What's Next for DOCSIS®: Modulation Options and Impacts, Part 1 of 2

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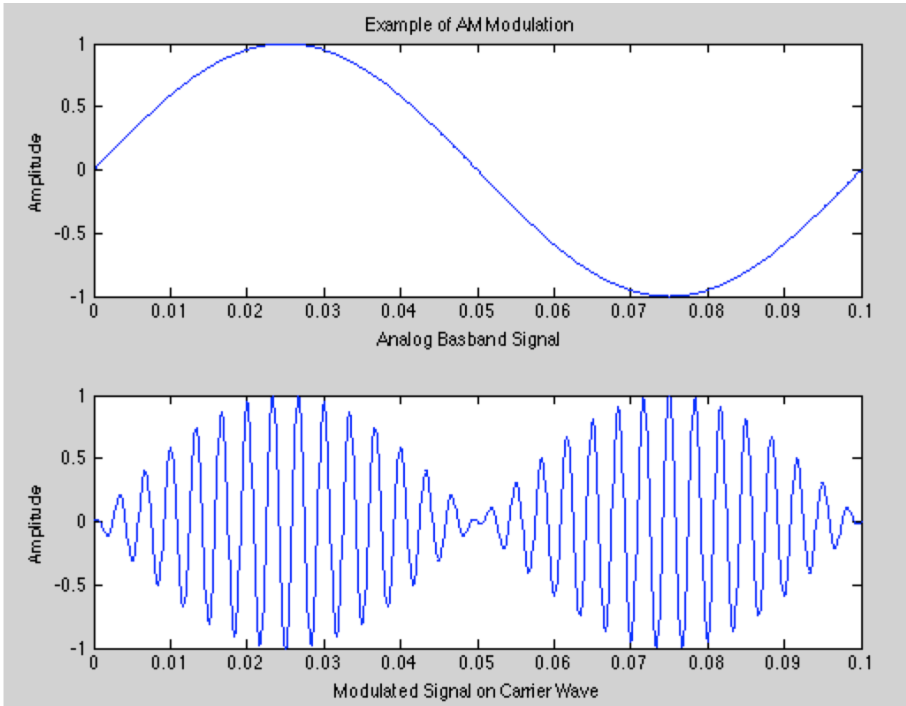
What's Next for DOCSIS®

It has been seven years since the initial release of the Data Over Cable Service Interface Specification (DOCSIS®) 3.0 specification and the pace of subscriber demand for and consumption of high-speed data (HSD) remains unchecked. With the help of tools like DOCSIS® 3.0, the cable industry's hybrid fiber coaxial (HFC) network has scaled in HSD delivery capacity to meet this ever growing demand for HSD service. However, in addition to seemingly insatiable subscriber HSD demand, competition from telephone service providers (telcos) employing fiber to the home (FTTH) offers higher down- and upstream HSD rates than DOCSIS® 3.0 HFC networks can supply. One option available to extend the performance of DOCSIS® enabled HFC networks is to pack more bits per available bandwidth through the use of new modulation and error correction methods.

What is Modulation Anyway?

Modulation is the process of transmitting data, such as digital data or an analog signal. This is done particularly in the cable television (CATV) industry such that the baseband data can be converted to RF frequencies and transmitted on the hybrid-fiber coaxial (HFC) plant. Key characteristics of a signal usually modulated are its phase, frequency and amplitude. A device that performs modulation is known as a modulator and a device that performs demodulation is known as a demodulator. A device that can do both operations is a modem (a contraction of the two terms).

Amplitude Modulation



Amplitude Modulation (AM)

Amplitude modulation (AM) is a form of modulation in which the amplitude of a carrier wave is varied by modulating it with baseband signal (see figure above). AM is commonly used at radio frequencies (RF) and was the first method used to broadcast commercial radio. The term "AM" is sometimes used generically to refer to the AM broadcast (medium wave) band. The output of this process is a signal with the same frequency as the carrier but with peaks and troughs that vary in proportion to the strength of the modulating signal. AM signals are usually amplified and then applied to the input of large antennas for wireless broadcasts.

Frequency Modulation

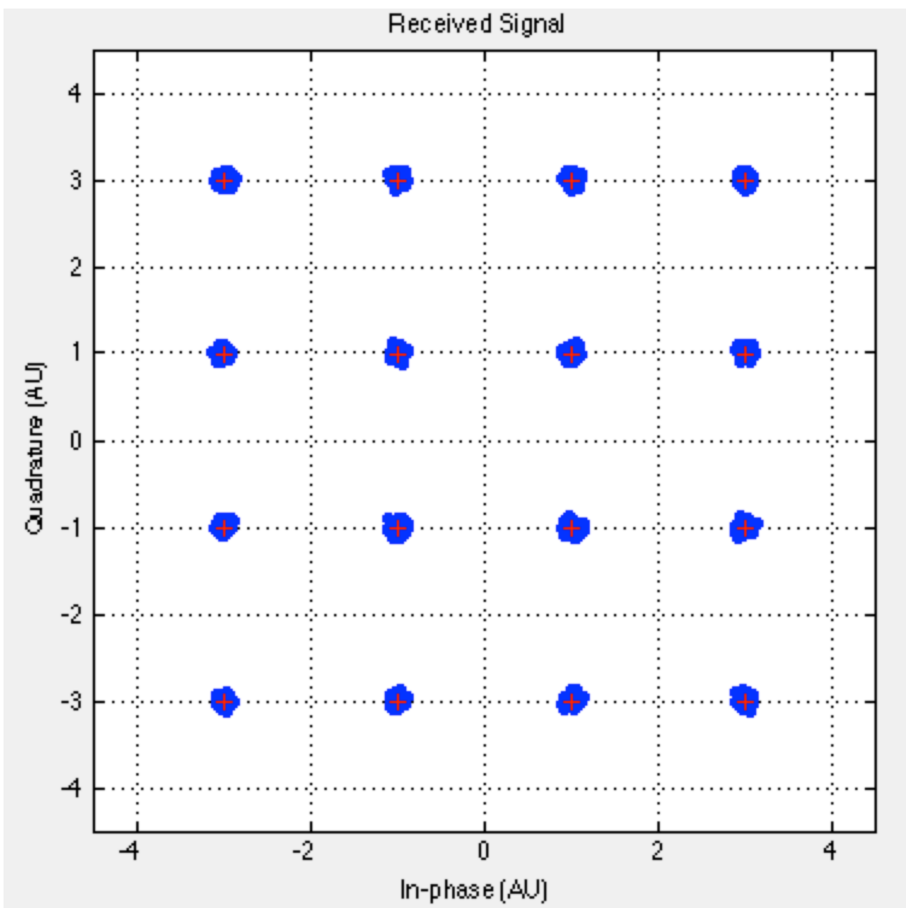
Frequency modulation (FM) is a form of modulation, which represents analog or digital data as variations in the frequency of a carrier wave. In analog applications, the carrier frequency increases as the amplitude of the baseband signal increases; similarly the frequency decreases as the amplitude of the baseband signal decreases. Shifting the carrier frequency between a set of high and low frequency values can represent digital data. FM is commonly used at VHF RF broadcasts of music and speech, which is well known as FM stereo. Analog TV sound also uses FM for transmission of the audio in CATV and over-the-air broadcasts.

Phase Modulation

Phase modulation (PM) is a form of modulation which represents information as changes in the phase of a carrier wave. The changes of phase represent increasing or decreasing amplitudes of the baseband signal. Similarly, fixed blocks of phase shifts representing ones' and zeros' can represent digital data. By itself, PM is not very widely used. This is because it tends to require more complex receiving hardware and/or software algorithms and there can be problems with determining whether, for example, the signal has 0° phase or 180° phase.

Complex Modulation

Typically low order modulation, such as AM, FM and PM just discussed, are not effective for carrying lots of data. However when more than one type of modulation are combined together more data can be transmitted over the same frequency. More data in the same bandwidth is the objective of many communication systems and DOCSIS® is no exception. Therefore, when AM and PM modulation are combined along with some additional math, Quadrature Amplitude Modulation (QAM) is achieved. This is the fundamental building block of digital video and data communications in modern CATV networks. For display purposes, industry test equipment takes the analog QAM signal, samples it at discrete times and displays a QAM constellation diagram as shown below:



16-QAM Constellation Diagram

Many in the CATV industry are familiar with constellation diagrams and understand how to analyze them for impairments in the QAM signal. The analog signals themselves do not differ greatly from AM, FM or PM modulation other than the fact that they are a little more complex. The tools that are used in the industry to present the content of the data contained in QAM modulation sometimes allow us to forget that QAM signals are analog signals.

What is DOCSIS® 3.1 and Why Do We Need It?

DOCSIS® 3.1 is the fourth generation DOCSIS® (Data Over Cable Service Interface Specifications) standard currently under development by CableLabs®. The standard has a number of objectives, the most significant of which is to enable downstream bandwidth capabilities of 10 Gigabit per second speeds and upstream speeds of one Gigabit per second. Some may question why these speeds required. To answer this question the history of DOCSIS® speed growth is examined.

Legacy DOCSIS® Speed Comparison

The DOCSIS® standards began with DOCSIS® 1.0 and then DOCSIS® 1.1, which are often referred to as DOCSIS® 1.x since only minor changes were made between the two standards. DOCSIS® 2.0 followed 1.x, which had significant speed improvements, not mentioning impairment deterrent features, in addition to numerous other features that made DOCSIS® competitive against telecom operators such as Verizon and AT&T. DOCSIS® 3.0 arrived, providing four to eight or more times the speed of DOCSIS® 2.0. At the time this provided industry-shattering speeds thought to last for a decade or more. Follows is a chart comparing the speeds between DOCSIS® 1.x, 2.0 and 3.0.

DOCSIS Version	Max Downstream Throughput (net)	Max Upstream Throughput (net)
1.x	42.88 (38) Mbit/s	10.24 (9) Mbit/s
2.0	42.88 (38) Mbit/s	30.72 (27) Mbit/s
3.0	n x 42.88 (38) Mbit/s 8 x 38 = 304 Mbit/s	n x 30.72 (27) Mbit/s 4 x 27 = 108 Mbit/sec

DOCSIS® Version Throughput Comparison

From the figure it is evident that the downstream net throughput speed increased nearly 10x, from 38 Mbps to over 300 Mbps. Similarly, the same 10x increase occurred in the upstream from 9 Mbps to over 100 Mbps. The increase occurred between the years 1997 to 2006, roughly 10 years, which is the time between the release of the DOCSIS® 1.0 standard and the DOCSIS® 3.0 standard.

By simply applying this logic to standards moving forward, one could assume that in 10 more years a standard would be required needing 3 Gbps in the downstream and 1 Gbps in the upstream using the

10x multiplier. However history and experience provides additional information that can be used to show the 10x multiplier is not the wisest choice to follow. First, companies such as Cisco have performed extensive studies indicating that DOCSIS® traffic is growing in the downstream by 50% each year and 30% on the upstream. Further, competition is providing data services far in excess of the 10x multiplier using passive optical network (PON) technologies. Therefore the DOCSIS® working group has the objective to provide a standard to support 10 Gbps in the downstream and 1 Gbps in the upstream with room for growth.

Understanding Bits Per Hertz (Spectral Efficiency)

How will these goals be achieved? By using higher order modulations and thus packing more bits per Hertz. Bits per Hertz is a term used to describe how efficient (spectral efficiency) a given modulation is at transmitting data in a given bandwidth. It is generally expressed as bits/s/Hz, which is the proper mathematical expression, however many people will verbally refer to it as bits per Hertz, so it is important to understand both the notation and verbal expression. Calculating the spectral efficiency of any modulation and presenting it in bits/s/Hz is simple. Just divide its data rate in bps by the bandwidth it occupies. Here is an example:

DOCSIS® 2.0 has a maximum downstream net throughput of 38 Mbps in 256-QAM. We know that a DOCSIS® channel occupies 6 MHz of bandwidth. Therefore the spectral efficiency of a DOCSIS® 256-QAM channel is:

- 38 Mbps / 6 MHz = 6.33 bits/s/Hz

Comparing Spectral Efficiency

Now that a reference point has been made for 256-QAM, it can be compared to other modulation. For example, the spectral efficiency of 16-QAM in a 3.2 MHz bandwidth (common in the upstream for cable modems) is 2.5 bits/s/Hz. This shows 256-QAM is 2.5 times more efficient than 16-QAM.

One way to get more data in the downstream is to increase the number of QAM constellations. What would be the spectral efficiency of 4096-QAM? The formula is as follows:

- throughput = log2(modulation) * rate,

where modulation = 4096 and rate is the symbol rate, which will be left the same as in 256-QAM of 5.360537 MSym/sec. This rate is based on the ITU-T J.83 Annex B specification.

- throughput = log2(4096) * 5.360537 MSym/sec = 64.33 Mbps

Due to DOCSIS® overhead the net throughput will drop to about 54 Mbps. Now the spectral efficiency in a 6 MHz bandwidth can be calculated as:

- 54 Mbps / 6 MHz = 9 bits/s/Hz

By using 4096-QAM an increase of 40% in data rate can be achieved in the same bandwidth. This is a driving force behind the DOCSIS® 3.1 standard. Part 2 of 2 of this paper describes how another form of modulation, called coded orthogonal frequency division multiplex (COFDM) combines with QAM and error coding to help DOCSIS® 3.1 get to its data rate goals.