COMTECH EF DATA

Improved Capacity For Delivery Of Digital Video Via Satellite

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IMPROVED CAPACITY FOR DELIVERY OF DIGITAL VIDEO VIA SATELLITE

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ABSTRACT

Affiliate broadcast networks and cable headend systems have unique characteristics that encourage the use of high order modulation and coding for satellite delivery of digital video programming. When these techniques are deployed, there is a dramatic increase in the data rate transferred over the satellite link, and this translates into increased revenue through the delivery of additional program material and other services. These impressive gains in capacity are achieved by employing higher order modulation schemes like 8PSK and 16QAM with error correction to boost performance.

INTRODUCTION

Historically, video transmission via satellite transformed television broadcast forever. Another wave of change is permanently altering satellite delivery of video as the industry embraces digital techniques, and the success of digital video broadcasting (DVB) testifies to this. One area where digital techniques offer significant new opportunities is the distribution of video program material to terrestrial broadcast stations and to cable headends.

Two applications are pushing data rates higher in North America. First, there is an accelerating thrust to deploy high definition television (HDTV) with 19.39 Mbit/s anchoring the over-the-air HDTV data rate, and rates in excess of 30 Mbit/s planned for even higher quality contribution links. Second, existing analog television programming is delivered to network affiliates as pristine 4:2:2 video, and the equivalent data rate for delivery of this ranges from 18 to 45 Mbit/s.

Cable headends generally receive MPEG2 4:2:0 quality video at rates between 2 to 6 Mbit/s, but the dilemma is the same. QPSK limits the amount of programming ultimately delivered. However, high order modulation and coding can help.

CAPACITY

For the satellite delivery system there are two prominent measures of performance. At the video encoder, the data rate per stream is key because it relates the amount of bandwidth required for program material. Over the satellite link, the data rate per transponder, measured in Mbit/s, is the bottom-line measure of performance because it determines the number of streams delivered. The interaction of these two is illustrated in Figure 1, which shows the number of channels delivered over the satellite link versus the capacity through a satellite transponder.

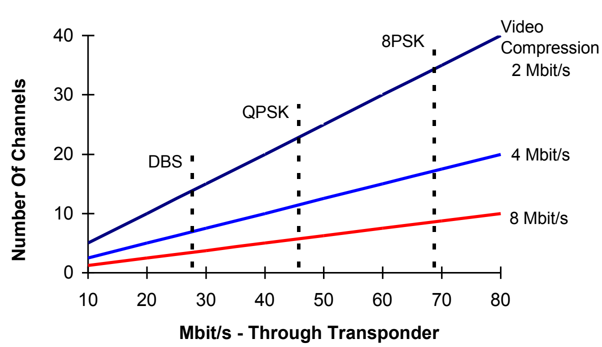

Figure 1. Number of Channels versus Transponder Capacity

UNIQUE CIRCUMSTANCES

One of the basic differences that broadcast affiliates and cable headends have compared to direct broadcast systems is the size of the antenna. This ranges from 4.5 to 7.3 meters, compared to 0.5 meter for a home unit. Even after taking into account the differences between C-Band and Ku-Band operation, the relative performance measure of the receive earth station, its gain-to-temperature ratio (G/T), is quite different. The G/T for a typical consumer receiver is 12.5 dB/K, while that of a broadcast or headend receive terminal is 25 dB. This leads to a number of opportunities.

MAIN TRANSMISSION COMPONENTS

Both the compression and satellite transmission are crucial to the complete delivery system. However, the primary area of concentration for the remaining discussion focuses on transmission and improving capacity over the satellite link.

The most common type of distribution system for these applications is a hub type network. Here, a network center originates a single carrier per transponder that is received by many receive sites for redistribution over terrestrial or cable plants. The main elements of the transmission system are listed below and shown in Figure 2.

- Modulator / Demodulator
- Modulation And Coding
- Up Converter, HPA, Antenna
- Satellite Transponder
- Receive Station (G/T)

At the starting point, a digital stream from a video encoder or a transport multiplexer is delivered to a video modulator. Error correction and a modulation scheme transform the signal to an intermediate frequency carrier.

An up converter and high powered amplifier (HPA) convert the signal to C- or Ku-Band for satellite transmission and boost its power. An antenna transmits the signal to a satellite, which rebroadcasts the signal over a much wider geographical area than is possible from a ground based transmitter.

The signal from the satellite is received by an antenna and low noise block converter (LNB) that convert the satellite signal to a lower frequency for delivery to a demodulator. The demodulator locks to the incoming signal and delivers it to a video decoder. The main goal of this entire process is to maximize capacity for the available power and bandwidth.

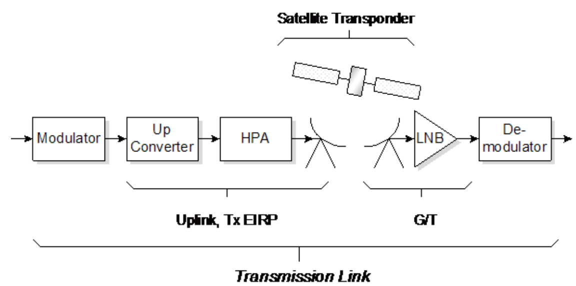

Figure 2. Transmission Model

Modulator / Demodulator

The digital modulator and demodulator (collectively, the modem) establish key link parameters relating to power and bandwidth. The modulator transforms the signal using two techniques that are crucial to capacity: modulation and forward error correction (FEC). Together, these two items shape the power and bandwidth usage of the entire system and are critical to the overall system design.

The bandwidth of the transmitted digital carrier is established by the modulator. Its 3 dB bandwidth is readily calculated and is given by:

$$BW_{3dB} = SR = \frac{DR}{m \times CRv \times CRrs}, \quad (1)$$

where:

BW_{3dB}	=	3 dB Bandwidth
SR	=	Symbol Rate (sym/s)
DR	=	Data Rate (bit/s)
m	=	Modulation factor (order of modulation)
	=	2 QPSK, 3 8PSK, 4 16QAM
CRv	=	Viterbi code rate (i.e., 5/6)
CRrs	=	Reed Solomon code rate (i.e., 188/204)

Notice that the symbol rate (SR) is the same as the 3dB bandwidth for this class of signals. The modulation factor, m, is an integer. For this type of digital modulation scheme, the modulator groups together m bits to form a symbol for transmission, producing up to 2^m possible symbols. Since m is an exponent, it is referred to as the order of the system. Hence, higher values of m are associated with higher orders of modulation.

The states are mapped into a signal space or constellation as indicated in Figure 3. This shows the mapping for three constellations in common use, but other variations are possible. The figure illustrates the signal mapping for m = 2 (QPSK), 3 (8PSK), and 4 (16QAM).

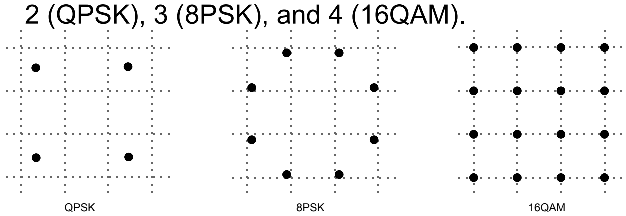

Figure 3. Signal Constellations

It may appear to be necessary only to increase the order of modulation until the desired capacity is obtained; that is, until the required data rate fits into the available bandwidth. However, there is a drawback to this approach. As the order of modulation is increased, a higher-power carrier is needed from the transmitter to maintain the same level of signal quality at the receiver. This means that improved bandwidth efficiency is obtained at the expense of requiring additional power.

One way of counteracting the increased demand for power as bandwidth decreases (larger m) is to add coding or forward error correction. Coding adds information to the transmitted signal that permits the receiver to correct errors, and this improves the quality of the signal. A major benefit of improved signal quality is a reduction in the transmitted carrier level! This explains why coding is universally used on satellite links.

The beneficial effect of error correction also comes at a cost, because the information added during the coding process increases the bandwidth of the transmitted signal. The amount of coding is designated by the code rate (CR), which is a dimensionless ratio less than unity, indicating how many signal bits enter the coder compared to how many "coded" bits exit the coder. For example, if CR = 5/6, then five bits enter and six bits exit the coder. When concatenated coding is used, there are two code rates, CRv (Viterbi or trellis) and CRrs (Reed Solomon) used in tandem and the combined code rate is (CRv x CRrs).

The measure of power required to produce a level of quality in a modem is the energy per bit in 1 Hz noise bandwidth (referred to as Eb/No). Coding has a direct effect on this. Eb/No is a signal-to-noise ratio measure that permits the comparison of various modulation and coding schemes. Usually, digital systems are rated by noting the required Eb/No to produce a specified bit error rate (BER).

A more vivid illustration of the impact of modulation and coding upon bandwidth and power is presented in Figure 4.

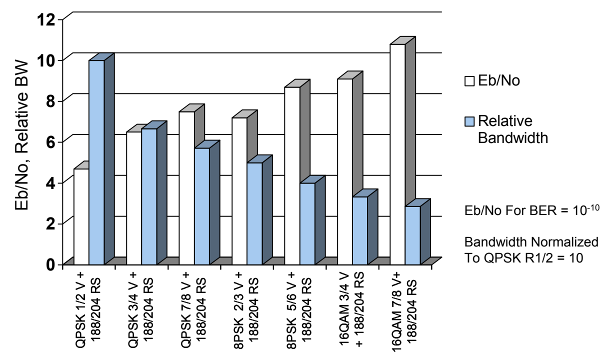

Figure 4. Power (Eb/N0) And Bandwidth Versus Modulation And Coding

The baseline of the plot lists different modulation and coding schemes progressing from lower order QPSK on the left through higher order 8PSK and 16QAM toward the right. A number of code rates are also shown with each modulation to show their effect. The left bar above each modulation and coding type corresponds to the Eb/No required to produce a BER of 10^{-10}, while the bar on the right corresponds to normalized bandwidth. The general trend reveals that a larger Eb/No is required as the order of modulation increases from left to right. Bandwidth has an inverse function and decreases from left to right.

Up Converter HPA, Tx Antenna

The up converter, HPA, and transmit antenna serve to translate the output of the modulator to the operating frequency band and boost the power to a level required to drive the satellite transponder. The chief concerns are to maintain linearity, low phase noise, minimal amplitude variation, and negligible group delay over the operating band, so the uplink does not impair the transmitted carrier before it leaves the earth station.

Satellite Transponder

The most critical resource in the transmission chain is the satellite transponder. The two main resources it offers are power and bandwidth, both in limited supply. Under ideal conditions, all other elements in the satellite link are tuned to make optimum use of the available power and bandwidth from the satellite transponder while also dealing with any imperfections in the system. Of course, optimum use depends largely upon the application and the goals of the delivery system.

A model of a satellite transponder is shown in Figure 5. The role of the transponder is to return the carrier to earth at a new frequency and provide geographic coverage over a selected segment of the earth. The received signal is channelized (filtered), translated to a selected operating band, and amplified before the signal is rebroadcast back to earth.

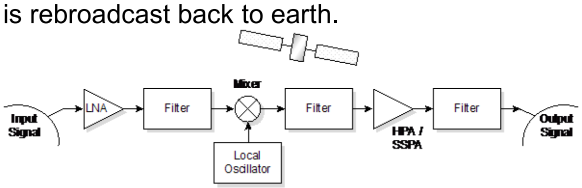

Figure 5. Satellite Transponder Model

The satellite transponder must contend with earth noise, signals intended for adjacent satellites, leakage from cross-polarized radiation and other outside forces. However, one of the most difficult impairments often originates from within the satellite. This is the non-linearity of the power amplifier that drives the desired carrier back toward the ground.

For lower order modulation types like QPSK, the impact of the non-linear operation is minimal; but as the order increases, so does the demand for greater linearity. Many of the newer C-Band satellites carry solid state power amplifiers (SSPAs) that are very linear. However, older C-Band satellites and many of the Ku-Band amplifiers are traveling wave tube (TWT) types whose non-linearity can severely impair operation with higher order carriers.

Figure 6 plots the output power and phase versus input power of a tube type amplifier and shows the characteristic of a TWT plotted next to a linear reference line. The usual remedy to improve linearity is to operate the amplifier backed off from the maximum attainable power output. An obvious drawback of backoff is that it reduces the available power and therefore restricts capacity. To alleviate the difficulty, linearizers are added to the newer transponders to correct the non-linearity and permit operation at a higher power level.

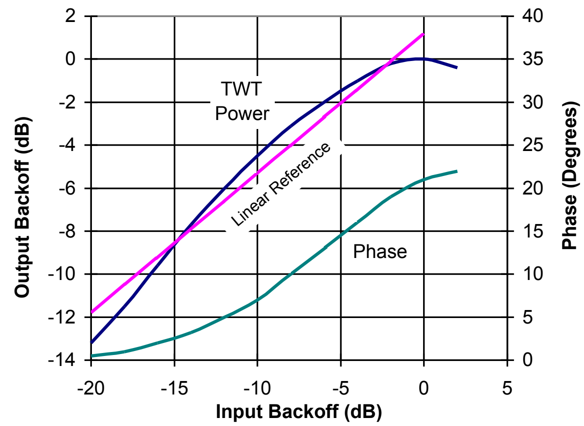

Figure 6. TWT Amplitude And Phase

The drawback of non-linear operation is that it imparts distortion to the digital modulated carrier. This warps the trajectories of the time waveform in the demodulator and reduces the effective Eb/No and increases BER of the recovered data. Figure 7 shows 16QAM signal subjected to severe satellite non-linearity.

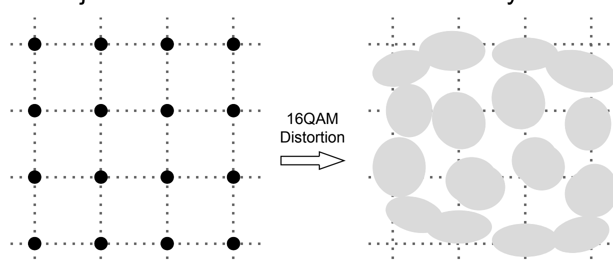

Figure 7. Signal Distortion

The signal constellation on the left side of the figure is the desired waveform, while the one on the right passed through a non-linear satellite transponder. The impairment to 8PSK and QPSK is progressively less because these constellations exhibit reduced sensitivity to this type of distortion, and the constellation points have larger separation.

Notice that the crisp circular dots of the 16QAM constellation degenerated into ellipsoids. They have also moved non-uniformly from the desired positions, with some points moving closer together and others touching, while others have moved apart. The effect of the distorted waveform trajectories is easily observed in the constellation plot. Another influence visible on the constellation is the appearance of AM/PM conversion. Visualize the constellation as 4 interior dots surrounded by 12 dots, and notice that the interior group of 4 dots is rotated with respect to their 12 outside neighbors.

An onerous by-product of this type of impairment is that the satellite link becomes carrier-to-distortion (C/D) limited. When this happens, the C/D dominates the link performance, rather than the carrier-to-noise (C/N), as is desired. At this point, increasing the size of the receive antenna produces no improvement in the equivalent Eb/No of the link. Similarly, raising satellite output power also degrades the performance because it increases distortion..

Satellite Transponder Bandwidth

Previously, the bandwidth of the signal from the modulator was described. The transponder is also a frequency device, and it is necessary to contain the modulated carriers within the bounds imposed by the transponder. There are two scenarios to address for transmission: single- and multiple-carrier operation, as shown in Figure 8. Since the concern is with high data rate carriers, only the one- and two-carrier cases are shown. However, generalizing to more carriers is straightforward.

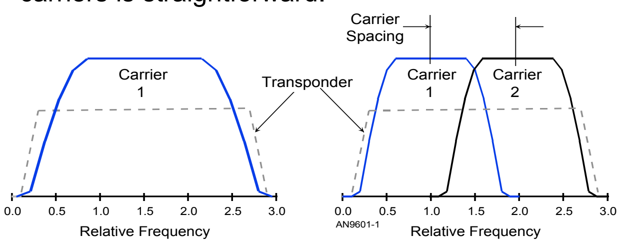

Figure 8. Multiple- and Single-Carrier Operation

The figure shows carriers positioned within the transponder. In all instances the carriers are completely contained within the transponder. There is also some space needed between the edge of the carrier and the edge of the transponder, where the amplitude variation and group delay increase.

Because of these effects, two general rules for usable transponder bandwidth and carrier spacing are given below:

Carrier Spacing $\approx$ 1.3 x SR, (2)

Useable Bandwidth $\approx$ BWxpndr / 1.2, (3)

where:

SR = Symbol Rate

BWxpndr = 1dB Bandwidth of Transponder

Receive Earth Station

The gain-to-temperature ratio (G/T) is the figure of merit for the receive terminal. The main elements determining G/T are the gain of the receive antenna and combined noise temperature of the antenna and low noise block converter (LNB). The G/T of the terminal has a direct effect on capacity. The gain of the receive antenna is proportional to the square of the antenna diameter as well as the square of the operating frequency. The antenna noise temperature is relatively constant with diameter, but increases as the elevation angle decreases. LNB noise temperature is a function of available low noise transistors.

LINK BUDGET

A useful tool for estimating capacity is the link budget. A complete estimate combines an uplink budget, downlink budget, and several additional factors, and examines both the power and bandwidth of the link.

A typical link budget is shown in Figure 9 to size the capacity of a system. The intent is to demonstrate the basic concept of a link budget and not include all the details for a complete analysis. The starting point is the transmitted effective isotropic radiated power (EIRP), from which the path loss and fade between the earth station and the satellite are subtracted. The G/T is added to this, and Boltzman's constant is subtracted to find the carrier-to-noise in a 1 Hz bandwidth (C/No).

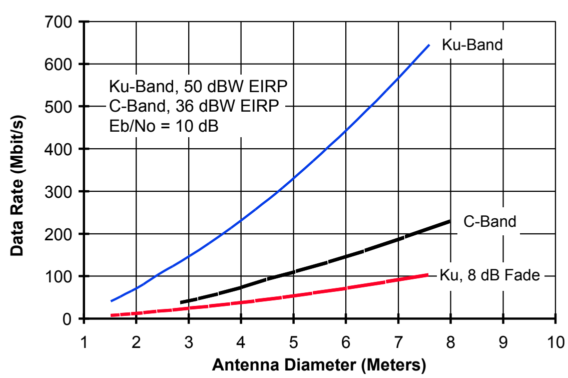

Figure 10. Maximum Capacity

Link Budget

Uplink	Downlink	Other	Item	Units
71.8	33.2		+EIRP	dBW
-200.0	-196.3		-Path_loss	dB
-0.2	-0.2		-Fade	dB
0.1	25.0		+G/T	dB/K
228.6	228.6		-k	dBW/K-Hz
100.3	90.3	98.7	C/No	dBW-Hz
	89.3		Total C/No	dBW-Hz
	-9.3		-Eb/No_req	dB
	-1.2		-Margin	dB
	78.8		Data_Rate_dB	dB
	75.8		Data_Rate	Mbit/s

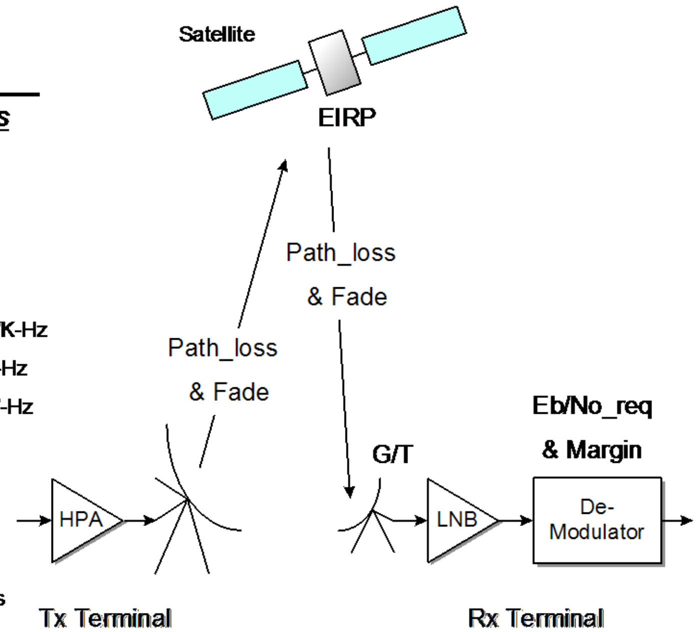

Figure 9. Typical Link Budget

There is another term shown as "other" that is an estimate of adjacent carrier leakage, cross-polarization leakage and any added items that affect the link. The C/No for the uplink, downlink and other are combined to determine the Total C/No for the system. From this is subtracted the required Eb/No and margin to give the estimated data rate in dB. The data rate in Mbit/s is found by taking the anti-log of this to find the estimated capacity.

The link budget reveals the importance of a number of factors. Items including the satellite EIRP, G/T, and Eb/No have a direct effect on that influence capacity. If the satellite EIRP and Eb/No are fixed, and G/T is varied, it is possible to gauge capacity in Mbit/s. Since the antenna gain is proportional to the square of its diameter, a logical next step is to estimate capacity based upon antenna diameter. This is just the case shown in Figure 10, which plots capacity in Mbit/s versus antenna diameter.

Caution is recommended when using this plot, because it is made for a particular set of assumptions and does not apply to all situations. The figure also represents a maximum throughput estimate, because it does not account for bandwidth or other factors that may limit capacity. For example, if QPSK is used with a 36 MHz transponder then the maximum capacity is 45 Mbit/s, due to bandwidth limitations. With 8PSK, the bandwidth limit is near 70 Mbit/s, which is very close to the power limit for a 4.5 meter antenna with a receive site G/T of 25 dB/K.

TESTING

Satellite tests were conducted with both 8PSK and 16QAM. Most of the tests were conducted over 36 MHz transponders in both C- and Ku-Band. The tests with 8PSK were performed with 8PSK and R5/6 coding. In this case, two 34 Mbit/s (E3) carriers were carried by a single transponder, so the composite data rate was 68 Mbit/s. The tests were conducted in conjunction with ETSI video compression codecs and included up to 5 levels of concatenation, with excellent results.

Tests were also performed with two 45 Mbit/s (T3) carriers using 16QAM and R7/8 coding. The results were mixed. In some cases, performance was very good, while in others the BER was worse than expected. In these cases, the distortion was present, and the link was C/D limited with the effects described earlier. In one case, performance was good until an FM video carrier appeared on the cross-polarized transponder. The FM carrier degraded performance below an acceptable level.

CONCLUSIONS

High order modulation plus forward error correction is useful for increasing capacity in satellite links. Systems with larger antennas, such as those found at broadcast affiliate sites or cable headends, and a G/T of 25 or larger are good candidates for 8PSK modulation. Testing has demonstrated that 8PSK is a particularly good candidate, while 16QAM requires greater linearity and careful selection of the satellite transponder. A number of other considerations were presented along with capacity estimates as a function of antenna diameter.