Performance Measures for Cable Data Transmission

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ABSTRACT

Different services require different error performance and different data rates. For example, a service such as status monitoring with polling may be able to tolerate more errors and lower transmission speeds than a time-critical application such as video telephony or "twitch" video games where re-transmission of errored frames cannot be tolerated. Each service will require different operating characteristics for satisfactory performance.

Three important indicators used to evaluate the performance of modems in a cable television network, in the presence of continuous or impulsive noise, are carrier-to-noise ratio (CNR), frame-loss-ratio (FLR), and bandwidth efficiency (BWE). These three parameters are related to each other and are bounded by the channel capacity limit of Shannon. Actual cable modem performance in different operating modes can be described parametrically using measurements in these three indicated dimensions. When the value of CNR in the transmission channel is known, the value of BWE at an arbitrarily small FLR can be deduced. The resulting operating point can be compared to minimum service requirements.

This paper describes how these useful performance indicators can be used to evaluate and to compare the performance of different cable modem transmission system modes in the presence of continuous or impulsive noise. Determination of satisfactory regions of operation under various transmission channel conditions is discussed. An example of the use of the described performance indicators for determining satisfactory service delivery is provided.

INTRODUCTION

Accessing information in an efficient and timely manner has risen to the forefront of visibility not only in high tech circles, but also in the everyday lives of people around the world. The cable modem has become one of highest profile communication appliances in the race to provide high-speed data communications. This is a result of Internet growth and the development of the interoperable CableLabs® Certified™ cable modem, the cable modem compliant with the data over cable system interface specification (DOCSIS) by the Multimedia Cable Network System consortium (MCNS), and Cable Television Laboratories, Inc. (CableLabs®). To heighten the understanding of current cable modem technology and its impact on the cable industry, CableLabs has evaluated current modem technologies available for the bi-directional transmission of data through the cable plant. This technique for characterization of modem technology using the three performance indicators, CNR, BWE, FLR has been used at CableLabs to evaluate the performance of prior proprietary modems, the current DOCSIS technology, and possible future extensions to the DOCSIS physical layer.

One of the cable industry's competitive advantages is the wide bandwidth available in the hybrid fiber coax (HFC) network. There are many trade-offs in the best utilization of the bandwidth and power resources in delivering different digital services in a reliable, cost-effective manner. To assist cable service providers in making these trade-offs, evaluations of proprietary commercially available cable modems from several different vendors have been completed. The comparisons presented here between modems, (without identifying the specific manufacturer), are based on laboratory testing performed by CableLabs and theoretical calculations for DOCSIS modems. Some typical measurement results are presented here to demonstrate a technique which can be used to select the modem technology and operating parameters which will meet the requirements of a service based on the quality (lack of transmission impairments) of the HFC network.

PERFORMANCE METRICS

Three important metrics have been used successfully and are recommended to evaluate the performance of modems in a modern HFC cable television network in the presence of continuous or impulsive noise. The metrics are listed below.

Carrier-to-Noise Ratio (CNR): This is the widely used indicator of the noise characteristics of a transmission channel. A metric descriptive of the characteristics of the channel noise can be expressed in terms of additive white Gaussian noise, or of impulsive noise bursts of specified amplitude, duration, and repetition rate. This is an indicator of the performance of the transmission network. Since the signal power is limited in the HFC network by the dynamic range of the active components, the CNR can be improved only by reallocating the power budget, changing the network structure, or improving conditions by proper maintenance. A metric descriptive of the channel noise type and severity in relation to the signal can be expressed in many forms such as:

- Carrier-to-Noise Ratio (CNR);
- Signal-to-Noise Ratio (SNR);
- Energy-per-bit-per-noise power spectral density (Eb/No), i.e., the SNR per bit;
- Carrier to interference (C/I);
- Impulse noise amplitude, duration, and repetition rate statistics.

All of these metrics are useful in their context. This paper will refer to the channel condition with a general metric of CNR because the cable industry is most familiar with this term (and it has been used historically). CNR is typically defined as the ratio of signal power-to-noise power in the channel before demodulation, while SNR is the metric that typically refers to the ratio after demodulation. Eb/No is usually the appropriate metric when comparing modems of different modulation formats, bandwidths, and symbol rates. CNR is an easily measurable metric in the laboratory and the field.

Frame Loss Ratio (FLR): FLR is the ratio of errored data frames with respect to the total number of frames transmitted, when the data frames are transmitted over an impaired channel. This indicator can be applied to a variety of data packet types, including Ethernet-type frames consisting of 64 bytes to 1518 bytes each, but it also can refer to 53-byte frames as used in asynchronous transfer mode (ATM) transmission protocols. The desired accuracy and quality of service that the network should provide for a given service dictates the value of this metric.

Bandwidth Efficiency (BWE): BWE indicates the data capacity that can be transmitted through the channel. It is expressed in terms of the amount of data transmitted per unit of time through the unit of bandwidth (bits/sec/Hz). The value of this indicator is governed by the design of the modem. It should be noted that the transmittable data only includes the useful message data; provision must be made for any overhead needed for forward error correction (FEC) and media access control (MAC) overhead. As overhead is increased, the efficiency is reduced and a lower data rate is transmitted per allocated channel bandwidth. A modem without provision for FEC overhead may have a high bandwidth efficiency, but it will fail rapidly on a noisy transmission channel. A compromise of FLR and BWE must be found case by case for an existing channel condition.

The three indicators defined above are related to each other and are bounded by the law of Shannon. The Shanon-Hartley theorem is expressed as:

$$C = BW \log_2(1+S/N)$$

Where C is the maximum capacity in bits/second for an arbitrarily small error ratio, BW is the equivalent noise bandwidth, S is the signal power, and N is the power of additive white Gaussian noise (AWGN). When the value of CNR is known, the upper limit to the value of BWE = C/BW, for effectively error-free transmission can be computed by applying that theorem.

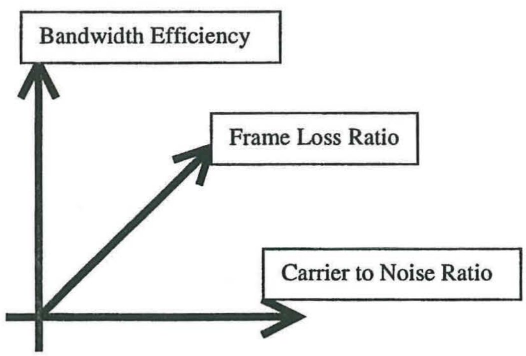

Figure 1: Three-dimensional Modem Performance Space

The values of the three indicators can be plotted on a three-dimensional graph as shown in Figure 1. In practice, cross sections of the three-dimensional graph, perpendicular to the FLR axis, are often used instead for the sake of convenience. The line that represents Shannon's limit also can be plotted on those bi-dimensional cross-section graphs. That line describes the maximum theoretical performance possible for any combination of BWE and CNR at an arbitrarily low FLR approaching zero (with appropriate forward error correction).

The most common type of comparison between modem technologies, which indicates the robustness of the physical (PHY) layer format, is the error rate vs. CNR in an additive AWGN channel. The type of error rate used here is the 64-byte Ethernet FLR. Figure 2 shows the theoretical FLR vs. CNR for a couple of different FEC modes of the DOCSIS 16-QAM-modulation format. In Figure 2, the parameter t indicates the number of bytes the FEC can correct in each codeword. Similar data has been obtained for several commercially available modems and for the other DOCSIS formats.

The transmission robustness in the upstream direction of the HFC network is often determined by the impulsive burst noise characteristics of the channel as opposed to AWGN limitations. Tests also have been performed to characterize a modem's error correction performance in a burst noise channel. A broadband CNR of 0 dB was established during the noise burst. The noise pulse width was set for one of three determined lengths, 1 μs, 10 μs, or 100 μs. The frequency (number of noise pulses per second) was increased and the error rate was recorded along with the noise pulse repetition rate (PRR). Figure 3 shows an example of the interfering signal. Figure 4 shows the result of the impulsive noise test for a 0 dB CNR noise pulse duration of 10 μs.

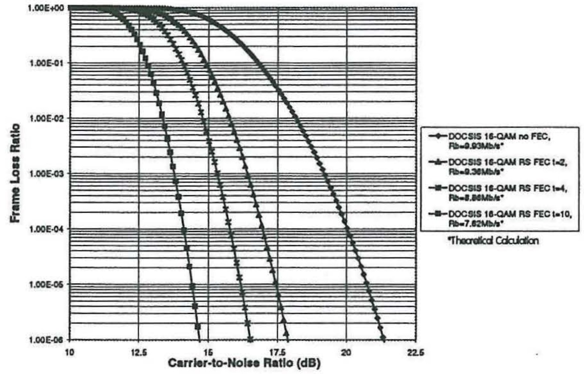

Figure 2: FLR vs. CNR for DOCSIS 16-QAM FEC Modes

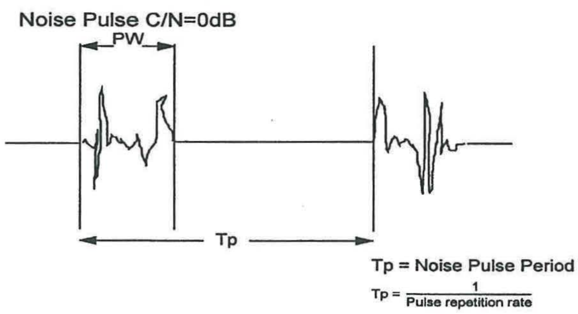

Figure 3: Interfering Burst Noise Signal

BANDWIDTH EFFICIENCY

As stated earlier, the bi-directional bandwidth resource is one of the big infrastructure advantages that cable has over its competitors. Bandwidth efficiency indicates the amount of data, which can be transmitted through a unit of bandwidth per unit of time. In other words, a high bandwidth efficiency makes the best use of the HFC network bandwidth resources. Figure 5 and Figure 6 present data demonstrating the trade-offs made between power robustness and bandwidth efficiency. The data rates used in calculating bandwidth efficiency are corrected for overhead. Graphs of this type can be used to determine what technology will need to be utilized, based on the type of service and the quality of the HFC network. These bandwidth efficiency graphs can be created from the performance data given in a format similar to Figure 2 and Figure 4.

Continuous Noise

Figure 5 is based on an error performance of 1% FLR in an AWGN channel. This type of graph can also be created for other FLR values like FLR=10%. Each point on the graph indicates the bandwidth efficiency and CNR at which the specific modem can achieve a 1% FLR. The bandwidth efficiency for vendor A and DOCSIS 16-QAM is very good, but they require the highest CNR. The CNR for the DOCSIS 16-QAM modem is less than 20 dB, which is reasonable for a return path node. The CNR required for 1% FLR for vendor D is very low, but the sacrifice in bandwidth efficiency is very significant. Increasing the coding depth and robustness typically results in the loss of bandwidth efficiency. Note that if a line is drawn through the points for no FEC, t=2, t=4, and t=10, for the DOCSIS QPSK or 16-QAM modes, it is not linear and starts to fall off quickly. For the AWGN channel half of the possible t=10 coding gain can be achieved by using only t=2. One is always able to get the most out of compromises. Looking at Figure 5, the highest bandwidth efficiency for a given CNR will provide the highest data throughput under impaired transmission conditions. Conversely, the lowest CNR for a given bandwidth efficiency yields the largest noise margin. What this graph does not show is the advantage of extensive coding during high powered burst noise.

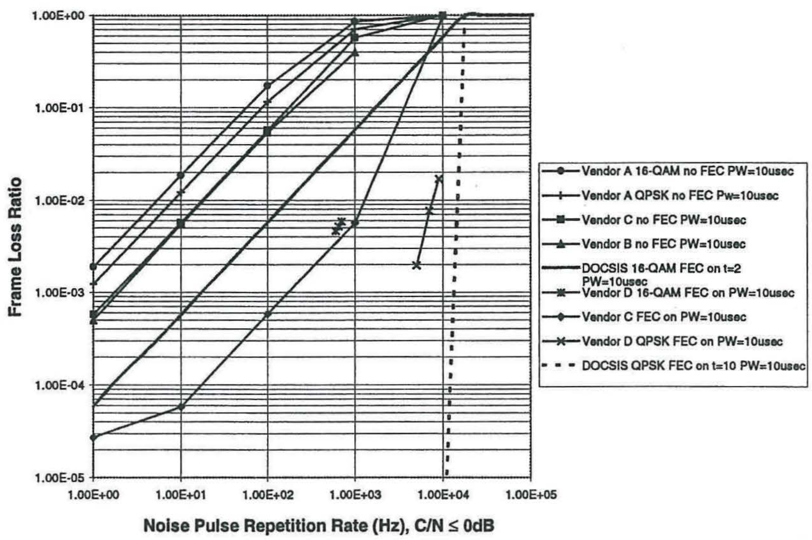

Figure 4: FLR vs. Noise Pulse Repetition Rate for PW=10 μs Burst Noise

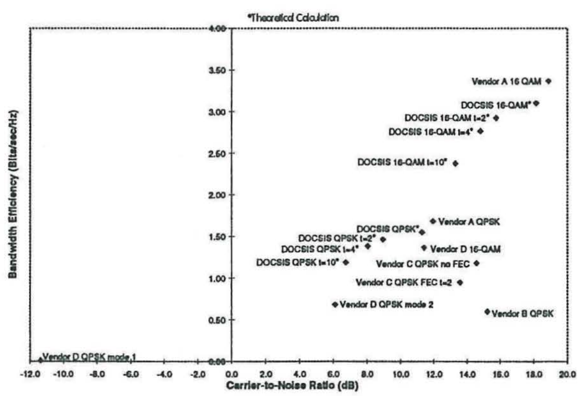

Figure 5: Bandwidth Efficiency vs. CNR for 1% FLR

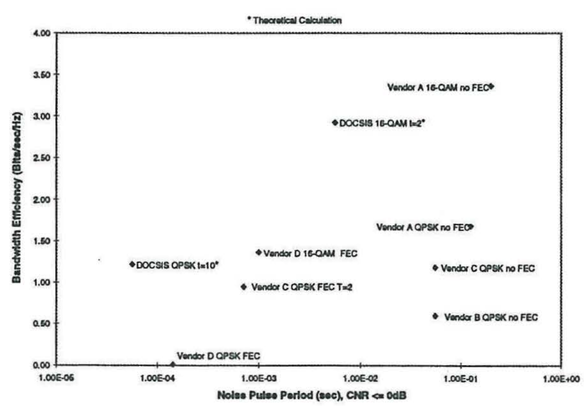

Figure 6: Bandwidth Efficiency vs. Noise Pulse Period for 1% FLR and 10 μs Noise Burst

Burst Noise

Figure 6 is based on an error performance of 1% FLR. This graph presents the bandwidth efficiency vs. the pulse repetition period for burst noise injected into the channel at a 0 dB CNR level (or high enough to cause errors during its duration). The best performance is obtained by maintaining a high bandwidth efficiency and operating at the smallest noise pulse period possible while maintaining a FLR=1%. The data is presented for a noise burst duration of 10 μs. Similar graphs can be created for 1 μs and 100 μs noise pulse widths and for other FLR values such as 10%. This data is obtained from the measurements similar to those presented in Figure 4. Figure 6 verifies the fact that a trade-off for robustness is made with bandwidth efficiency. For this scenario, the DOCSIS QPSK t=10 modem is very robust by reducing bandwidth efficiency. Operation in this mode provides burst-error correction, which gives an advantage in burst-noise mitigation. Because of their FEC, the Vendor C modem with FEC, the DOCSIS 16-QAM, and Vendor D modem in 16-QAM mode also performed well. The Vendor A 16-QAM modem has the highest bandwidth efficiency but, with no error correction, it is not as robust in a high-power burst-noise channel.

USE OF BANDWIDTH EFFICIENCY DATA

Detailed in this section is a technique of how bandwidth efficiency data can be used to choose the appropriate modem technology. Several of these modems have a set bandwidth and FEC capability. Therefore, the system designer is limited to what is available. Some of these modems have varying parameters that can be used to move to different points on the bandwidth efficiency graphs. For the modems with several modes shown on the graphs, such as DOCSIS, the system engineer could add points to create more of a continuous trace and could choose the operating point to be somewhere along the trace. All of these modems operate with a discrete set of parameters. In an operational system, FEC options, data rates, or bandwidths, can be adjusted dynamically to compensate for the changing channel and traffic conditions.

Different services have different error performance requirements and data rates. For example, a service such as status monitoring or polling may be able to tolerate more errors than some time-critical data application, such as video telephony or "twitch" video games, where re-transmission of errored frames can not be tolerated. One can use the information presented here to make decisions on optimal technologies for cable services as shown in the steps below.

Create tables or graphs similar to Figure 5 and Figure 6 corresponding to the error performance needed for the service provided.

Characterize the quality of the HFC plant from a CNR and burst noise distribution point-of-view. If the plant can only support a 16 dB CNR, then draw a vertical line on the graph at 16 dB, as shown in Figure 7.

Determine the minimum acceptable data rate for the service and the amount of bandwidth, which can be dedicated to that particular service. There are several issues associated with this decision.

The bandwidth decision may be limited to a range between strong ingress sources.

It may be a low revenue-generating service and the service provider may not want to allocate a wide channel or multiple smaller channels for the service. It may be a high revenue-generating service for which the service provider is willing to use a large part of the bandwidth in the best part of the return spectrum.

The amount of users supported per channel and the number of homes passed needs to be considered.

Consider how to fit all of the bi-directional services into a limited return band between 5 MHz and 42 MHz.

After deciding on the minimum data rate needed and the maximum bandwidth, which can be allocated, the minimum bandwidth efficiency can be calculated by dividing data rate by bandwidth. A horizontal line can be drawn through this point and any modems falling below it will not meet the required efficiency.

For example, if that line is drawn at 1.3 bits/sec/Hz, as in Figure 7, all the modems falling in the upper left quadrant will meet the minimum needs of the specific service. The system engineer could use a table in the same way by crossing out all the modems, which do not meet the CNR requirement, and then the modems that do not meet the bandwidth efficiency requirement. The ones that are left will meet the requirements of the service.

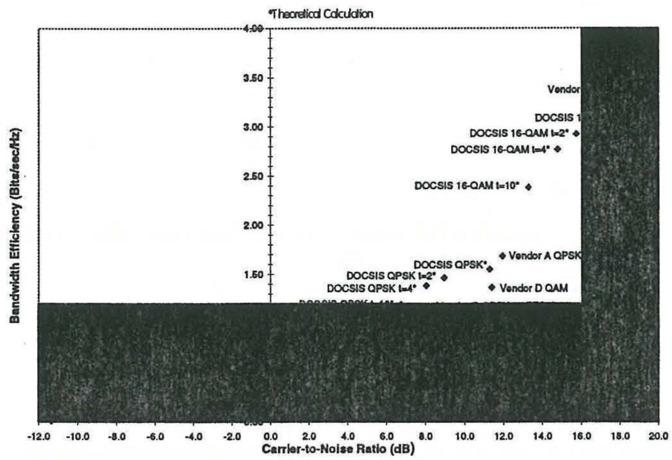

Figure 7: Bandwidth efficiency vs. CNR for 1% FLR

One also needs to consider the quality of the HFC plant from an impulsive noise point-of-view. If knowledge of the average length of time impulsive noise is present, from test equipment such as CableLabs CWTester™, this can be used to determine the amount of error correction needed. A similar procedure, shown in Figure 7, can be used with Figure 4. After choosing FEC depth, it should be verified that the error correction mode still falls into the quadrant of the graph chosen for CNR and BWE. If the constraints of the service will be difficult to implement in the current HFC network, this may be the justification necessary to upgrade the network by dividing an optical node or increasing the maintenance to improve the ingress performance.

CONCLUSION

Cable modem technologies have been compared to each other by the three performance metrics described herein. This data has been presented in a format detailing which technologies make the best use of the HFC networks' valuable bandwidth and power resources. The comparison also demonstrates how trade-offs in bandwidth efficiency must be made for robustness.

The type of analysis presented here can enable service providers to make system design decisions based on knowledge of the services they want to provide. This type of data can be used to help make decisions on which modem technology best suits their needs for the particular service. It can also be used to help make decisions on the amount of time and capital that needs to be spent on upgrading and maintaining the quality of the HFC plant. This data can also provide service providers with the information to determine if they are optimally and reliably utilizing their valuable bandwidth resource. The optimal use of HFC infrastructure will help ensure that the cable modem is the premium communication appliance in delivering high-speed data.