Digital Video Bandwidth Requirements for Large Flat-panel Televisions

A. Boh Ruffin
Corning Incorporated, 1 Riverfront Plaza, Corning, NY 14831
ruffinab@corning.com

Abstract: Consumer expectations for high quality high-definition programming will place greater demand on access networks as flat-panel display sizes increase. Herein, we investigate the bandwidth requirement to deliver high quality HD viewing experience for larger displays.

OCIS codes: (060.2330) Fiber optics communications;(330.5510) Psychophysics

The manufacturability of LCD glass substrates as large as 100 ft^2 has both stimulated and fueled consumer demand for large flat-panel high-definition (HD) televisions. The aesthetics and features of the modern-day LCD display, such as dynamic contrast ratios exceeding 10^6:1, 10-bit color depth, digital input ports, internet connectivity, and high refresh rates are enabling a new excitement towards television[1]. In the last five years, penetration of HD LCD TVs has rapidly increased to meet broadening consumer and corporate demands. Larger LCD glass substrates have helped to improve the economies of scale in manufacturing. Consequently, average screen sizes have increased from 27” to over 32”. Currently, the largest size available through retail is 65”, but in the near future 80” and larger can be expected. Display resolutions have also evolved from 720p in 2003 to 1080p in 2005. Looking ahead, consumers will want higher-resolution displays with increasingly complex capabilities, such as 3D viewing. But while more consumers are buying HD television sets, the viewing experience from broadcast or streaming HD video services is not consistently meeting their expectations of quality associated with digital console sources (Blu-ray^{TM}, gaming consoles, *etc.*). It is unfortunate that early adopter consumers of large-screen displays have been dissatisfied with the quality of HD content delivered to their HD displays over the access network [2]. The problem of video quality, however, is not caused by the display, given the previously mentioned technological advancements in thin-film transistor display technology. Instead, poor video quality is often due to bandwidth limitations in the access network which is challenged to delivery adequate video data rates to the display. While standard-definition, MPEG-encoded video can require as little as 1-4 Mbps per program, video services featuring compressed HD content (1280x720 or 1920x1080 pixels) can require substantially more bandwidth to replicate the Blu-ray viewing experience. Given the inherent costs and bandwidth limitations to distribute HD video over the access network, service providers rely on video compression technology to deliver video programming at data rates appropriate for their network’s capacity. Compression algorithms such as MPEG-2 and MPEG-4 are commonly implemented to reduce the bandwidth load during the transmission of HD content over the access network[3]. While lossy video compression methods make it possible to allocate bandwidth for a variety of other services over the access network, this reduction of visual information can be problematic when compressed video streams are decoded then viewed on large-screen (> 42”) televisions[4]. Consider the digital video bandwidth allocations for the access network noted in Table 1. While these values alone may not offer any context of video quality for the reader, however, we have measured video quality as a function of the video data rate, as well as screen size and resolution, CODEC, and broadcast method.

Table 1. Digital Video Bandwidth for Example Access Networks Types

Network	Modulation	BW [MHz]	Ch. BW [MHz/ch]	Ch. Data Rate [Mbps]	MPEG CODEC	Vid. Data Rate [Mbps]
CATV	m-QAM	700	6	38	2	8-19
SATV	QPSK	1000	27	59	4	8-9
VDSL (IPTV)	DMT	30			4	6-10
FTTH	m-QAM	800-1000	6	38	2	8-19
FTTH (IPTV)	NRZ	< 100		40-80	2 or 4	40-80

To quantify this objectively, we transmitted video using two common transport protocols for video delivery:

256-QAM (HFC and FTTH RF video) and ethernet/DMT (xDSL IPTV), as illustrated in Fig. 1a. Here, an uncompressed video clip is processed by an MPEG-2 or MPEG-4 encoder. Characteristics of the video sequence used in our experiments include saturated colors, high spatial frequencies, as well as fast and slow temporal changes within frames. The compressed baseband transport stream from the encoder was used to drive a 256-QAM modulator/optical transmitter or a 1000BASE-ZX SFP transmitter, respectively. After both signals propagated through 20-km of single-mode optical fiber and were detected with a photodetector, we perturb the electrical signals by injecting additive white Gaussian noise (AGWN) noise between the detector and decoder. The 256-QAM electrical signal was loaded with various levels of AGWN to simulate a variety of possible transport issues which reduce the received SNR. The fidelity of the 256-QAM digital signal is typically characterized through a measure of the error vector magnitude (EVM) [5]; as demonstrated in Fig. 1b the EVM increases as the SNR is reduced. The data rate of the 6-MHz wide, 256-QAM signal remains constant at 38.8 Mbps in the presence of noise, however, when the EVM is greater than 2.5%rms the error rate will exceed the limit of forward-error correction. In the IPTV tributary of Fig. 1a, the IP video signal was loaded with noise after it was first converted from a base-band signal to a DMT signal via the digital subscriber line access multiplexer (DSLAM)[6]. Next, this converted signal propagated through a wireline simulator, where a noise load consisting of 12 near-end and 12 far-end cross talk (NEXT/FEXT) terms was imposed on the signal before terminating at the modem and decoder. Fig. 1c demonstrates the effects the loop length and 12 term NEXT/FEXT noise profile has on the downstream throughput. Unlike the single carrier 256-QAM used in HFC or FTTH RF video broadcasts, the DMT modulation used in xDSL networks will reduce the number of sub-carriers in the presence of line noise or attenuation in order to maintain an ideal SNR for error-free transmission. However, the reduction in number of sub-carriers also lowers the maximum throughput.

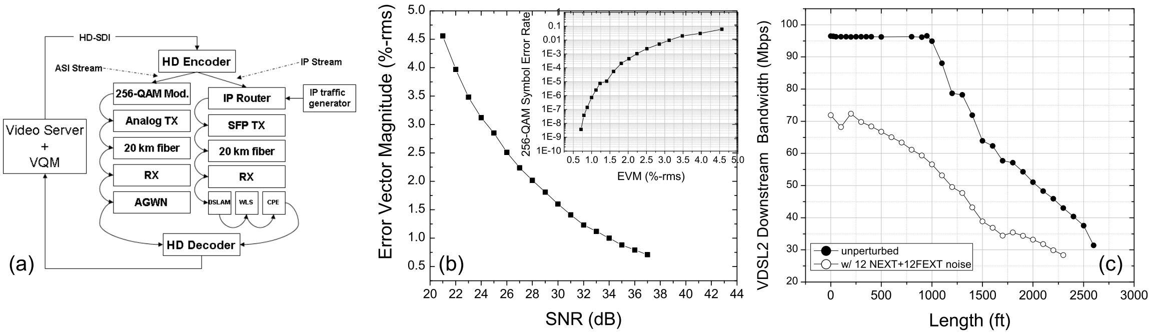

Fig. 1. (a) Experimental setup, (b) EVM v SNR for 6-MHz, 256-QAM video channel[5], (c) and measured VDSL2 throughput v loop length for unperturbed and noise impaired link

The video quality results for the noise impaired RF 256-QAM and DMT/IPTV broadcasts are shown in Fig. 2a. Here, we plot the video quality metric over a range of data rates using the Sarnoff Just Noticeable Difference (JND) model[7, 8]. Unlike other quality of experience metrics, such as the media delay index (MDI), the JND method objectively predicts the subjective video quality rating by a group of human testers using an analysis based on the human visual system (HVS). For all pixels in every frame or field this metric compares an encoded test sequence to a reference sequence (preferably uncompressed), then analyzes differences arising from compression artifacts, digital noise, and luminous variations to predict a video quality score. Though the JND scale ranges between 0 and 100, a subjective interpretation for values $0 - 7$ is noted on Fig. 2. In Fig. 2a, we established a reference configuration using only the encoder and decoder. Directly comparing the reference configuration to the noise impaired RF and IP video broadcasts shows that over a wide range of video data rates, the quality scores agree with the reference case with infinitesimal differences. The exception, however, is with the extreme condition for the RF HD video broadcast where the EVM exceeded 2.5%rms; here the random noise generated dropped frames and macroblock errors over the duration of the sequence thus resulting in high JND scores (poor quality) over most of the bit rate range (Fig. 2a). While the noise-impaired, VDSL2 link does not suffer from transmission errors, the video quality can be limited by restricting the total available bandwidth because of electrical crosstalk or loop length, as suggested by Fig. 1c.

Scores from the JND method can be scaled for viewing distance, making it possible to compare screen sizes for fixed viewing distances. In Fig. 2b we compare JND scores for the same video sequence over a wide range of compression rates with encoding algorithms and resolutions typically used during an RF or IP video broadcast. Here, we consider the video quality at $1920x1080$ and $1280x720$ pixel resolutions for screen diagonal sizes of 65" and 36", respectively, at the fixed viewing distance of 8 ft (considered an average viewing distance). In the JND convention, it is preferred that test sequences score less than 3; this typically will correspond to Blu-ray quality and video data rates similar to Blu-ray video (35-40 Mbps). Given the threshold for scoring JND < 3 for high quality HD video broadcast, we can now ascertain the data rate for the various resolution and encoding formats to meet this criteria. Using the video data rate ranges in Table 1 for RF and IP broadcasts we can identify that JND scores within these ranges are several units above the JND $= 3$ threshold. While today's average display size is 36" at $1280x720$, the JND within this same range fails to meet the quality threshold. Current displays can support $1920x1080$ progressive formats, but HD content is typically encoded and broadcast as interlaced. To meet the JND quality threshold for the $1080i$ format, video data rates can be significantly higher at the JND$= 3$ threshold. This suggests that 1080p content could indeed be transmitted at a lower data rate (40 Mbps) than the data rate (> 50 Mbps) for 1080i content.

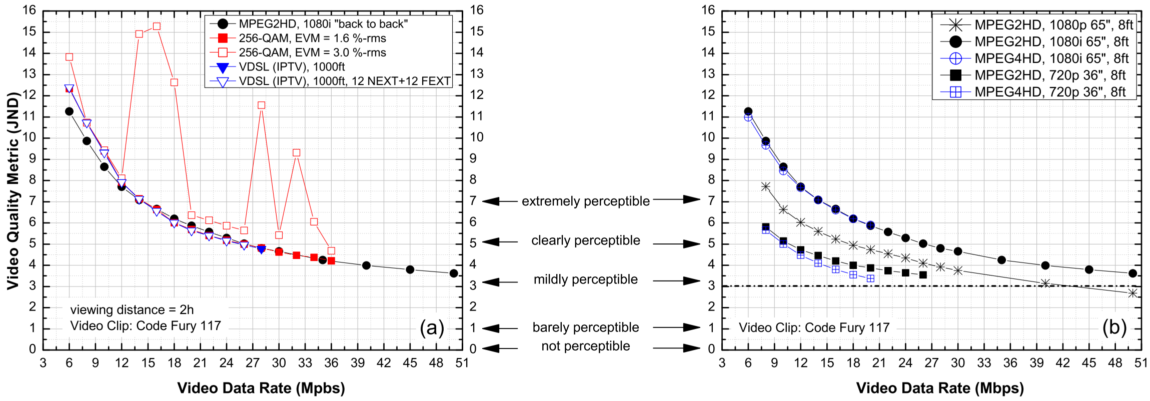

Fig. 2. Just Noticeable Difference (JND) video quality scores for a complex video sequence broadcast over (a) back-to-back configuration and noise impaired RF 256-QAM and VDSL2 systems with the 1080i MPEG-2 CODEC; (b) JND scores using the reference configuration for 1080p, 1080i, and 720p MPEG-2 formats and 1080i and 720p MPEG4 formats at a fixed viewing distance of 8-ft.

Clearly, RF and IP methods for broadcasting video are effective means to deliver HD video services over the access network, as suggested by Fig. 2a, but for the video data rates noted in Table 1 the perceived video quality will not satisfy consumer expectations for the larger displays. Consumers are demanding larger flat-panel TVs for an immersive viewing experience. It is our assessment that network providers could not have anticipated the rapid developments in display technology which have fueled the consumer's demand for large flat-panel displays. The allocated video data rates per HD program listed in Table 1 are adequate for yesterday's smaller displays, but tomorrow's displays will require higher data rates. Our suggested 40 Mbps per HD program projections challenge the capabilities of today's access network; however, the deployment of optical fiber deeper into access network will increase the capacity of the network to support high-speed data and HD video services.

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