COMPARISON OF TECHNIQUES FOR HFC UPSTREAM CAPACITY INCREASE

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Abstract

This paper compares three techniques for increasing the upstream capacity and peak upload speeds for a hybrid fiber coaxial cable network. The first technique is to increase the spectrum utilization and signal robustness in the 5-42 MHz band. The second technique is to allocate more upstream spectrum by changing the mid-split cross over point between the upstream and downstream bands. This paper shows some measurement results to help quantify the levels and extent of interference to televisions, set top boxes, and digital transport adapters to upstream transmission in the 42-85 MHz band with downstream signals in the 108-750/860/1002 MHz band. The last technique is the use of spectrum above 1 GHz. The advantage of this approach is that it can be built incrementally as needed without impacting the 5-1002 MHz HFC plant and services.

Considering these three alternatives for upstream capacity increase, begin by fully utilizing the 5-42 MHz spectrum. If in the future, it gets to the point where the 5-42 MHz is close to being fully utilized and node segmentation reaches its practical limits, then a change in mid-split cross over point between the upstream and downstream spectrum can be implemented with a mid-split RF protection circuit that transmits upstream signals in the 42-85 MHz band while protecting in home devices from interference. A mid-split RF protection circuit works with existing devices and standards, and adds significant upstream capacity with a small sacrifice in downstream capacity. Use of 1200-1800 MHz spectrum is an approach to incrementally add 1 Gbps symmetrical services while preserving current HFC services.

INTRODUCTION

DOCSIS 3.0 with an upstream spectrum allocation of 5-42 MHz as built in North American hybrid fiber coaxial network architectures has greatly increased the upstream capacity and peak speeds when compared to DOCSIS 2.0. With single carrier DOCSIS 2.0, customers enjoy upstream speeds in the 2-10 Mbps range and with DOCSIS 3.0 upstream channel bonding customers can look forward to even higher speeds. DOCSIS 3.0 includes features such S-CDMA with maximum scheduled codes and selectable active codes that provide plenty of headroom for these speeds to grow. Using 64-QAM upstream modulation, four upstream carriers with 6.4 MHz channel width, three 3.2 MHz channel width upstream carriers, and one 1.6 MHz channel width upstream carrier will completely fill up the 5-42 MHz spectrum and provide a total upstream capacity of about 155 Mbps. DOCSIS 3.0 cable modems can bond four upstream carriers for peak upload speeds of 100 Mbps. Getting the upstream capacity to 155 Mbps with DOCSIS 3.0 in the 5-42 MHz spectrum faces challenges. Impulse noises from sources such as motors and lighting fixtures have short time duration. S-CDMA uses a long symbol time so that the impulse noise only impacts a fraction of the symbol. Ingress noise from sources such as short wave radio signals are narrow in spectrum but have long time durations, good ingress cancellation techniques are essential for fully utilizing the upstream spectrum. Portions of the upstream spectrum are used for digital cable set top box return path signaling, converting these devices to DOCSIS is necessary to fill up the 5-42 MHz spectrum entirely with DOCSIS carriers. Televisions in the home tend to be behind more splitters than data cable modems and

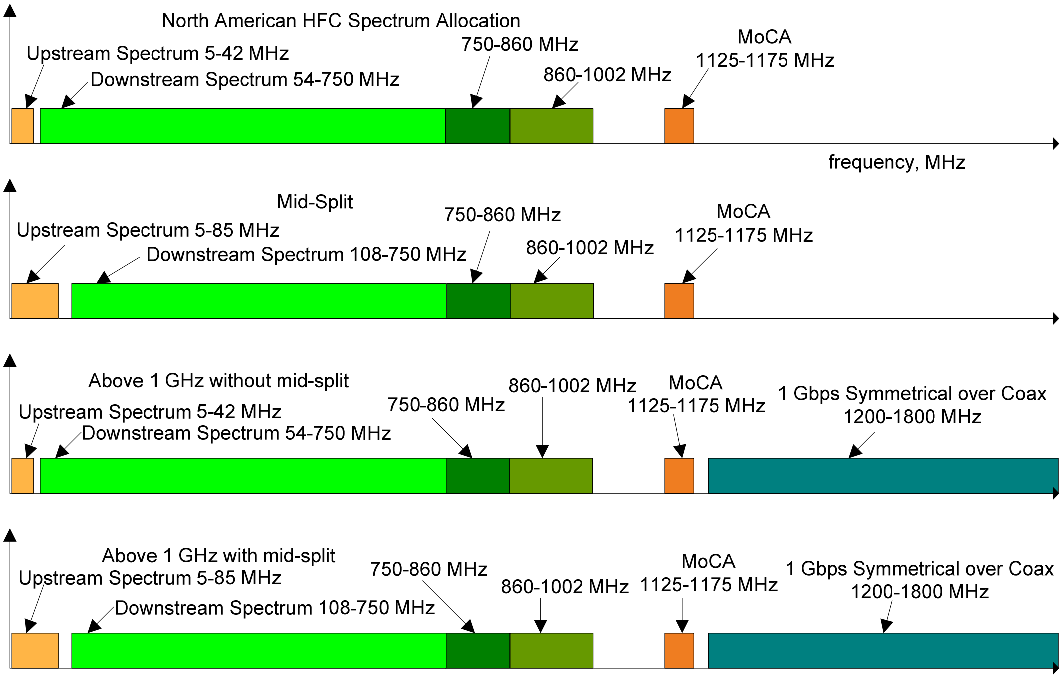


Figure 1. Spectrum Allocation Options for Upstream Capacity Increase.

voice cable modems; this makes it important to be able to operate with high attenuation in the upstream signal path. Regardless, 155 Mbps is the capacity using the highest order modulation for DOCSIS 3.0 and fully filling up the 5-42 MHz so something clearly will have to change to get any more than this.

This paper compares three techniques to surpass the 155 Mbps upstream capacity ceiling. The three techniques are 1) non-linear harmonic ranging and pre-distortion along with Hybrid ARQ (automatic repeat request with variable forward error correction), and adaptive modulation and coding for the 5-42 MHz upstream band, 2) upstream HFC mid-split to increase the spectrum allocated to upstream, and 3) use of HFC spectrum above 1 GHz. These options are illustrated in Figure 1 highlighting that a change in mid-split can be done alone, use of spectrum above 1 GHz can be done alone, or both mid-split and above 1 GHz can be done in conjunction. The downstream rolloff of fiber nodes and amplifiers is commonly 750 MHz or 860 MHz and can be as high as 1002 MHz. This paper addresses upstream capacity and all methods described are applicable to 750, 860, and 1002 MHz HFC plant.

The upstream capacity in HFC networks can be increased as needed by adding more upstream carriers and serving smaller groups of users. Capacity can be increased to match demand by first reducing the number of fiber nodes that share a common 5-42 MHz spectrum and adding multiple upstream carriers, then segmenting the fiber nodes into multiple upstream legs each with its own set of upstream demodulators and optical transmitter and receiver, and finally splitting nodes further in order to serve a small number of homes with the 5-42 MHz upstream spectrum. At some point, however, more practical methods to add capacity than further node splitting make sense. For example, rather than add an upstream carrier to a low portion of the upstream band that has interference issues, it may be better to work at a higher portion of the upstream spectrum that has less noise. Rather than adding more QPSK carriers, it may be more efficient to increase the modulation rate to 16

QAM, 32 QAM, 64 QAM, or even higher. Rather than continually serving a smaller and smaller number of customers with a given amount of bandwidth, it may make sense to keep the serving group size the same and increase the bandwidth.

The same situation occurred in early AMP (Advanced Mobile Phone system based on wideband FM) cellular deployments, in theory AMP cellular systems could be split into smaller and smaller base station sizes to provide whatever voice capacity was needed. However, the unattractive prospect of a base station outside everyone's home led to the development of more spectrally efficient solutions, TDMA then CDMA, then WCDMA, and finally OFDMA.

The upstream capacity and peak upload speed can be increased in three ways, 1) better spectral efficiency in the 5-42 MHz band, 2) a mid split to increase the upstream spectrum allocation, and 3) use of spectrum above 1 GHz.

A rough estimate of the upstream channel capacity for several of these techniques is shown in Table 1. The spectral efficiency used is estimated based upon the spectral efficiency of upstream carriers operating in cable plants today, 27 Mbps in a 6.4 MHz channel width is 4.2 bps/Hz. The 5.6 bps/Hz assumed for a more spectrally efficient use of the 5-42 MHz is the spectral efficiency of 256-QAM replacing 64-QAM. This is not to say that these spectral efficiencies are always possible under all channel conditions but hopefully the table provides an understanding of the relative potential of each approach.

Table 2 shows a rough comparison of the plant and CPE impacts for several options in upstream spectrum allocation. Sticking with the 5-42 MHz upstream allocation requires no changes to plant passives or actives, works with all set top boxes without the loss of any downstream spectrum and requires no new transceivers. Increasing the upstream spectrum to 65, 85, or 200 MHz requires changes to amplifiers and fiber nodes in the plant but no changes to plant passives, the forward data channel signaling to digital cable set top boxes is impacted by the choice of cross over frequency so some set top boxes may not be supported after a change in downstream spectrum allocation, a loss in HD streams is a tradeoff with more upstream spectrum allocation, mid-split approaches will work with DOCSIS 3.0 cable modems so that new transceivers are not required. Table 2 uses a loss of 3 HD streams for each loss of a 6 MHz wide spectrum slot and makes some rough estimates of diplexer separation requirements. The 5-200 MHz upstream band is not supported by DOCSIS devices, however, DOCSIS type devices could be extended in frequency or new transceivers could be developed to fully take advantage of the increased upstream spectrum. This is why the 5-200 MHz transceiver column is listed as a maybe. Use of spectrum in the 1200-1800 MHz bandwidth does not require changes to plant actives if fiber optic cable is run to the last active. Plant passives such as splitters, directional couplers, and taps need to be changed in order to pass 1200-1800 MHz signals. New coaxial transceivers are required for operation in the 1200-1800 MHz band. The column for "All STBs?" and "Most STBs?" is intended to indicate whether the solution will work with all digital cable set top boxes or most digital cable set top boxes and this is determined by the adjustments required for the out of band forward data channel center frequency.

The next section begins by taking a look at the first technique, getting more capacity out of the current 5-42 MHz upstream allocation.

Solution	Total Spectrum	Spectral efficiency	Upstream Capacity
Units	MHz	bps/Hz	Mbps
5-42 MHz DOCSIS 3.0	37	4.2	155
5-42 MHz 256-QAM	37	5.6	207
5-65 MHz mid-split	60	4.2	252
5-85 MHz mid-split	80	4.2	336
5-200 MHz mid-split	195	4.2	819
1200-1800 MHz	600	4.2	2520

Table 1. Comparison of spectrum allocation, spectral efficiency, and upstream capacity.

upstream band	Amp/Node changes?	Tap/DC changes?	STB Interference?	All STBs?	Most STBs?	HD loss?	New Transceivers?
5-42 MHz	NO	NO	NO	YES	YES	0	NO
5-65 MHz	YES	NO	YES	YES	YES	9 streams	NO
5-85 MHz	YES	NO	YES	NO	YES	27 streams	NO
5-200 MHz	YES	NO	YES	NO	NO	99 streams	Maybe
1200-1800 MHz	NO	YES	NO	YES	YES	0	YES

Table 2. Comparison of plant and CPE impact for several options.

Better Use of 5-42 MHz Upstream Spectrum

A common upstream carrier setting is 6.4 MHz channel width and 64-QAM modulation A-TDMA which has a TCP/IP data rate of about 27 Mbps after accounting for all the headers and error correction. A common upstream spectrum allocation is a 6.4 MHz 64-QAM A-TDMA upstream carrier with a 32.2 MHz center frequency and a 3.2 MHz 16-QAM TDMA upstream carrier with a center frequency of 37 MHz. The A-TDMA carrier has about a 27 Mbps data capacity and the TDMA carrier has about a 9 Mbps data capacity. The total upstream capacity is about 36 Mbps which is 23% of the upstream channel capacity of the 5-42 MHz spectrum entirely filled with 64-QAM carriers. Thus, it may be possible to increase the upstream capacity by a factor of four by adding upstream carriers and increasing the modulation rate while staying with DOCSIS 3.0 technology. By segmenting fiber nodes into four legs, another factor of four increase in upstream capacity can be obtained provided that four times the upstream demodulators are added. So the potential exists for as much as a 16 times increase in upstream capacity within the constraints of the 5-42 MHz upstream spectrum allocation and DOCSIS 3.0 technology.

This section of the paper on increasing upstream capacity within the 5-42 MHz band looks at two approaches. The first approach allows for a new OFDMA multiplexing technique while the second looks at how most of the benefits of the first approach can be applied using DOCSIS 3.0 cable modems by using S-CDMA. OFDMA stands for orthogonal frequency division multiple access and it is a common technique used in DSL, terrestrial broadcast, cellular, and wireless home networking which breaks spectrum up into very narrow tones so that symbol times are very long while the combined data rate is high. S-CDMA stands for synchronous code division multiple access and it is implemented in DOCSIS 2.0 and 3.0 cable modems using 128 orthogonal codes to again realize a long symbol time and still have a high aggregate data rate. Since there are so many cable modems deployed with S-CDMA capability, it makes sense to fully utilize this technology first. Nonetheless, we'll begin by discussing the potential of OFDMA and then take a look at how similar benefits can be realized with S-CDMA.

DTAB Discrete Tone Adaptive Bandwidth

OFDMA with pilot, ranging, and data tones, time and frequency coordination for compatibility with DOCSIS 1.0, 1.1, 2.0 and 3.0 cable modems, nonlinear harmonic ranging and pre-distortion, hybrid automatic repeat request, non-contention based scheduling should be looked at for their potential to increase the upstream capacity in the 5-42 MHz band.

The combination of these techniques to increase the upstream capacity is introduced in this paper as DTAB for Discrete Tone Adaptive Bandwidth. DTAB uses OFDMA to create sub-channels whereby each sub-channel consists of ranging tones, pilot tones, and data tones as shown in Figure 2. The ranging tones sweep through the 5-42 MHz spectrum and perform linear and non-linear harmonic ranging for each cable modem. Pilot tones use CMDA to support many cable modems at the same time and pilot tones also sweep through the entire 5-42 MHz spectrum in order to measure the channel quality for adaptive modulation and coding and adaptive amplitude control. Pilot tones are continuously sent by all cable modems and thus bandwidth requests for upstream transmission can always be made by every cable modem without delay or collisions using the pilot tones. Finally the data tones send upstream data transmissions using adaptive modulation and coding and adaptive amplitude level control, non-linear and harmonic pre-distortion, and hybrid automatic repeat request. DTAB is backwards compatible with DOCSIS 1.0, 1.1, 2.0, and 3.0 cable modems by allocating spectrum and time slots for these cable modems as shown in Figure 2. Figure 3 shows a break out of a sub-channel to illustrate the pilot, ranging and data tones that make up a sub-channel. Table 3 shows calculations of the data rate, sub-channels and pilots for DTAB.

OFDMA reduces spectral efficiency proportionately to the ratio of the cyclic prefix to the symbol rate. The cyclic prefix is needed to reduce inter-symbol interference due to multi-path reflections. A DOCSIS 3.0 cable modem has a pre-equalizer with 24 taps which has an equalization window of 4.7 microseconds. As an example, an unterminated 1,150 foot length of RG6 cable will have a reflection with 30 dB attenuation and a time delay of 2.75 microseconds at 32 MHz. With an OFDM symbol rate of 100 microseconds and the guard time of the cyclic prefix set to 5 microseconds to allow for a 5 microsecond reflection then 5% of the upstream channel capacity is lost.

How much guard time needs to be allocated for OFDM? Consider an amplifier spacing of 1,000 feet. The difference in travel time between a direct signal traveling from one amplifier to the other and a signal reflecting off the input of the second amplifier, traveling back to the first amplifier, reflecting off the output of the first amplifier and then back to the input of the second amplifier is 2.3 microseconds for 87% velocity factor cable. If the input and output return loss is 16 dB and the cable attenuation is 0.4 dB/100ft at 30 MHz for 8 dB cable loss then the channel impulse response will include a component with a 2.3 microsecond delay and a 40 dB down amplitude. An example of such a micro-reflection taken from plant data is shown in Figure 4. This reflection will need to be equalized for modulation schemes requiring high signal to noise ratio. Since 64-QAM is such a modulation scheme then the OFDM guard time should be a minimum of 4.6 microseconds to allow for a window of +/- 2.3 microseconds.

Looking at pre-equalization coefficients for DOCSIS 2.0 and 3.0 cable modems in operation, the tap energy is mostly concentrated in the three taps before and after the main tap as shown in Figure 5. Thus, there is considerable energy within a delay spread of 1.2 microseconds.

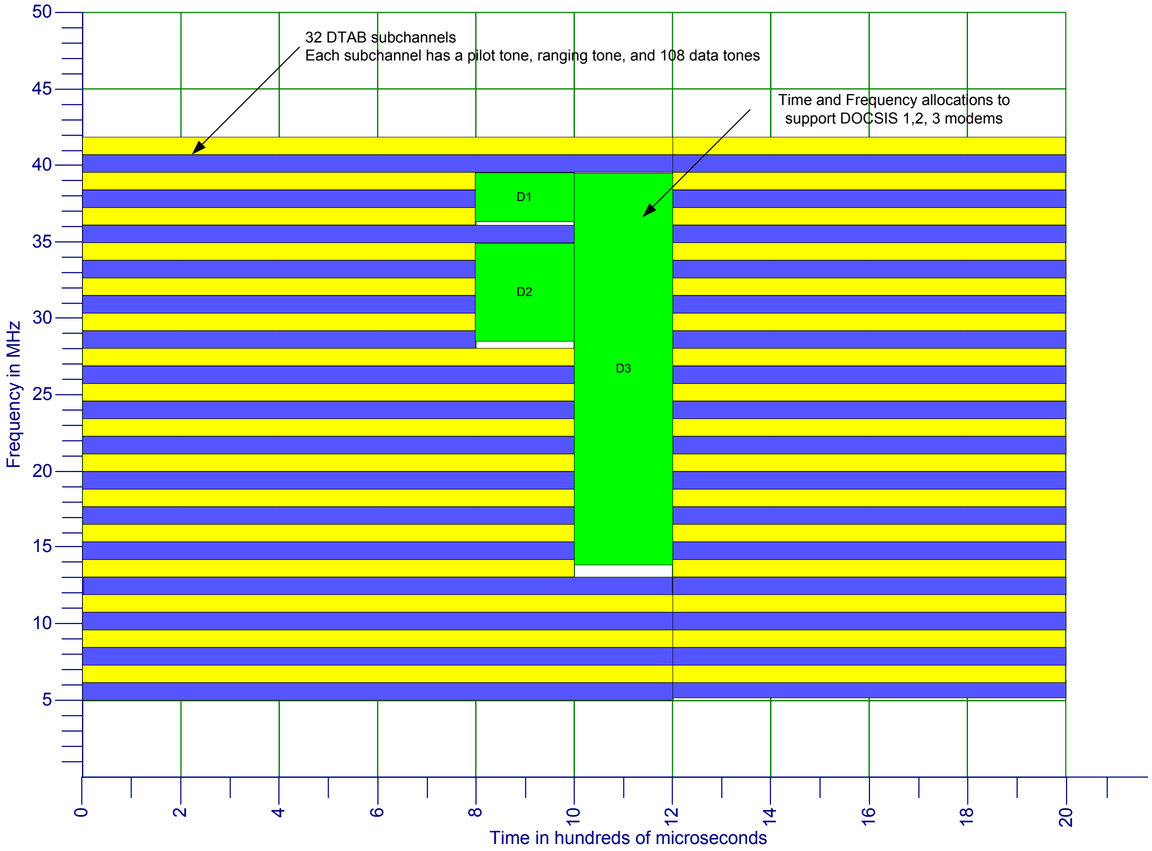


Figure 2. DTAB time and frequency domain showing backwards compatibility with DOCSIS 1.1, 2.0, and 3.0 cable modems.

Generally much further down in amplitude, energy is present in taps as far out as tap 24 as shown in Figure 6. This indicates that the full 4.8 microsecond equalization window is useful in correcting for reflections in the cable plant. Thus, metrics from the tens of millions of cable modems in operation support the minimum OFDM guard time of 4.8 microseconds.

Limiting the loss in data capacity to 5%, the minimum OFDM symbol time is 100 microseconds to allow for a 5 microsecond guard time.

Adaptive modulation with real time channel measurement can be used to increase the upstream capacity for a given availability. OFDMA with pilot tones that constantly scan the upstream spectrum can assign data tones 256-QAM modulation during times of good signal to noise ratio conditions and fall back to 16-QAM modulation during poor signal to noise ratio conditions. If the OFDMA pilot tones have narrow bandwidth and employ CDMA to support multiple modems on the same pilot tone then the upstream capacity sacrificed in order to make measurements of the real time channel conditions for each modem will be small. With a real time measurement of the upstream channel conditions, the optimal modulation for any given part of the spectrum at any given time frame can be chosen. This can result in a significant increase in upstream capacity with much higher availability. Surveys of upstream channel conditions reveal that a 33 dB SNR threshold allowing for 256-QAM is met for a significant portion of the upstream spectrum for significant time periods.

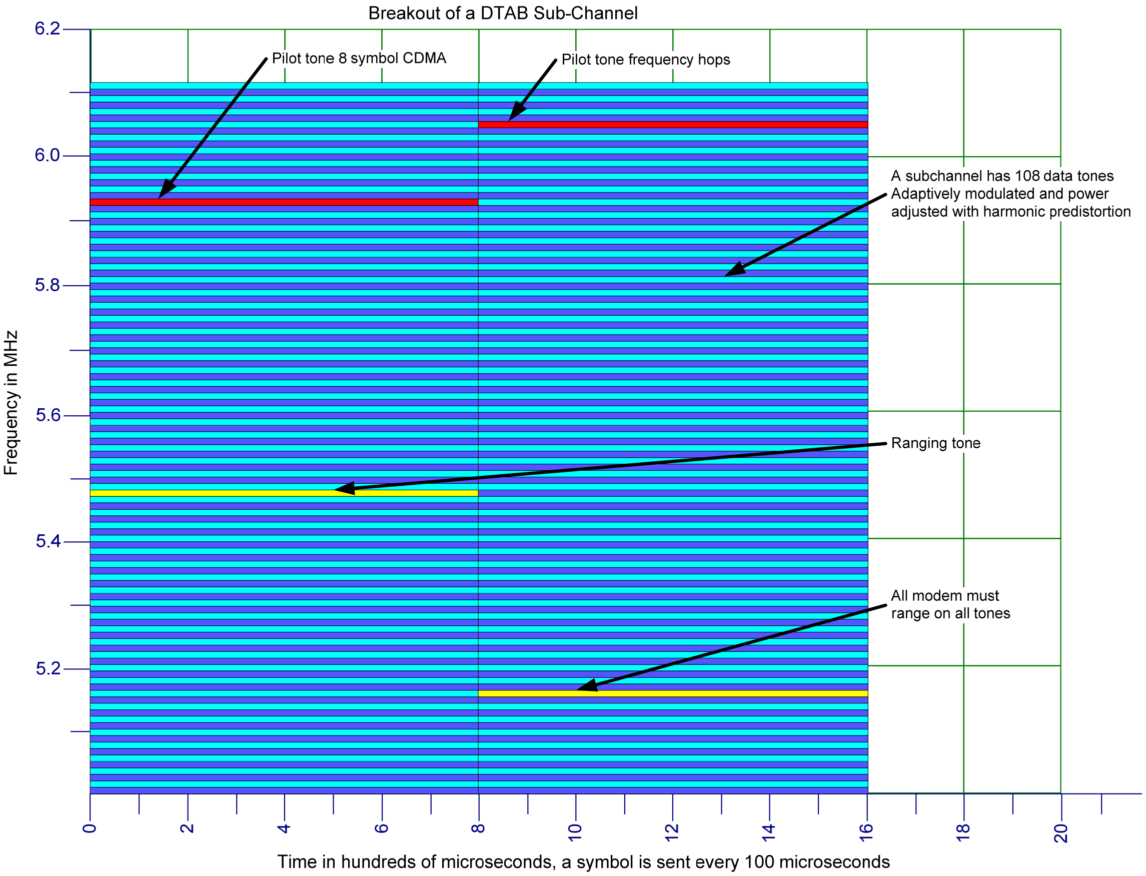
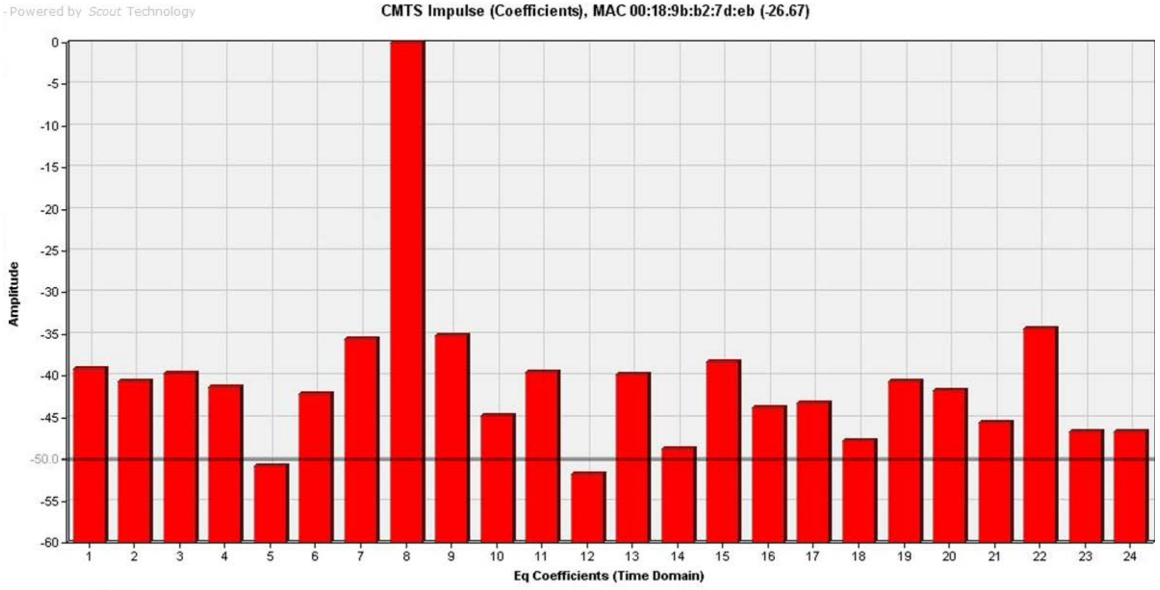


Figure 3. Breakout of DTAB Sub-Channel showing the Pilot and Ranging Tones Hopping and the length of the Pilot CDMA symbol time.

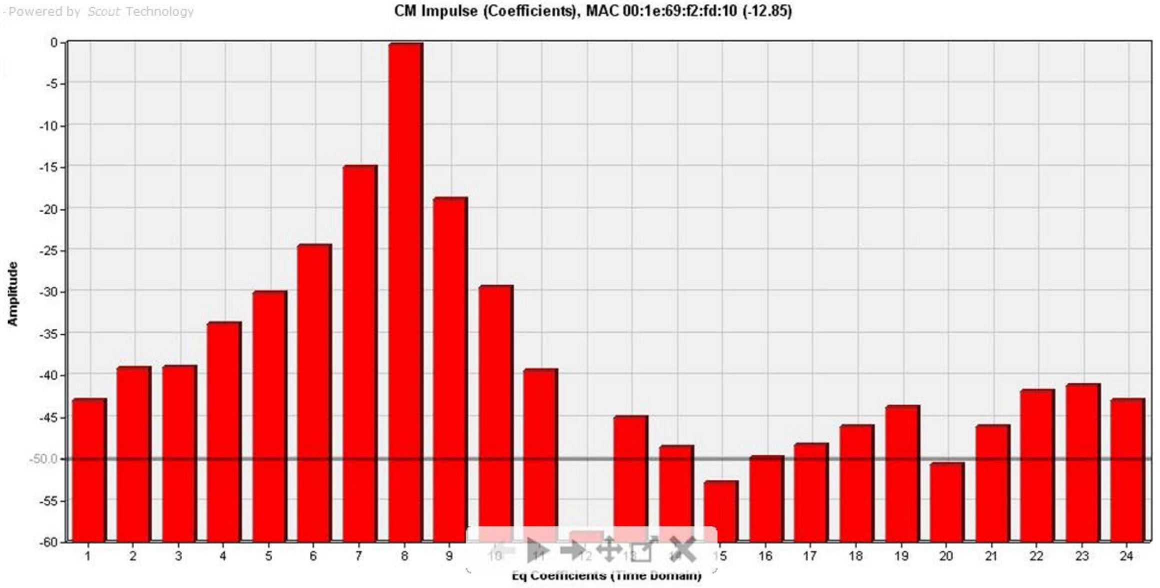
symbol period	100E-06	s
lowest frequency	5,000,000	Hz
highest frequency	42,000,000	Hz
BW	37,000,000	Hz
pilot tones	32	
data tones per pilot tone	108	
ranging tones per pilot tone	1	
number of tones	3,520	
carrier spacing	10,511.36	Hz
useful symbol period	95.135E-6	s
cyclic prefix (guard time)	4.865E-6	s
Spectral Efficiency	8	bps/Hz
total raw data rate	276E+06	bps
data tones	3456	
data rate per tone	80,000	bps

Table 3. Example of Sub-Channels, Pilots, and data tones for DTAB.



CMTS Coefficients

Figure 4. Example of reflection at 2.7 microsecond delay from main signal.



CM Coefficients

Figure 5. Tap energy is mostly focused within a 1.2 microsecond window.

A fundamental determinant of the upstream signal-to-noise ratio is the nonlinear and noise characteristics of the return path laser transmitter commonly illustrated by the noise power ratio (NPR) curve. If the input power to the laser is set to the optimum level, DFB laser transmitters can have a noise power ratio of 40 dB. However, it is wise to set the input level at a reasonable back-off below the optimal level to account for changes in temperature and measurement uncertainties. This is due to the fact that at input levels above the optimum NPR point, the noise is dominated by nonlinear third order intermodulation distortion whose degradation is much steeper (2 to 1 vs. 1 to 1). This allows for a significant opportunity to increase the total upstream capacity using nonlinear harmonic ranging and pre-distortion.

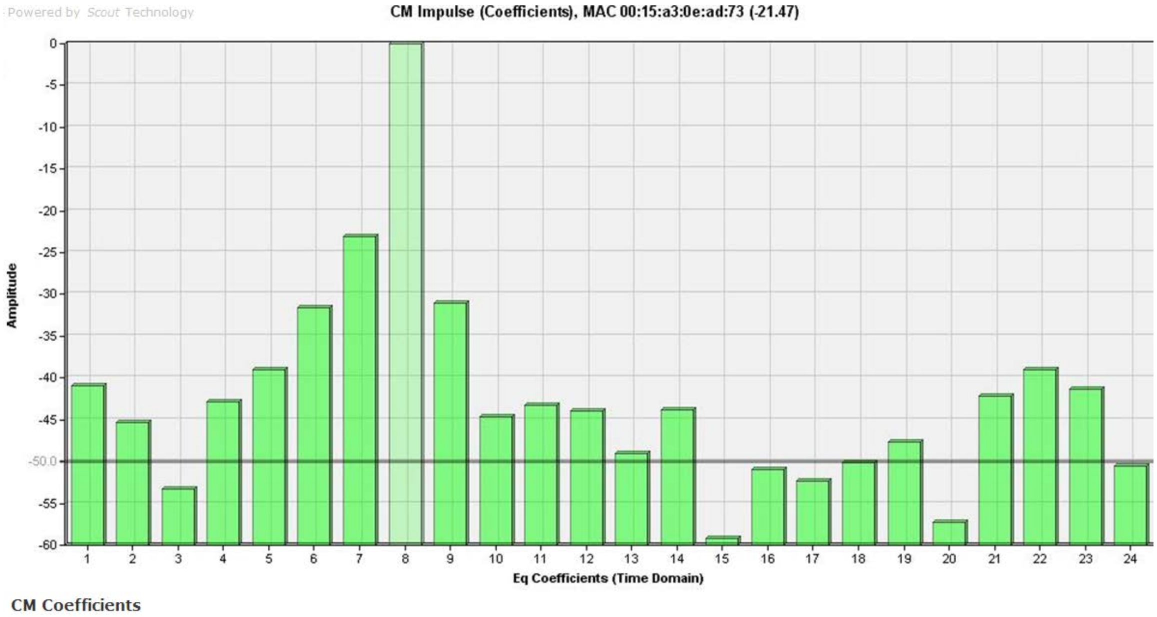


Figure 6. Pre-equalization tap with energy at taps 21, 22, and 23.

With OFDMA, tones can be assigned for ranging with the linear ranging for frequency, amplitude and time delay performed in the same fashion as DOCSIS 3.0. In addition to linear ranging, a harmonic nonlinear ranging can be performed, whereby a tone is adjusted in amplitude and the resulting 2nd, 3rd, 4th, 5th harmonics are measured at the headend receiver. By doing this the full nonlinear characteristics of the return path have been measured.

This nonlinear response is dominated by the return path laser transmitter but also includes the impact of the cascade of return amplifiers and even in home amplifiers. Since the ranging tones are used to fully characterize the return path nonlinear response in real time, the optimum set point of the NPR curve can always be used. Today, many upstream channels have signal to noise ratios below 30 dB so if nonlinear ranging results in a consistent 40 dB NPR, the net results could be an improvement in upstream signal to noise ratio of 10 dB. This would allow for the use of higher modulations and increased upstream capacity.

In addition, to using a control loop to find and set the level into the return path laser at the point of optimal NPR, since the OFDMA modems are capable of outputting tones throughout the entire 5-42 MHz spectrum and since the nonlinear response of the return path has been measured in the nonlinear harmonic ranging process, non-linear pre-distortion can be used to reduce harmonic and intermodulation distortion. This will further improve the modulation error rate of the upstream symbols and increase upstream capacity by allowing higher order modulation at low error rates.

Much of the interference levels in the 5-42 MHz band are due to shortwave radio signals, communications band radio signals, electrical lighting, electric motors. This type of interference is not consistently present and its occurrence is not predictable. For this type of interference, hybrid ARQ is more efficient than the RS-FEC and interleaving used in DOCSIS 3.0 upstream. RS-FEC adds parity bytes to every code word. This is wasted bandwidth when the interfering signals are not present. On the other hand, when the interfering signals are present and reach a certain level, uncorrectable codewords result. Uncorrectable codewords can be seen in almost every cable modem if looked at over a long enough time period. With hybrid ARQ, very little FEC is applied during times when the interfering signals are not present. And when interfering signals show up and result in packet loss, those packets are re-transmitted when the interference goes away. Thus hybrid ARQ can increase the capacity and the availability at the same time for typical HFC upstream interference that occurs intermittently at very high levels.

OFMDA is power efficient for cable modem upstream transmitters since each modem can transmit a small portion of the total upstream spectrum. This helps with high attenuation cable modems such as those behind many splitters in the home. OFDMA is proven to be very robust against micro-reflections, narrowband ingress noise, and impulse noise due to the guard band of the cyclic prefix and long symbol times. Thus, the robustness of OFDMA will add capacity to the upstream in cases where parts of the spectrum are unusable with single carrier modulation.

S-CDMA with adaptive coding, channel measurement, ARQ, non-linear ranging

The cable modems in digital video set top boxes, data cable modems, and voice cable modems as well as next generation high data rate DOCSIS 3.0 chip sets are limited to S-CDMA upstream since they are not capable of OFDMA. While OFDMA does have some advantages over S-CDMA as indicated by the move from 3G cellular networks based upon CDMA to 4G networks based upon OFDMA, S-CDMA performance if fully developed can be very comparable to OFDMA, particularly for the static micro-reflections of a cable plant.

In fact, the 4G LTE (long term evolution standard for cellular networks) does not use OFMDA for upstream transmission but instead adopted variable bandwidth single carrier modulation to improve battery life of handheld devices. Several important techniques to increase upstream capacity in the 5-42 MHz band proposed in DTAB can also be implemented with S-CDMA and thus work with DOCSIS 3.0 cable modems.

Noise and interference conditions exist in portions of the 5-42 MHz return spectrum at certain periods of time that result in codeword errors with DOCSIS 3.0. As a result, the cable operator is faced with two unappealing options, to set the modulation rate overly conservative so that cable modems work most of the time or to operate at higher modulations and allow for longer periods of errors.

Periods of time can easily be observed in nearly all parts of the upstream spectrum with interference levels above the threshold for 64-QAM so that a fixed setting of 64-QAM will experience periods of time with codeword errors. Adaptive modulation with real time channel measurement provides a capacity increase by allowing higher orders of upstream modulation than one would dare with a fixed setting while at the same time improving reliability. Some versions of adaptive modulation and channel measurements have already been developed for DOCSIS. The developments to date show that even within the constraints of DOCSIS 3.0, adaptive modulation and channel measurement is possible. S-CDMA with maximum scheduled codes has been demonstrated to perform an equivalent function by reducing the number of active codes as the noise level rises. This is the fundamental technique used in 3G WCDMA cellular networks using a variable spreading factor. While a permanent reduction in the number of active codes would be inefficient, for example a 3 dB gain in noise immunity is realized by using half the codes, the noise level in upstream receivers can be observed to drift by several dB over time. This allows for the use of most of the active codes under normal noise levels with slightly less codes being used during brief periods where the noise level rises.

Hybrid ARQ has been proposed for some systems such as PON (passive optical networks) for implementation at a higher layer in the OSI stack than MAC and PHY, using this approach it would be possible to implement hybrid ARQ with DOCSIS 3.0 S-CDMA upstream cable modems.

OFDM breaks the channel width into narrow frequency bands resulting in a long symbol time. Likewise, S-CDMA uses codes to spread narrowband input signals over a wide channel width resulting in a long symbol time. Since, OFDM consists of a number of narrowband carriers, or tones, tones that fall on top of narrowband interference sources can be turned off or reduced in modulation level. This gives OFDM the property of good ingress cancellation. With S-CDMA each code has a unique frequency response and a narrow bandwidth interference source will impact some codes more than others. Selectable active codes with S-CDMA can be used to effectively operate in the presence of narrow bandwidth ingress noise.

S-CDMA has many of the same properties of OFDM and it is proposed in this paper to investigate the idea of supporting adaptive coding, hybrid ARQ, and non-linear harmonic ranging and pre-distortion to S-CDMA systems. To further explore this idea, the next section shows some measurements of the non-linear harmonic distortion characteristics of a DFB (distributed feed back) return path laser with the notion of applying non-linear harmonic ranging and pre-distortion to DOCSIS 3.0 systems.

Using non-linear ranging and pre-distortion to increase upstream capacity.

There are many sources of interference in the HFC upstream 5-42 MHz and the observed interference varies with frequency, time, and amplitude. One trick to deal with the interference levels is to increase the upstream transmit level of the cable modem above the levels of the interfering sources. The upstream transmit level can be increased relative to the amplitude levels of the interference sources in order to operate error free at higher orders of modulation. However, this approach is limited by two hard ceilings; the cable modem maximum transmit level and the clipping threshold of the return path amplifiers and lasers. Figure 7 shows the distortion products from an overdriven DFB return path laser. The distortion products consist of spectral re-growth adjacent to the fundamental signal waveform and 2nd, 3rd, and 4th harmonics.

The following use case illustrates the conceptual implementation of non-linear pre-distortion to increase the upstream capacity. In this example, a high level interference source is present at low frequencies. Figure 8 shows a field measurement of this condition. In order to operate a carrier at 10 MHz center frequency with equal SNR to that of carriers centered at 20 MHz and 30 MHz, the 10 MHz center frequency carrier must transmit at a 20 dB higher level than the 20 MHz and 30 MHz carriers.

Figure 9 shows the output signal from the sample port of an optical receiver with a cable modem connected to a fiber node with 25 km fiber link between the upstream return path laser and optical receiver. The return path laser transmitter is a DFB. The cable modem signal is set to a 20 MHz center frequency with a 2.56 MHz symbol rate and 16 QAM in TDMA mode. The level of the cable modem transmit power was increased until the SNR was 33 dB.

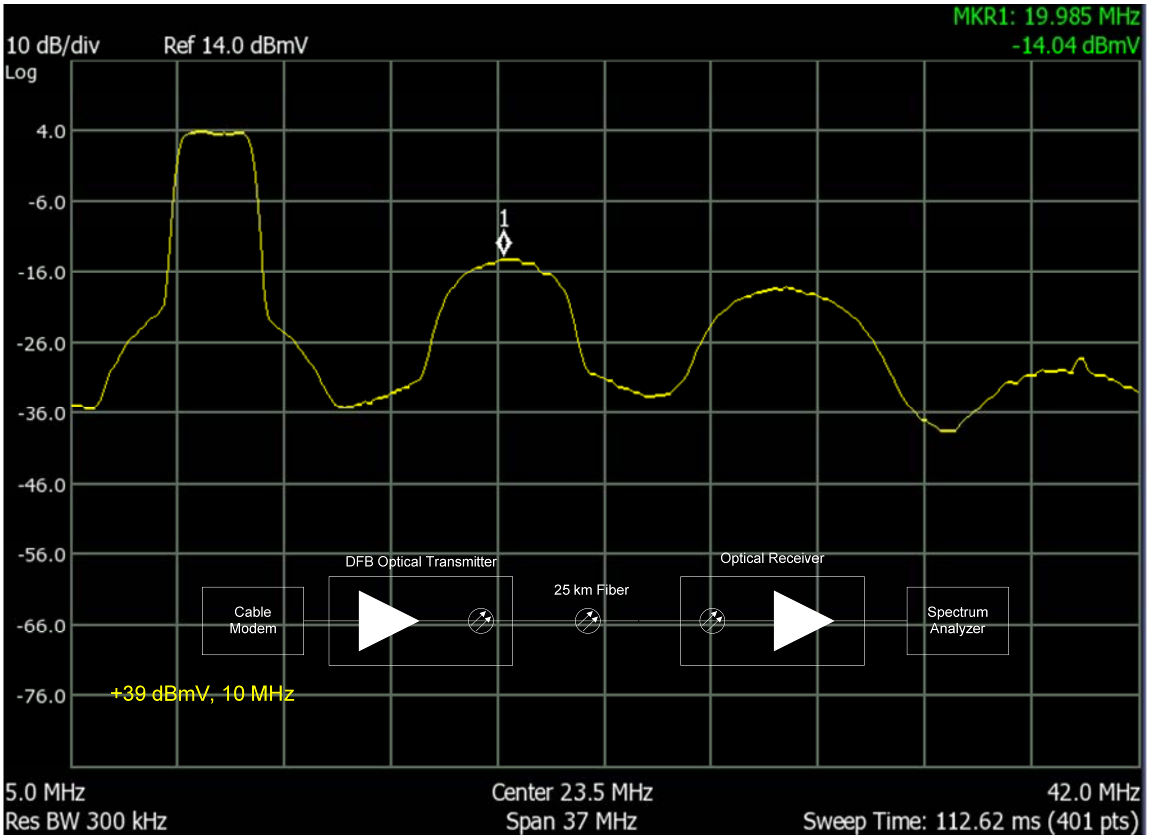


Figure 7. Overdriven Return Path Laser Showing Harmonic Distortion.

Figure 9 thus shows the lowest possible transmit power from a cable modem that will maintain at least a 33 dB SNR through the return path optical transmitter and receiver. Note that 33 dB SNR only includes the noise level from the return path laser and receiver, other noise and interference sources would further degrade the total SNR at the demodulator output.

Figure 10 shows a 10 MHz center frequency upstream signal with the cable modem transmit level set 20 dB higher than the level shown in Figure 9. The distortion produced at the 2nd, 3rd, and 4th harmonics would prevent the reception of signals at 20, 30, and 40 MHz. So in the case where external interference sources raise the noise level at 10 MHz 20 dB higher than the noise level at 20, 30, and 40 MHz, one cannot maintain a constant SNR across carriers by simply increasing the 10 MHz transmit power by 20 dB. The dynamic range of the return path does not allow this due to harmonic distortions.

What if the 10 MHz carrier could somehow transmit at high power without creating harmonic distortion? In fact it is possible using a very common technique in RF power amplifiers and downstream optical transmitters, non-linear pre-distortion. The cable modem could send up a test signal that varies in amplitude that is received by the CMTS. The CMTS could measure the spectral re-growth, harmonics, AM-AM, and AM-PM nonlinear distortion produced as the CM signal level is varied and precisely characterize the non-linear channel response of the return path. This non-linear channel response could then be communicated to the CM. The CM could then apply the inverse of this response so that the distortion produced by the return path laser will cancel.

Figure 11 shows conceptually how this circuit could be implemented.

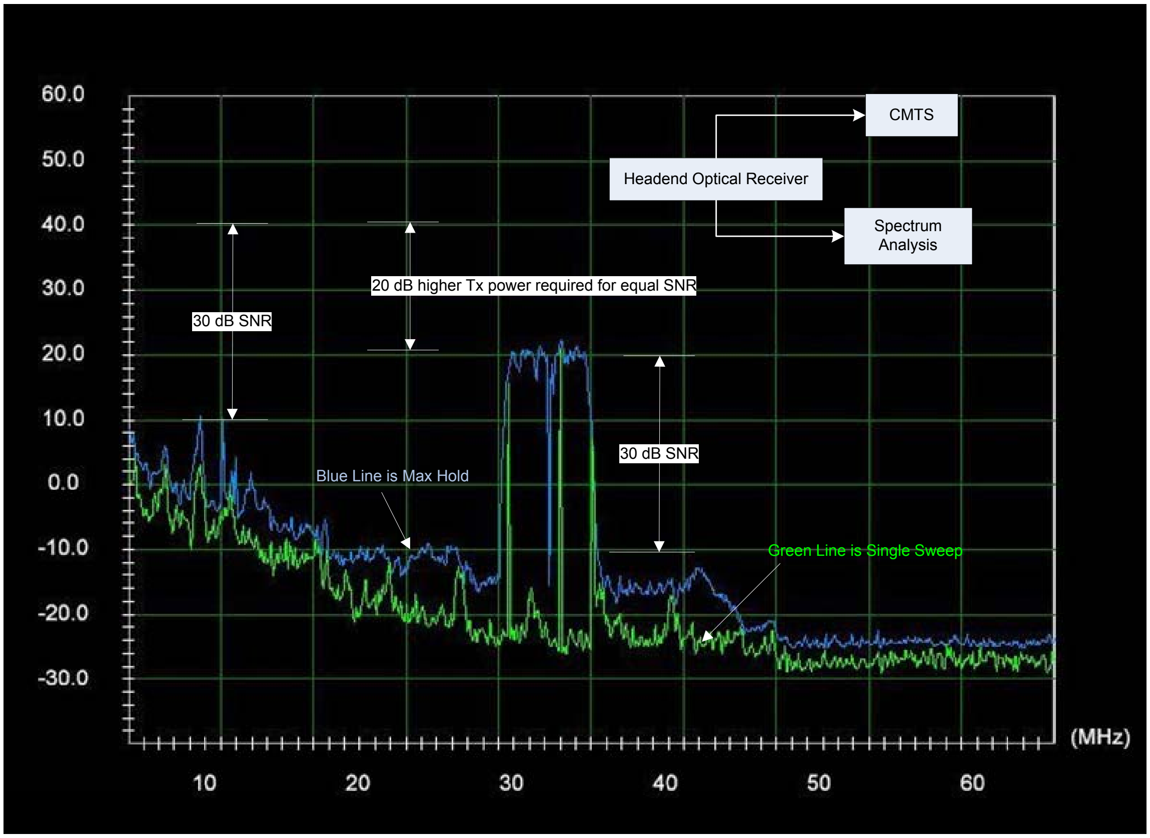


Figure 8. Field Measurement showing increased interference levels below 20 MHz

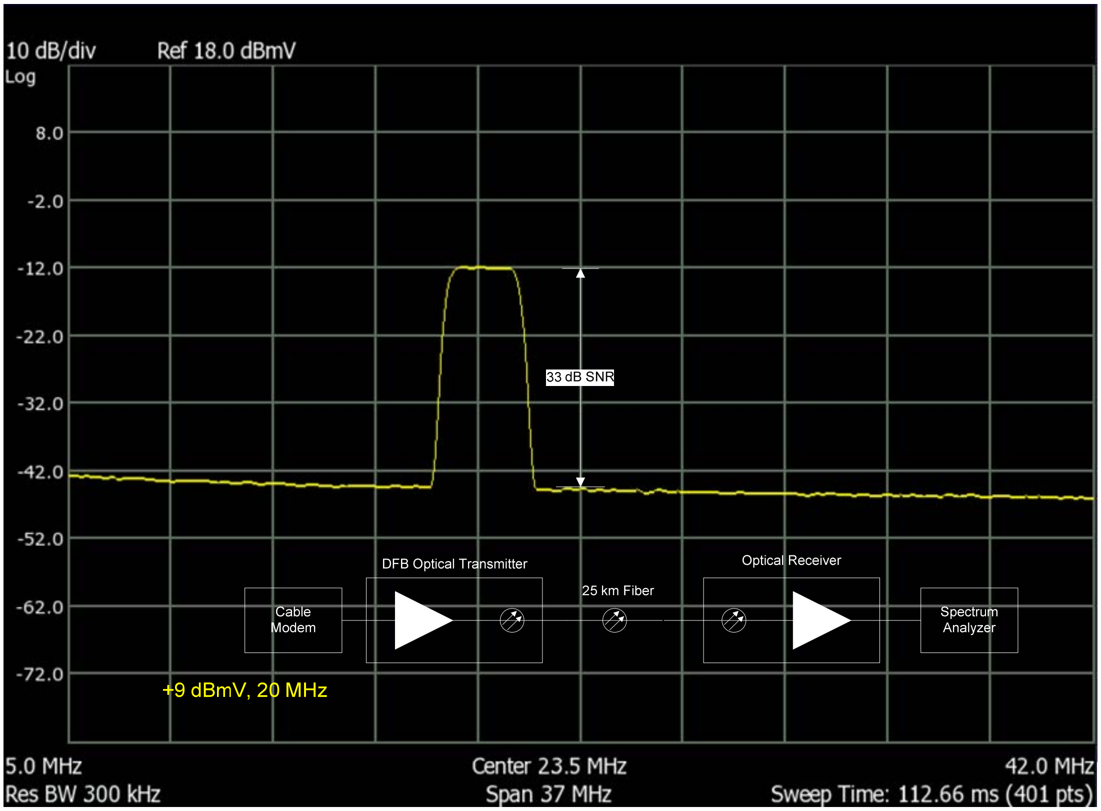


Figure 9. Lowest Amplitude Level Signal for 33 dB SNR over 25 km of fiber.

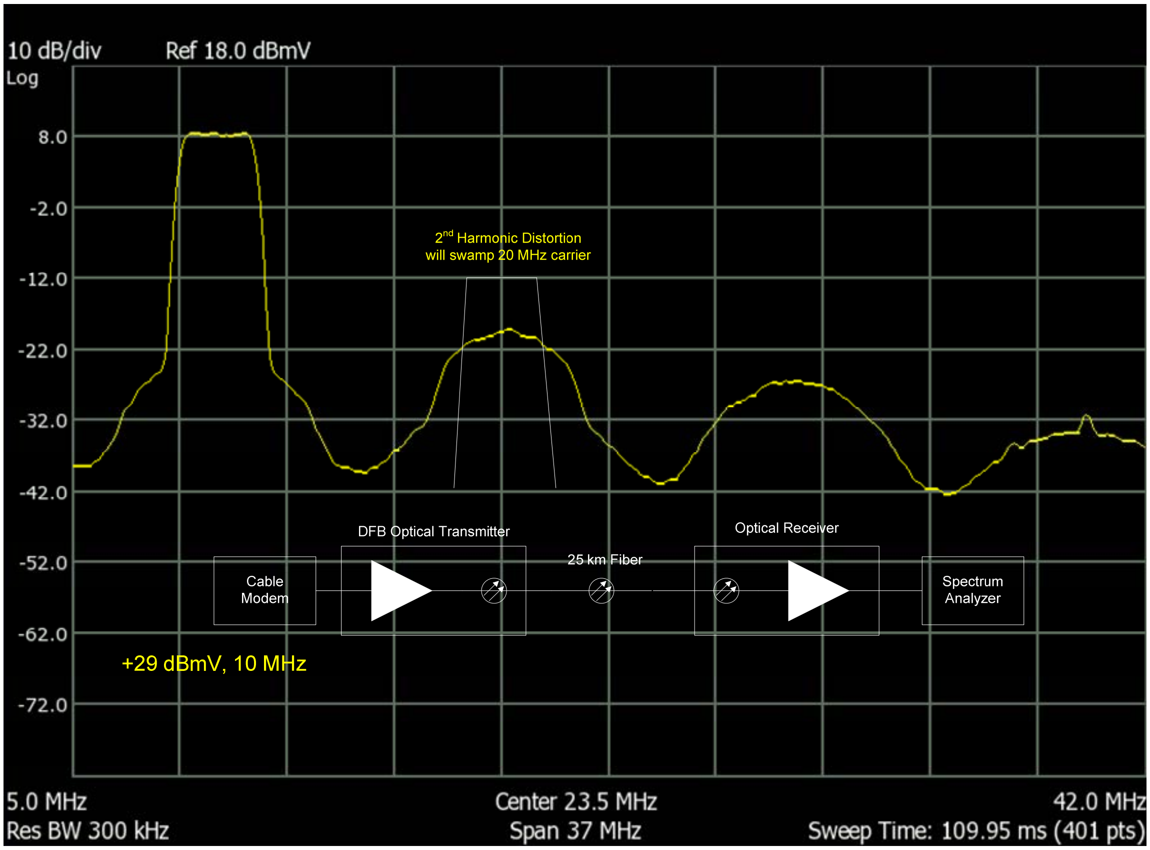


Figure 10. Increasing the level at 10 MHz by 20 dB adds significant distortion.

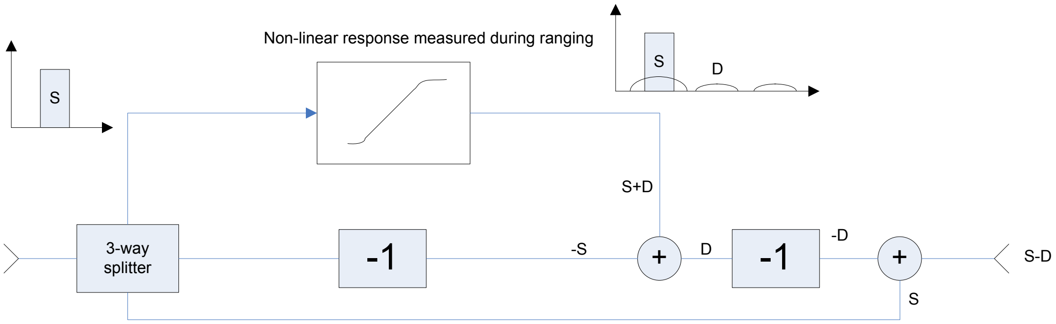


Figure 11. Conceptual Diagram of cable modem pre-distortion circuit.

This circuit could be built with common RF components, however, it is anticipated that practical implementations would perform the equivalent functions in the digital domain prior to the digital to analog converter. The signal is split with one side being subjected to the same non-linear characteristics measured by the CMTS during non-linear harmonic ranging. The output of the non-linear channel simulator would have signal, S, and distortion, D components, i.e. S+D. The signal sample from the splitter is shifted in phase by 180 degrees; equivalent to multiplying by -1, i.e. the output of the phase shifter is -S. These two signals are added, S+D-S=D, and the output is the distortion components since the signal has been cancelled. The distortion components are then shifted in phase by 180 degrees and added to another sample of the original signal. The CM output is thus S-D.

When this signal hits the return path laser, distortion components will be produced that are 180 degrees out of phase with the distortion components artificially produced in the cable modem, S-D+D=S. The distortion components cancel and only the signal is present at the output of the optical receiver.

This can be adjusted in an adaptive closed loop system so that the CMTS measures errors and adjusts pre-distortion parameters to minimize the mean squared error. By doing this the carriers at 10, 20, 30, and 40 MHz are all usable. Since a carrier can have as much as 25 Mbps data throughput, this method could potentially add as much as 25 Mbps of upstream capacity.

Simpler methods could also be used that have less benefit, but still provide substantial capacity increase. For example, by varying the CM transmit power and monitoring the harmonic distortion during a ranging process, the optimum SNR input level to the return path amplifiers and fiber node has been measured. Thus the CMTS could always direct the CM to transmit at the highest possible SNR. Since the return path characteristics change over time and temperature and there is measurement uncertainty in the manual set up of the return path input levels, the automatic optimization of the return path SNR would provide a significant improvement in SNR and thus upstream capacity.

These are just two examples of how non-linear harmonic ranging and pre-distortion can be implemented. The nonlinear response of the return path is determined by the composite signal of the superposition of all carrier waveforms from all cable modems. The non-linear pre-distortion could account for the composite waveform which would require precision control and timing from multiple cable modems and upstream carriers. The pre-distortion circuit could account for just one dominant carrier while restricting other carriers to low levels that do not impact the non-linear characteristics. The pre-distortion circuit could require that only one cable modem transmit at high power for specified time slots so that only the non-linear response from a single cable modem need be accounted for in the pre-distortion circuit. The simplest method is to just sum the average powers of all the cable modems and set the amplitude of the cable modems so that the average power into the return path laser is at the highest level and yet still in the linear operating range. More work needs to be done to make pre-distortion in the cable modem practical, hopefully these test results and ideas will serve to stimulate progress.

CHANGE IN MID-SPLIT CROSS-OVER POINT BETWEEN UPSTREAM AND DOWNSTREAM

The second technique for upstream capacity expansion is a mid-split whereby the 5-42 MHz upstream spectrum is expanded to 5-65 MHz, 5-85 MHz, or even a higher upstream to downstream crossover point. A change in the mid-split cross-over point between upstream and downstream is not compatible with the downstream transmission of analog NTSC low band VHF TV channels 2, 3, 4, 5, and 6. Analog viewers over the years have come to expect their local broadcast stations to be at a particular setting on the dial. As digital becomes the standard the downstream transmission of analog NTSC television in the low band VHF spectrum will no longer be a requirement so that the upstream spectrum can be expanded. For purposes of this paper, it is assumed that low band VHF spectrum can be reclaimed for upstream use in the future. The increase in upstream capacity is linearly proportional to the increase in allocated upstream spectrum and no changes need to be made to DOCSIS 3.0 in order to realize the capacity increase. The peak upstream speed of an individual

DOCSIS 3.0 cable modem is proportional to the number of upstream channels it can transmit. Most DOCSIS 3.0 cable modems can transmit the minimum of 4 upstream carriers and thus can reach upload speeds of 100 Mbps. More noise and interference is observed in the lower portion of the 5-42 MHz spectrum, below 20 MHz. DOCSIS upstream carriers are rarely if ever set to the lower portion of the 5-42 MHz spectrum. Narrower channel width QPSK signals for set top box return path data are often the only signals below 20 MHz, with 10.4 MHz being a commonly used frequency. In addition to adding more spectrum with a mid-split approach, the spectrum, since it is higher in frequency should have less noise and interference than that of spectrum below 20 MHz. An increase in the mid-split cross over point between upstream and downstream adds more upstream spectrum and also allows for higher order modulation due to lower levels of noise and interference.

It is important to remember that digital televisions connected to antennas, digital transport adaptors, digital cable set top boxes, and digital televisions connected directly to the cable plant at no time tune to NTSC analog television signals on channels 2-6. In Philadelphia, channel 3 is a familiar local TV station. There is no longer a broadcast over the air TV signal on channel 3 which is 60-66 MHz. When an antenna is connected to a television, the auto-program function will map the over the air broadcast ATSC signal centered at 573 MHz to TV channel 3.1. Likewise, with a digital transport adaptor or set top box, selecting channel 3 with the remote control will tune to the familiar local station because an SD stream carried on a 256 QAM signal centered at 545 MHz is mapped to channel 3. The digital transport adaptor will convert the SD stream to NTSC on EIA channel 3 or 4 for reception on an analog TV. With a digital HDTV, the customer will get a better picture if tuned to the HD stream, so as a convenience when a customer tunes to channel 3 with an HD STB, a reminder to "watch in HD" appears which if clicked will tune the TV to channel 803, the HD version of the local broadcast station which happens to be a stream in the 256 QAM RF carrier centered at 633 MHz. Only an analog NTSC television set connected directly to the cable plant utilizes the analog NTSC signal at 60-66 MHz. Thus, at a point in time whereby all customers are equipped with digital transport adaptors for NTSC analog televisions, digital televisions, and digital set top boxes then the NTSC 60-66 MHz signal will no longer be used and can be turned off without anyone being the wiser. Once this happens then a mid-split to allocate 42-85 MHz for upstream transmission will be possible.

The amplifiers in an HFC plant have a diplexer at the input and the output consisting of two filters that separate the upstream 5-42 MHz signals and the downstream 54-1002 MHz signals. Likewise, the fiber node has a diplexer at the coaxial output to separate the upstream and downstream signals. The optical receiver in the fiber node will input downstream signals into the 54-1002 MHz filter of the diplexer while the 5-42 MHz filter of the diplexer will direct upstream signals into the optical transmitter. A mid-split approach requires that all diplexers in fiber nodes and amplifiers be replaced with diplexers compatible with the chosen diplexer split, for example 5-85 MHz upstream and 108-1002 MHz downstream. Passive components in the HFC plant such as directional couplers, splitters, taps, trunk cable and drop cable as well as in home splitters and cable do not need to be changed in order to change the upstream and downstream spectrum split. Amplifiers in customer’s homes will not work with a change in upstream and downstream spectrum split and thus will need to be eliminated or replaced.

A mid-split increases upstream capacity by increasing the amount of spectrum allocated to upstream transmission. Potential new upstream bands are 5-65 MHz, 5-85 MHz and 5-200 MHz. 5-85 MHz seems to be the most desirable mid-split since it provides significantly more upstream spectrum than 5-65 MHz and still allows most set top boxes to receive their forward data channel which is not the case with a 5-200 MHz split. 5-65 MHz has some advantages in that it matches the mid-split frequency used in many countries, in particular EuroDOCSIS, and it may still allow for the forward data signal of set top boxes to remain at 72-76 MHz, although this would not allow for much of a filter transition. 5-200 MHz has the advantage of providing a significant amount of upstream bandwidth; enough to potentially reach 1 Gbps upstream speeds. The disadvantage to 5-200 MHz is the significant amount of downstream spectrum lost and the loss of the forward data channel for set top boxes. Set top boxes could run in DSG mode with a 5-200 MHz mid-split. Still, all in all, the 5-85 MHz mid-split cross over point seems to be a good choice. Increasing the upstream high frequency cutoff from 42 MHz to 85 MHz provides an additional 43 MHz of upstream spectrum which is enough for six 6.4 MHz wide upstream carriers. This adds as much as 162 Mbps of upstream capacity. With four 27 Mbps upstream carriers in the 5-42 MHz band, the total upstream capacity of a 5-85 MHz mid-split is 270 Mbps.

The DOCSIS 3.0 specification includes an optional 5-85 MHz upstream mode. Adding upstream spectrum will necessarily reduce downstream spectrum. The stop band attenuation of a low pass filter is determined by the number of elements and the ratio of the stop band frequency to the pass band frequency. A 12 element Tchebyscheff low pass filter with a 0.1 dB ripple and a 42 MHz pass band will have 55 dB attenuation at 54 MHz. Likewise, a 12 element Tchebyscheff low pass filter with a 0.1 dB ripple and an 85 MHz pass band will have 55 dB attenuation at 108 MHz. Thus the downstream pass band must be changed from 54-1002 MHz to 108-1002 MHz if the upstream spectrum is changed from 5-42 MHz to 5-85 MHz in order to have comparable upstream diplexer filter requirements [1]. The downstream spectrum in the 54-108 MHz spectrum that would have to be sacrificed in order to mid-split 5-85 MHz is today used mostly for analog TV NTSC signals and set top box out of band signaling. TV channels 2, 3, 4, 5, 6, 95, 96, 97 fall in the 54-108 MHz band and 72-76 MHz is often used for SCTE-55 digital video set top box signaling out of band modulation (OOB) [3]. Analog NTSC TV signals in low band VHF likely will not be needed in the future due to digital set top boxes, digital TVs, digital transport adapters. SCTE 55-1 has a default carrier center frequency of 75.25 MHz for the Out-Of-Band channel with a footnote that includes 72.75 and 104.2 MHz OOB center frequency. So the OOB can be moved to 104.2 MHz and digital cable set top boxes can still operate after a 5-85 MHz mid-split. There may be temporary disruptions when set top boxes are first asked to change OOB frequency and there may be a small percentage of set top boxes that are fixed tuned and cannot change to a 104.2 MHz OOB center frequency.

Prior to the launch of a change in mid-split cross over point between upstream and downstream, care must be taken to protect television receiving devices that have been designed to receive signals that are now part of the upstream transmission spectrum. A change in mid-split must be executed without degradation or disruption to existing services. This requires filters or protection circuits to prevent interference. Since this is such an important issue and because it is so critical that a change in mid-split does not create interference issues, this paper will explain the mechanisms for potential interference, provide measurement results of interference tests, and propose a specific circuit to prevent interference from upstream transmissions in the 42-85 MHz band to television receiving devices designed to receive in this band.

Cable modems and set top boxes must have diplexers at their coaxial input to allow them to receive signals in the 54-1002 MHz band and transmit signals in the 5-42 MHz band. There can be cases where a set top box can transmit a 6.4 MHz channel width signal at +54 dBmV with a 38.8 MHz center frequency while receiving a video signal at channel 2 with a 6 MHz channel width and a 57 MHz center frequency with a level of -15 dBmV. Within the same box the transmit level is 69 dB higher than the receive level. Typically, consumer electronics receivers can operate with adjacent channel levels about 10 dB higher than the desired signal, thus the diplexer must at least provide 59 dB of attenuation between the receiver input and the transmitter output for signals in the 54-1002 MHz band. The transition region between 42 and 54 MHz allows for a filter to be built that has a pass band of 54-1002 MHz and a rejection of 60 dB for 5-42 MHz signals. Since such a diplexer must be in every set top box, these devices will need to be exchanged for devices with a different diplexer split in order to benefit from the upstream capacity enhancement of a mid-split. However, it would instead be anticipated that these devices continue to use the 5-42 MHz for upstream transmission. Since in the past, the low VHF band was used for video signals and mostly NTSC analog signals, cable modems were often not designed to receive signals below 108 MHz. Thus cable modems have more relaxed diplex filter requirements. These cable modems may have filters to protect the receive chain in the 54-108 MHz range. Typical 2.0 cable modems have a downstream receive band 88-860 MHz while DOCSIS 3.0 cable modems typically have a downstream receive bandwidth of 108-1002 MHz. The upstream transmit band for both DOCSIS 2.0 and 3.0 in North America is 5-42 MHz.

Upstream transmission in the 42-85 MHz band can be shown to interfere with devices that are designed to tune to 54-108 MHz downstream signals. Such devices include televisions, digital cable set top boxes, digital transport adapters. The IF frequency of many TV tuners is 41 to 47 MHz which will be in the upstream transmit band after a change in mid-split frequency. To tune into channel 2, the voltage controlled oscillator, VCO, is set to 57+44=101 MHz and the mixer output will be SAW filtered to the lower sideband centered at 44 MHz. Thus transmitters operating in the 41-47 MHz band have to be well isolated from traditional single conversion TV tuners, if it gets into the IF chain it will result in co-channel interference. The single conversion TV RF tuner front end is illustrated in Figure 12.

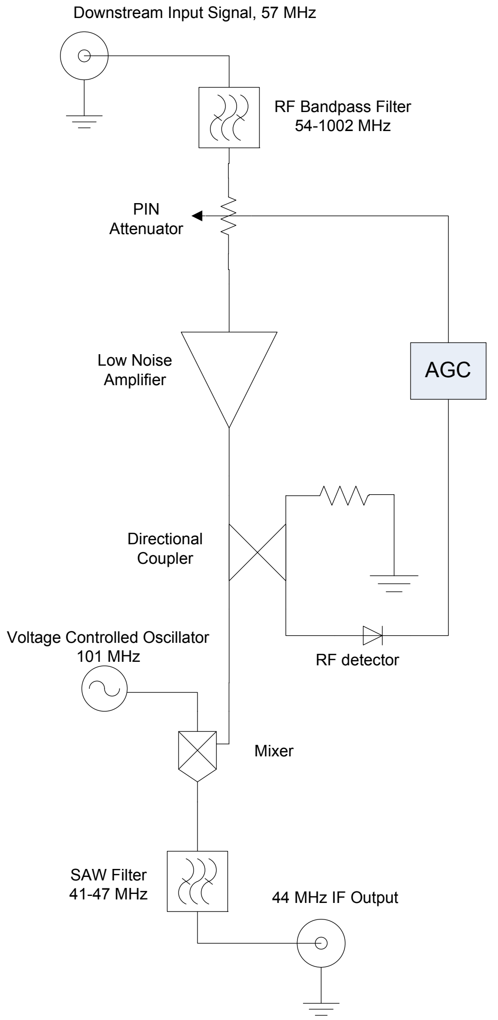


Figure 12. Block Diagram of Single Conversion TV Downconverter.

Figure 12 is helpful in understanding why mid-split upstream transmission as well as other sources of overload interference can cause picture degradation. The AGC (automatic gain control) adjusts the receiver's front end gain so that at low input levels the gain is cranked up while at high input levels the gain is set very low. This allows the front end to have high receiver sensitivity for low level signals since a dB of attenuation prior to the low noise amplifier adds a dB of noise figure to the receiver and thus degrades the signal to noise ratio by a dB. At the same time, the attenuation kicks in for high level signals so that the low noise amplifier does not get overloaded and create intermodulation distortion which also degrades the signal to noise ratio. Degradation in signal to noise ratio due to out of band high level interference arises when the diode detector circuit picks up interfering signals that are much higher than the desired signal. If the high level interfering signal is picked up by the diode detector then the AGC circuit will add attenuation. If the desired signal is very low then the attenuation prior to the low noise amplifier will degrade the signal to noise ratio of the amplifier output. This can lead to picture degradation and even to no reception at all.

A simple test was conducted whereby a cable modem was set to output at a center frequency of 55.5 MHz and a digital TV was tuned to receive a center frequency of 111 MHz, the lowest frequency downstream channel for a 108-1002 MHz downstream spectrum allocation. The mid-split frequency was chosen to be at half the desired digital video center frequency so that second harmonic components of the distortion would fall co-channel to the video signal. The mid-split signal was set to TDMA 16-QAM with a 5.12 MHz symbol rate. The digital TV showed visible macro-blocking artifacts when the upstream transmitter signal at the TV input was 27 dB higher than the desired signal. When the upstream signal was less than 26 dB higher than the desired video QAM signal then no visible distortion was observed. For interference 28 dB or more higher than the desired signal, no TV reception was possible. The spectrum analyzer plot from this test is shown in Figure 13.

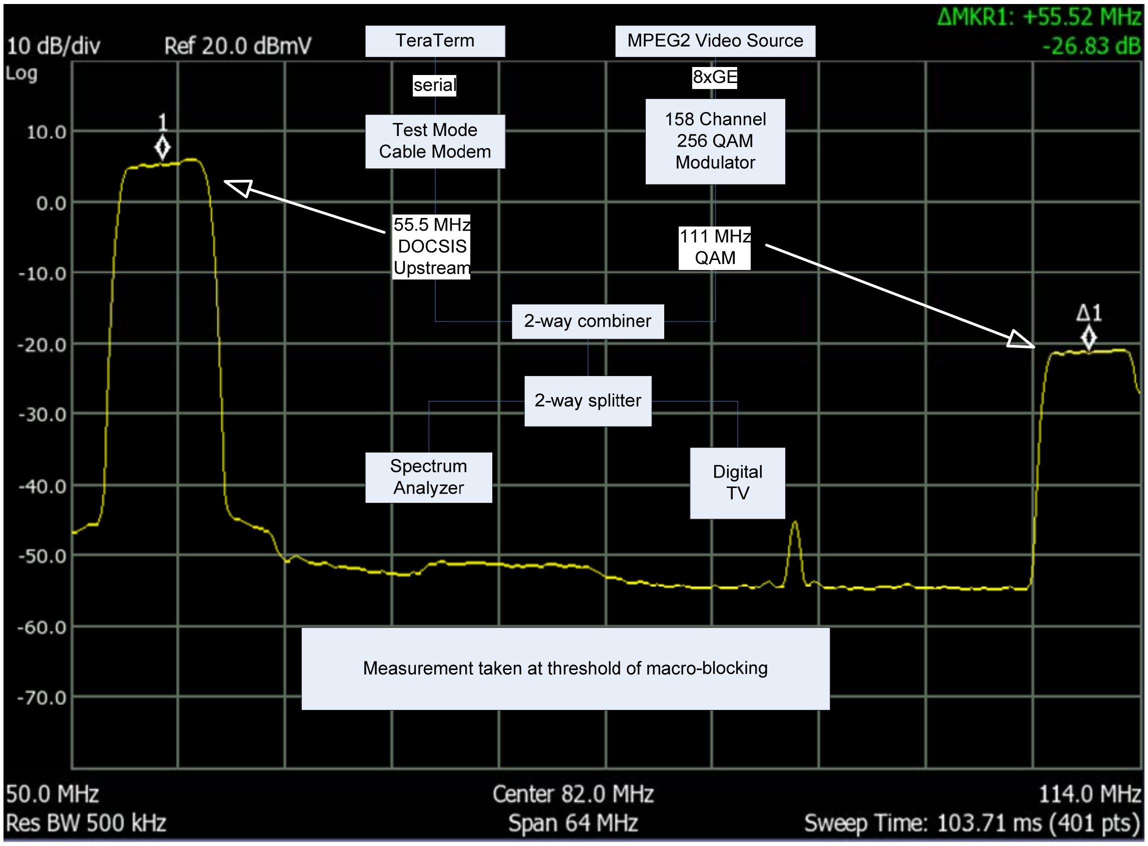


Figure 13. Interference from a mid-split cable modem to a digital television.

Another test was performed at the author's home. A set top box was tuned to a 256 QAM digital video carrier with a 97 MHz center frequency. A two way splitter was added to feed the set top box and a test mode cable modem. The test modem cable modem was set to transmit an upstream signal with 16 QAM TDMA using a 5.12 MHz symbol rate with a 48.5 MHz center frequency. It was found that a +55 dBmV upstream transmit level caused visible tiling and any level +56 dBmV or higher prevented any reception at all.

In another test a splitter was used to feed a digital transport adapter, DTA, and the test cable modem. The DTA was tuned to a 97 MHz center frequency, the input level of the 256 QAM carrier was reported in the DTA diagnostics as -18 dBmV with a 30 dB SNR. The cable modem was put in a test mode to transmit an upstream 16-QAM TDMA signal at a center frequency of 48.5 MHz and a 5.12 MHz symbol rate. An upstream transmit level of +47 dBmV was found to produce severe tiling in the picture. Transmit levels above +48 dBmV prevented any reception of the digital video signal. These tests show that DTA devices, like digital televisions and digital video set top boxes, can suffer interference from upstream transmission in the 42-85 MHz band.

Figure 14 shows the insertion loss sweep from one tap port to another for a 14 dB directional coupler and 4-way tap. The port to port tap isolation is 37 dB at 85 MHz. A 100 foot drop cable of RG-11 has a loss of about 1 dB at 55 MHz so about 2 dB of loss can be expected for a mid-split upstream signal traversing a 100 foot drop from home to tap and another 100 foot drop from tap to another home. If one home is transmitting in the mid-split upstream band at +58 dBmV with 2 dB of cable loss and 37 dB port to port tap isolation, then the input level of the upstream transmission is +19 dBmV at the neighbor ground block. With downstream video levels of -8 dBmV the difference between the upstream transmission and the downstream receive level in the neighbor's home is 27 dB which has been show to impact video picture quality. Home to home isolation needs to be considered to protect television receiving devices with upstream transmission in the 42-85 MHz band.

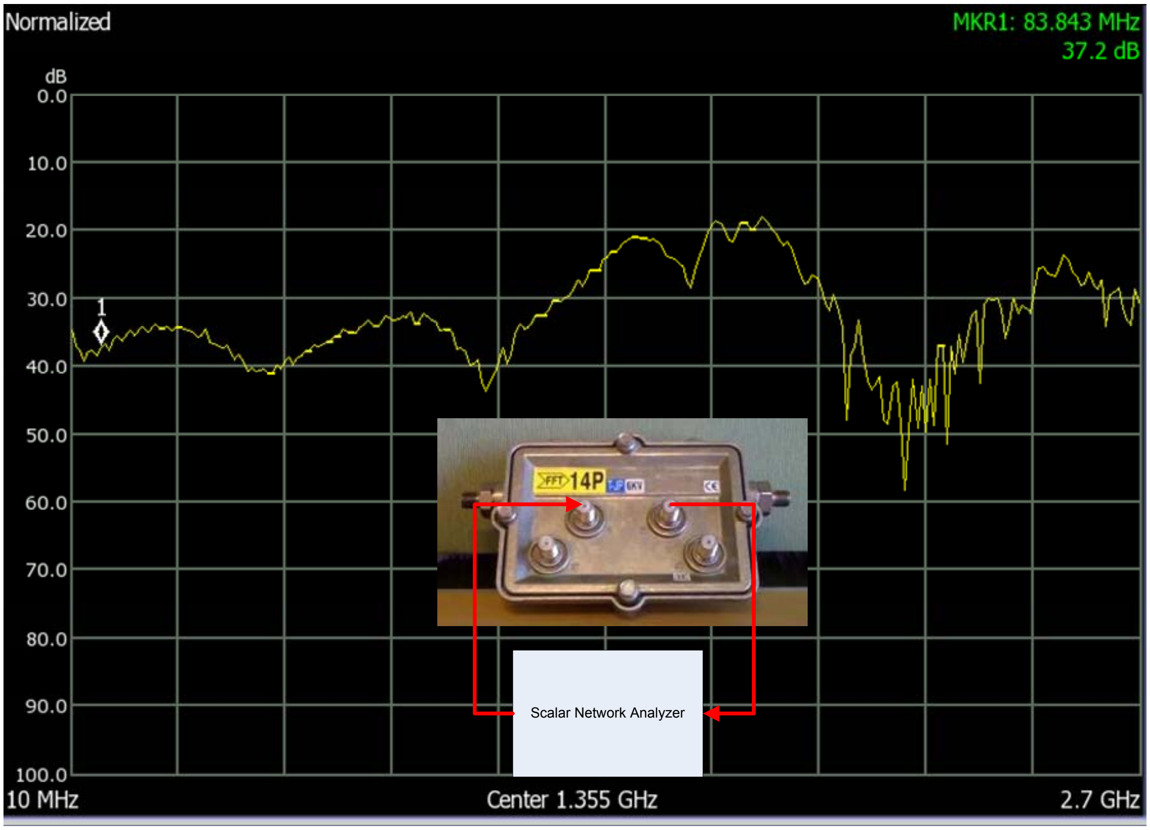


Figure 14. Tap to Tap Isolation measured for a 14 dB Coupler.

An illustrative block diagram of a mid-split protection circuit is shown in Figure 15. The upstream and downstream signals from the HFC plant are split with a diplex filter having an upstream band of 5-85 MHz and a downstream band of 108-1002 MHz. The mid-split RF protection circuit has a DOCSIS 3.0 Cable Modem, in this case with the capability of bonding 16 downstream channels and 4 upstream channels. The four upstream channels would most likely fall within the 42-85 MHz spectrum band so that upstream capacity for the mid-split protection circuit is additive to upstream capacity of cable modems within the home transmitting in the 5-42 MHz band

The mid-split RF protection circuit physical connector to the home coaxial cable is fed with a diplex filter separating the downstream 108-1002 MHz signals and the 5-42 MHz upstream signals from devices in the home such as SCTE-55 STBs, DSG STBs, CMs, and eMTAs. In this case an optional downstream amplifier with AGC is added so that the home network is always fed with an optimal downstream signal level. Likewise, the diagram includes an optional upstream amplifier to help with high attenuation cable modems, particularly DSG STBs. The 5-42 MHz diplex filter and the upstream amplifier provide high isolation between the mid-split upstream signals in the 42-85 MHz range and the in home devices that could suffer interference from such signals.

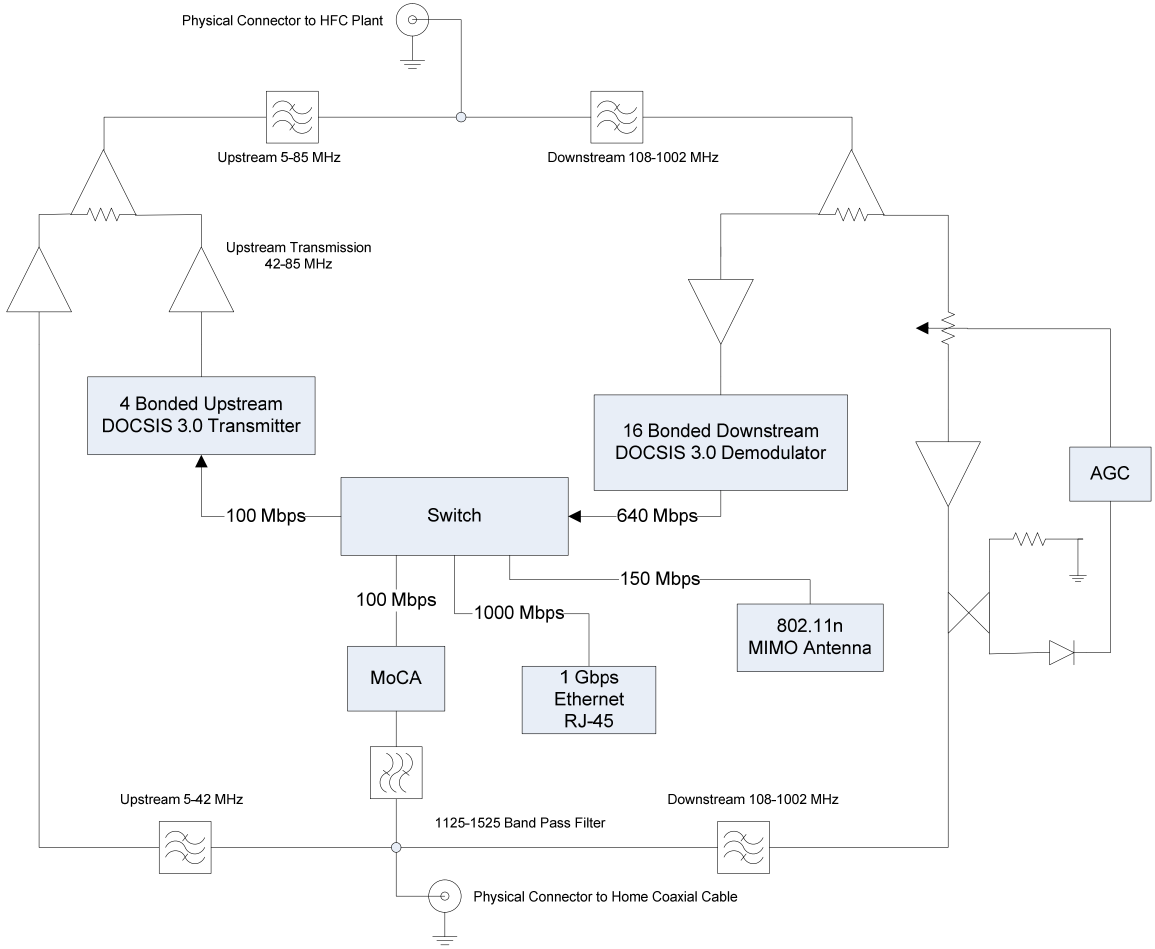


Figure 15. Mid-Split RF Protection Circuit between the HFC RF and home RF

INCREASING UPSTREAM CAPACITY BY USING SPECTRUM ABOVE 1 GHZ

Trunk cable and drop cable can support frequencies in the 1-3 GHz range at reasonable attenuations. Fiber nodes, amplifiers, directional couplers, splitters and taps in the plant will need to be modified to support the use of spectrum above 1 GHz signals. In home coaxial cables, splitters, and amplifiers add too much attenuation for practical use of signals in the 1-3 GHz range traveling all the way from the cable headend to the end user device within the home. Figure 16 shows a divided network architecture for using spectrum above 1 GHz with a fiber optic cable section, a 1200-1800 MHz over trunk and drop coaxial cable, and an in home coaxial MoCA section. The fiber node and amplifiers are bypassed with fiber optic cable to the last active. The directional couplers and taps between the coaxial 1200-1800 MHz transceivers are replaced with units supporting these frequencies. A coaxial transceiver is placed at the last active and at the customer entrance. The 1200-1800 MHz signals are terminated at the customer entrance and transported over home networking technology such as 1 Gbps Ethernet, MoCA, or 802.11n so that in home wiring does not need to support the high spectrum signals.

Trunk cable 750 feet in length will have about 25 dB of loss at 1500 MHz with a variation from 1200 to 1800 MHz of about 5 dB. Drop cable of 214 feet length will have a loss of about 17 dB with a variation from 1200 to 1800 MHz of about 3 dB. In the case where the path from the last active to the home includes a 3 dB splitter and two directional couplers with 2 dB of through loss and an 11 dB tap, the total attenuation is 60 dB using the trunk and drop length above. If the transmit power is +60 dBmV then the receive level is 0 dBmV which is equal to -49 dBm. If the receiver noise figure is 4 dB then since the thermal noise at room temperature is -174 dBm/Hz, the SNR is 34 dB using a 500 MHz equivalent noise bandwidth. This is a high enough signal to noise ratio for 64-QAM which has a spectral efficiency of 6 bps/Hz. Allowing for forward error correction and overhead, a final spectral efficiency of 4 bps/Hz seems reasonable. With a 500 MHz bandwidth and 4 bps/Hz spectral efficiency, the total channel capacity is 2000 Mbps. Using time division duplexing, 1 Gbps can be allocated for downstream and 1 Gbps can be allocated for upstream. The 500 MHz equivalent noise bandwidth can fit in the 600 MHz channel width within the 1200-1800 MHz band with reasonable OFDM guard bands on either side.

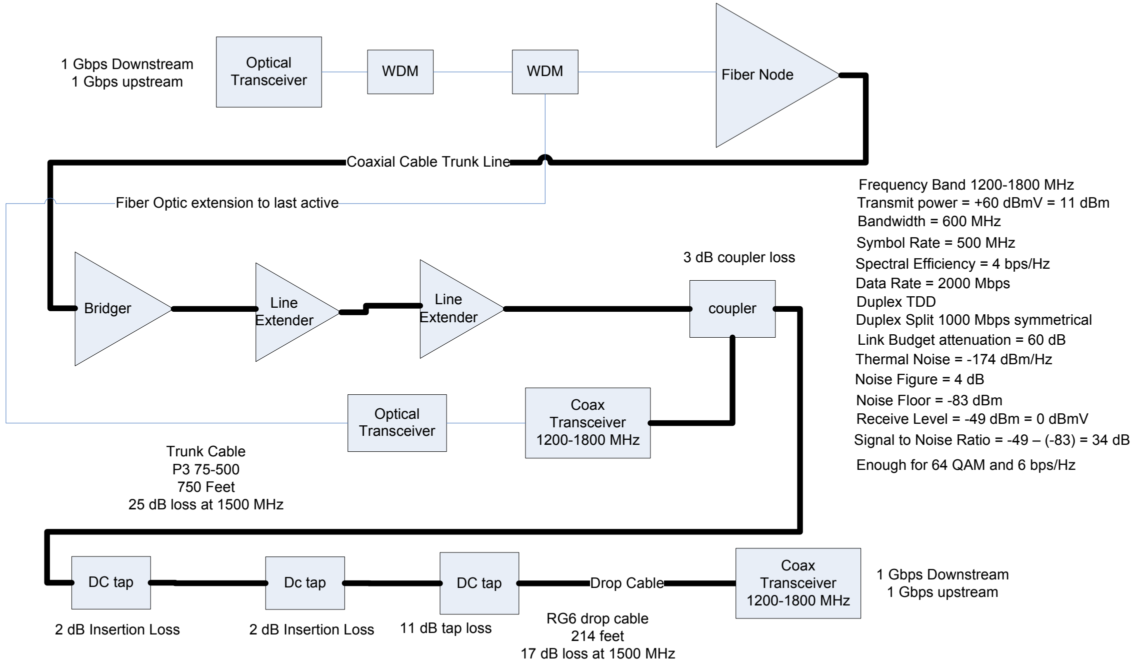


Figure 16. Block Diagram of 1 Gbps over coaxial cable network architecture.

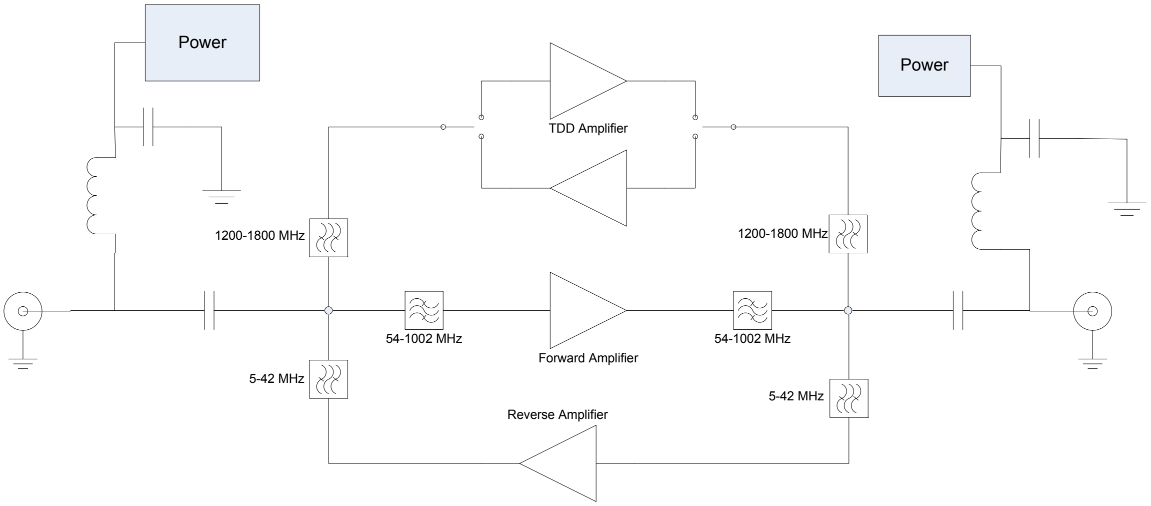


Figure 17. Block Diagram of TDD Triplexer to support HFC and high spectrum operation.

Further work needs to be done to better understand the actual channel characteristics above 1 GHz over the coaxial plant. Field measurement and lab measurements are underway to develop channel models to use in evaluating proposed system solutions. Data is needed on interference such as harmonics, MoCA, radar, and radio communication networks. Reflections and multi-path as well as frequency notches due to impedance imperfections at high frequencies need to be accounted for in evaluation.

The fiber optic cable does not always need to be run all the way to the last active. 2-3 GHz spectrum could be used for point to point backhaul to eliminate the need for running the fiber all the way to the last active. Another method is to use amplifiers as shown in Figure 17. In order to inject 1200-1800 MHz TDD prior to the last active, new amplifiers will have to replace the old amplifiers between the 1200-1800 MHz transceivers. The new amplifiers will require triplex filters at the input and output and an additional TDD amplifier for 1200-1800 MHz signals.

CONCLUSION

Today, a common upstream frequency plan includes a 6.4 MHz channel width 64-QAM modulation carrier centered at 34.2 MHz and another 3.2 MHz channel width 16-QAM carrier centered at 37 MHz. The total upstream capacity is about 36 Mbps which is about 23% of the potential capacity in the 5-42 MHz band when compared to the full spectrum being filled with 64-QAM carriers. By segmenting nodes with four upstream optical transmitters, the upstream capacity can be increased another four times. Thus, within the 5-42 MHz upstream band increased upstream capacity demands of 16-fold can be addressed. Beyond that, new spectrum for upstream carriers further increases capacity.

The logical first step to increase upstream capacity is to increase the spectral efficiency and utilization of the 5-42 MHz. Better utilization requires the use of more upstream carriers which in turn requires the use of noisier parts of the 5-42 MHz band. The objective is to increase the upstream capacity and at the same time improve the reliability. Placing upstream carriers in noisier parts of the spectrum risks reducing the reliability and availability of upstream signals, to deal with higher levels of noise and work with higher reliability and availability substantial improvements are required in the upstream signal robustness. Three methods have been described in this paper that will work with OFDMA systems as well as S-CDMA systems. The first is adaptive modulation and coding with real time channel measurement, with S-CDMA this can be accomplished by allowing the number of active codes to be reduced during noise bursts. The second method is hybrid automatic repeat request which uses very little error correction while seeking acknowledgement of successful packet transmission, when packet transmission is unsuccessful then the upstream transmission in repeated. Hybrid ARQ works well for the intermittent and unpredictable noise characteristic of the HFC 5-42 MHz upstream path. Third, since a fundamental determinant of the upstream channel signal to noise ratio is the dynamic range limits and changes over time and temperature of the return path optical transmitter and upstream amplifiers, a non-linear harmonic ranging technique with pre-distortion could be investigated further as a means to increase the upstream capacity.

If at a point in the future the 5-42 MHz upstream appears to be headed towards full utilization, then a mid-split to 5-85 MHz will add significant upstream capacity with a small sacrifice in the downstream. The diplexers in fiber nodes and amplifiers will have to be exchanged for diplexers compatible with the new upstream to downstream spectrum split. So a mid-split will require extensive work to the HFC plant. The out of band modulator downstream signaling carrier for digital video set top boxes in most cases will need to change center frequency and televisions, set top boxes, digital transport adapters will have to be protected against upstream transmission in the 42-85 MHz band. A mid-split RF protection circuit that will be the only device to transmit in the 42-85 MHz upstream band with filters and amplifiers to protect devices in the home from interference is a good approach for mid-split upstream capacity enhancement.

Finally, for incremental addition of 1 Gbps symmetrical services, primarily for large businesses, office parks, and multi-dwelling units, a frequency overlay approach using spectrum above 1 GHz has been introduced. While this requires bypassing the fiber nodes and amplifiers with a fiber overlay or replacing the fiber nodes and amplifiers with devices having above 1 GHz capability, this can be done on an as needed basis without disruption to the existing HFC infrastructure and the services running over the HFC infrastructure. More study and most importantly field measurements are needed to better characterize the interference levels and the channel characteristics of the HFC plant modified to support frequencies above 1 GHz. This paper has tried to begin this process by including link budget, bandwidth and duplexing scheme based upon insertion loss sweeps above 1 GHz.

In conclusion, the HFC plant has a healthy upstream capacity with room to grow within the 5-42 MHz band, further room to grow in the 5-85 MHz band, and even more capacity growth is possible above 1 GHz.

Glossary of Terms and Abbreviations:

HFC Hybrid Fiber Coax a network architecture that transports upstream RF signals over fiber optic cable over long distances and then coaxial cable over short distances to homes and businesses.

CPE Customer premise equipment typically refers to digital cable set to boxes, televisions, cable modems, home routers, digital voice adapters.

CM cable modem

CMTS cable modem termination system

eMTA embedded media transport adapter for cable modem voice over IP

OFDMA orthogonal frequency division multiplexing a technique that divides an RF channel into many small frequency segments to realize protection from multi-path interference

S-CDMA synchronous code division multiple access a DOCSIS 2.0 and 3.0 upstream technique that assigns 128 orthogonal codes which can be synchronously transmitted and detected over the same RF frequency without interference, multiple cable modems can share an upstream channel by the assignment of unique orthogonal codes.

Digital Transport Adapter, DTA, device that receives digital 256 QAM signals and converts them to channel 3 or 4 NTSC analog signals.

TDD, time division duplex, using a single frequency band shared for both upstream and downstream transmission separated in time.

FDD, frequency division duplex, using a separate upstream and downstream frequency band.

DC directional coupler, part of HFC tap or stand alone to couple upstream and downstream signals to the truck cable.

DTAB discrete tone adaptive bandwidth a method introduced in the paper for increasing HFC upstream capacity.

WDM wavelength division multiplexing allows multiple signals to be sent on the same fiber optic cable using different wavelengths

Hybrid ARQ automatic repeat request a technique to use acknowledgements to repeat upstream transmissions while adding error correction as needed.

NPR noise power ratio, the return path laser is tested with a noise source having a notch, the input level is varied and the ratio of the power spectral density of the input signal to the distortion components at the notch frequency is measured.

OOB Out-Of-Band downstream signaling for digital cable set top boxes SCTE-55 [3]

MoCA multimedia over coax a standard for home networking over coaxial cable.

802.11n the latest WiFi standard for wireless home networking.

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