HFC- The Gift That Keeps on Giving?

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1. Introduction

Since the early days in cable our networks and our systems have been constantly evolving to address our customers' changing needs, from the early end-to-end one-way coaxial environment for analog video services to a two-way hybrid-fiber-coax (HFC) environment to support data services and then to a fiber deeper distributed access architecture (DAA) to meet the exponential growth in demand for capacity supporting all type of internet protocol (IP) based services for residential and business customers.

Even though it is always hard to imagine what type of applications and services will continue to drive such demand, these growth trends have not subsided. We need to transform our networks to remain a relevant choice to our subscriber base. This paper explores how we, in cable, can continue to address this demand through a comprehensive examination of our architectures and topologies, our distribution network components, our end-devices, our protocols and the way we provide services so that by intelligently evolving them we can continue to leverage our HFC infrastructure. Likewise, this assessment will also be useful in determining under what circumstances an HFC based platform may no longer be practically leveraged and how a transition to fiber-to-the-home (FTTH) could be executed alongside our proposed HFC evolution steps.

In this paper we review the capabilities of our network and its elements both current and future. Being this a holistic assessment, all the elements, that may play a role in data-over-cable services, are examined and could be impacted in this proposed evolution.

2. Background

Before embarking on any evolution proposal, we need to assess what are the capabilities of our current infrastructure, its architecture, our systems and resources.

2.1. State of the HFC Network

One of the defining evolution steps in our industry has been the migration from an all-coax network to a hybrid-fiber-coax environment where from a central hub location dedicated fiber strands connect to a fiber node. From that fiber node the transport transitions from the optical domain to the electrical domain as the signals continue through a coaxial network reaching subscribers within that fiber node serving area. The distance between hub and fiber node varies significantly depending on how close the fiber node is located from the hub, which could range from a few kilometers to 80 km or more with a median between 20 and 30 km depending on deployment density. This coaxial transport portion leverages the active and passive distribution network elements such as radio frequency (RF) amplifiers, couplers, splitters, coaxial splices, conditioning devices and taps. While the coaxial transport takes place through a rigid coaxial cable of different calibers, also known as hardline cable, from the tap to the customer premises, a flexible coaxial cable called drop cable is used. Figure 1 shows a logical depiction of a fiber node serving area representative of the popular serving area size of around 500 households passed (HHP) that took place in the migration to an HFC architecture.

In this 500 HHP serving area, signals would typically traverse 4 to 5 amplifiers in cascade before reaching the furthest customer. These topologies are called N+4 or N+5 indicating the node plus 4 or 5 actives that would be traversed in that serving area.

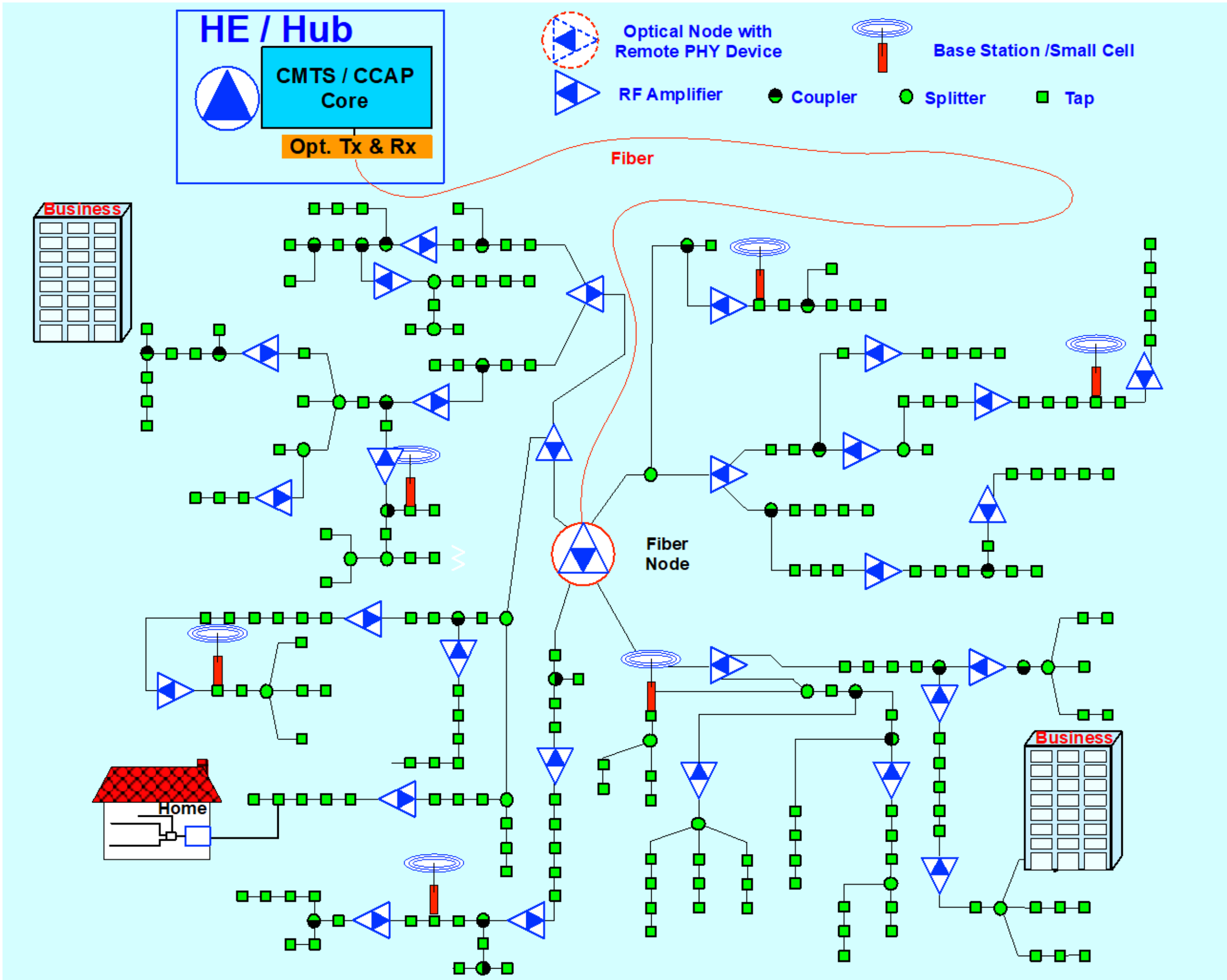


Figure 1 - N+4 Cascade 500 HHP Fiber Node Serving Area

While the coaxial hardline cable generally remains unchanged after initial deployment, the active and passive devices have been upgraded several times as our industry has been increasing the maximum frequency of operations. These high frequency coaxial limits included 550 MHz, 750 MHz, 860 MHz, 1002 MHz, 1218 MHz and more recently 1794 MHz with the introduction of the Data Over Cable Service-Interface-Specifications (DOCSIS®) 4.0 specifications [1]. The frequency performance of active and passive devices was defined in the device design while the coaxial cable continues to be leveraged "as-is" through these distribution plant frequency upgrades. Coaxial cable attenuation at higher frequency impacts system performance but the delta in performance has been addressed with higher performance amplifiers and/or by adjusting amplifier spacing.

Special attention needs to be given to the taps in an upgrade as taps exist in larger numbers within a fiber node serving area. In North America more than half of the taps are 4-port taps, while the 2-port and 8-port taps are less prevalent, and their use could depend on whether a dense or sparse deployment scenario is considered or if expected subscriber growth may be anticipated.

Traditionally deployed tap coupling values have been selected to receive a video channel at about the same power level whether a downstream home is closest to the node or amplifier or furthest downstream from it. So high tap values would be deployed close to the node or amplifier, while lower tap values are used in taps further away downstream from node or amplifier (Figure 2).

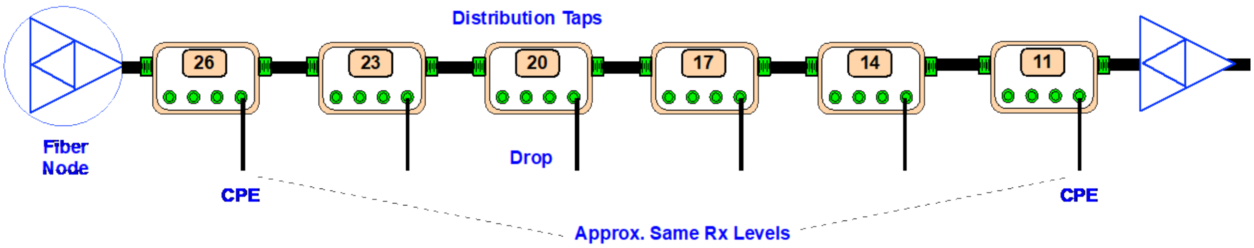


Figure 2 – Coaxial segment following node with decreasing taps values (26dB to 11dB)

Figure 3 was obtained by averaging tap data from many operators in North America indicating the distribution of tap values deployed.

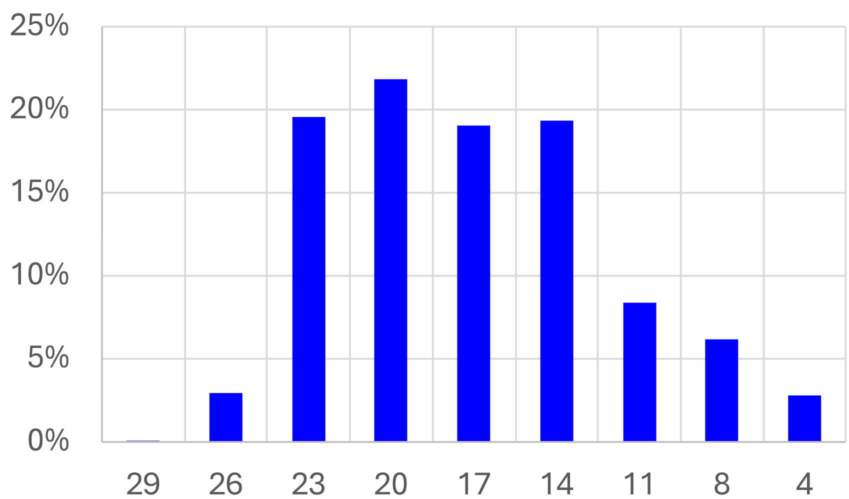


Figure 3 - Percentage of tap values deployed

One key characteristic in Figure 3, that will be used later is that most of tap values are 14 dB or higher. Another important coaxial network characteristic is tap spacing, meaning the coaxial length between tap and tap, which is dependent on the density of properties served by a network provider. Even within a fiber node serving area, the spacing between one tap and the next may vary significantly.

Amplifier gain will determine spacing of amplifiers given an aggregate loss from the combination of taps or passives through loss along with cable attenuation. Amplifier spacing dictates the numbers of amplifiers in a serving area and impacts cost efficiency of a fiber deeper or fiber node segmentation strategy. As we move to higher frequencies, higher gains are required.

2.2. HFC Evolution Since Original Deployment

It was not long after the HFC architecture migration that certain nodes required more capacity. This was answered with node splitting, meaning that the original fiber node serving area was segmented or split into smaller node serving areas. Typically having fiber terminating at the next active replacing an amplifier by a fiber node to dedicate a subset of subscribers with the same resources the original node is capable of. These newer child nodes originated from a node serving area that has been split in two, three or four newer smaller subset serving areas. Node splitting may not even require new fiber deployment through a virtual node split. A virtual node split is implemented at the original optical node by adding optical links that connect to individual coaxial branches within that fiber node. Our industry's fiber node segmentation practice has resulted in our fiber node serving areas to reduce in size from the original 500 HHP design average to 200 to 400 HHP per fiber node. The number of amplifiers in cascade has also reduced from > 5 amplifiers in cascade to 3 to 4 actives in cascade.

2.3. State of Data over HFC

Our DOCSIS end-devices have also been evolving. Cable's transition from DOCSIS 3.0 [2] to DOCSIS 3.1 [3] represented a transition from Single-Carrier Quadrature-Amplitude-Modulation (SC-QAM) to orthogonal frequency-division multiplexing (OFDM) and orthogonal frequency-division multiple access (OFDMA) carriers. In North America a single carrier 256-QAM channel occupies 6 MHz resulting, after forward error correction (FEC) overhead, in 38.8 Mbps capacity that increases after multiple channels are aggregated through channel bonding. The efficiency has improved as we have transitioned from DOCSIS 3.0 to DOCSIS 3.1 and so has been the access to spectrum. A DOCSIS 3.1 channel occupies up to 192 MHz and using 4096-QAM modulation provides a capacity of about 1.9 Gbps after FEC. DOCSIS 3.1 defines an upper frequency edge of 1218 MHz, which means that 5 192 MHz channels can be placed between 259 MHz and 1218 MHz resulting in a total downstream capacity of around 9.6 Gbps. DOCSIS 4.0 has enabled further spectrum by defining an upper frequency edge of 1794 MHz or 8 192 MHz channels starting at 258 MHz resulting in a total downstream capacity of around 15.36 Gbps using 4096-QAM. Cable networks today use a combination of SC-QAM and OFDM/OFDMA channels.

2.4. General Evolution Considerations and Approaches

Network evolution may have many drivers that could influence how the evolved network may look like. In our case, we are including not just the transport infrastructure but also end-device capabilities, network architecture, communication protocol etc. Achieving higher capacity may be an obvious metric but others including lower latency, higher reliability, lower energy consumption, lower complexity, scalability and service optimization could play an important role in shaping the future network. In this paper the primary focus is in achieving higher capacity while other metrics are also considered at a secondary level.

3. Capacity Enhancement Tools

There are only a few approaches that any network can leverage to increase capacity. These techniques have been and continue to be leveraged in cable, in DSL and in mobile. The first one is to increase the efficiency of transport, meaning to put more information in the signals we carry. The second technique is segmentation which in cable, it is associated with node splitting or deeper nodes so that the same capacity that is delivered to the original node serving area could also be delivered to the subset child nodes, thereby multiplying the total aggregate capacity. The third technique is increasing the amount of spectrum used so that more signals can be carried. We explore these options now in more detail.

3.1. Efficiency

In the DOCSIS 3.1 specification [3], the efficiency within the coaxial cable is approaching its pinnacle. In the downstream, the DOCSIS 3.1 specification mandates a modulation order of 4096-QAM allowing also the option of 16384-QAM. 4096-QAM results in 12 bits/symbol while 16384-QAM in 14 bits/symbol. The DOCSIS specification assumes a carrier-to-noise ratio (CNR) of 41 dB to support 4096-QAM transport while 16384-QAM would require about 7 dB above that. It is worth mentioning that in a traditional architecture using analog optics, the transmit power of the laser would have to be extremely high to meet the CNR requirement. This not only incurs in high laser cost but impacts efficient use of fiber resources because at high optical Tx powers, fiber enters a non-linear mode and only very limited wavelength multiplexing would be possible in this power limited environment. Our industry avoided that by leveraging DAA architectures where baseband optical signals are used between hub and node and the DOCSIS RF signals are generated by the remote PHY device (RPD) or remote MAC-PHY device (RMD) at the node. Still after removing the analog laser challenge, we still need a very clean coaxial plant to carry the highest efficiency signals and operators need to invest in OPEX to maintain the required CNR levels.

It is also worth discussing how much RF power is needed to maintain high efficiency coaxial transport. Figure 4 shows in blue, the signal CNR needed for modulations using the different downstream square constellations according to the DOCSIS specification. Figure 4 also shows in red the spectral efficiencies of the corresponding downstream modulation orders.

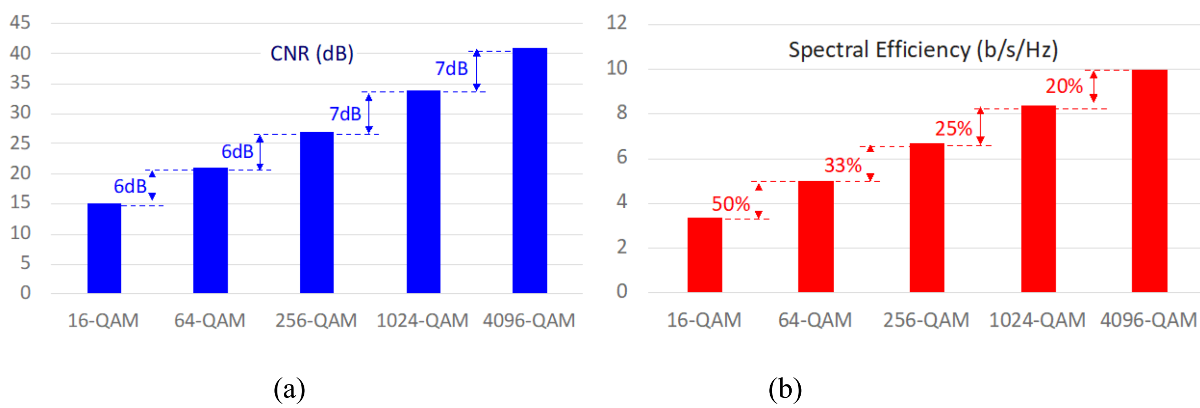


Figure 4 – CNR (a) and Spectral Efficiency (b) Increase with Modulation

Figure 4 also shows the CNR gap in dB to go from one modulation example to the next of about 6 dB below 256-QAM and 7 dB above 256-QAM. In other words, to go from one square constellation to the next, we need at least a 6 dB increase in power or an increase in power by a factor of four. The efficiency chart in red shows that when going from 16-QAM to 64-QAM a 50% increase in efficiency is obtained but that increase in efficiency is gradually reduced. When transitioning from 1024-QAM to 4096-QAM the efficiency improvement is only 20%. This efficiency behavior prompts the question, is it worth to increase the power by a factor of 4 to achieve a 20% increase in efficiency? Do we allocate this power to increase in efficiency or to increase the amount of spectrum? There has been significant work towards increasing the efficiency in DOCSIS systems and perhaps we are reaching a point of diminishing returns with further efficiency improvements efforts.

3.2. Fiber Deeper Segmentation

Initial node splitting happened gradually in localized areas to address a particular shortage in capacity. As the increase in average consumption generated more widespread upgrade needs, a change in the HFC architecture in high traffic growth areas has been considered. Service providers have different perspectives on the next fiber-deeper evolution step but two alternatives that have gained some traction are N+2 and N+0 architectures. In both scenarios, the overall capacity potential is multiplied by the number of child nodes that result from that upgrade. In N+2 architectures the number of child nodes that can be obtained from the original legacy node could range from 4 to 8 child nodes while in an N+0 migration the number of child nodes may range from 10 to 18. The resulting number child nodes have multiple dependencies including original fiber node topology, amplifier gain, highest plant frequency, etc. In such an upgrade, the amount of labor along with the number of fiber nodes or RPDs/RMDs cost and the additional fiber needed to the new endpoints must be considered.

For example, a legacy 500 HHP fiber node serving area with 1.2 GHz of spectrum, would have approximately 10 Gbps of aggregate capacity. If the same legacy node would be segmented using an N+2 upgrade into 5 child nodes, the aggregate capacity could reach 50 Gbps and if the legacy fiber node would be segmented into 12 N+0 child nodes, it would result in an aggregate capacity of 120 Gbps. Through segmentation, aggregate capacity is augmented while the peak capacity available to a CM in that serving area would be the same as in the in the original legacy node.

From an implementation cost perspective, the number of child nodes, the additional fiber deployed to these deeper nodes and whether these nodes are conventional analog nodes or whether they are RPDs or RMDs are important cost complexity considerations. In a fiber-deeper upgrade, it is desirable to achieve as lower number of actives in cascade as possible incurring fewer child nodes. Figure 5 shows the original Figure 1 fiber node segmented into a N+2 architecture.

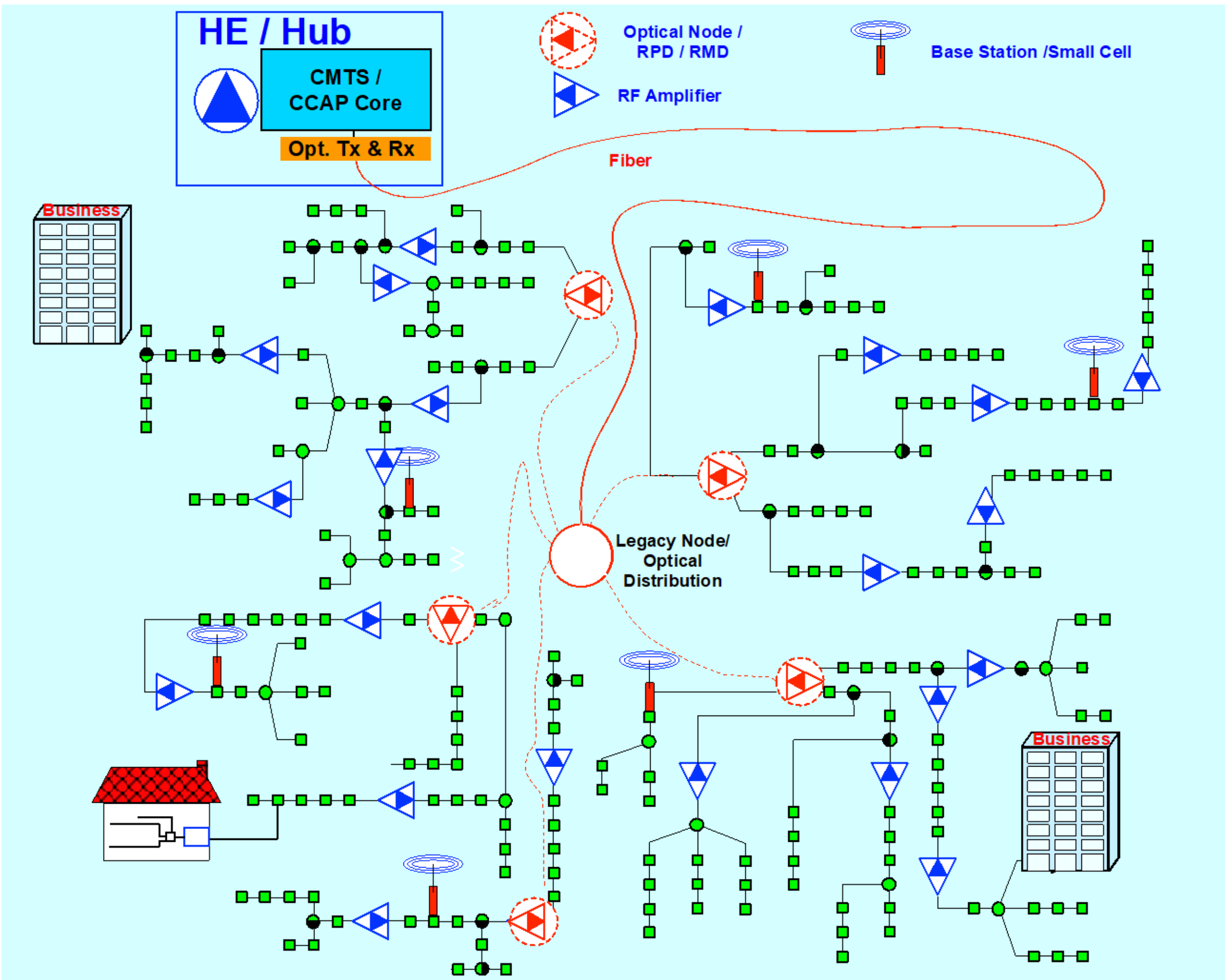


Figure 5 - Original 500 HHP fiber node serving area upgraded to 5 N+2 child nodes

Figure 6 shows the original Figure 1 fiber node further segmented into a N+0 architecture.

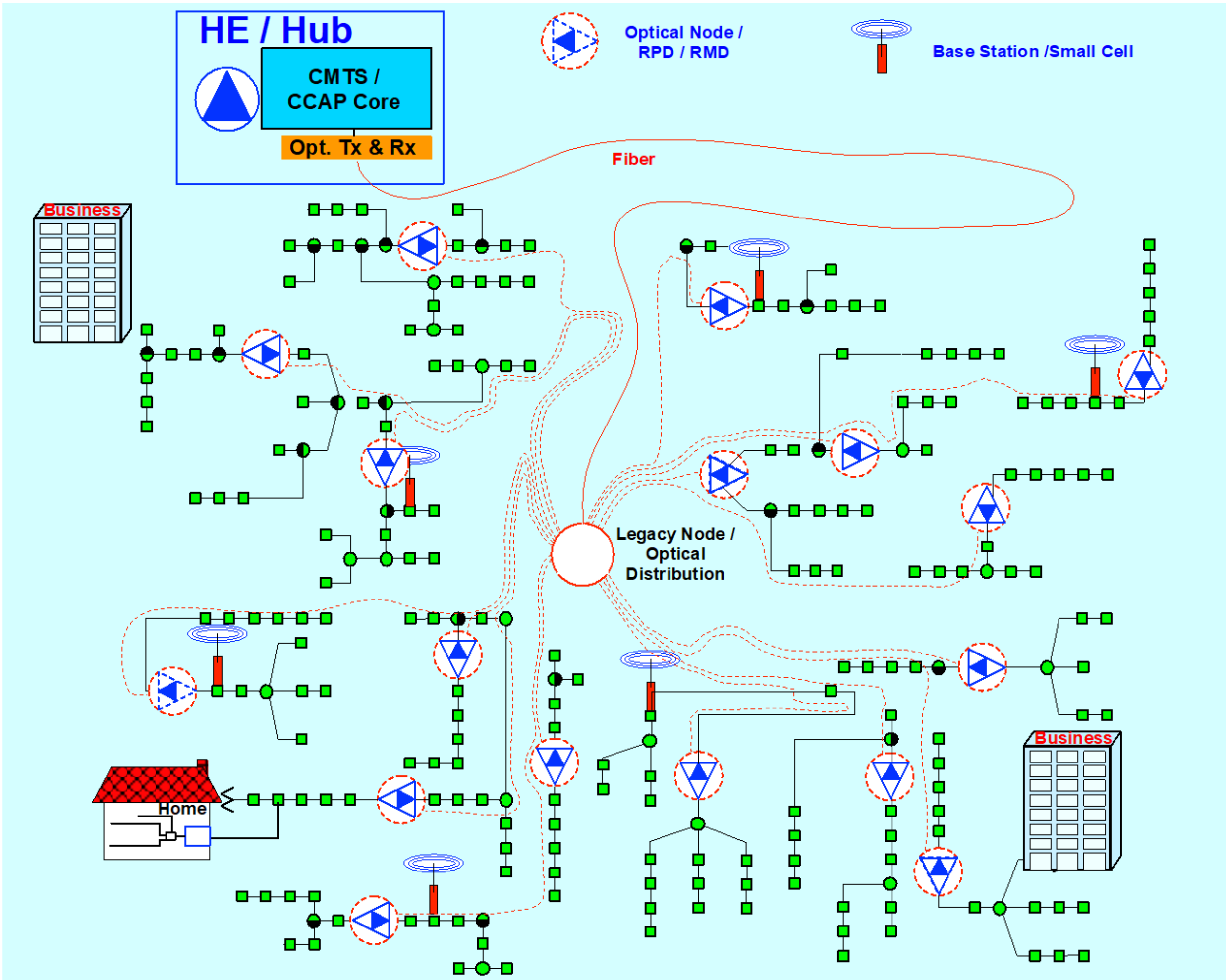


Figure 6 - Original 500 HHP fiber node serving area upgraded to 17 N+0 child nodes

In this theoretical node segmentation exercise, the spacing of amplifiers has been maintained and some taps have been reversed. In upcoming sections, we will explore what changes could help us extend the coaxial segment lengths to reduce the number of child nodes. Our industry is currently leveraging segmentation heavily and the optimization of segmentation could still enable further gains in capacity.

3.3. Coaxial Spectrum Increase

The third technique to increase capacity relies on making more spectrum available. Despite our industry having historically experienced multiple phases of spectrum increase by transitioning from 250 to 350, 450, 550 750, 860, 1002 and 1218 MHz and now embarking to 1794 MHz leveraging DOCSIS 4.0 specification, it still is a very promising approach to further increase capacity. Upper frequency limits reaching 3, 4 and 7 GHz could be within reach. We explore next how we can make the most out of our coaxial system resources.

In earlier plant upgrades to higher frequencies, the actives and passives have been updated and in some cases the amplifiers have been respaced. More recently, instead of amplifier respacing higher gain amplifiers have been used. Gallium Nitride (GaN) technology has been an enabler in amplifier performance.

3.3.1. Frequency Characteristics of Distribution Network Components

One reason why components have been replaced after a frequency upgrade is that their design did not consider higher frequencies and it has been by chance when components were still usable beyond the designed frequency. The robustness of DOCSIS end-devices along with a general gradual performance roll-off of the components at the upper frequency edge has been leveraged to operate beyond the plant components design frequencies.. As we examine potential use of the plant at the higher frequencies, we need to characterize granularly how each of the distribution components traversed behave at higher frequencies.

3.3.1.1. Coaxial Cable

Coaxial transport is key in the evolution of the HFC at higher frequencies. We have shown in [4] how to model cable attenuation and the cut-off frequency limits for the different cable types used in our access network. Assessing the impact of these cable characteristics is key to optimize resources in the cable portion of our network. Figure 7 summarizes these findings.

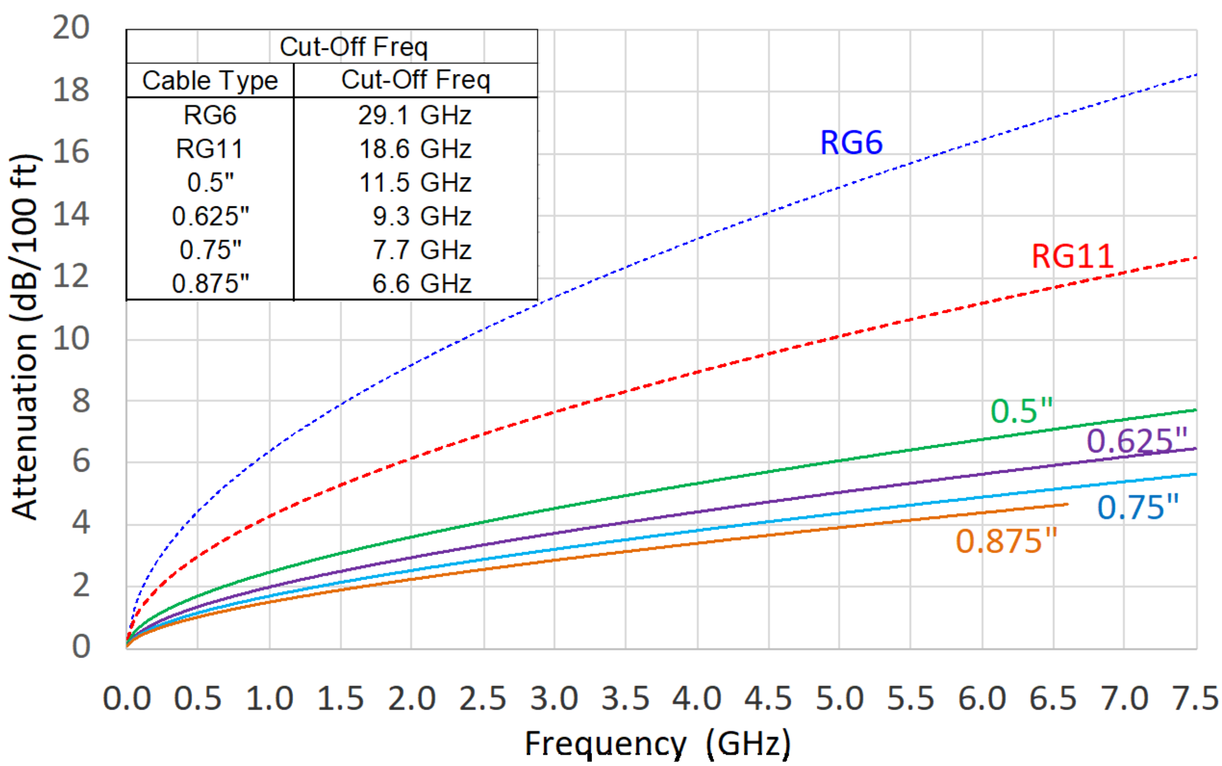


Figure 7 - Attenuation and Cut-Off Frequencies of Coaxial Cable Types

When the wavelength of signals traversing the coaxial cable are similar in size to the diameter of the coax as described in [5] by the cut-off frequency formula, higher order modes that interfere with the main mode began to appear. This represents a high frequency limit in coaxial transport. The cut-off frequency and attenuation are dependent on the geometry of the cable. While smaller geometries have much higher cut-off frequencies, smaller geometries have also higher attenuation which Figure 7 highlights with the smaller diameter flexible RG6 and RG11 cable showing much higher attenuation than the hardline cables. Even though the flexible coax has a much higher cut-off frequency than the hardline, the overall limitation is determined by the lowest cut-off frequency of all the cable types in a concatenated coaxial path, which is the largest size hardline. Figure 7 shows that only the 0.875” hardline cable has a cut-off frequency limit below 7 GHz. The thicker hardline (0.875”, 0.75”) is generally used in the longer express cable runs rather than the distribution portion of the network interconnecting taps, but is still suitable up to 6.6 GHz.

3.3.1.2. Tap Housing and Faceplate

Besides coaxial cable, taps are the most prevalent component in the network and its high frequency behavior, and any limitations need to be carefully studied.

Traditionally taps consisted of a housing and a removable faceplate (Figure 8). The faceplate contained the coupling and drop port distribution circuitry. Having removable taps allow faceplates to be designed with different tap values so that the signal levels exiting the tap could reach the receiver at about the same level (Figure 2), which has been a practice since early days of cable and analog video distribution. At deployment, a technician would install the appropriate tap value/faceplate to meet the target Rx levels.

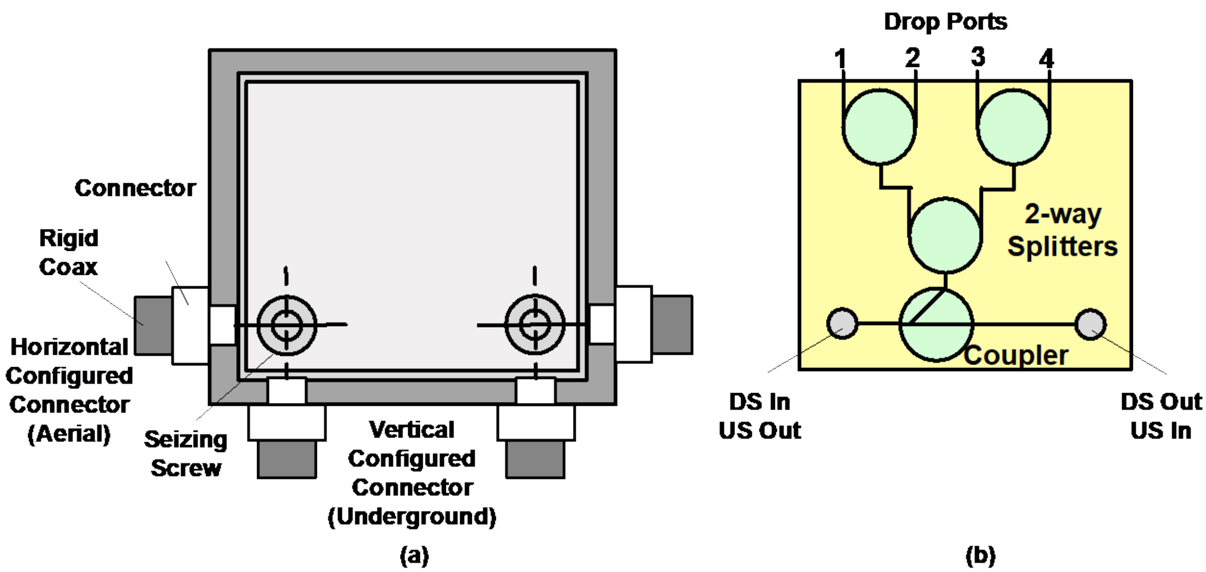


Figure 8 – Tap Housing (a) and Faceplate (b)

Taps’ housing have been flexibly designed to support either aerial or underground deployments. In underground deployment both hardline cables come out from the ground and are better suited to use the connectors exiting the housing from the same side while in aerial deployment the tap connectors facing opposite sides that are in-line are better suited for deployment (Figure 8). A mechanism in the tap housing through rotation or one that allows connections from both vertical and horizontal directions is implemented. While this mechanism is suitable at lower frequencies it is challenging to implement at higher frequencies without performance impact.

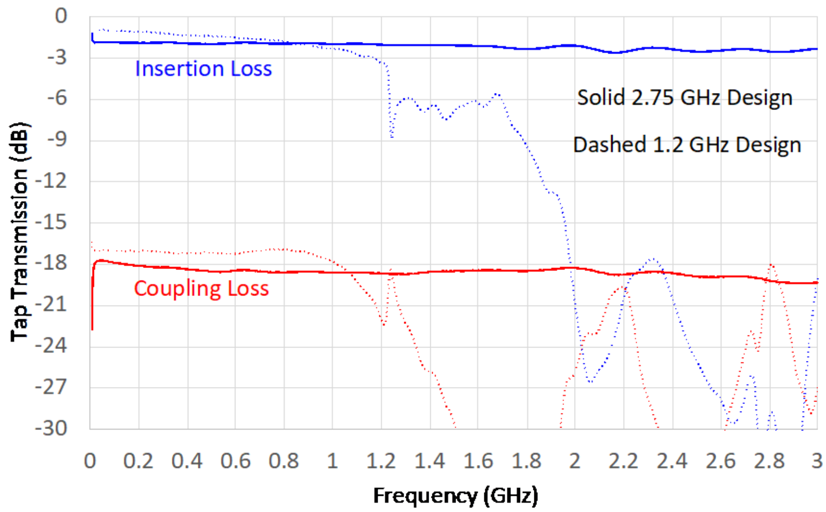


Figure 9 – Transmission Characteristics of Sampled 1.2 GHz and 2.75 GHz Taps

Figure 9 highlights the difference in performance from two products designed for different frequencies. While the 1.2 GHz tap barely meets its insertion loss design target at 1.2 GHz and falls slightly short of its coupling loss target at the upper frequency edge, the 2.75 GHz tap exceeds its insertion and coupling loss targets even at 3 GHz. This potential variability around design targets prompt us to characterize all distribution components in a very granular fashion. Only then, system capacity at higher frequencies would be accurately quantified.

Some of the challenges in high frequency tap performance reside in the housing and aerial/underground switching mechanisms as well as the KS connector center pin variability. The upcoming sections review approaches to address these challenges.

3.3.1.3. KS Connector and Splice

Other key distribution network element in the extension of the plant frequency range includes the KS connector and the hardline splice. While the KS connector is simple and perhaps without an inherent high frequency limitation, it is when it mates with other structures that issues could arise. The coaxial splice, a fairly prevalent element and with two KS connector mating interfaces is of particular interest. Figure 10 depicts KS connectors and a splice before and after mating. It also highlights potential transmission discontinuities. This potential problem also could be present when a KS connector interfaces with another distribution network device such as a coupler, splitter, tap or amplifier.

A roundtrip of 180 degrees or λ/2 results in a one-way λ/4 length to encounter resonances when reflections are present. We assume a PTFE dielectric (e_r =1.71), which is typically used flexible coax, and calculate a λ/4 resonant length at 3 GHz of 19 mm or 0.75”. This means that the structures in a KS connector could in principle resonate at the frequencies considered if proper impedance matching is not considered in the design. These design considerations applies equally well in structures that may be larger in size such as taps, splitters and couplers.

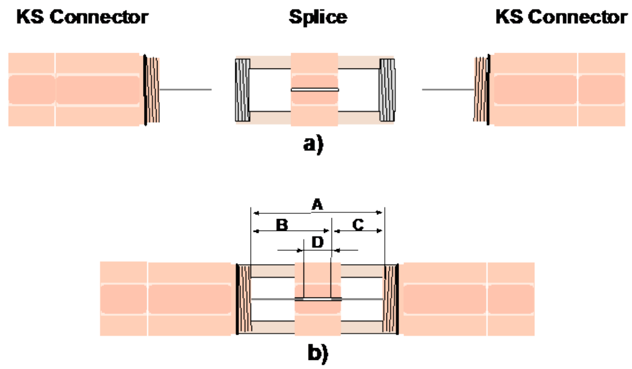
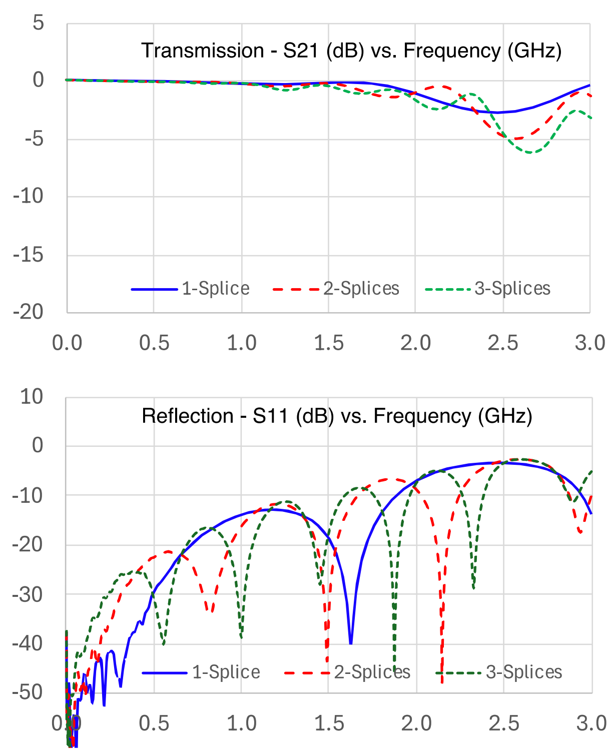


Figure 10 – KS Connectors and Splice before (a) and after Mating (b)

Figure 11 shows the transmission (a) and reflection (b) frequency measurements we conducted on a single and cascaded hardline splices designed to mate 0.625” hardline cable. All the cascaded splices tested were connected with element-to-element pin based KS connectors and have used KS-F adapters on both ends to connect to our Vector Network Analyzer for characterization.



(a) (b)

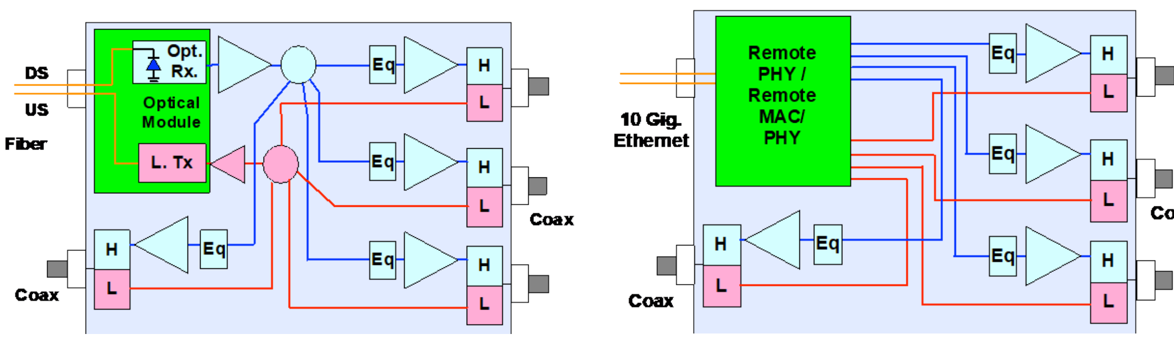
Figure 11 – Frequency Response of Single and Cascaded Coaxial Hardline Splices

A resonance in the single KS splice, generated a shallow frequency notch at 2.5 GHz (blue trace Figure 11a). That notch would accentuate deeper and slightly wider if many of the splices with the same characteristics are traversed. This compounding effect of the cascaded splices is shown in the red trace (2 splices in cascade) and green trace (3 splices in cascade) of Figure 11a. If only one type of splice would be used, one could efficiently work around it by excluding the subcarriers corresponding to the notch frequency. If different models of splices with different dimensions and characteristics would be used, notches would appear at other frequencies which would require a larger number of excluded subcarriers and result in lower efficiency transmission. This assumes that splice impedance discontinuities are present which is why careful characterization of the different types of deployed splices is needed to evolve to multi-gigahertz frequencies. Additionally, beyond transmission losses induced by the splice design, the length and mating methods may cause the splice to become a frequency selective reflector (Figure 11b).

Future work is needed to characterize the elements shown using modern 3D EM simulation tools, as well as other various setups. It has been noted in CableLabs tests that reflections in a splice can depend on the condition of the surrounding hardline or other active/passive devices.

3.3.1.4. Fiber Node and Amplifier

Earlier we discussed that with the transition to DAA architectures came a transition from the analog fiber node to a Remote Phy Device (RPD) or remote MAC/PHY device where the CMTS PHY or the CMTS MAC and PHY functionalities take place in the fiber node location instead of being performed at integrated CMTS typically in the hub. This split in functionality, enabled higher fidelity transport over coax and more efficient use of fiber resources. Figure 12 shows a schematic representation of the legacy analog fiber node along with the remote digital node.



(a) (b)

Figure 12 – Analog Fiber Node and RPD/RMD Node

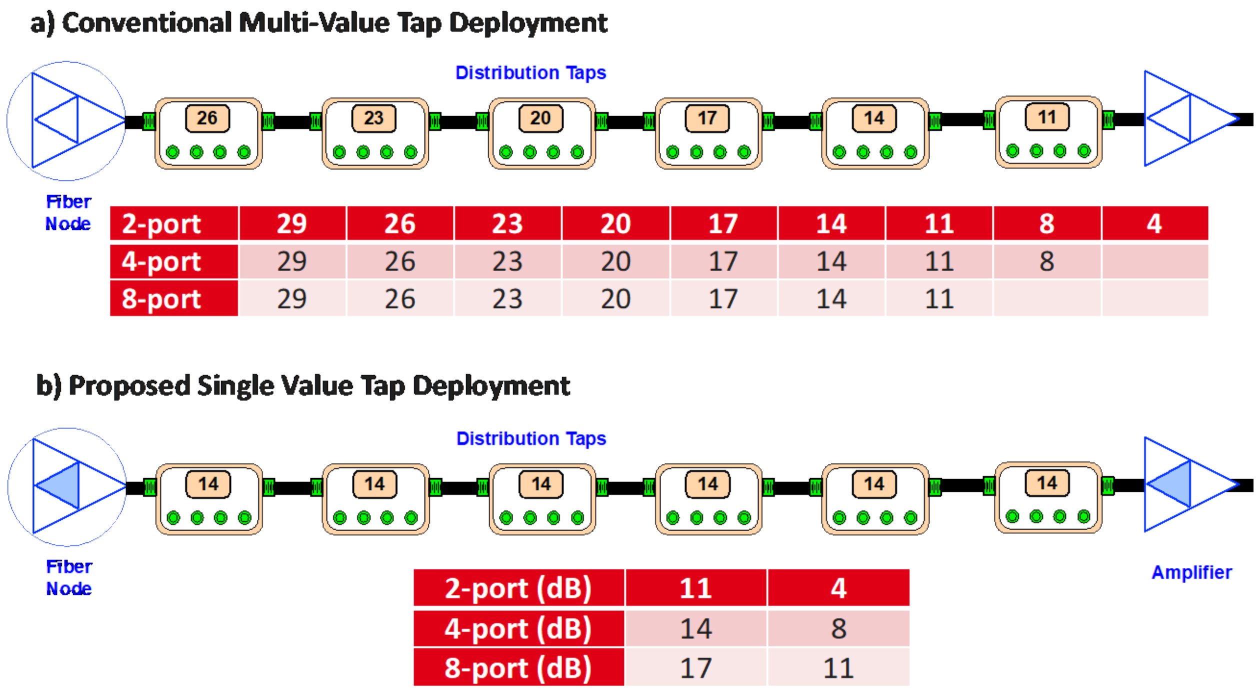
We focus now on the DAA node (Figure 12b) to consider evolution to frequencies beyond 1.8 GHz. The processing capabilities the digital module (Figure 12b in green) have to increase as a result to the higher frequency and higher capacity demanded. In addition, the amplification and filtering stages outside the digital module would also need to be upgraded including the interfaces connecting the digital and analog modules to the housing and KS connectors. Figure 12 is a simplified depiction of a node with decoupled digital and analog subsystems, an efficient implementation would have a greater integration between the digital and analog subsystems to account for frequency band modules and to have greater control of the transmitted signal, flexible spectrum coverage and related power savings modes of operations. Along with the increase in frequency, higher gain at the higher frequencies needs to be considered to overcome cable attenuation.

3.4. Exploring Distribution Network Component Evolution

The growth in demand of capacity continuous and an increase in capacity of the HFC network cannot be incremental but would probably have to address that demand beyond a decade. In this section we review the different components that we could improve upon to meet our frequency and corresponding capacity targets.

3.4.1. Single Value Tap Concept

In cable we have had the practice that every subscriber device should receive the signals from the hub at about the same level. This was true since the early days of cable when analog video was received within a narrow range of power levels. At that time this power level equalization was achieved using hardware, by designing the network with decreasing taps values as more hardline was traversed (Figure 2) so that at the end the video-receive-levels were about the same regardless of whether a subscriber connects to the network through a tap that is close to the fiber node or amplifier or whether it is further away from it. Figure 13a shows a coaxial segment example that follows that approach. This approach also requires a large inventory of tap-types so that this hardware equalization approach can be implemented.



2-port	29	26	23	20	17	14	11	8	4
4-port	29	26	23	20	17	14	11	8	
8-port	29	26	23	20	17	14	11		

2-port (dB)	11	4
4-port (dB)	14	8
8-port (dB)	17	11

Figure 13 – Conventional (a) Versus Single-value-tap (b) Deployment Approaches

Figure 13a shows tap values you encounter in networks today. A 32 dB value tap has not been included because of its negligible numbers deployed.

Technology has made significant advances since the early cable days. This includes receivers with better sensitivity and greater dynamic range. In wireless for example, the receiver has the capability to receive signals whether these come from a radio far away or much stronger signals originating from a radio tower nearby. Leveraging such advances in receiver technology, we propose the use a single value tap approach where for the same number of tap ports, the same tap value is used. We consider an exception for the end-of-line tap where a splitter is used, and no coupling takes place. Figure 13b shows how the coaxial segment would look like, and the reduced tap inventory required. The implications of such a reduced tap inventory are critical in the evolution of the network to higher frequencies. The selection of a tap value 14 for 4-port taps follows from the fact that there is very minimal through-loss difference between the 14 dB value tap and all the higher tap values while there is a big difference in the coupling loss between taps. Therefore, with a negligible hardline path loss penalty, a significant increase in performance can be obtained in CMs that are attached to devices that connect to taps with 14 dB or higher coupling loss value. From Figure 3 we see that since most taps have tap values equal or higher than 14 dB, this approach will benefit most subscribers. Tap modelling and simulation to obtain the optimal single-value-tap coupling factor is described in Appendix A.

With such a reduced inventory it becomes practical first “NOT” to have taps with removable faceplates and second to have one housing designed for aerial deployments (horizontal connector entry) and one housing for underground deployment (vertical connector entry)

The above implications, particularly not having a removable faceplate, are that the tap can now be designed to be permanently closed. These implications mean “NO” switchable elements to accommodate for aerial or underground deployments which limits high frequency performance. No issues of improper RF shielding and water tightness with RF gaskets and water gaskets wearing out or out of place due to constant manipulation when removing and closing faceplates. KS connectors entering taps or other distribution network elements would have standard center pin length and not leave it up to the technician to trim center pin to the proper length. Longer center pins have inductive behavior limiting or impacting frequency response. There will be no issues of improper contact with seizure screws. Since the number of drop ports will rarely change. There would be no need to change taps assuming same tap values and if demand of additional drop ports is anticipated, taps with a large number of drop ports could preemptively be installed. Since there is no option to remove faceplates, there is no need to design a spring-loaded RF and AC bypass when faceplates are removed, which is a mechanism that impacts higher frequency operation.

Most importantly is that by using a permanently closed and sealed tap, it facilitates best practice microwave design and implementation resulting in optimized tap performance. Many of today’s tap designs leverage lumped or discrete circuit elements in their implementation using fiber glass based FR4 substrates. While this practice was suitable below 1 GHz, as we move to multi-gigahertz operation, the performance of components may become sub-optimal. Ceramic and PTFE (Polytetrafluoroethylene) based substrates have higher permittivity which helps confine the RF energy and reduce leakage. We can combine the best of both worlds by leveraging both lumped and distributed elements.

Different aspects that have been tied to the removable faceplates and adaptable aerial/underground tap configuration have resulted also in limited performance at higher frequencies. A permanently closed housing approach will improve performance and the link budget of our coaxial segments

In addition to the performance improving aspects of a single value tap strategy, there are drastic operational implications. Technician would carry a greatly reduced inventory of components in their trucks. There will be fewer truck rolls since there is no need of “power level adjustment” in the plant leveraging the flexibility of the end devices.

3.4.2. F-Connector Upgrade or Replacement

The cable industry has used F-connectors since they were invented in the 1950s. To continue evolving our network, it is important to understand the performance of F-connectors at multi-GHz frequencies. This would entail not only connectors that reside in the home environment but also outdoor connectors in the tap drop-ports. Some F-connectors have been successfully tested all the way to 3 GHz but not all F-connectors are manufactured the same way, and it is important to verify performance particularly if we are exploring to operate above 3 GHz. In addition to the performance of a well tightened F-connector, it is critical to examine susceptibility of F-connectors becoming loose over time, including connectors on terminated cables that are subject to vibration and/or wind motion. While at lower frequencies an F-connector may still operate well after becoming loose by a few rotations, at higher frequencies there is greater chance such loose connectors would cause an impedance mismatch impacting performance. CableLabs® evaluated commercially available 75-ohm connectors for flexible coaxial cable showing operation to 10 GHz (Figure 14). Our industry should seriously examine if the time has come to adopt a new connector standard for the high frequency environment we are considering evolving to.

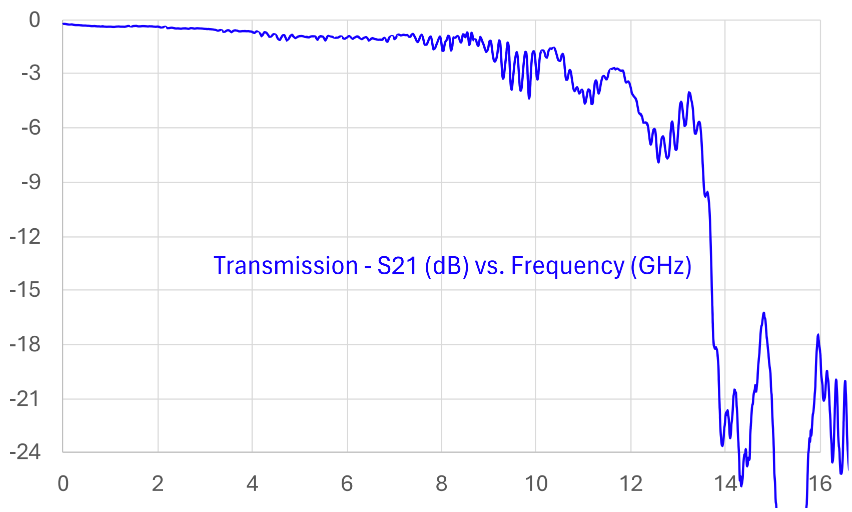


Figure 14 –75 Ohm NDX Connector Transmission S21 Parameter

3.4.3. CPE Shielding

It is important to isolate the HFC plant from unwanted external signals entering the plant (ingress) and to avoid signals within the coaxial network leaking outside the plant. As we entertain the use of higher frequencies, the CPE could become a source of leakage and ingress. Probability of radiation leakage (egress), as well as outside signals entering the coaxial plant (ingress), will increase as we use higher frequencies. Proper shielding practices should be incorporated in our evolution to higher frequencies, including isolating the RF components in the CPE from the baseband components. Not only signals generated within the CPE could enter the coaxial network but also free space signals such as WiFi and mobile signals could be coupled into the plant. Moving to higher multi-GHz frequencies also implies a greater scrutiny our industry needs to exert in our end-devices' shielding properties.

3.4.4. No Signal Conditioning At Passives

At higher frequencies, due to the significant attenuation in the coaxial environment, it is particularly important to make best use of all the available power. In cable, we have used signal conditioning through stand-alone devices or with embedded circuits within the taps. This signal conditioning, while it enables spectrum flattening at specific bands, it does that by lowering signal levels at portions of the spectrum running at higher power levels. Our contention is that this leaves power on the table. In the operational environment we are discussing to evolve to, with modern high dynamic range receivers, it is best to leave the signal untouched and let the receiver optimize signal reception. This approach applies not just at the tap or stand-alone conditioner device but also in the amplifier or node. While the signal at the amplifier or node may be uptilted or conditioned by the DAC or an initial amplification stage, to best leverage power available the signal should not be conditioned after the power amplifier.

3.4.5. Home Network

We have discussed optimizing power as well as ingress and leakage as critical to the evolution to higher frequencies. These two evolution drivers are key in shaping our home network high-frequency topology criteria. As we move to IP video delivery within the home and to better manage higher frequency signals delivered into the home, it is time to consider a single gateway device within the home. This means a

DOCSIS home network topology leveraging whenever possible, existing home coax to establish a single coaxial cable run from drop port to CM without splitters and with shielded and properly grounded cable. Ideally the shortest in-home coaxial run that is followed by an effective in-home WiFi environment to distribute IP services within the home. This simple home environment not only optimizes high frequency performance but also simplifies operations.

3.5. Evolving Data-Over-Cable End-Devices – The CMTS and CM

Our end devices play a critical role in our evolution to higher frequencies. Increased capacity means greater capture bandwidth and more processing which impacts the cost of the device. As we increase the amount of spectrum covered in coax, managing this variation in channel conditions with frequency becomes a key attribute of our next generation systems. Next, we will discuss evolutionary changes in the CMTS and CM to better leverage higher frequency spectrum.

3.5.1. Higher Tx Power and Higher Dynamic Range

We have discussed earlier how improvements in transmit power and sensitivity of our end devices facilitates use of higher frequencies in the cable plant. These enhancements increase the dynamic range of the DOCSIS system so that the attenuation at higher frequencies shown in Figure 7, can be better compensated. The lower frequency behavior will be more robust since attenuation is lower at the lower frequencies.

In our DAA nodes, that include RPDs and RMDs, it is advantageous to digitally generate the downstream signal uptilted in frequency. Digitally generating such a transmit power profile, likely at the DAC, allows the flexible adjustment of this Tx power profile to maximize the power of the signal reaching the modem and minimize power consumption of our system.

While the DOCSIS 3.1 specification calls for a CMTS transmit power up to 60 dBmV, DOCSIS 3.1 remote devices at the node have been implemented with total composite power (TCP) levels reaching 65 dBmV. Furthermore, DOCSIS 4.0 specification requires a TCP transmit signal of 72 dBmV at the node. In an uptilted signal, the higher frequency channels, will consume most of the TCP budget. Ideally, we should have the flexibility to transmit at the highest power level that the TCP requirement allows while also compensating for the cable loss.

Maximum signal amplitude limitations, lead to transmit power profiles using a response step down at higher frequencies. Nevertheless, it is worth considering implementations where that signal amplitude limitation has been addressed. Figure 15 shows a DOCSIS channel distribution with uptilt compensating a hardline and drop cable loss

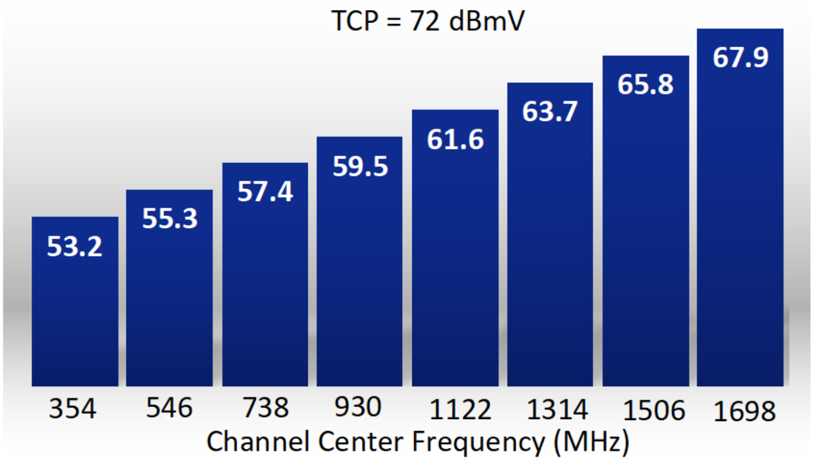


Figure 15 –Uptilted Downstream Spectrum Example (258 MHz-to-1794 MHz)

This uptilted power profile approach is particularly useful if transmission to 4 GHz and higher frequencies are considered and should also be considered in the upstream since the TCP mandated in the DOCSIS specification is 65 dBmV.

3.5.2. System/RPD Bandwidth versus CPE Bandwidth

Operators' DAA deployments vary but as a rough estimate we have around 100 CMs for every RPD/RMD. Since the cost of the RPD is shared among a large population of users, the CM cost is dominant and requires a cost-effective implementation strategy. This asymmetry in numbers also prompt us to consider asymmetry in capabilities and performance to maintain CM costs low. The cost of basic CM depends among other things on the amount of power it is required to transmit, the bandwidth it is capable of capturing, and the amount of data it requires to process.

We need to decide what the ultimate plant maximum frequency could be. This would be based not only on the challenges to upgrade the coaxial distribution network but also on the challenges and cost to upgrade the end-devices. Should this maximum frequency be 4 GHz? Should it be 7 GHz?

If the maximum HFC plant frequency could reach 4 GHz or higher frequencies, the implementation of a CM that could simultaneously leverage the entire HFC spectrum may not be cost-effective. It is probably wise to separately analyze the aggregate resources that can be obtained from the HFC plant from the practical performance capabilities a CM. Decoupling aggregate plant capacity from CM peak speed will allow us greater flexibility in optimizing CM cost and deciding what should be the highest plant frequency. If cost complexity analysis shows that the aggregate plant capacity and the CM peak speed could be the same, then we can couple them as a result of analysis but not as a starting premise.

As a result, we consider the following parameters independently:

RPD Transmit bandwidth = DS System bandwidth

RPD Receive bandwidth = US system bandwidth

CM - contiguous Rx capture bandwidth (downstream)

CM - contiguous Tx bandwidth (upstream)

Today DOCSIS 3.1 CM implementations support 2 192MHz OFDM channels along with 32 SC-QAM channels. That is 3x192 MHz spectrum processing capabilities. It is expected that DOCSIS 4.0 implementations would be capable of processing 5x192 MHz. The above indicates that CM implementations due to practical reasons process a subset of the entire spectrum that is available by the spec. Following the same trend, we expect that from a practical implementation capability perspective, a future CM that would be capable to use a subset of the entire available spectrum. From an RPD/RMD and HFC plant perspective we could entertain the following downstream capabilities

8x192 MHz = 1536 MHz (DOCSIS 4.0 today)

16x192 MHz = 3072 MHz

24x192 MHz = 4608 MHz

32x192 MHz = 6144 MHz

Which when assuming a lower edge of 258 MHz, we respectively have an upper edge of 1794 MHz, 3328 MHz, 4864 MHz and 6400 MHz. The above bands represent what the entire available spectrum would be. A logical question that follows is; What could be the subset of spectrum a CM could tune to and process? Perhaps 8x192 MHz=1536 MHz or 12x192 MHz = 2304 MHz are reasonable estimates of capture bandwidths and corresponding processing capabilities. The 12x192 MHz scenario would lead to a downstream CM peak rate beyond 20 Gbps.

3.5.3. Implementation Scalability

In the DOCSIS 3.0 to DOCSIS 3.1 transition, we migrated from the wider 6 MHz (or 8 MHz) single carrier downstream channels to channels up to 192 MHz wide made up of large number of orthogonal frequency-multiplexed 25 KHz or 50 KHz sub-carriers. In the case of 25 KHz subcarrier spacing, a total of 7600 subcarriers are used and 3800 subcarriers for 50 KHz subcarrier spacing. As we consider potential aggregation of many channels in the downstream and the upstream to increase capacity, we should explore whether aggregating so many subcarriers is scalable and doesn't impose undue burden to the processing tasks. If that is the case, potential evolution to wider subcarrier spacing should be considered as well as wider channels. In addition to the 25 KHz and 50 KHz subcarriers perhaps 100 KHz and 200 KHz subcarriers could be explored along with wider (i.e. 384 MHz?) channels. In addition to processing overhead, there may be advantages from a management perspective if fewer subcarriers and fewer channels need to be managed.

3.5.4. Increasing RPD/RMD & CM Number of Profiles

As discussed earlier, the channel conditions vary with frequency and with respect to where within the coaxial segment topology the CM is attached. This variability in frequency and MER would benefit from greater number of profiles. Currently RPD/RMD implementations support 7 profiles in the DS and CMs are mandated by the DOCSIS specification [6] to support at least 4 profiles per channel. In the high frequency environment where significant variation in channel conditions is expected, an increase in the number of profiles supported should be explored. Alternatively assuming CMTS awareness of where the CM is attached to the network, the number of profiles could remain at 4 but the intelligent system could decide which profiles would be optimal for a particular CM across the entire range of channels. The RPD/RMD on the other hand should support the maximum 16 profiles per channel and we need to evaluate if greater than 16 profiles are beneficial in our evolution to higher frequencies.

3.5.5. Holistic Management of Entire Spectrum Resources

The channel conditions measured using MER and the resources that can be obtained from the different channels will depend on frequency and on coaxial cable types and lengths derived from CPE location within the coaxial topology and characteristics of components traversed. This variability in conditions and number of resources prompt us to manage and schedule resources holistically, viewing the entire spectrum resources, analyzing CM conditions across the entire coaxial spectrum and CM capabilities to assess how to best configure and use our coaxial spectrum resources.

This environment can be illustrated by the example discussed in [4]. The coaxial segment shown in Figure 16 has CMs connected to different drop ports along the coaxial segment using RG6 drop cables of varying lengths. A total of 12 CMs distributed along 600 feet of 0.5" diameter hardline cable.

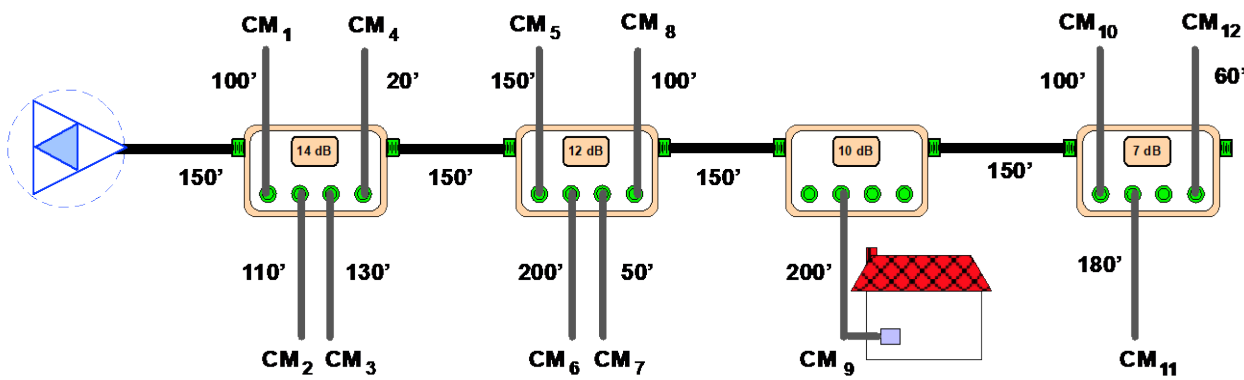


Figure 16 –Coaxial Segment Example For Ultimate Capacity Estimate

Some CMs are closer to the fiber node and have shorter drop cable lengths while others are further downstream from the node and have longer drops. Due to the frequency characteristics of cable and components traversed we expect different transport efficiency versus frequency which is shown in Figure 17. A maximum frequency of 11.5 GHz was used to examine resources up to the cut-off frequency of 0.5" hardline cable.

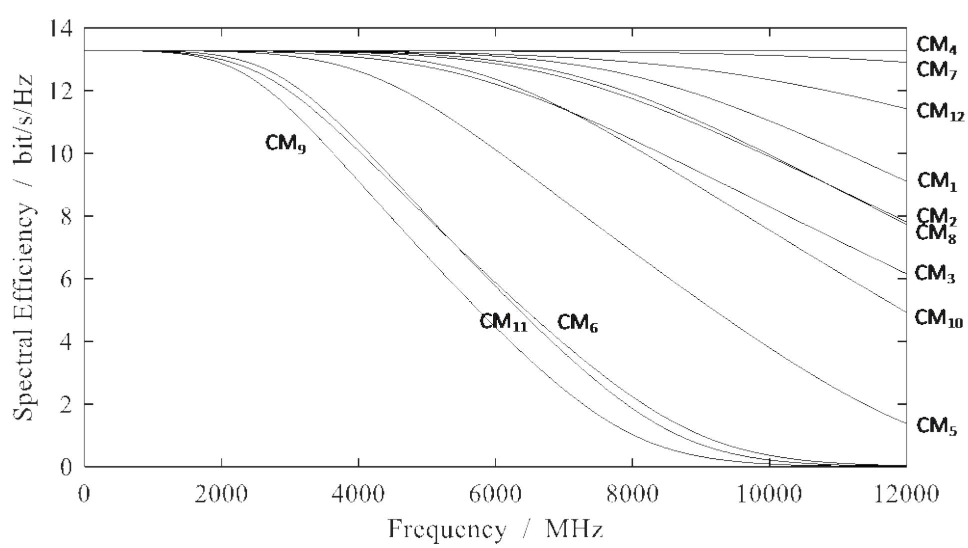


Figure 17 –Spectral Efficiency Versus Frequency Of CMs Within Topology Example

In Figure 17, we see that CM_9, that traversed a long length of hardline and has a long drop, experienced greater frequency limitation while CM_4 with a short hardline segment at the first tap and a short drop shows good efficiency across the entire spectrum.

To optimally leverage resources, the CMs with lower high-frequency MER are allocated the lower portion of the spectrum while the CMs that exhibit good MER at the higher frequencies are allocated the higher frequencies (Figure 18).

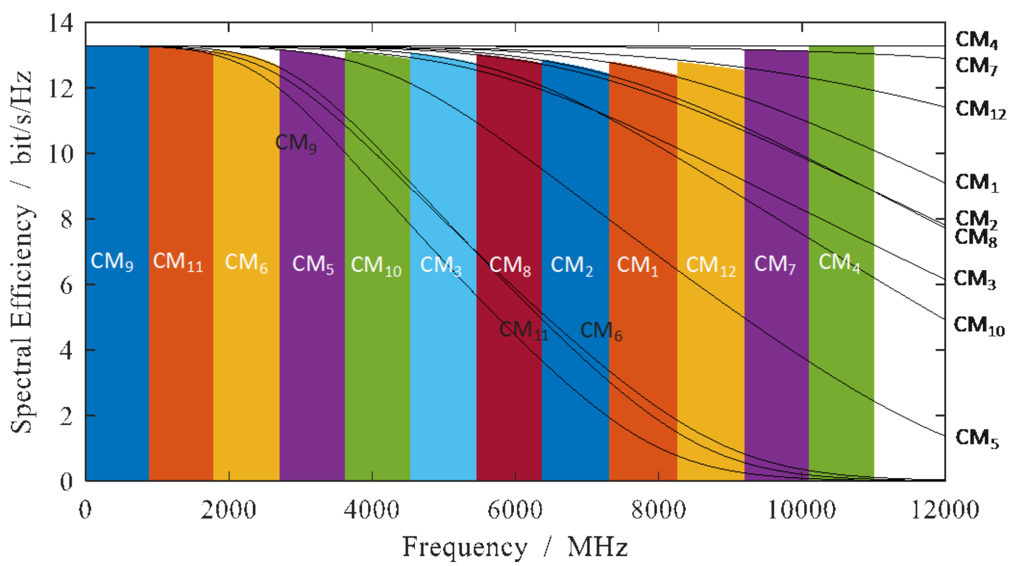


Figure 18 –CM Capacity Allocation Leveraging Frequency/MER Awareness CMs

This frequency and MER aware scheduling approach result in all CMs operating at higher efficiencies, thereby maximizing the overall aggregate capacity. The intelligent scheduling shown in Figure 16 can be further expanded to the upstream and include transmit power capabilities as well as to manage spectrum usage in a selective and agile manner to detect, avoid and troubleshoot ingress and leakage

3.5.6. A New Dimension of Frequency/MER Aware Scheduling

In the previous section we have seen how to optimize capacity in a high frequency environment where the MER changes depending on where in the network you are and what frequencies you are operating at. Figure 19a shows the attenuation versus frequency behavior of different coaxial cable types used in the distribution network which drives the frequency/MER resource allocation approach we have discussed.

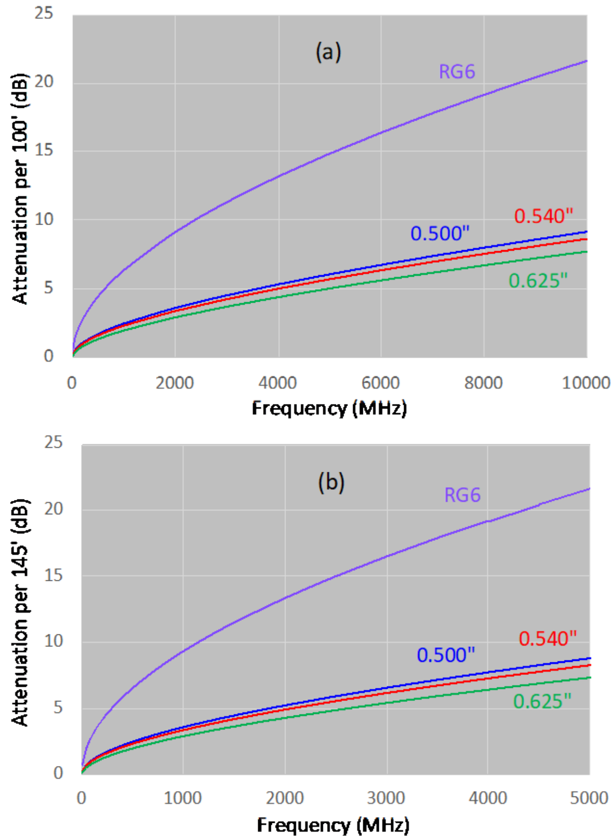


Figure 19 –Similar attenuation vs. frequency behavior a) and b), indicative that approach to increase frequency is also applicable to extend coaxial segment length

Figure 19b, also shows attenuation versus frequency of the same cable types as Figure 19a. At first glance the behaviors of 19a and 19b looked identical. The difference lies in the attenuation and the frequency scales. In 19a the attenuation is given per 100’ while in 19b attenuation is per 145’. Also, the horizontal scale in 19a reaches 10 GHz while in 19b reaches 5 GHz. The point of these two curves is that the resource allocation approach proposed can be used not only to extend and optimize operation at higher frequencies, but it can also be used to extend and optimize operation using longer coaxial segments. Next, we leverage this MER and frequency aware allocation approach to explore extending coaxial segment lengths.

3.6. Revisiting Coaxial Segmentation

We have reviewed several techniques to increase capacity in the coaxial environment. We contend that leveraging these techniques will also help in extending coaxial segment length. We have taken a sample set of HFC field scenarios consisting of a pair of cascaded segments, meaning a combination of coaxial-segment/amplifier/coaxial-segment. CPEs connected to the taps are used to estimate capacity and performance of these cascaded segments bypassing the amplifier that connects them. Figure 20 shows the 5 field scenarios. In this simulation, we leverage the principles of single value tap, Tx power profile optimization, MER/frequency aware resource allocation as well as high Tx power and optimized Rx sensitivity.

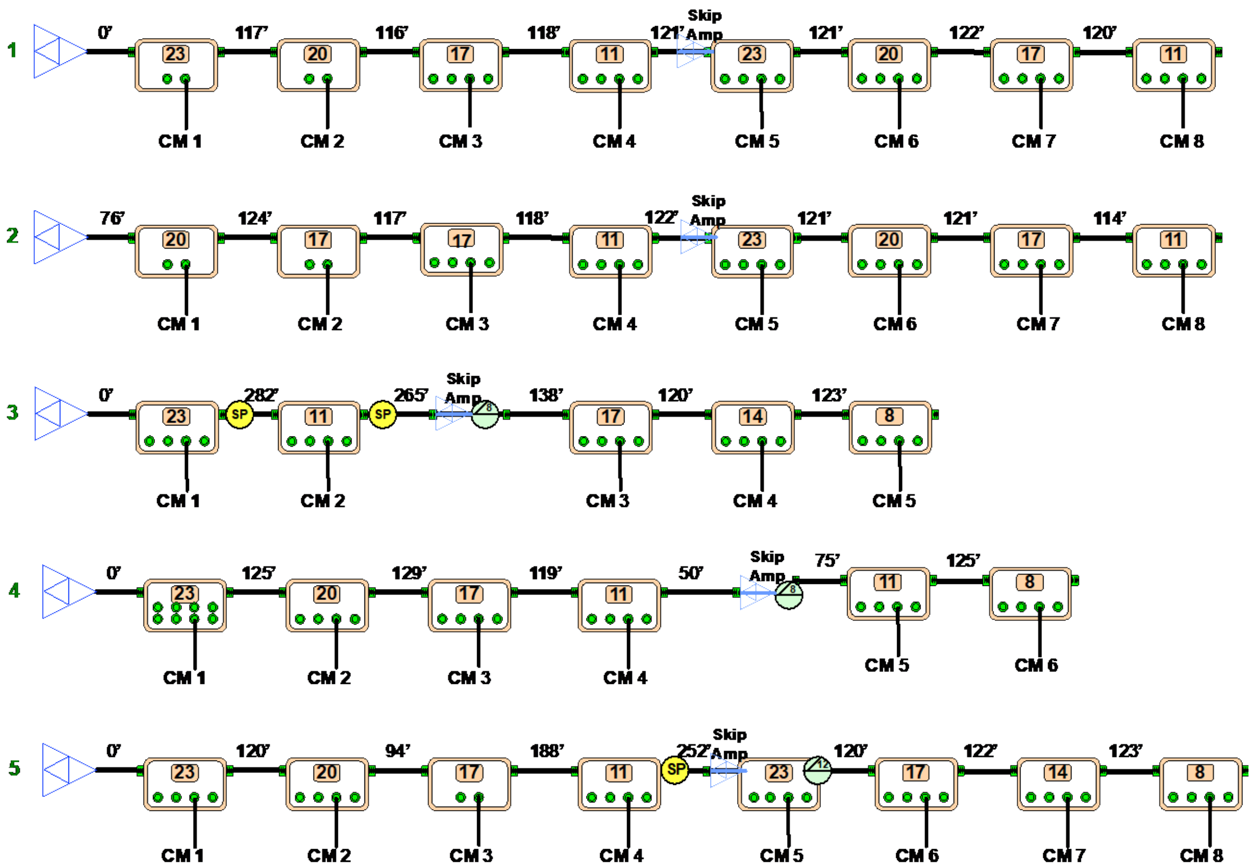


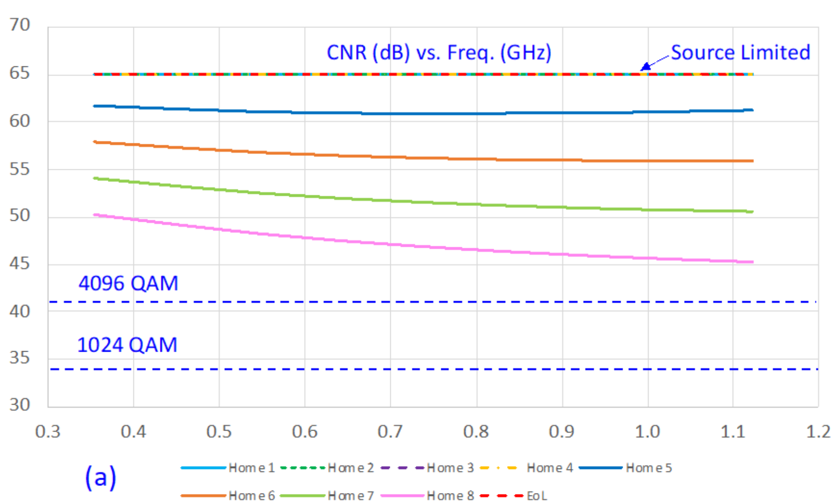
Figure 20 –Field HFC Topology Scenarios of Cascaded Coaxial Segment Pairs

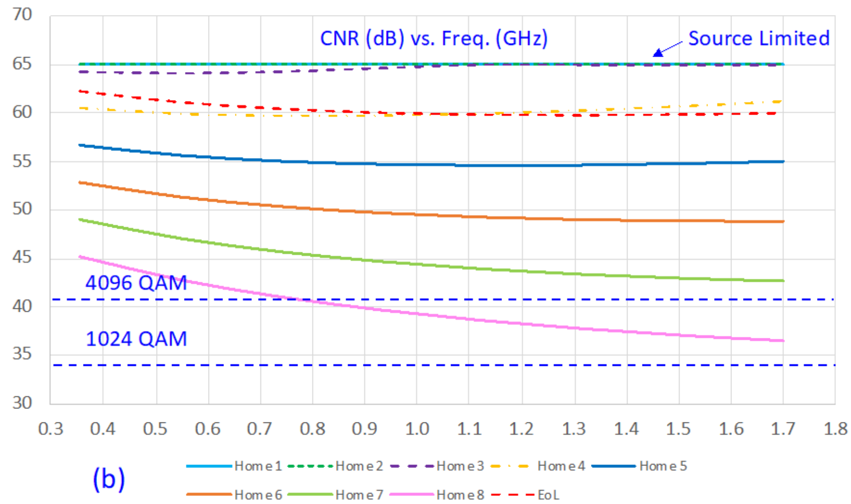
Figure 21 evaluates performance in the following 3 frequency ranges of the first scenario in Figure 20

a) 258 MHz to 1218 MHz

b) 258 MHz to 1794 MHz

c) 258 MHz to 3330 MHz.





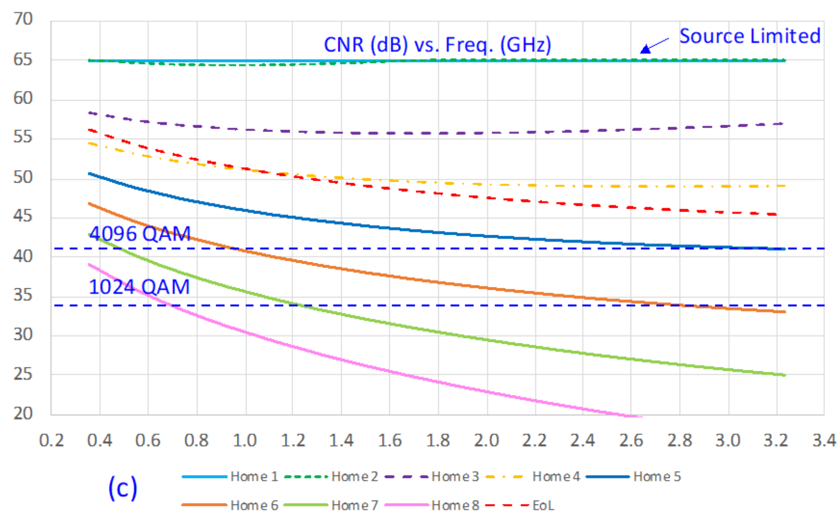


Figure 21 –Field Scenario 1 CNR vs. Frequency on Cascaded Coaxial Segments

The TCP at the RPD assumed in all the scenarios in Figure 21 is 72 dBmV along with a receiver noise figure of 5 dB. Figure 21a shows that all CMs along the cascaded coaxial segments can operate at 4096-QAM in this 1.2 GHz setup. Figure 21b shows that in the 1.8 GHz setup, the first seven CMs along the cascaded coaxial segments can operate at 4096-QAM and the 8th CM can operate using 4096-QAM up to 1.2 GHz. Figure 21c shows that in the 3.3 GHz setup, the first 5 CMs along the cascaded coaxial segments can operate at 4096-QAM while CMs 6 through 8 operate using 4096-QAM in the lower portion of the spectrum and CMs 7 and 8 don't have 1024-QAM efficiency across the entire 3.3 GHz. The 3.3 GHz case in particular benefits from the frequency/MER awareness when allocating resources so that even though not all CMs can take full advantage of the entire coaxial spectrum at maximum efficiency. The data-over-cable system as a whole, can take full advantage of its resources when resource-allocation techniques highlighted in Figure 18 are used. Figure 21 assumes a transmitter using a 12 bit DAC with an ENOB = 10.5 resulting in a signal source SNR~65dB. While the topology scenarios show 2 complete coaxial segments in cascade, more granular and flexible coaxial segment extension is possible if an operator is willing to re-position amplifiers. Appendix B shows CNR versus frequency of the remaining coaxial cascaded segment scenarios 2 to 5.

To highlight the approach on a diagram (Figure 22), we segment the original fiber node serving area in Figure 1 using the different capacity enhancement and segmentation techniques reviewed in this paper.

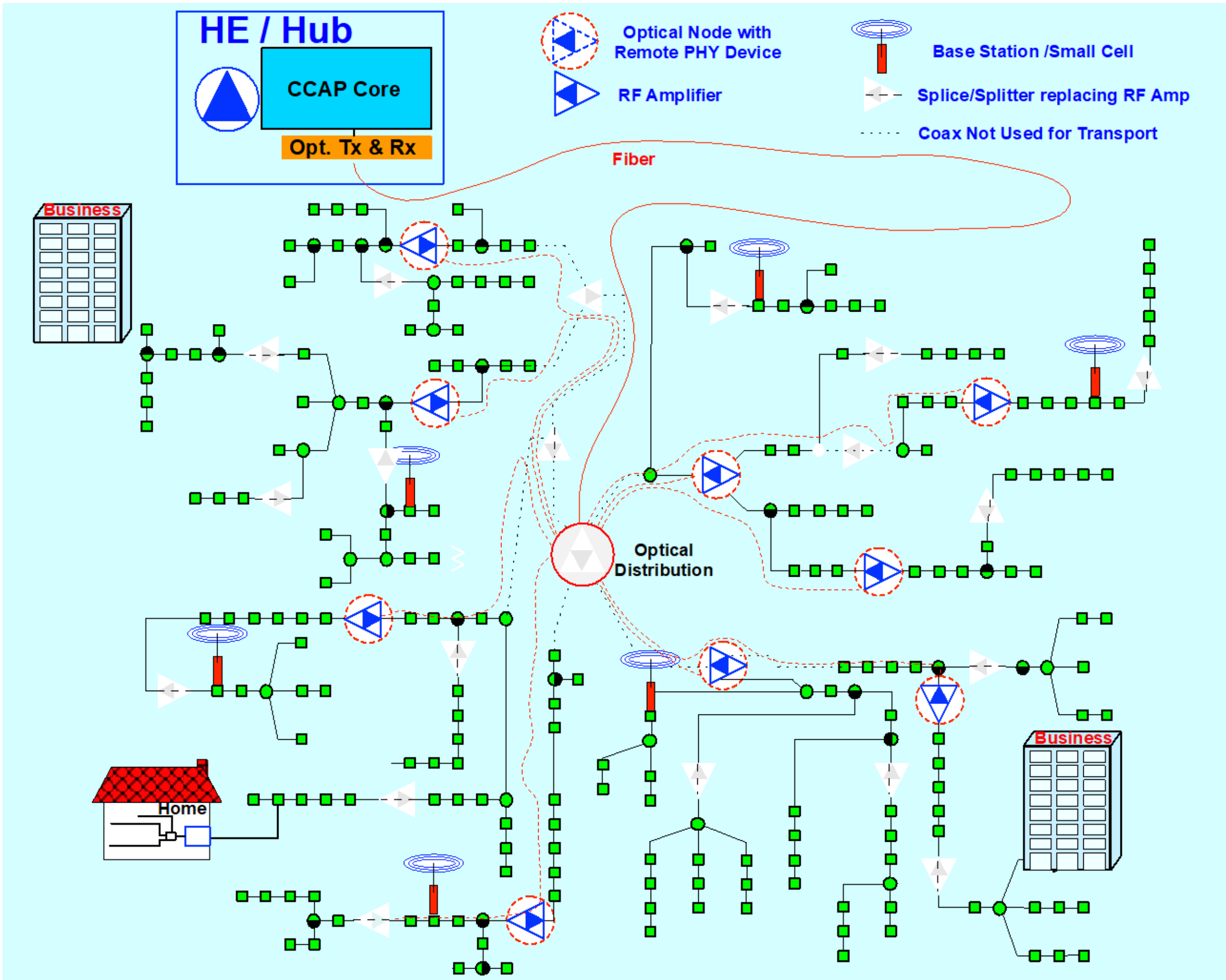


Figure 22 –Original 500 HHP fiber node serving area upgraded to 9 N+0 child nodes leveraging techniques to extend coaxial segment by skipping amplifier deployment

The node segmentation exercise shown in Figure 22 resulted in 9 N+0 child nodes compared to a conventional segmentation shown in Figure 6 that resulted in 17 child nodes. Figure 22 shows the amplifiers removed in white to highlight the number of amplifiers bypassed. This is an example of what could happen in an environment where efficient coaxial segment extension is succesfully applied. The benefit is that the number of nodes is reduced by extending the coaxial segment lengths, implying CAPEX reduction due to fewer nodes and lower OPEX by reducing the number of fiber runs to deeper nodes.

The HFC environment can have a diversity of topologies that can make this type of upgrade challenging. As we have shown, coaxial segment extension plays against spectrum increase. It is most effective at 1.2 GHz and becomes less effective as the maximum frequency is increased to 1.8 GHz and 3.3 GHz. Nevertheless, is a tool to leverage in gauging how much spectrum and/or how much coaxial segment extension can optimize our evolved transport and its deployment cost.

3.7. Service Implications

As we examine the capabilities of our industry's DOCSIS platform, we also explore potential evolution to FTTH, perhaps in a Coherent PON (CPON) embodiment [7]. We should explore what is the transport medium that makes most sense for our industry based on our existing infrastructure and the specific service demand of our customers. We have seen how leveraging coaxial resources at high efficiency is still possible beyond 3.3 GHz in an extended coaxial environment and even higher frequencies if we don't leverage our resources to extend the length of coaxial segments but just to increase spectrum. Different evolution paths may be better suited depending on subscribers' consumption forecasts and trends indicating level of service required from the network. We have shown how coax can be used reach very high levels of aggregate capacity. Aggregate capacity can be tied to average consumption, but peak capacity will require future CMs to be able to capture a large amount of spectrum and process its corresponding data. Further cost complexity analysis is required to assess the timeline of the practical peak performance a CM can achieve. Nevertheless, to avoid a lowest common denominator effect and gain flexibility, it is best to decouple highest speed or highest service tier from maximum aggregate coaxial capacity.

We have had the practice of upgrading capacity based on high end-user demand as it will trigger metrics indicating insufficient capacity. In a platform like HFC with flexible aggregate capacity growth but potentially costly in addressing peak capacity trends from an end-device perspective, it is worth to explore service delivery alternatives. We discuss next a transition to FTTH that considers the evolved HFC network discussed as a starting point to a gradual evolution to FTTH.

4. Transition To Fiber-To-The-Home

Transition to fiber-to-the-home may look different for different operators as they have different legacy to leverage as a starting point and different customer make-up with different service requirements. Therefore, we explore here optionality that could be leveraged depending on the unique conditions of every environment.

Based on our earlier analysis, we have that extending capacity in HFC through segmentation and spectrum increase, could be very suitable to address the service requirements for most of the subscribers as the resources that can be made available by the coaxial platform would be able to cost effectively handle average data consumption for the foreseeable future. However, there is a smaller percentage of high-end users with data consumption that is much higher than the average subscriber. These high-end subscribers are the ones that have driven the increase in service tier rates. The peak data rate is tied to the service tier and the cost-complexity to increasing it, needs to be carefully assessed. Alternatives to increasing the service tier rates could be:

a) Loose some high-end customers with data consumption and peak rate requirements that cannot be cost effectively addressed in HFC.

b) Implement and deploy both high-end CMs along with regular CMs (2 SKUs) to address peak rate as well as average consumption needs.

c) Leverage a surgical success-based fiber-to-to-the-home strategy to high-end users requiring performance beyond what data-over-HFC can cost effectively provide

We know how to execute options a) and b), let's explore now the challenges and advantages of option c).

Our industry has been moving either gradually or through large scale N+x rollouts into fiber-deeper architectures. This fiber deeper transition is not just accelerated by the residential growth in demand for capacity, but it has also been triggered by fiber connectivity to businesses and by connectivity to mobile radios or access points. Not currently a driver today but perhaps one in the future could be the desire to improve reliability by closing the access fiber loops. This fiber-deeper trend has resulted in fiber passing much closer to customers so that if there is need to connect fiber to a high-end data-over-HFC customer, this connection would represent a success-based extension of the FTTH network that gradually takes place and runs in parallel to the existing HFC network.

For this FTTH transition to succeed, the ultimate FTTH design should already be in place, so that when demand for connectivity occurs, there is a blue-print ready for advancing migration to FTTH. Every success-based install brings fiber closer to more subscribers so that future installations are lower cost than the earlier ones, an activity that feeds on itself towards the ultimate FTTH network.

This success based FTTH transition would be happening throughout cable systems so that even though in one node serving area only one or a few homes may be connected with fiber, within the entire cable system there would be enough mass to maintain a truck fleet in charge of this success-based rollout. There would be some inefficiencies as a large area will not be upgraded all at once, but we contend that based on the amount of strand or conduit availability, this could be more cost effective than blanket upgrades to areas that don't have high percentage customer penetration. It might be worthwhile to explore other success based FTTH transition approaches.

5. Conclusion

We have reviewed technology, architecture and service delivery changes that could be leveraged in extending the capacity, thereby the lifespan, of our HFC network. Our premise in developing this evolution toolbox has been to make such transition both feasible and practical. This evolution exercise includes changes in the plant. So, the corresponding investment that a plant upgrade entail cannot lead to an incremental improvement, such capacity improvement needs to be substantial. A set of evolution tools including changes in the plant, changes in end-devices, protocols and deployment strategy was discussed. The proposed evolution does not rely on single technique or parameter to increase capacity, but it is a collection of tools and techniques that build on each other for a substantial increase in aggregate capacity. We reviewed, spectrum increase, segmentation optimization, increase transmit power, receiver sensitivity improvement, transmit power profile optimization, tap best microwave design practices, single value tap concept, single coaxial run to CPE at home, scalable PHY, intelligent frequency/MER aware scheduling and the decoupling of peak and aggregate capacity to optimize CM cost.

Nevertheless, planning for a smooth transition to FTTH is imperative as the demand on resources of our HFC network is not uniform across our deployed systems. A gradual success-based FTTH transition could be driven by high-end users, business customers, radio/access point connectivity and reliability/redundancy improvement strategy. In such transition scenario, the HFC and FTTH networks will coexist where the bulk of the subscribers would be on the HFC network while the high-end users and enterprise customers will be handled by the FTTH specifically covering the high-end consumers.

So, answering the papers' title question; HFC still has plenty of resources to leverage effectively for years to come in our evolution path.

Abbreviations

CAPEX	capital expenditure
CCAP	converged cable access platform
CM	cable modem
CMTS	cable modem termination system
CNR	carrier to noise ratio
CPE	customer premise equipment
CPON	coherent passive optical network
DAA	distributed access architecture
DAC	digital to analog converter
dB	decibels
dBmV	decibels relative to one millivolt
DOCSIS	data over cable service interface specification
DS	downstream
EM	electromagnetic
ENOB	effective number of bits
FEC	forward error correction
FR4	flame retardant 4 circuit
FTTH	fiber to the home
GaN	gallium nitride
Gbps	gigabit per second
GHz	gigahertz
HFC	hybrid fiber coax
HHP	household passed
IP	internet protocol
KS	klemmschrauben (clamp screw)
MAC	medium access control layer
MER	modulation error ratio
MHz	megahertz
OFDM	orthogonal frequency-division multiplexing
OFDMA	orthogonal frequency-division multiple access
OPEX	operational expenditure
PHY	physical layer
PON	passive optical network
PTFE	polytetrafluoroethylene
QAM	quadrature amplitude modulation
RF	radio frequency
RG	radio grade
RPD	remote PHY device
RMD	remote MAC-PHY device
Rx	receiver
SC-QAM	single channel quadrature amplitude modulation
SKU	stock keeping unit
SNR	signal to noise ratio
TCP	total composite power

Tx	transmitter
US	upstream

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Appendix A

Figure 23 shows a distribution tap diagram highlighting its sub-components definitions and theoretical losses that have been used in earlier analysis.

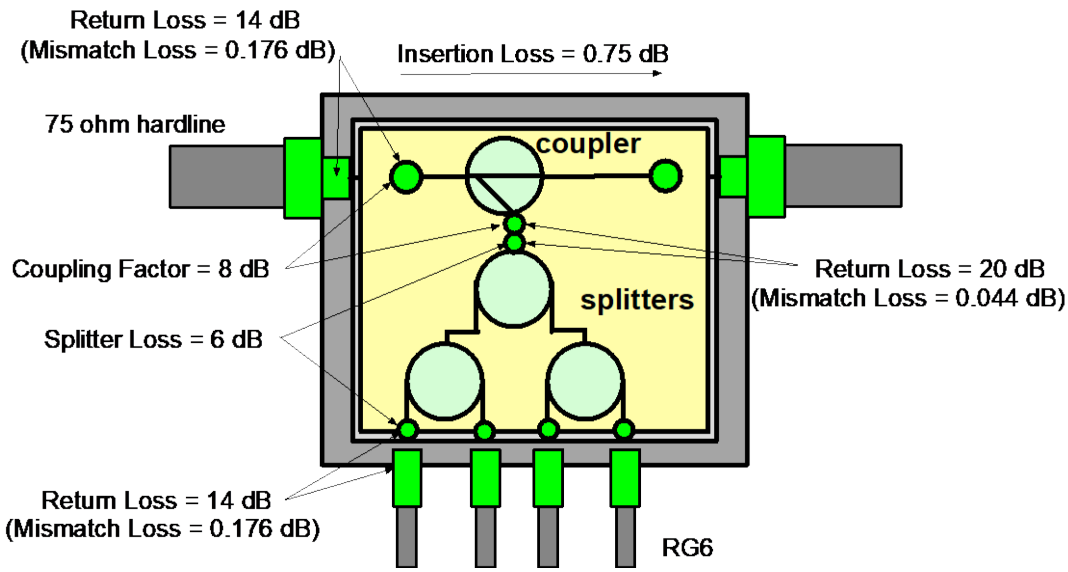
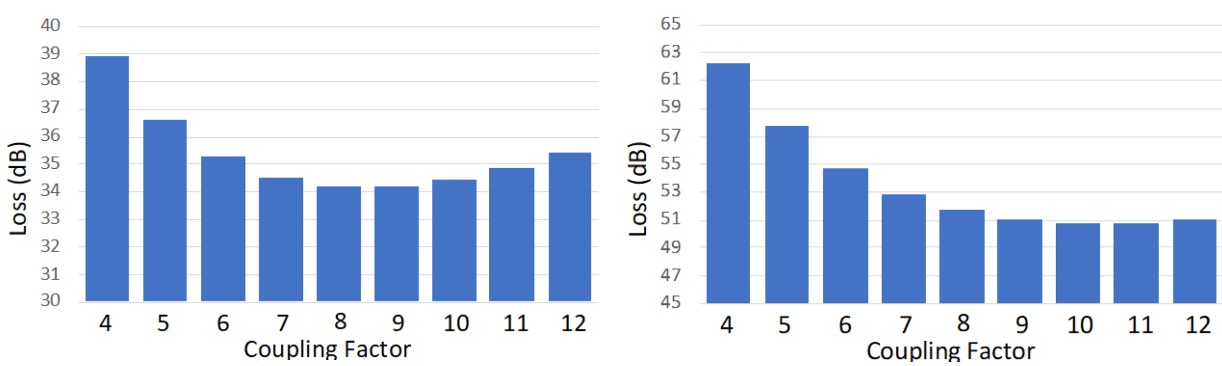


Figure 23 – Tap Parameter Definitions and Assumptions

The tap coupling loss that is associated to the tap value is given by the addition of the mismatch loss between KS connector attached to the hardline and the tap, the coupling factor, the internal mismatch loss between coupler and splitter, the splitter loss and the mismatch loss between splitter and F connector.

The tap through loss is given by the addition of the mismatch loss between KS connector attached to the hardline and the tap, the coupler insertion loss and again the mismatch loss between tap and KS connector.

Figure 24 shows the tap coupling factor optimization for a single value tap.



(a) (b)

Figure 24 – Tap Coupling Factor Optimization for 600' Hardline Segment Scenario (a) and 1000' Hardline Segment Scenario (b)

Appendix B

Figure 25 through Figure 28 evaluate performance in the following 3 frequency ranges of the second through fifth scenarios in Figure 20. Figure 21 evaluates the performance of the frequency ranges below for the first scenario in Figure 20.

a) 258 MHz to 1218 MHz

b) 258 MHz to 1794 MHz

c) 258 MHz to 3330 MHz.

Table 1 summarizes results of modulation efficiencies across spectrum regions modeled in Figure 21, and Figures 25-28.

Table 1 - CM Modulation Efficiency Across Spectrum For Coaxial Extension Scenarios

		4096-QAM			1024-QAM	
CM Spectrum Coverage		Full	Partial (G=GHz)	No Cvg	Full	Partial (G=GHz)
	1.2 GHz	All			All	
Scenario 1	1.8 GHz	1-7	8 (<0.8G)		All	
	3.3 GHz	1-5	6(<0.9G), 7 (<0.5G)		1-5	6(2.8G),7 (<1.2G), 8(<0.7G)
	1.2 GHz	1-7	8(<1.05)		All	
Scenario 2	1.8 GHz	1-6	7 (<0.6 G), 8(<0.45 G)		1-6	7(<1.7G), 8(<1.2G)
	3.3 GHz	1-4	5(<1.9G), 6(<0.7G)	7-8	1-5	6(<1.5G), 7 (<0.7G), 8(<0.6 G)
	1.2 GHz	All			All	
Scenario 3	1.8 GHz	1-3	4 (<0.6 G), 5(<0.9 G)		All	
	3.3 GHz	1-2	3(<0.6 G), 5(<0.4G)	4	1-2	3(<1.5G), 4 (<0.7G), 5(<0.9 G)
	1.2 GHz	All			All	
Scenario 4	1.8 GHz	All			All	
	3.3 GHz	1-4	5(<0.5 G), 6(<0.8G)		1-4	5(<2.1 G), 6(<2.7G)
	1.2 GHz	1-6	7 (<0.7G), 8(<1.05G)		All	
Scenario 5	1.8 GHz	1-5	6 (<0.8G), 8(<0.5G)	7	1-6	7 (<0.85G), 8(<1.15G)
	3.3 GHz	1-4	5(<0.7G)	6,7,8	1-4	5(<1.9G), 6(<0.8G), 7 (<0.4G), 8(<0.6G)

While not all CMs distributed along the cascaded coaxial segments operate at 4096-QAM and 1024 -QAM across the entire spectrum. Most CMs operate at 4096-QAM using at some portion of the spectrum so that frequency/MER aware allocation of resources allow full aggregate capacity for the entire system.

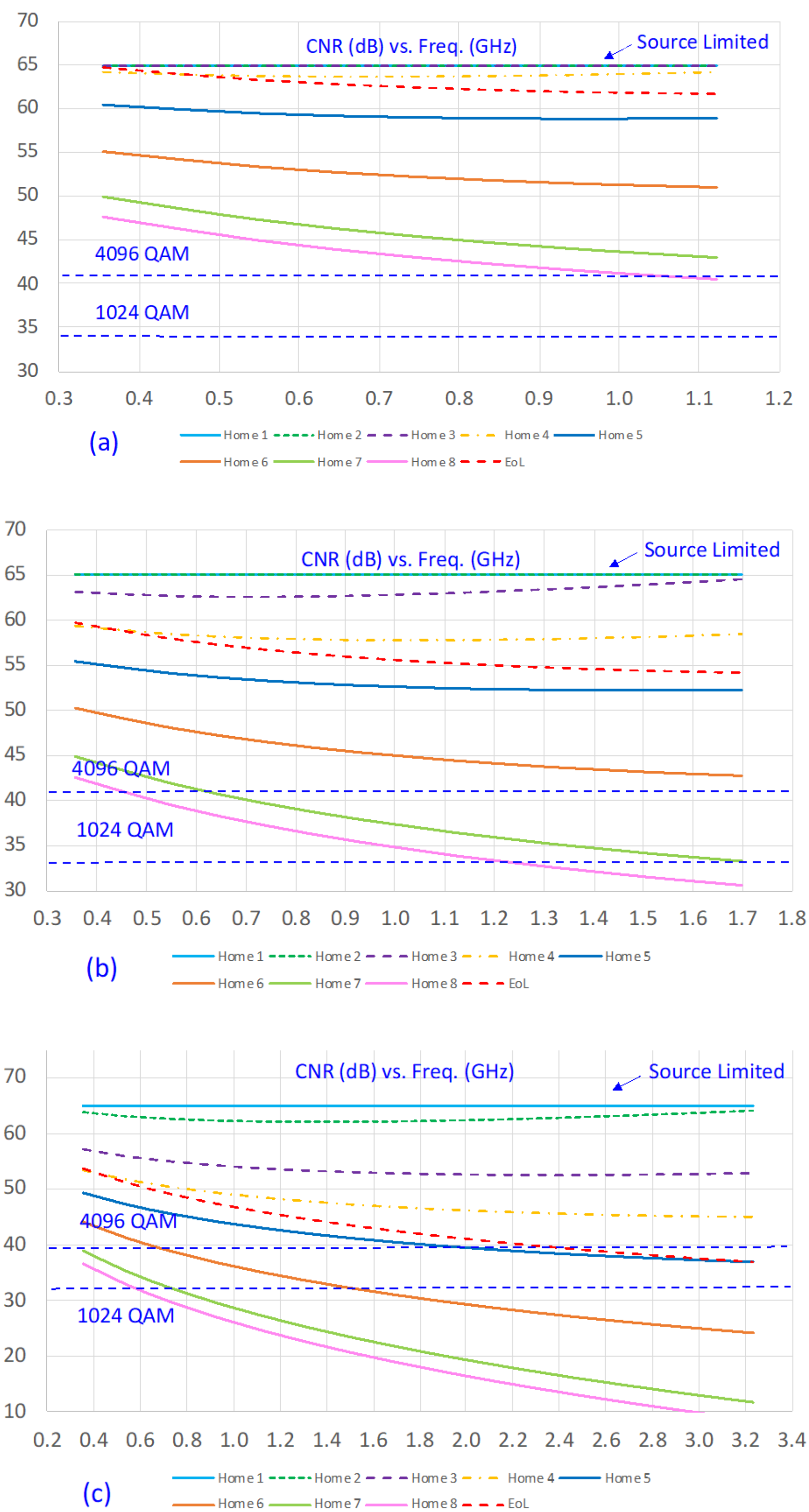


Figure 25 – Field Scenario 2 – CNR vs. Frequency of Cascaded Coaxial Segments

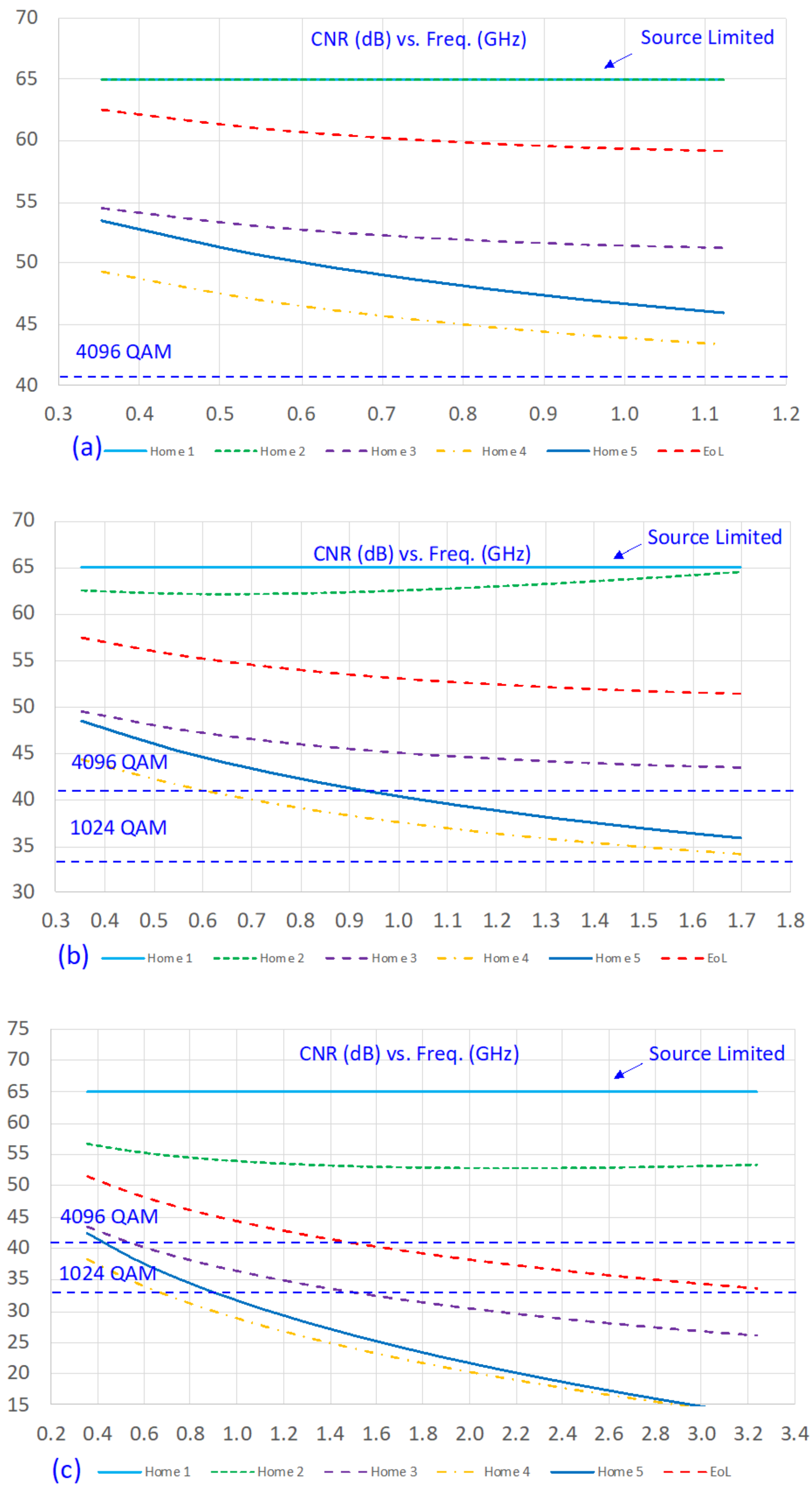


Figure 26 – Field Scenario 3 – CNR vs. Frequency of Cascaded Coaxial Segments

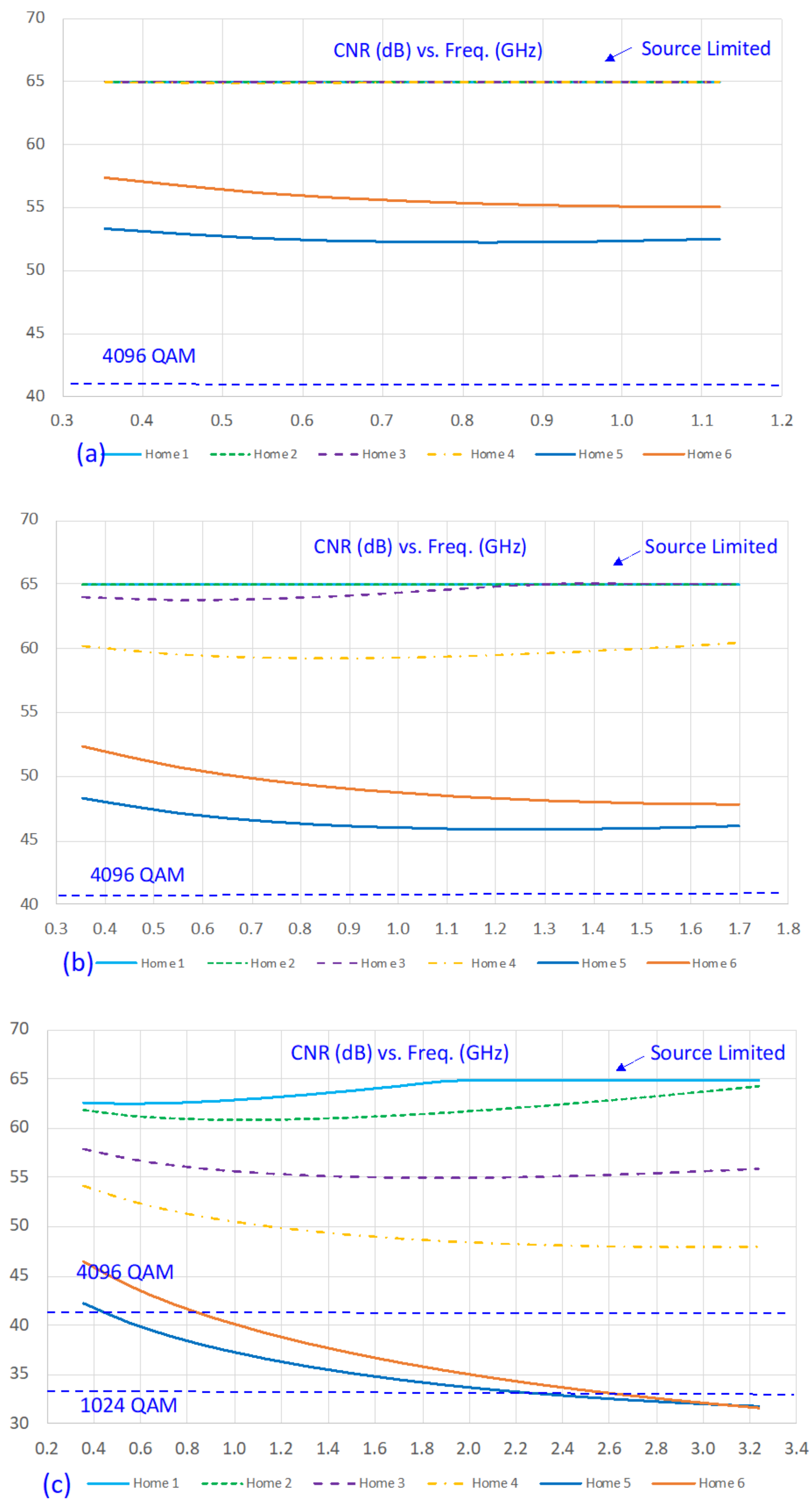


Figure 27 – Field Scenario 4 – CNR vs. Frequency of Cascaded Coaxial Segments

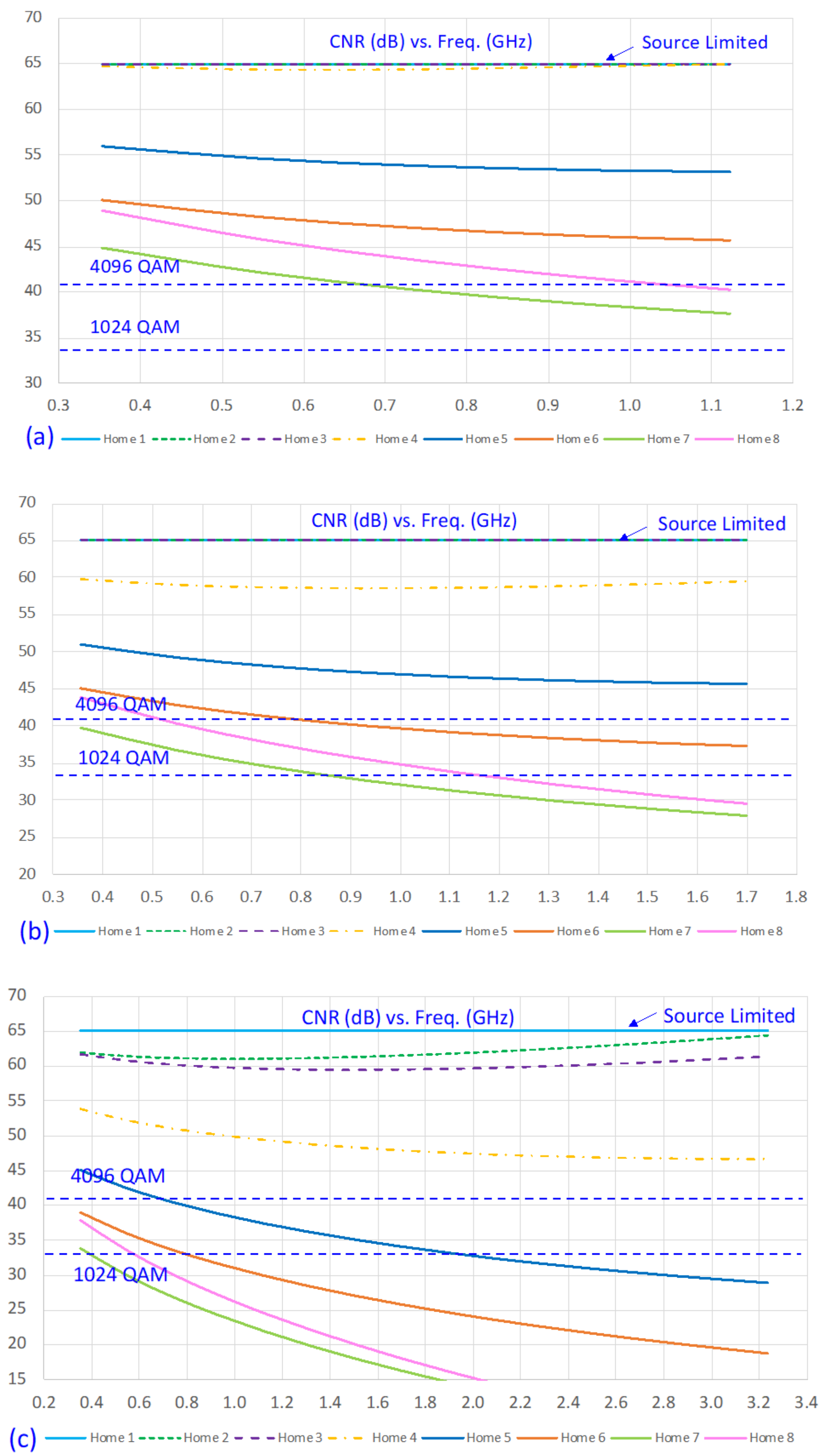


Figure 28 – Field Scenario 5 – CNR vs. Frequency of Cascaded Coaxial Segments