designs with many dependencies and interactions in both the electrical and optical domains. While there will be design challenges, it is likely that these can be overcome, keeping analog optical transport a viable option even at these extended frequencies.

Digital Optical Transport

DOCSIS 3.1 technology precipitated the development of the Distributed Access Architecture (DAA), wherein analog optical transport is replaced by a digital optical transport infrastructure and the RF spectrum for each serving group is generated by a device in the node. These devices fall under the descriptions of remote PHY devices (RPDs), remote MAC-PHY devices (RMDs) flexible MAC architecture (FMA) devices and the architecture utilizing them is referred to as DAA.

At Layer 1, each of these DAA devices performs essentially the same function, with the differences between them existing in higher layers of the architecture. The primary advantage of these devices is that the signal quality we would normally expect to see in the hub site is now able to be generated in the field with equal quality and without the variations inherent to a traditional headend combiner network feeding an analog optical transmitter. That quality then translates into the ability to support increasingly complex modulation schemes in the field. For purposes of this paper, the use of these devices and the digital optical transport improve our signal quality, at the node by about 6dB, and this headroom is useful in the design process for the network beyond the node.

While DAA devices are in active deployment today, many are designed to operate at frequencies up to 1,218 MHz and provide a single forward and either one or two return segments. It is anticipated that generational improvements in the digital signal processors (DSPs) and field programmable gate arrays (FPGAs) that are the core of RPDs and RMDs will track with the development of the DOCSIS 4.0 specifications. Reduced power consumption and thermal management will need to be key design considerations in this process as we approach heat dissipation requirements that exceed the physical limitations of housing sizes for strand mounting. A migration toward application specific integrated circuits (ASICs) would help reduce power consumption, but this is not practical while the technology is evolving.

RF Amplifiers

1. Total Composite Power Requirements

RF amplifiers represent one of the more significant challenges in designing an extended spectrum network. The expansion from 1,002 MHz to 1,794 MHz represents an increase in channel loading of 105%, and the RF power levels of the individual channels increase with frequency in order to match the existing design and provide for a flat spectrum at the customer premise. For example, a typical 1,002 MHz design might call for RF output levels at the node of +50 dBmV at 1,002 MHz and +38 dBmV at 54 MHz. To drop into this design and continue the linear slope to 1,794 MHz would require RF levels of +60 dBmV at 1,794 MHz and +40.5 dBmV at 258 MHz. Figure 1 illustrates this approach. This is typical of most upgrades to our HFC networks over the past decades. Its simplicity lies in providing a relatively flat spectrum at the customer premise.

By graphing the total composite power in watts as the load is increased from 1 to 253 channels from 258 MHz to 1,794 MHz we can see how the extension of the spectrum affects the TCP at the output of the amplifier. In this example the TCP required to generate this spectrum is 77.5 dBmV, a level that is unattainable across such a wide spectrum using today's Gallium nitride (GaN) gain blocks. Even if this were possible the power consumption of the gain block would be unacceptably high and current amplifier housings would be incapable of dissipating the heat they would generate. There may be many cases where current levels output from nodes and amplifiers allow a "continuous slope" design approach such as this, but it is unlikely that this will be a universally viable approach. Networks originally designed to 550 MHz are unlikely to be candidates for a continuous slope drop-in design.

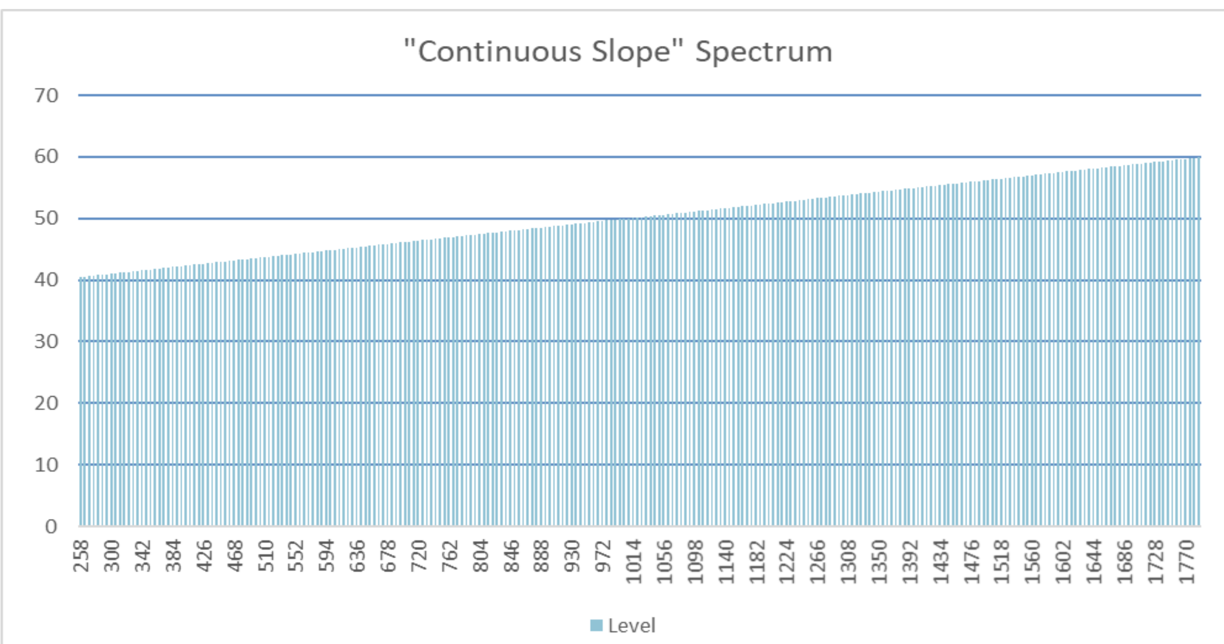

Figure 1 - Continuous Slope Extension 258MHz to 1,794 MHz

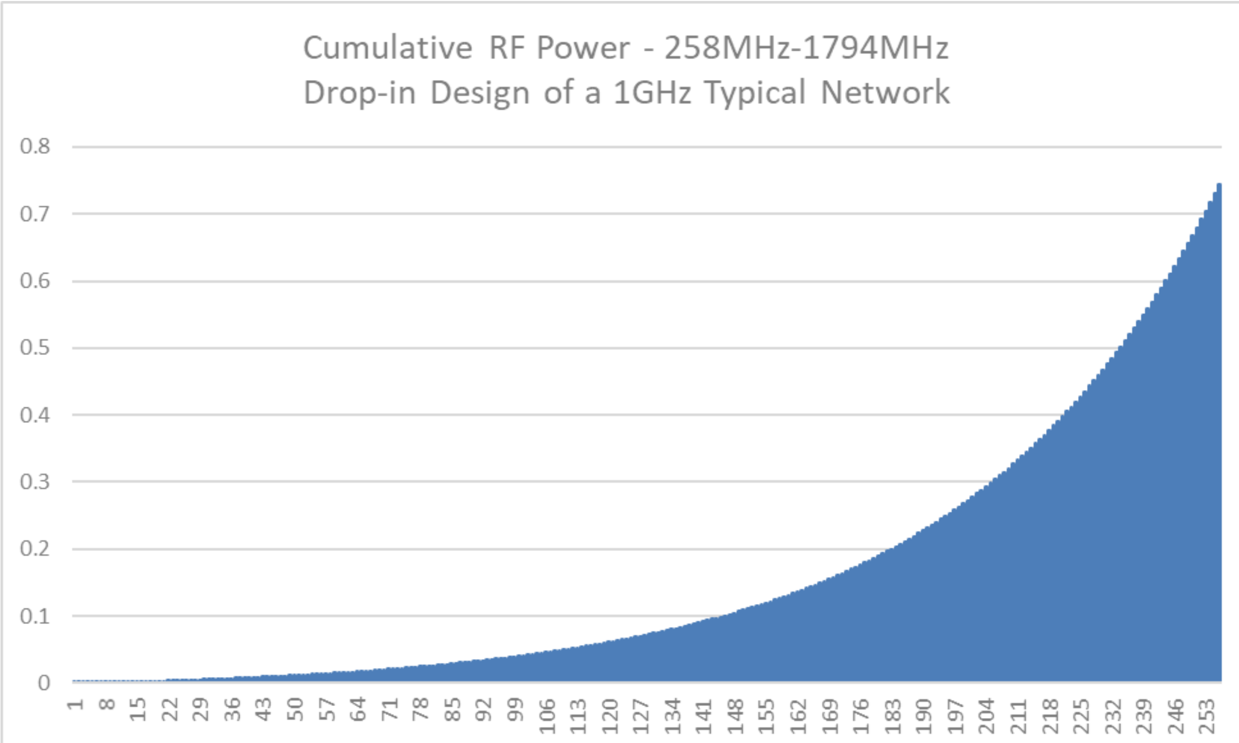

Figure 2 - Total Composite Power with Increasing Channel Load

In most cases, engineers are considering a slope pattern that maintains current tap output levels up to 1,002 MHz then restarting a parallel slope line at 6 to 8 dB lower than the legacy plant levels. There are two advantages to this approach. First, it preserves the legacy design levels, making this an effective approach to brown field upgrades, where existing services and customer premise equipment (CPE) is designed to operate effectively. Second, the carriers at higher frequencies are the largest contributors to the TCP curve, and reducing their levels has a higher beneficial impact on the TCP than reducing lower frequencies. The resulting RF spectrum takes on a staggered look when viewed on a spectrum analyzer, as illustrated in Figure 3.

This reduction of 8dB in the carrier levels at frequencies will obviously have to be accounted for in the design of the customer premise network and some possible solutions are discussed briefly later in this document. The resulting TCP of this "Zig-Zag" sloped spectrum is 71.2 dB, which is within the reach with the newest generation of GaN amplifiers. Figure 4 is the resulting TCP graph of the carriers.

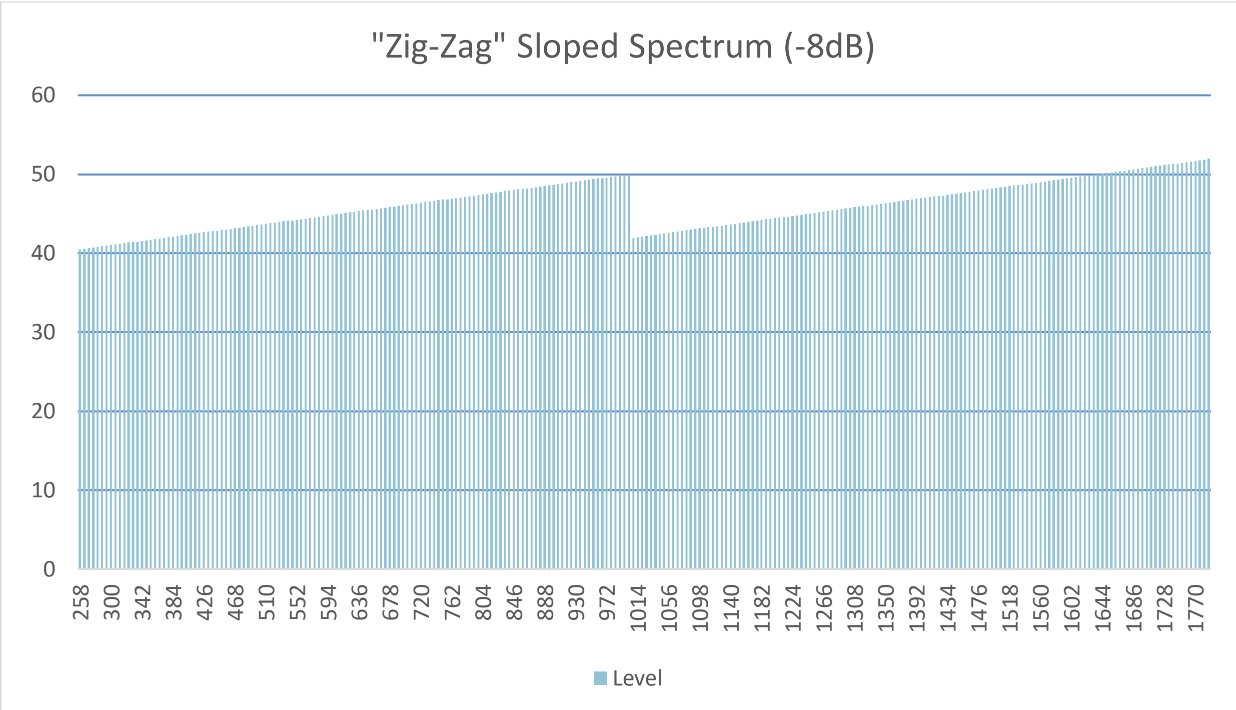

Figure 3 - "Zig-Zag" Sloped Spectrum

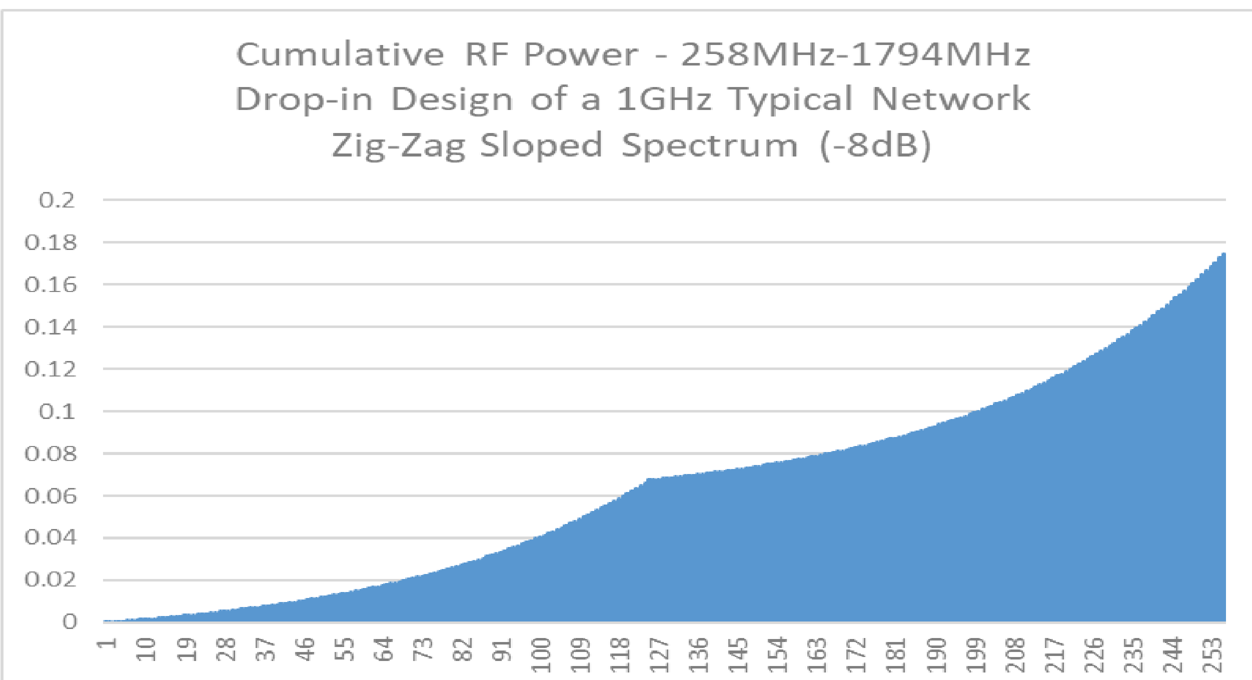

Figure 4 - Total Composite Power with Zig-Zag Sloped Spectrum

2. Forward and Return Transition

Since our early use of bidirectional amplifier stations that contain both forward and return amplifiers, we have relied on diplexers to keeps signals in one direction from interfering with signals travelling in the opposite direction. Diplexers exist on the input ports of the amplifier. Although high quality components and manufacturing techniques have improved over the years, there is still a need for a "guard band" between the forward and return frequencies, as illustrated in Figure 5. The frequency at which the network is provisioned is often referred to as the "split" frequency and indicated by a combination of the highest return frequency and the lowest forward frequency. As the center frequency of the diplexer increases, more bandwidth is allocated to the return network and less to the forward, thereby enabling a higher degree of symmetry between the downstream and upstream capacity. However, the width of the guard band for the diplexer also increases, in this case from 12 MHz in a traditional diplexer to 54 MHz for a 5-204 MHz / 258-1,218 MHz, consistent with today's DOCSIS 3.1 specifications. Traditional diplexers have a guard band that is roughly equal to 23% to 25% of the center frequency. It is probably reasonable to assume that higher quality filters can reduce this to 20% or a bit less,

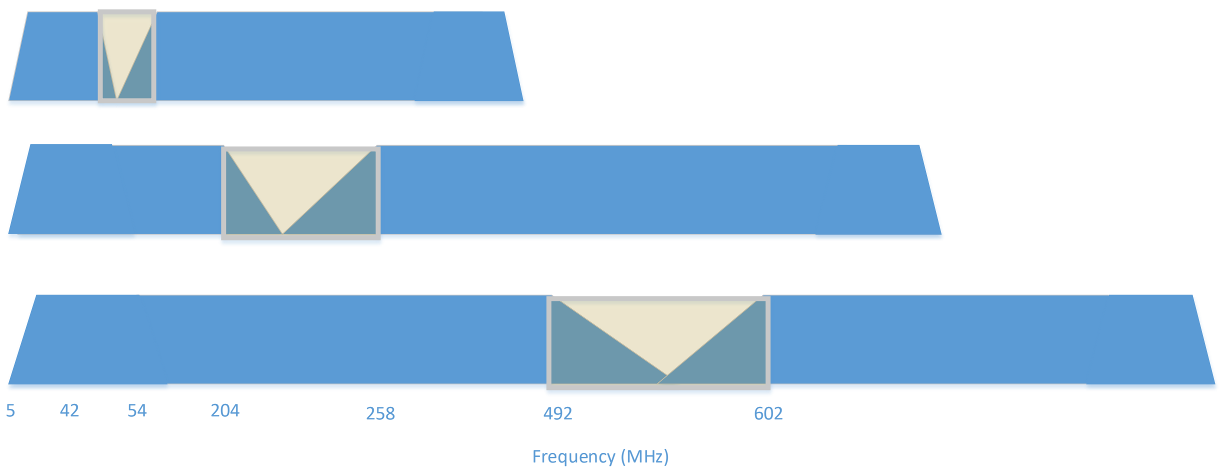

Figure 5 - Guard Band Width vs Center Frequency

Although the specifications have not yet been drafted, there is a desire to incorporate even higher split frequencies, for example 492 MHz or 684 MHz as the highest return frequency. These splits would incorporate diplexers that would require guard bands of approximately 110 MHz and 160 MHz respectively, even after accounting for better quality filters, the amount of usable spectrum lost to the guard bands is a high cost to pay for the increase in return spectrum, and for this reason service providers are exploring alternatives.

3. Echo Cancellation

One approach that has received a good deal of attention in recent months is to utilize echo cancellation technology to provide isolation between the forward and return paths in place of diplexers. Echo cancellation allows the forward and return path to transition with almost no loss of spectrum between the two. Echo cancellation will be a requirement for a full duplex (FDX) DOCSIS solution, and leveraging this for statically duplexed applications benefits both solutions through scale. While designs for echo cancellers can be complex, particularly for multi-output amplifiers, they do certainly deserve further research and engineering to determine performance and price points. Ultimately, if the cost of echo cancellation can be comparable to the value of the spectrum reclaimed it will likely be successful.

4. Power Consumption and Heat Dissipation

As always, the contribution to the power consumption of the amplifier is a matter of concern. Next generation GaN amplifiers have a significantly higher TCP capability, but that comes with a higher power consumption. These devices also dissipate more heat than current generation RF amplifiers, and some compact amplifiers may be challenged to sufficiently dissipate the heat load of a high wattage RF Gain block and it's supporting circuitry, particularly amplifiers with multiple output ports.

Taps and Passives

There are very few, if any taps installed in HFC networks today that are capable of satisfactory performance to 1,794 MHz, meaning there will need to be at a minimum a faceplate change required. This may prove to be a satisfactory option for some service providers, but there are considerations in the housing, sometimes referred to as the "back box" and the seizing mechanism that affect performance at frequencies higher than about 1,200 MHz. Often these are due to transmission characteristics and construction of the seizing mechanism and power bypass devices designed to maintain power when faceplates are removed.

Initial product samples of taps specified for performance to 3 GHz has been promising, with early samples showing satisfactory performance and an ability to improve on the loss performance at frequencies up to 1,002 MHz. This makes it feasible that a same value extended spectrum tap may be inserted into the same design location. The higher levels at amplifier and node outputs will likely make conditioning plug-ins a requirement, with cable simulators for higher value taps and equalizers for lower value taps.

Taps with amplification have also been discussed as a possible solution to placing full amplifier stations into spans that are prohibitively long to maintain the existing spacing. These "gain taps" could be spaced in optimal locations to minimize their impact on cascade performance.

Customer Premise Equipment

While customer premise is beyond the scope of this paper, the development of CPE specifications will represent one of the most significant challenges in the extended spectrum development and implementation. There are no currently deployed set-top boxes or modems that support reception or transmission of signals above 1,218 MHz. This means that a new modem will be required to utilize this spectrum. The transmit frequency of most deployed modems ends at 85 MHz and that too will need to change to support at a minimum 204 MHz, and possibly as high as 684 MHz. With the increased loss of the coaxial cable and taps between the modem and the nearest amplifier, return transmitter power will need to be increased as well. All of this presents an opportunity to rethink how we deploy CPE in our networks.

1. Modems as Gateways

Today's customer premise installation typically consists of a drop feeding a 4-way splitter, one port of which serves the DOCSIS modem and the other three serving set-top boxes. If we were to transition the customer premise to an all IP network we could realize the elimination of the loss of that 4-way splitter. The drop could terminate on the modem and the set-top boxes could be replaced with IP set-top boxes connected to the network either by wireless or using the existing coax in a coaxial Ethernet network. By eliminating this loss, we can offset the loss of the drop at the higher frequencies and potentially open the door to using higher value taps that have less through loss. This is a scenario worth exploring with the condition that it must maintain compatibility with legacy customers who may be served by the same tap on a different port.

Conclusion and Evolutionary Outlook

In the early 1990's cable service providers deployed HFC networks with an eye toward the future, and with the understanding that coaxial cable had enormous potential for capacity expansion beyond the limits of the technical limitations of electro-optical and RF components that comprise the active portion of the network. Extended spectrum operation to 1,794 MHz is a significant evolutionary step for HFC networks, but there is no reason to believe it is the last such step. Every HFC network is different in some way from others, so there is no single design approach that will work in every case. The most challenging requirements lie in the RF amplifier designs to support the additional spectral loading, the need for higher transmit power from CPE to overcome the greater coaxial losses at higher frequencies, addressing the guard band loss of capacity due to higher split frequency diplexers and management of power consumption and heat dissipation. From my experience in the industry, I am confident that these and other challenges will be overcome and that the incremental bandwidth and capacity made available through extended spectrum upgrades will position the industry to be competitive for years to come.

While it is true that most current efforts are focused on an evolutionary step that supports the needs of DOCSIS 4.0 technology, the spectrum beyond 1,794 MHz should also be considered for transport of other technologies. There are solutions for example that could utilize this upper end of the spectrum to transport Ethernet signals over the coax. This could be used to feed new DAA nodes for future segmentation, or to provide other Ethernet based solutions without the need to extend fiber. The same technology could be used to distribute IP traffic to IP set-top boxes within the customer premise. While this paper is based on operation of the network to 1,794 MHz, service providers are working with vendors to provide an infrastructure of cables, connectors and housings that support drop-in upgrades to 3 GHz.

There are significant challenges to overcome in the development of network specifications for performance to 1.8 GHz and beyond, but none of these challenges appear insurmountable. By next year's Cable-Tec EXPO it is likely that several manufacturers will be introducing products designed for operation to 1.8 GHz and even 3 GHz.

Abbreviations

ASIC	application specific integrated circuit
CPE	customer premise equipment
DAA	distributed access architecture
dBmV	decibels relative to 1 millivolt

DOCSIS	data over cable service interface specifications
DSP	digital signal processor
FDX	full duplex
FMA	flexible MAC architecture
FPGA	field programmable gate array
GaN	gallium nitride
GHz	gigahertz (1 billion cycles per second)
HFC	hybrid fiber-coax
IP	internet protocol
ISBE	International Society of Broadband Experts
MAC	media access control
MHz	megahertz (1 million cycles per second)
OMI	optical modulation index
OSP	outside plant
PHY	physical layer
RF	radio frequency
RMD	remote MAC/PHY device
RPD	remote PHY device
SCTE	Society of Cable Telecommunications Engineers
TCP	total composite power

Bibliography & References

Broadband Library: *Total Power and Power Spectral Density*; May 25, 2019 by Ron Hranac

With the exception of the aforementioned, specific documents were not used in the production of this document. The document is the product of numerous discussions on the topic with subject matter experts from other service providers and from industry suppliers.

The author wishes to acknowledge and thank the following companies for their advice and insights.

Amphenol Broadband Solutions

ATX Networks

Cisco Systems

CommScope/Arris

Cox Communications

GenXComm

Qorvo

Shaw Communications

Technetix