256-QAM FOR UPSTREAM HFC

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Abstract

Increased throughput demands, driven by applications like Peer-2-Peer file sharing and social networking, has intensified the demands placed on upstream spectrum. Those demands have been met with advanced DOCSIS tools like SCDMA and Channel Bonding. Additionally, plant architectures are evolving towards fiber-rich networks with reduced RF cascades, potentially improving overall plant performance and creating opportunity to support higher-order modulation schemes.

The benefits of advancing modulation to 256-QAM over 64-QAM is well-understood for the downstream. For example, a 33% throughput increase would also apply to the upstream. As previously explored for downstream spectrum, this throughput increase comes at the expense of increased sensitivity to noise, distortion, and interference. However, the upstream spectrum hosts a different class of impairments as well as DSP tools available to overcome them including equalization, forward error correction, spread-spectrum techniques, ingress cancellation, and interleaving.

The goal of this paper will be to identify the critical engineering requirements for supporting 256-QAM in an upstream environment and the implications for the HFC network performance.

INTRODUCTION

Upstream Service Growth

Growth patterns in Hybrid Fiber Coax, HFC, upstream have been described using Moore's law in [1] to show that service rates increase by a factor of 10 every 5 to 7 years. Specifically, demand for today's service rates, which are in the range of 2-10 Mbps, will increase to approximately 20-100 Mbps in 5 to 7 years. DOCSIS 2.0 links will support the lower end of the 5 to 7 year projections. However DOCSIS 3.0 technology, with channel bonding was designed to help cable operators deliver a 100 Mbps service rate. It was shown in [1] how S-CDMA could help cable operators use spectrum below 15 MHz to achieve this goal. This paper proposes another possible solution through the use of fewer, but more bandwidth efficient signals that will leverage modulation schemes such as 128-QAM or 256-QAM.

HFC Evolution

Technological enhancements and increasingly competitive pressure on cable operators to deliver more capacity is resulting in fiber-rich architectures with reduced RF cascades, shown in [2]. These developments may create opportunity to use higher-order modulation schemes.

Assuming identical upstream RF amplifiers, a cascade's signal-to-noise ratio, SNR, based upon noise figure, NF, of the RF amplifiers could improve by approximately 3 dB with reduction to half as many cascaded actives. The effects of non-linear distortion, specifically composite-intermodulation-noise, CIN, may also be reduced by approximately 7 – 9 dB under similar circumstances.

However, upstream performance is not necessarily limited by cascaded performance, but rather the upstream noise introduced at both intentional and unintentional entry points. Noise comes in multiple forms, including ingress, impulse, etc. and ultimately places a greater limit on upstream SNR due to the high input levels of the upstream hybrids.

Shorter cascades reduce the impact of noise funneling, improving upstream SNR perhaps further. It has been seen that reducing the cascade by half could reduce the number of actives fed from a node by 4 or more. Generally speaking, SNR changes can be described as a function of the total number of actives in a given node and the typical performance of one of those upstream actives. Thus making the standard assumptions including, everything else being equal, and monitoring at a common point, the SNR should reduce as the total number of actives are reduced. However, noise funneling due to the cable plant itself has been found to be only a small contributor to total SNR performance.

The downstream benefits of reduced RF cascade discussed in [2] are applicable in the upstream as well. Reductions in ingress, common path distortion, CPD, interference, impulse noise, linear and nonlinear distortion can all be expected in the upstream. Overall, less opportunity exists for corrosion, poor connectivity, water seepage, etc. because of less coax, components, and connectors in the upstream path.

Shorter cascades should also have less variation in RF levels. There is typically no automatic gain control in upstream RF amplifiers and there can be significant gain changes across a long cascade. Cutting the cascade in half would reduce the gain variation of the return plant due to causes such as seasonal change of temperature.

Distributed Feedback (DFB) laser or digital return (DR) upgrades from older generation Fabry-Perot (FP) lasers may have been a necessity for some cable operators wishing to deploy 64-QAM DOCSIS signaling in the upstream spectrum. A comparison of laser technologies has been documented in [3] et al. A 5 dB improvement in optical link SNR could be realized with upgrading a FP laser with a DFB, thus providing 64-QAM with adequate margin to operate successfully.

It is reasonable to suggest that the previously discussed evolutionary developments could combine to result in an appreciable improvement in upstream HFC performance. Whether or not this improvement in upstream HFC performance could support more efficient, yet sensitive, modulation schemes will be explored in more detail in the following sections of this paper.

Upstream Efficiency

Multiple digital communication references, including [4], discuss the Shannon-Hartley capacity theorem. The following equation from [4] et al. describes the system capacity, *C*, of a channel impaired by Additive White Gaussian Noise (AWGN) and is a function of *SNR* and channel bandwidth, *W*.

Equation 1

$$C = W \log_2\left(1 + \frac{S}{N}\right)$$

Part of the chart from [4], which illustrates Equation 1, has been included as Figure 1. Figure 1 illustrates the modulation method efficiency for multiple QAM scenarios. The bit-error-rate, BER, is 1E-8 for QAM scenarios shown in the figure. The dark blue curve represents Equation 1 or the normalized channel capacity over a range of SNR values. The purpose of this figure is to show improvement in efficiency via the use of 128-QAM and 256-QAM relative to lower-order modulation schemes.

64-QAM offers an efficiency of 6 bits/s/Hz, which translates to approximately 30.72 Mbps for a 6.4 MHz channel with a BER = 1E-8. The theoretical capacity of a channel with the same characteristics is 59.54 Mbps, based upon Equation 1. Table 1 compares efficiency and capacity of 64, 128, and 256-QAM, based upon a 6.4 MHz channel with a BER = 1E-8.

Table 1 - Modulation Method Efficiency and Capacity

M-QAM	Efficiency (bits/s/Hz)	Data Rate (Mbps)	Theory (Mbps)
64	6	30.72	59.54
128	7	35.84	65.91
256	8	40.96	72.29

The increased efficiency of 256-QAM represents a 33% improvement over 64-QAM or approximately 10 Mbps more throughput for a 6.4 MHz channel. The increased efficiency of 128-QAM represents a 17% improvement over 64-QAM or approximately 5 Mbps more throughput for a 6.4 MHz channel.

Shannon-Hartley capacity theorem, from Equation 1, provides useful insight into the limits of today's HFC networks. However, the formula is truly much worse than what has been presented thus far because it was intended more for estimating the entire channel capacity rather than the capacity limits of an arbitrarily divided subset. Therefore, the Table 2 illustrates the capacity associated with a 37 MHz upstream bandwidth.

Table 2 – Theoretical Upstream Capacity vs. SNR

SNR (dB)	Capacity (Mbps)
28	344.236
31	381.067
34	417.919
40	481.651

Compare the results of Table 2 above to a practical system capacity, specifically a channel bonding scenario using 6, 6.4 MHz carriers in Table 3. Note, not all modulation levels represented in Table 3 are part of the DOCSIS specification. This isn't an apples-to-apples comparison because 38.4 MHz of bonded channels should result in an even higher capacity, per Equation 1, than what has been previously illustrated using 37 MHz.

Table 3 - Practical Upstream Capacity vs. SNR

M-QAM	SNR (dB)	Capacity (Mbps)
64	28	184.32
128	31	215.04
256	34	245.76
256	40	245.76

When the Shannon limit was first pushed at V.34 and V.90 limits, the maximum SNR of 34 dB was assumed and in reality 36 dB was the upper limit. V.34 and V.90 being the standards supporting 33.6 kbps and 56 kbps rates associated with applications including dialup data service. The usable bandwidth was 200 Hz to 3,700 Hz or 3,500 Hz. The symbol rate was 3,429 sym/s with an alpha = 0.08. The theoretical capacity was 40.695 kbps and the capacity of V.34 maximum was 33.6 kbps.

V.34 had attained 82.56% of the theoretical limit while DOCSIS 3.0 using 6 bonded channels attains only 58.8% of the Shannon-Hartley limit. It's clear that significant opportunity to improve efficiency for HFC networks still exists.

<u>Fidelity Requirements</u>

The increased efficiency unfortunately comes at the expense of higher fidelity requirements. The following equation from [4] et al. describes the BER for a rectangular constellation, impaired by AWGN. Both a matched filter reception and Gray encoding are assumed.

Equation 2

$$P_B \approx \frac{2\left(1-L^{-1}\right)}{\log_2 L} Q\left[\sqrt{\left(\frac{3\log_2 L}{L^2-1}\right)\frac{2E_b}{N_0}}\right]$$

Q(x) is the complementary error function and L represents the number of amplitude levels in one dimension. Using Equation 2, waterfall curves for 64, 128, and 256-QAM have been illustrated in Figure 2. These waterfall curves illustrate the required SNR necessary to support a given BER. The results presented in Figure 2 assume no forward error correction, FEC, gain.

The waterfall curves show that an additional 3 dB SNR over 64-QAM is required to support equivalent BER performance at 128-QAM. Additionally, 6 dB SNR over 64-QAM is required to support equivalent BER performance at 256-QAM. Specifically, in order to support BER = 1E-8 the following SNR requirements must be met for a communication channel dominated by AWGN.

64-QAM SNR = 28 dB
128-QAM SNR = 31 dB
256-QAM SNR = 34 dB

Signal-to-interference levels for both 64 and 256-QAM have previously been documented in [5] and [6]. 256-QAM was shown to be approximately 12 dB more sensitive to narrowband interference than 64-QAM. The sensitivity was consistent regardless of whether the interfering tone was at the center frequency are at a location consistent with a CTB beat (-1.75 MHz). Additional variation in sensitivity was documented when CTB was generated using a live video. Given a delta of 12 dB in sensitivity between 64 and 256-QAM, it is reasonable to expect that 128-QAM could be 6 dB more sensitive to narrowband interference than 64-QAM.

DOCSIS upstream equalization had been documented to be approximately 2 dB less effective on average for 64-QAM than 16-QAM in [7]. DOCSIS upstream equalization is actually comprised to two distinct parts, transmit pre-equalization which is defined in the DOCSIS specifications, and post-equalization in the cable modem termination system, CMTS. Both processes are driven by estimations made in the post-equalization function of the CMTS receiver. It was simulation of post-equalization that revealed the decreased effectiveness of the equalizer to correct for single dominant micro-reflections of varying delay and maximum amplitude characteristics when comparing modulation levels.

The interaction of the post-equalization process was confirmed in laboratory measurements. However, the magnitude of single dominant micro-reflections being corrected was appreciably higher than what had been assumed by DOCSIS to be present in the HFC environment. For example, [7] showed that single dominant micro-reflections, with a delay characteristic of one symbol period, were corrected at levels approximately 5 dB higher than DOCSIS assumption of 10 dBc, with similar characteristics. Only 6.4 MHz signals were evaluated. The micro-reflection delay of one symbol period is the inverse of the symbol rate or approximately 195 ns. Micro-reflections with such short delay and high amplitude characteristics may be encountered more frequently within the customer premise, because of multiple factors including short lengths of coaxial cable and loss characteristics associated with drop plant.

Given a delta of 2 dB in sensitivity between 16 and 64-QAM documented in [7], it is reasonable to expect that 2 dB degradation in equalization performance when comparing 256-QAM to 64-QAM under equivalent conditions. However, equalization should still be robust, thus correcting for single dominant micro-reflections greater than what has been assumed by DOCSIS.

Documented phase noise requirements from [5] show how 35 dB signal-to-phase noise ratio or less is required to assure small degradation (1-2 dB) of the BER curve of 64-QAM. Similarly, 41 dB signal-to-phase noise ratio would be required for 256-QAM. Thus resulting in a reasonable expectation for 128-QAM being half the difference, or 38 dB signal-to-phase noise ratio.

Substantial research exists to aid in the discovery of fidelity requirements for both 128 and 256-QAM use for the upstream HFC. This information is useful in focusing laboratory investigation and validation of necessary fidelity requirements.

HFC Evolutionary Considerations

DOCSIS 3.0 has provided cable operators with the option of extending upstream bandwidth to 85 MHz. This upstream expansion may create a greater range of useable center frequencies for 128 and 256-QAM. However, optical links could have an additional loss of 3-4 dB SNR due to sharing optical link dynamic range with at least twice as much upstream bandwidth.

Introduction of enhanced hybrid technology, such as GaN, may slow down cascade reductions. It's possible that the improved downstream reach of these RF amplifiers could encourage the continued use of longer RF cascades. It could also just mean improved reach for fiber-to-the-last-active, FTTLA, or node plus zero architectures, N+0.

The combination of the previous two considerations could negate some of the gains possible with previously explored HFC evolutionary changes. The more pertinent goal of this paper is simply to raise awareness of these HFC changes and the potential for performance improvement of the upstream HFC rather than enumerate permutations and performance estimations thereof.

MER, CER PERFORMANCE EVALUATION

A performance evaluation was conducted to measure modulation sensitivity. The three modulation levels measured were 64, 128, and 256-QAM. Each modulation level was subjected to varying impairment levels that resulted in both a 0.5%, and 1% codeword error rate, CER. In other words, the data recorded reflects impairment levels that resulted in approximately 0.5%, and 1% combined CER (corrected codeword error rate plus uncorrected codeword error rate). MER was also recorded for each data point.

Test Topology

The test topology, shown in Figure 3, was designed to simulate an HFC network comprised of a FP or DFB optical link and an N+6 RF cascade. The combined SNR performance, which includes contributions from the DOCSIS link and HFC, using an FP optical link was equal to 31.5 dB. The combined SNR performance using a DFB optical link was equal to 33 dB. Multiple vector signal generators were used to produce the impairment permutations, which were also measured using vector signal analyzer.

The CMTS was configured such that; (1) DOCSIS transmit pre-equalization was enabled, (2) ingress cancellation was enabled, (3) channel width was 6.4 MHz, (4) center frequency was 25.2 MHz, (5) modulation profiles supported were 64, 128, and 256-QAM, (6) modulation profiles disabled byte interleaving, (7) modulation profiles supported FEC = 219, T=16.

The CMs were configured such that they were very large packets (4,000-byte) to simulate a heavy usage condition which would result in maximum exposure of codewords to each of the impairment conditions.

For each impairment permutation, the DOCSIS links were allowed time to settle into a steady state, giving the adaptive processes ample time to converge on an estimate of the communication channel impairments. During steady state, FEC and MER statistics were recorded. This process was repeated until the targeted 0.5% and 1% CER were measured. Recordings were made of CER, MER, and impairment contributions.

Impairment Library

A mid-band frequency of 25.2 MHz was chosen because the authors assumed that cable operators would primarily be interested in increasing modulation levels on channels with a known history of reliable 64-QAM performance. Ingress and noise were the most relevant impairments given the above assumption. Below is a list of impairment characteristics. Each value of AWGN was first measured as a baseline, and then combined with only one static ingress case for each impairment permutation.

AWGN

- SNR = 33 dB
- SNR = 31.5 dB

Static Ingress

- Single QPSK modulated carrier, f_c = -1.5 MHz offset, rate = 10 ksym/s, bandwidth = 12 kHz
- Single FSK (2-level) modulated carrier, f_c = -1.5 MHz offset, rate = 320 ksym/s, bandwidth = 400 kHz
- Single FM modulated carrier, f_c = -1.5 MHz offset, rate = 400 Hz, deviation = 20 kHz, waveform = sinusoid
- Three modulated carriers simulating CPD
  - Two outer Global System for Mobile, GSM, carriers at f_c = ±1.5 MHz offset, MSK modulation, rate = 270.833 ksym/s, 0.3 Gaussian
  - One inner π/4 Differential QPSK modulated carrier, 384 ksym/s, alpha = 0.5

31.5 to 33 dB AWGN represents an error free range of operation for 64-QAM. These SNR values translate to BER = 6.5E-17 to BER = 0 respectively. SNR margin ranges from +3.5 to +5 dB, based upon the 28 dB needed to support BER = 1E-8. This margin should make it easy for other digital signal processes, DSP, like ingress cancellation and equalization to function without issue.

For 128-QAM, the same SNR values translate to BER = 2E-9 to BER = 1.7E-12 or an SNR margin range of +0.5 to +2 dB respectively. This represents a comfortable region of operation, which likely introduces small variations into the adaptive DSP systems.

256-QAM appears to be in uncomfortable range with SNR values translating to BER = 1.1E-5 to BER = 3E-7. This represents negative margin relative to BER = 1E-8, specifically -2.5 to -1 dB. It is expected that some of the FEC margin will be consumed in this range. Additionally, this level of noise is expected to introduce appreciable variation into adaptive DSP systems.

A set of single static ingress was selected to make some initial assessment of ingress cancellation performance relative to ingress most likely expected to show up in mid-band frequencies. QPSK modulated ingress was chosen to represent ingress with appreciable amplitude modulation component. The FSK modulated ingress was chosen to represent a 2nd harmonic component associated with a set-top box carrier. FM modulated ingress was chosen to represent shortwave radio from fire, police, and/or public safety systems. CPD was modeled after samples retrieved from the field. GSM and π/4 DQPSK carriers were selected because their spectral characteristics closely matched that of the CPD field samples.

The goal of establishing this impairment library was capture some reference points for discussion and develop a process of evaluating higher-order modulation performance suitability in the upstream HFC.

Laboratory Measurements

Tables have been included at the end of this paper that tabulate performance for 256, 128, and 64-QAM subject to impairments described in the previous section. Each table represents a modulation level. The left-hand side of each chart represents the combined performance including DOCSIS link, and HFC using DFB return optics. The right-hand side of each chart represents the combined performance including DOCSIS link, and HFC using FP return optics. Level represents the level measured on the vector signal analyzer, which is the same level input to the CMTS receiver. UNCORR% represents the uncorrected codeword error rate, which is the percentage of uncorrected codewords out of the total codewords received in each measurement. Total codewords is the sum of corrected, uncorrected and unerrored codewords. CORR% represents the corrected codeword error rate, which is the percentage of corrected codewords out of the total codewords received in each measurement. The first row of each chart represents the baseline case with AWGN impairment. Subsequent rows identify the type of ingress and the target CER. CER = 0.5% targets were measured prior to CER = 1.0% targets.

In Table 4, note that the -1 to -2.5 dB margin range for 256-QAM with no other impairments is already creating countable codeword errors. In fact, a baseline starting with 0.880% corrected codeword errors would easily exceed 1% threshold if any additional impairment to the network with the FP return optics were to be added. Also note that the delta between 128-QAM and 256-QAM is well beyond the predicted minimum 6 dB based on previous work [5] and [6]. The likely cause for this variation in performance is the baseline BER performance, which is already consuming FEC margin as well as introducing noise variation into vital DSP functions such as ingress cancellation. This range of 256-QAM operation represents a challenging environment for ingress cancellation success.

In Table 5, note that the +2 to +0.5 dB margin range for 128-QAM with no other impairments has no codeword errors. Ingress cancellation performance has degraded with increased sensitivity and decreased margin compared to 64-QAM. FM and QPSK ingress is only 5 dB lower for 128-QAM compared to 64-QAM. This suggests that ingress cancellation is capable of overcoming increased sensitivity associated with increased modulation complexity, provided there is adequate SNR margin.

In Table 6, note that the +5 to +3.5 dB margin range for 64-QAM with no other impairments has no codeword errors. There is negligible difference between ingress cancellation performance at +3.5 to +5 dB margin range. The noise performance appears to be more than adequate at this range.

It's clear that ingress cancellation performance is affected by bandwidth and modulation characteristics of ingress. The ingress canceller corrected for FM and QPSK-type ingress far more effectively than any other ingress evaluated. FSK and CPD-type ingress represented the most challenging ingress conditions, which suggest increased sensitivity to bandwidth. Considering 128-QAM, the disparity between dBc levels of FM and FSK is appreciably higher than the other modulation levels. With the reduced margin, the ingress canceller had more trouble with the wider bandwidth ingress (320 kHz FSK) than with the narrower ingress (20 kHz FM).

CONCLUSIONS

Various HFC plant improvements may create opportunity for increased modulation efficiency in the upstream. This paper has described some of the critical requirements associated with supporting higher than 64-QAM modulation levels.

Based on the measured data presented in this paper, 128-QAM, with its 5 Mbps throughput improvement over 64-QAM, is well suited to be the next step in modulation level increase. It seems reasonable that ingress cancellation performance comparable to 128-QAM could be achieved with 256-QAM, provided similar SNR margin, specifically SNR = 34.6 dB to SNR = 36 dB.

Future work in this area could more fully develop and explore specific applications leveraging the use of higher-order modulations in upstream HFC. Development for applications such as Cellular backhaul or local public school video applications could drive further refinement of relevant requirements. In these two applications, packet size is much larger (>1000 bytes) than that typically encountered on "normal" internet and Voice over IP, VoIP, traffic situations (<384 bytes). Because the packet size is larger, modulation profiles could take advantage of byte interleaving and reap its benefits to increase FEC performance and counter higher impulse environments.

ACKNOWLEDGEMENTS

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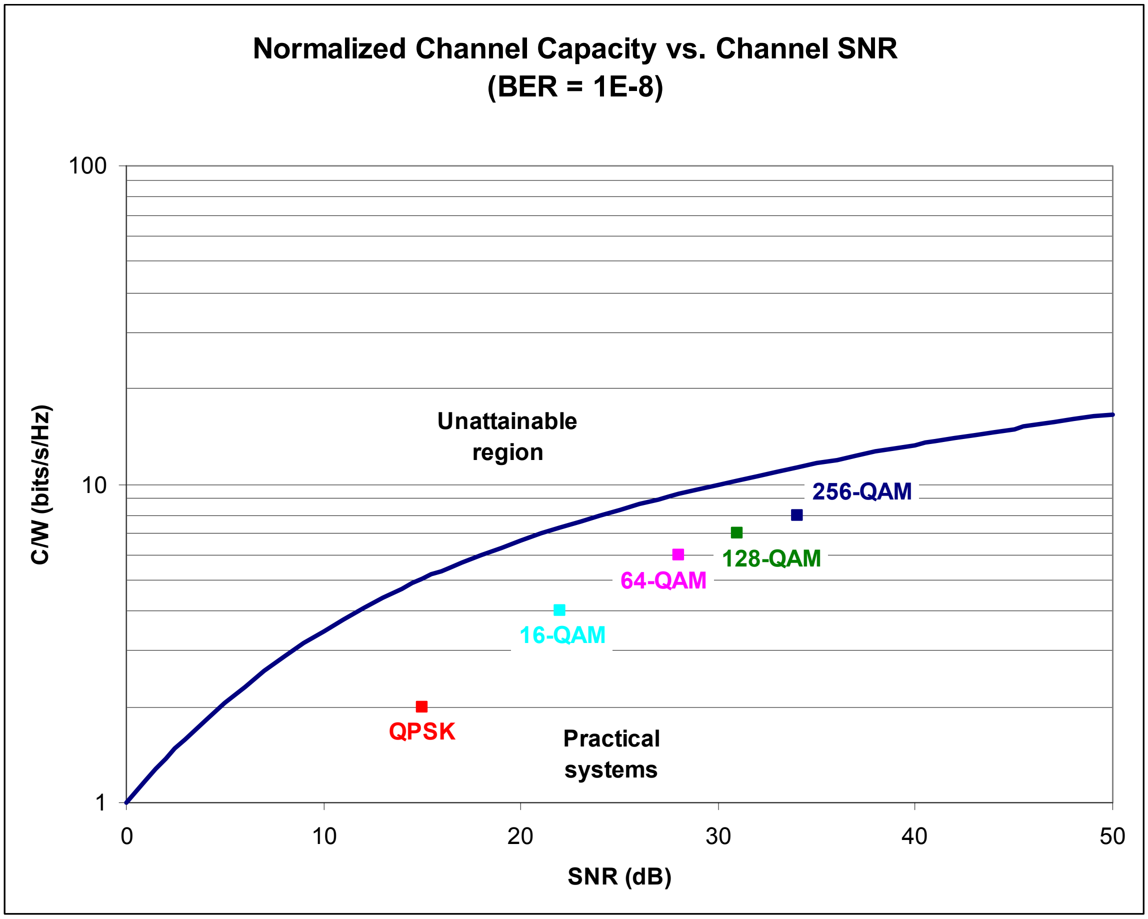

Figure 1 - Modulation Method Efficiency at BER = 1E-8

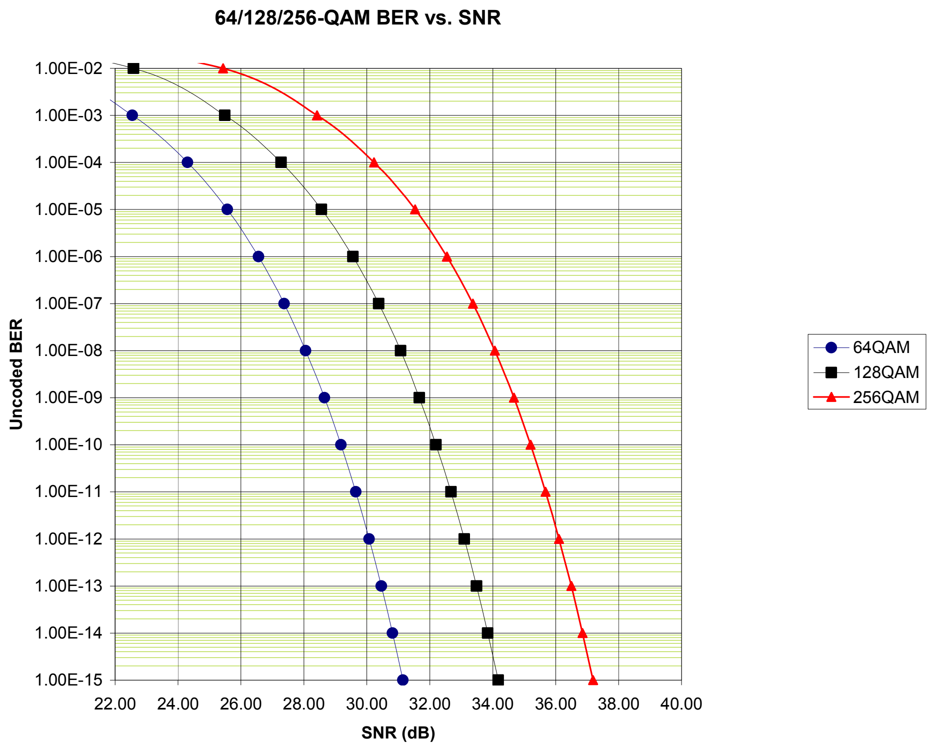

Figure 2 - Modulation Method BER

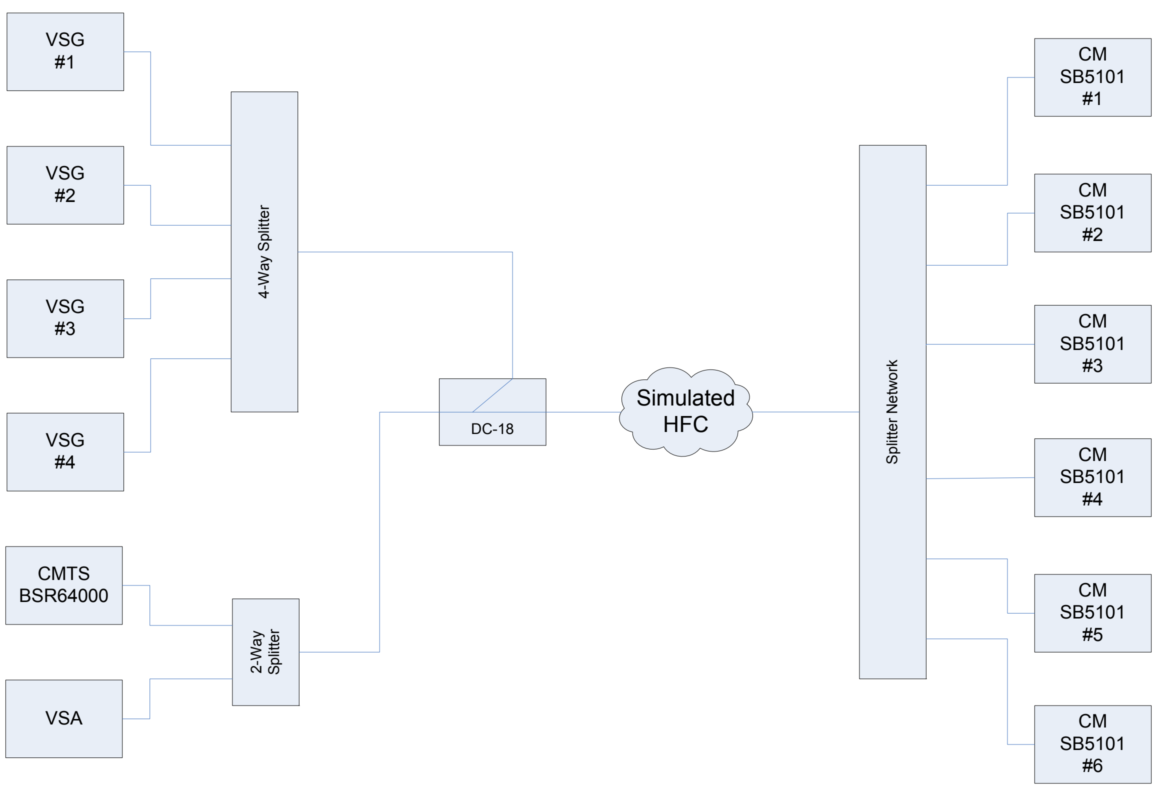

Figure 3 - 64, 128, 256-QAM Sensitivity Test Topology

Table 4 - 256-QAM Performance

	256-QAM							
	Level (dB, dBc)	UNCORR %	CORR %	MER (dB)	Level (dB, dBc)	UNCORR %	CORR %	MER (dB)
Baseline - AWGN	33	0.000%	0.174%	34.20	31.5	0.000%	0.880%	33.30
Single Ingressor Case								
QPSK 12 kHz 0.5%	23.3	0.000%	0.671%	33.60				
QPSK 12 kHz 1.0%	21.4	0.002%	0.911%	33.50				
FSK 320 kHz 0.5%	34.15	0.000%	0.533%	34.00				
FSK 320 kHz 1.0%	21.15	0.018%	1.185%	33.50				
FM 20 kHz 0.5%	27.8	0.000%	0.625%	33.80				
FM 20 kHz 1.0%	22.2	0.000%	0.911%	33.80				
Three Ingressor Case								
CPD 0.5%	37.9	0.000%	0.713%	33.60				
CPD 1.0%	36.8	0.000%	1.034%	33.30				

Table 5 - 128-QAM Performance

	128-QAM							
	Level (dB, dBc)	UNCORR %	CORR %	MER (dB)	Level (dB, dBc)	UNCORR %	CORR %	MER (dB)
Baseline - AWGN	33	0.000%	0.000%	34.20	31.5	0.000%	0.000%	33.30
Single Ingressor Case								
QPSK 12 kHz 0.5%	-1.6	0.014%	0.432%	31.20	0.5	0.004%	0.307%	31.40
QPSK 12 kHz 1.0%	-2.4	0.063%	1.495%	30.90	-0.7	0.009%	0.522%	31.30
FSK 320 kHz 0.5%	16.7	0.058%	0.543%	31.20	17.7	0.013%	0.411%	31.30
FSK 320 kHz 1.0%	15.7	0.072%	0.968%	30.80	15.7	0.053%	1.267%	30.30
FM 20 kHz 0.5%	-0.9	0.119%	0.305%	32.30	0.3	0.125%	0.315%	31.50
FM 20 kHz 1.0%	-2.3	0.331%	0.436%	32.20	-1.0	0.280%	0.449%	31.30
Three Ingressor Case								
CPD 0.5%	24.5	0.172%	0.273%	31.00	26.3	0.071%	0.452%	30.70
CPD 1.0%	22.5	0.575%	0.476%	30.40	25.4	0.214%	0.606%	30.40

Table 6 - 64-QAM Performance

	64-QAM							
	Level (dB, dBc)	UNCORR %	CORR %	MER (dB)	Level (dB, dBc)	UNCORR %	CORR %	MER (dB)
Baseline - AWGN	33	0.000%	0.000%	34.20	31.5	0.000%	0.000%	33.30
Single Ingressor Case								
QPSK 12 kHz 0.5%	-6.4	0.104%	0.312%	28.70	-5.7	0.124%	0.502%	28.40
QPSK 12 kHz 1.0%	-7.5	0.279%	1.090%	27.60	-7.5	0.528%	1.581%	27.60
FSK 320 kHz 0.5%	-3.8	0.029%	0.244%	27.60	-3.8	0.065%	0.347%	27.60
FSK 320 kHz 1.0%	-4.8	0.311%	1.025%	27.00	-4.8	0.329%	1.433%	26.90
FM 20 kHz 0.5%	-4.7	0.229%	0.117%	30.40	-5.5	0.254%	0.152%	28.80
FM 20 kHz 1.0%	-6.3	0.642%	0.246%	30.20	-6.2	0.218%	0.125%	30.20
Three Ingressor Case								
CPD 0.5%	14.6	0.251%	0.341%	27.60	15.6	0.248%	0.340%	27.60
CPD 1.0%	14.1	0.650%	0.784%	27.10	14.6	0.557%	0.719%	27.20