



TECHNICAL COLUMNS

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SPECTRAL EFFICIENCY

By RON HRANAC

What do you think of when you hear or see the phrase “spectral efficiency?” The answer, at least from a cable-network perspective, has to do with the amount of information that fits in a given RF channel bandwidth. In other words, just how efficiently can that piece of spectrum be used to transmit information from one point to another?

Before digging into the nuts and bolts of spectral efficiency, it’s important to realize there is a hard limit to how much data can be transmitted in a given bandwidth. The well-known Shannon-Hartley Theorem, a topic for another day, establishes what is commonly referred to as the Shannon limit.

Spectral efficiency usually is expressed in the format “bits per second per hertz,” abbreviated as bits/s/Hz. A common definition is the net data rate in bits per second (bps) divided by the bandwidth in hertz.

The aforementioned definition contains some terminology that deserves a closer look. One is net data rate – also called net bit rate – that is the usable data payload in bits per second, after subtracting the non-payload parts of the data stream used for Reed Solomon forward error correction (FEC), Trellis coding, Moving Picture Experts Group (MPEG) overhead, and DOCSIS and Internet protocol (IP) overhead. Symbol rate is the number of symbols transmitted per unit of time, typically seconds, and it’s the same as modulation rate or baud. My copy of the McGraw-Hill Dictionary of Scientific and Technical Terms, 4th Ed., defines baud as “a unit of telegraph signaling speed equal to the number of code elements (pulses and spaces) per second ...” An important point to remember is that symbol rate, or baud, may or may not equal the bit rate. Indeed, in the world of high-speed data communications, a single symbol generally represents multiple bits, so the symbol rate is less than the bit rate. More on this in a moment.

Net data rate and symbol rate are related to the raw data rate – also called raw bit rate – that includes the usable payload and all overhead.

Consider a quadrature amplitude modulation (QAM) signal carrying high-speed data. QAM is a form of modulation in which the phase and amplitude of the signal vary to represent the data being transmitted. In the case of, say, a DOCSIS upstream 16-QAM signal, each of 16 states, or combinations of amplitude and phase, represents a symbol. Each symbol represents a combination of four bits. For example, if the instantaneous phase of the RF signal is 45 degrees and its instantaneous amplitude is 1, that particular state of the signal represents a symbol comprising the bits 1111. If the instantaneous phase is 18.43 degrees and instantaneous amplitude is 0.75, the state of the signal represents a symbol comprising the bits 1110. (Quick side note: “Amplitude” as used here refers to the normalized magnitude in a square data constellation. Magnitude is equivalent to the length of a vector from the center, or origin of the constellation, to the symbol point in question. The constellation’s four outer-corner symbol points are assigned a normalized magnitude of 1. All other symbol points have a normalized magnitude less than 1.)

All versions of DOCSIS use some variation of QAM as the modulation type for transmission of the data payload, ranging from quadrature phase shift keying (QPSK, also called 4-QAM) to 256-QAM. The number of bits per symbol varies with order of modulation. The following is a summary of the number of bits per symbol for common DOCSIS orders of modulation:



Assuming the channel characteristics are suitable to support the desired modulation, then a higher-order modulation generally will support a higher raw data rate than a lower-order modulation, given the same channel bandwidth.

Let's look at an example, using downstream 256-QAM: The symbol rate of a DOCSIS downstream 256-QAM signal is 5,360,537 symbols per second (sym/s), or about 5.361 megasymbols per second (Msym/s). The channel bandwidth is 6 megahertz, and the QAM signal's -3 dB bandwidth is equal to the symbol rate (for more on this, see "Digital Transmission: Carrier-to-Noise, Signal-to-Noise, and Modulation Error Ratio," by Broadcom's Bruce Currivan and yours truly, available here).

Because there are eight bits per symbol with 256-QAM, the raw data rate is $5,360,537 \text{ sym/s} * 8 \text{ bits/sym} = 42,884,296 \text{ bps}$, or about 42.88 Mbps. Squeezing 42.88 Mbps into a 6 megahertz-wide channel seems to be a pretty efficient use of the spectrum. But some percentage of the total data being transmitted is used for overhead, leaving a smaller net data rate for the actual usable payload. The net data rate in a downstream DOCSIS 256-QAM signal is about 38 Mbps, give or take.

The approximate spectral efficiency of the example downstream 256-QAM signal is $38,000,000 \text{ bps} \div 6,000,000 \text{ Hz} = 6.33 \text{ bits/s/Hz}$.

How can one achieve higher spectral efficiency? If overhead could be reduced, the efficiency would go up somewhat. But an important part of overhead is the previously mentioned FEC, which provides data transmission robustness. The other pieces and parts of transmitted overhead are important, too. For the sake of this discussion, let's assume that reducing overhead is off limits. Another way to improve spectral efficiency is to use a higher order modulation. If the channel characteristics can support, say, 1024-QAM (10 bits per symbol), and assuming the same symbol rate as before, the raw data rate is $5,360,537 \text{ sym/s} * 10 \text{ bits/symbol} = 53,605,370 \text{ bps}$, or about 53.61 Mbps. Subtracting overhead yields a net data rate of somewhere around 47.5 Mbps. In this example the approximate spectral efficiency is $47,500,000 \text{ bps} \div 6,000,000 \text{ Hz} = 7.92 \text{ bits/s/Hz}$.

Determining DOCSIS upstream spectral efficiency can be a little tricky, largely because of the wide range of configurations possible with FEC and other overhead. Once overhead is known, the spectral efficiency in bits/s/Hz is calculated the same way as in the downstream: channel bandwidth in hertz divided by the net data rate in bps.

One cannot simply switch to a higher order modulation in an attempt to improve spectral efficiency. As mentioned before, the channel characteristics must be able to support the desired modulation. An example: Assume the only channel impairment is additive white Gaussian noise (AWGN, or thermal noise), the starting modulation is 64-QAM at a certain carrier-to-noise ratio (CNR) and bit error ratio (BER), and there is no FEC. In order to maintain the same BER with 256-QAM, the CNR must be 6 dB better than it was for 64-QAM.

Jumping to 1024-QAM requires another 6 dB CNR improvement if the same BER that existed with 64-QAM is desired. In the real world, there are channel impairments in addition to AWGN: ingress; impulse noise; such nonlinear distortions as composite triple beat and composite second order; such linear distortions as micro-reflections, amplitude ripple and group delay; and so forth. FEC can buy some wiggle room, as can such tools as adaptive equalization. Even so, a clean plant is required to support higher orders of modulation and the accompanying improvement in spectral efficiency.

Spectral efficiency provides a useful tool with which to sort out the amount of data that can be carried in our networks, and it puts the comparison on a level playing field. For instance, whether the pipe is a single 6-megahertz-wide channel carrying 256-QAM or four bonded 256-QAM channels occupying 24 megahertz of bandwidth, the spectral efficiency is the same: approximately 6.33 bits/s/Hz.

Should the cable industry someday adopt new physical layer data transmission technology, the spectral efficiency of that technology can be easily compared to today's single-carrier QAM (SC-QAM) using the methods just described.

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