An Analysis of the Technical and Economic Essentials for Providing Video over Fiber-to-the-Premises Networks

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This paper presents a cost comparison of two video transport methodologies on a passive optical network (PON): an out-of-band radio frequency (RF) video overlay and in-band video delivered as multicast Internet Protocol (IP) packets. The RF overlay approach has traditionally been favored for video transmission on a PON due to the availability of cable television (CATV)-like components, including CATV-ready televisions, but recently the lower network costs associated with converging voice, data, and video on an all-packet network (so called “Internet Protocol television” [IPTV]) have begun to be recognized. We have quantified the full cost of the RF video overlay, taking into account all the physical parameters that affect the cost of such deployments, allowing an accurate evaluation of the economics of this system under a variety of configurations. Our IP video model estimates the cost of a multicast IP video network, using analysis of viewer data to estimate the actual bandwidth requirements in real-world IPTV deployments. Using these models we compare the cost of RF video overlay and IP video technology for fiber to the premises (FTTP). We show that the choice of the lowest-cost video solution is sensitive to take-rate and channel lineup in particular, but that IPTV is the lowest-cost solution under the majority of likely deployment circumstances. © 2005 Lucent Technologies Inc.

Introduction

There has been much renewed interest in the subject of fiber-to-the-home (FTTH) technologies [2, 5, 6, 10, 17–19] due to decreasing component and system costs and increasing demand for high-bandwidth access connections that can seamlessly provide voice, data, and video services with ultra-high fidelity and reliability. A single network for all multi-media needs offers significant potential savings to the service provider in terms of reduced operating expense (OPEX) on maintenance, provisioning, and billing, as well as increased income through the addition of revenue-generating services not possible using the existing network infrastructure. These benefits will be experienced by the end customer as lower costs, improved ease-of-use, and one-stop billing for existing services; furthermore, the new services available will enhance the customer experience beyond that available today, which will serve to attract more
customers and improve customer retention, further reducing OPEX associated with churn.

It is these attractive attributes of a next-generation access network that have long focused attention on this topic. There has also been considerable action by service providers; incumbent telecommunications operators have systematically upgraded their central office (CO) facilities to provide digital subscriber line (DSL) service of ~1 Mb/s with a coverage approaching 80% in industrialized nations [12, 16]. Cable television (CATV) operators have similarly upgraded their plants to support two-way communication and an array of digital services.

Despite this, little has happened with respect to the deployment of true multimedia networks. In order to offer a full suite of video-intensive multimedia services, including tailored on-demand services, such networks typically require bandwidths on the order of 20 to 50 Mb/s [18] per subscriber and must be able to reach subscribers up to ~20 km away from a service provider’s point of presence (POP) or CO. These dual requirements, long reach and high bandwidth, can only be met with optical fiber-based technologies, whether they are true FTTH—i.e., fiber all the way to each home—or fiber-to-the-curb (FTTC)—i.e., fiber runs to within a few hundred feet from each home, with existing copper loops utilized to connect the individual homes.

The dearth of deployments of fiber-rich access networks can be attributed to two factors: the high cost of new (optical) network deployments, particularly those with new infrastructure, and the paucity
of true multimedia applications and services delivery mechanisms appropriate for the residential user. We have previously covered the former subject in detail [18] and have described how the costs of FTTH and FTTC networks have decreased to the point where they are nearly equivalent to those associated with deploying a traditional copper loop from the CO to the home; a long-awaited cost target. The latter element—multimedia services—has many components ranging from the hardware for encoding/decoding to the protocols necessary for session setup, monitoring, and delivery, to the actual multimedia applications software and the software for services management systems. There has been significant progress in these areas over the last decade, with protocols such as Session Initiation Protocol (SIP) and Real-Time Transport Protocol (RTP) becoming standardized, and media encoding algorithms such as MPEG-2 becoming the de facto standard for encoding digital video (and the Windows Media® 9 and MPEG-4 standards that offer higher compression emerging as alternatives), and also with many novel applications (e.g., Napster, video-on-demand (VoD), and TiVo® services) appearing on the scene. Not surprisingly, there is a significant additional cost—above and beyond that typical of a data-only fiber access network—associated with these services. The additional cost can be broadly thought of as arising from multimedia components and associated bandwidth in the home in the access part of the network, in the transport part of the network (e.g., the metropolitan area network [MAN]), or in the video head-end equipment.

Two competing video transport methodologies have emerged as possibilities: a RF video overlay-on-fiber broadcast approach that is an evolution of the coaxial cable-based CATV approach, and video delivered as multicast Internet Protocol (IP) packets using baseband data bandwidth. Many qualitative assertions have been made about the relative merits of the two approaches, with the RF overlay advocates touting the benefits of reuse of high-volume, mature CATV components including CATV-ready TVs and the IP video advocates highlighting the need for only one type of network—the baseband data network—rather than a data network and a separate RF overlay network, albeit it at the cost of needing set-top boxes (STBs) to convert from IP to RF in the home for display on a conventional TV set. However, to date there has been no comprehensive quantitative study of the relative merits of each approach, making the decision regarding the appropriate FTTH network to deploy fraught with uncertainty. We seek to address this deficiency by fully accounting for the essential costs of both approaches under a wide variety of different deployment scenarios and signal-to-noise environments. We have developed a flexible, adaptable model for quantifying video demand as a function of varying channel availability and user group size that allows us to fully estimate the true cost of a multicast IP video network for the first time. In this way, our results provide a basis for making a rational technology decision, based on the anticipated video needs, both now and in the future.

Video Access Network Essentials

In March 2001, the International Telecommunication Union (ITU) finalized a recommendation for an Asynchronous Transfer Mode (ATM)-based passive optical network (APON) with an enhancement band for extra services [11]. The enhancement band is specified as an extra downstream wavelength centered at 1,550 nm (in addition to the downstream data transmission wavelength at 1,490 nm) that can be used for services such as analog and digital CATV distribution. Upstream transmission occurs at 1,310 nm at 155 Mb/s, with bandwidth shared between the users attached to the PON according to a time division multiple access (TDMA) protocol that is administered by the PON control module and that provides fixed or variable grants of time to each user.

The addition of the enhancement band at 1,550 nm, coupled with the increase in downstream data rate to 622 Mb/s from the 155 Mb/s APON standard, resulted in an “enhanced” configuration, the broadband passive optical network (BPON), described in ITU standards G.983.1–G.983.4. Through the years, amendments were added to the BPON and APON standards, first to increase the upstream data rate to 622 Mb/s, and, most recently, to increase the downstream rate once more,
to 1.2 Gb/s. BPON was the first “new” PON standard to be completed (after APON), and it is the only one that is fully standardized to date—a fact that made it the favored PON in the recent announcements of the North American Regional Bell Operating Companies (RBOCs) concerning new plans to deploy fiber to the premises (FTTP), where “premises” (or “P”) denotes the combination of residences and businesses to be served.

Since the completion of the BPON standards work, two other PON standards have appeared: one championed by the Institute of Electrical and Electronics Engineers (IEEE)—Ethernet PON (EPON)—and the other, a second ITU specification [10]—Gigabit PON (GPON). Both standards specify downstream bandwidth of at least 1.2 Gb/s and also offer the same upstream bandwidth. The transport framing in the EPON is essentially native Ethernet, whereas the GPON has ATM and/or Synchronous Optical Network (SONET)-based partitions (using a version of the Generalized Framing Procedure [GFP] to encapsulate time division multiplexing [TDM] and packet traffic). These two latter PON standards are expected to be complete in late 2004/early 2005. Both currently reserve the enhancement band for potential use as described above, although it is widely expected that all video deployed over such next-generation PON systems will make use of the additional data bandwidth at 1,490 nm, utilizing a packet-video approach, rather than the RF video overlay in the enhancement band at 1,550 nm. We quantitatively compare and contrast these two approaches in this paper, starting by describing the essential price and performance elements of the video overlay approach. Later, we discuss the manifestly different metrics that define the in-band video approach.

**RF Video Overlay on the 1,550 nm Enhancement Band**

CATV systems have pioneered the use of a 54–870 MHz spectrum of RF carriers each with 6 MHz bandwidth (for a total of ~134 potential carriers available). Early CATV systems dedicated an entire 6 MHz carrier to a single video source (channel), modulating the carrier using amplitude modulation vestigial sideband (AM-VSB). More recently, advanced digital modulation schemes such as quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM) have been used to increase the effective carrier bandwidth by transmitting multiple bits/Hz, allowing many channels to share the same 6 MHz carrier, using multiplexing techniques. Today, typically eight to ten standard definition TV (SDTV) channels, or, alternatively, two high-definition TV (HDTV) channels, are transmitted on a single QAM-256 (8 bits/Hz) 6 MHz carrier, with the superior noise immunity that is typical of digital transmission schemes. The current cable spectrum is typically divided into an analog portion (e.g., the lower 65 carriers) and a digital portion (e.g., the upper 65 carriers) by the individual CATV multiple service operators (MSOs). The analog portion can be viewed without an STB (except for the premium analog content, which is scrambled and does require a decoder to view), but the digital portion can only be viewed using an STB to demodulate the QAM signal, de-multiplex the embedded channels, and decode the desired MPEG-2 stream. Thus, even in the standard CATV world, one of the key price/performance tradeoffs is already apparent: superior signal-to-noise signals are provided by digital modulation schemes, with higher channel densities made possible by the attendant digital compression techniques, but with the added cost of the QAM modulators in the network and the decoding equipment (STBs) in the home.

RF-modulated video over fiber is typically provided using a similar approach. However, there are many important differences that profoundly affect the price and performance metrics of such a fiber-based system. We will discuss each of the relevant phenomena in turn and then translate the effect into the net dependence of video cost on transmission parameters.

A typical PON RF video overlay system is shown in Figure 1. The composite video signal (comprising the desired mix of analog and digital [QAM-modulated] RF carriers) is generated in a video head-end and launched onto a transport fiber using a highly linearized, high-power (~10 dBm), CATV-type laser operating at 1,550 nm with a high stimulated Brillouin
scattering (SBS) suppression threshold (16–20 dBm). This optical signal is then typically split for distribution over a number of fibers (e.g., 4), which feed individual (more local) video serving offices. At each video serving office, the signal is amplified using an Erbium-doped fiber amplifier (EDFA) and split again to feed a number of different equipment racks (e.g., 16). Each such secondary video signal is then typically re-amplified using a second EDFA to allow sharing between several PON blades (e.g., 8). These tertiary signals are then transmitted over the individual PONs, being split once more in the PON to serve each attached end user. Each user’s optical network termination (ONT) equipment receives the (attenuated) 1,550 nm signal, isolates it from the lower power 1,490 nm data signal, and performs an optical-to-electronic conversion for distribution around the home over conventional 75 ohm coaxial cable that runs to each TV and/or decoder device.

Minimizing the cost of the video overlay requires maximum sharing of the CATV laser and EDFAs, since the combined cost of these components is on the order of $25,000 or more, depending on the exact specifications. In order to assess the possible extent of the sharing, the required power budget of the RF video overlay on each PON must be compared to the
maximum available optical power that can be launched into the network. The required power budget per PON of the video overlay depends primarily on the following parameters:

i) The desired signal-to-noise ratio (known as the carrier-to-noise ratio [CNR]) for the RF carrier lineup. This determines the minimum received optical power per user. The CNRs for analog and QAM-modulated digital carriers are different, with the analog requirements being more stringent by factors of 4 or more.

ii) The individual PON split ratio—i.e., the number of users intended to be served by a given PON. This is typically engineered to be 32, but it can also be 16, 64, or even 128.

iii) The PON reach (in km). This is the maximum distance an end user will be from the PON equipment; it determines the level of optical network signal attenuation over the PON.

The net power budget per PON is determined by referencing the required power per PON, defined by the above, to

iv) The maximum possible launch power, which is a function of both the level of SBS in the PON fiber and the level of SBS suppression implemented in the CATV transmitter.

Factors other than CNR requirements also impact the performance of RF video overlays on PONs. These include:

- Composite second order (CSO) and composite triple beat (CTB) distortions. CSO and CTB are important performance parameters for RF transmission in hybrid fiber-coax (HFC) systems. However, for the video overlay on fiber we are considering here, the distortion requirements are less stringent compared to a conventional HFC CATV network because the CNR pertains to reception at the home, rather than at an HFC optical node. The optical node in an HFC network typically serves between 500 and 2,000 homes, and the signal from the node therefore needs to travel some distance and be split several times before it gets to the input of the individual users’ TVs. This results in potentially increased distortion (higher noise) in the end users’ homes and the consequent need for more stringent linearity specifications (to reduce CSO/CTB) at the node. In contrast, the optical signal is delivered directly to the home in a PON, resulting in reduced distortion of the RF overlay video relative to the HFC case. Thus, the RF equipment considered herein always satisfies the linearity requirements in the PON case, because we assume that standard HFC CATV equipment will be used (recall that the reuse of such standard components is posited as one of the main advantages of the RF video overlay schema). Therefore, we conclude that CSO and CTB distortions do not result in substantial additional cost for a practical RF video overlay on a PON.

- Reflections and crosstalk. The reflection of the optical signal at the power splitters and fiber connectors, imperfect 1,550/1,490 nm wavelength division multiplexing (WDM) filters, and double Raleigh scattering in a PON can cause interfering intensity noise in the video receiver, which degrades the CNR. However, by selection of filters with good isolation and the use of angle-polished (as opposed to straight) fiber connectors, these factors can also be made small.

- Raman cross-talk noise. It has been shown that stimulated Raman scattering (SRS) causes crosstalk between two wavelengths within 150 nm of each other that are transmitted on one fiber [8]. However, in a PON with a video overlay (with propagating 1,490 and 1,550 nm signals), simple precautions like lowering the transmitted power of the data signal [4] and increasing the modulation index of the low frequency carriers [1] have been shown to make the penalty from Raman crosstalk also small.

We take all the preceding elements—distortions, reflections, crosstalk, and Raman crosstalk—into account by assuming an appropriate power penalty in the optical power budget (see equation 3).

Returning to our discussion of the critical performance factors that influence the cost analysis, the most critical metric that defines the PON video performance for a given physical layout is the CNR requirement per home. The CNR is defined by

\[
\text{CNR} = \frac{OMT^2}{2qI_p\Delta f N + i^2\Delta f N + (\text{RIN}_{\text{LASER}} + \text{RIN}_{\text{EDFA}} + \Delta f)}
\]  

(1)
where $OMI =$ optical modulation index, $N =$ number of RF carriers, $I_p =$ received photocurrent (A), $q =$ elementary charge (C), $\Delta f =$ noise bandwidth (Hz), $i_n =$ input noise-current variance (A/\sqrt{Hz}), $RIN_{LASER} =$ laser relative intensity noise (dB/Hz), and $RIN_{EDFA} =$ EDFA relative intensity noise (dB/Hz).

If we solve for $I_p$, the minimum received optical power allowed for a given CNR can be derived from
\[
P_{MIN \, RX} = 10 \log (R \cdot I_p),
\]
where $R =$ responsivity of the receiver diode. For all the results below, we assume $OMI = 0.25$, $i_n = 4 \, \text{pA}/\sqrt{\text{Hz}}$, $RIN_{LASER} + RIN_{EDFA} = -165 \, \text{dB/Hz}$, and $R = 0.9 \, \text{A/W}$.

The net power budget of the PON is then simply calculated from
\[
P_{NET} = P_{LAUNCHED} - P_{ATTENUATED} - P_{PENALTY} - P_{MIN \, RX},
\]
where $P_{LAUNCHED}$ is the power available by virtue of factor iv) above, $P_{PENALTY}$ is the optical path power penalty (the extra optical power required to account for degradations such distortions, reflections, crosstalk, and Raman crosstalk), and $P_{ATTENUATED}$ is determined by factors ii) and iii) above. $P_{NET}$ can be either negative (insufficient power) or positive (an excess of optical power), both of which have direct cost consequences: negative values require an offsetting reduction in sharing, or reach, or higher power equipment (= higher cost per user), and positive values require the opposite, resulting in a lower cost per user. Our goal is then to determine $P_{NET}$ for a wide variety of different deployment scenarios and to calculate the associated cost for each configuration.

The first step is to calculate $P_{MIN \, RX}$ under typical conditions and for a variety of different numbers of RF carriers, $N$. The CNR requirements for analog and digital RF carriers are quite different—e.g., the recent Request for Proposal (RFP) of the RBOCs specified that analog carriers should have $CNR = 48 \, \text{dB}$ and QAM-256 digital carriers should have $CNR = 42 \, \text{dB}$—a factor of $\sim 4$ difference. Thus, the $P_{MIN \, RX}$ required for a given number of analog or digital carriers will be different. Alternatively, the number of RF carriers that can be supported at a given $P_{MIN \, RX}$ will be a factor of $\sim 4$ different for the above specifications. This is quantitatively shown for a single physical PON configuration of 20 km reach and 32 users per PON (a 32-way split) in Figure 2.

We can extend this analysis to calculate the number of such digital and analog RF carriers supported as a function of both variable PON reach and variable split ratio, the results of which are shown in Figure 3. The number of carriers of either type that can be supported decreases exponentially with PON reach, with 4x as many digital carriers, compared to analog carriers, being supported at any given PON reach (for the assumed specifications of $CNR_{QAM} = 42 \, \text{dB}$ and $CNR_{analog} = 48 \, \text{dB}$). Alternatively, at any given number of RF carriers, changing from analog to digital increases the PON reach by on the order of 15 km (see the horizontal light green line on the plot). Decreasing the split ratio also increases the number of carriers of a given type supported at a fixed reach by a factor of $\sim 3$x (see vertical light green line on plot) or, alternatively, increases the reach by $\sim 12$ km for a given number of carriers (horizontal dark green line on plot).

So far we have discussed only the performance tradeoffs for different channel lineups, but we would like to convert this into a net cost per PON. To do this, we determine $P_{NET}$ from $P_{MIN \, RX}$ and convert this to a cost-sharing factor, $C_s$, equal to the antilog of $P_{NET}$.
which is used as the divisor for the relevant video equipment costs. Sample results for a 32-way split PON of 20 km reach are shown in Figure 4. The surprising result is that the cost per PON depends nearly linearly on the number of carriers. This result can be understood by the following reduction: From equations (1)–(3), \( P_{\text{NET}} \) (in dB) is approximately linear in \( \log(1/N) \), where \( N \) is the number of carriers. The cost per PON is obtained by dividing the nominal cost for a reference configuration by \( C_o \), which is proportional to antilog (\( \log(1/N) \)) by the preceding reasoning. Thus, the cost per PON is essentially linearly dependent on \( N \). The same result holds for both analog and digital carriers, with the cost gradient for analog carriers found to be 2–3x that for digital QAM carriers (Figure 4), meaning that each analog RF carrier costs 2–3x as much per PON as a digital carrier on the same PON.

The discussion so far has analyzed the effective metrics associated with separate “pure” analog and digital RF channel lineups. However, in real
deployments, it is anticipated that a mix of analog and digital carriers would be offered on the same PON in order to minimize the need for STBs for those happy with conventional analog channel capabilities, but also to offer the advantages of digital—more channels and better picture quality—to the remaining users. Therefore, to apply our cost analysis to real-world scenarios, it is desirable to talk in terms of only one net type of carrier. From the preceding analysis, it may be apparent that any given digital carrier can be converted into an effective number of analog carriers (or vice versa), using the relative difference in CNR. The formal relationship for the effective number of carriers for a mixture of analog and digital carriers, $N_E$, is given by

$$N_E = N_1 + \frac{N_2}{10^{(CNR_1 - CNR_2)/10}} + \cdots + \frac{N_q}{10^{(CNR_1 - CNR_q)/10}}, \quad (4)$$

where $N_1$ is the number of primary carriers (e.g., the number of analog carriers) with CNR1 and $N_2, \ldots, N_q$ are the number of secondary carriers with respective CNRs of CNR2$...$CNRq (e.g., different digital QAM carriers). By way of example, we consider the lineup proposed by the RBOCs, which has a mix of 82 AM-VSB ($CNR = 48$ dB) and 33 QAM-256 carriers ($CNR = 42$ dB), giving an effective number of analog carriers, $N_E = 91$.

Using this formalism, we can calculate the effect on cost of all the key parameters for any arbitrary channel lineup. These results are shown in Figure 5, where we see that the cost per PON increases non-linearly with reach, and, at a given reach, it increases linearly with the effective number of carriers (as expected from Figure 4). The cost per PON also increases nearly linearly with PON split ratio and, at a given split ratio, linearly with the number of carriers (again in accordance with Figure 4). These two observations can again be understood by reduction of equations (1)–(3): $P_{NET}$ is a linear function of $P_{ATTENUATED}$, which in turn is proportional to the logarithm of $(\beta^n/R)$, where $\beta$ is the fractional power lost per km, $D$ is the PON reach in km, and $R$ is the PON split ratio. As before, the cost per PON is proportional to $1/C_s = 1/\text{antilog}(P_{NET})$, which equates to $R/(\beta^n)$. Therefore, the cost per PON depends linearly on the split ratio, $R$, at fixed $D$, and it has an inverse power law relationship with PON reach, $D$, at fixed $R$.

In the final part of our analysis, we take a closer look at the effect of SBS on $P_{LAUNCHED}$ and therefore $P_{NET}$ and cost. The nonlinear SBS process puts a limit on the optical power level that can be launched into a fiber. SBS results from the electric field of the propagating radiation modifying the mechanical properties of the fiber by electrostriction, creating an effective index grating that in turn scatters the light, with the backscattered component being the only component that propagates in single mode fiber. Thus, the net effect is a clamping of the transmitted power and an increase of RIN in the receiver at low frequencies. A more extensive description of SBS in CATV transmission systems can be found in [13].

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The direct implication of the SBS effect on cost is the limit it puts on video transmitter sharing by limiting the available power budget, $P_{LAUNCHED}$. For externally modulated systems, the SBS effect [3, 15, 13] is described by

$$P_{SBS} = \frac{21A\alpha}{\gamma(1 - e^{-A})} + \Delta P_{SBS}, \quad (5)$$

where $P_{SBS} =$ SBS threshold power, $A =$ core area of fiber ($\text{cm}^2$), $\alpha =$ fiber loss ($\text{cm}^{-1}$), $\gamma =$ Brillouin gain coefficient ($\text{cm}/\text{W}$), $L =$ fiber length (cm), and $\Delta P_{SBS} =$ SBS threshold power increase through suppression techniques (W).

SBS can be actively suppressed by broadening the optical spectrum of the transmitter above the SBS linewidth or by distributing the optical power over a number of optical subcarriers (e.g., see [20]). Woodfin et al. [22] describe a passive method by proposing a new fiber design, which has an increased SBS threshold. In commercially available CATV transmitters, the spectrum broadening method is applied by dithering the optical frequency of the laser.

From equation 5, it is clear that the SBS threshold depends on the fiber length and therefore on the reach of the PON. From a cost point of view, this translates into a potentially lower cost per user due
Figure 5. 
**PON cost as a function of key parameters (for RF carriers with 48 dB CNR).**

To the increase in the potential split ratio that can be supported in a shorter-reach PON. We investigated this effect by calculating the maximum launchable power for different lengths of standard single mode fiber \((A = 80 \ \mu m^2, \ \alpha = 0.25 \ \text{dB/km}, \ \text{and} \ \gamma = 2 \times 10^{-9} \ \text{cm/W})\) and deriving the resulting cost per user (taking into account the extra cost involved with a higher output optical amplifier and costs involved with different levels of SBS suppression). The results are shown in Figure 5c. Interestingly, we find that optimizing the launched power to operate at the SBS threshold has a slightly disadvantageous effect on the total cost per home, as the additional costs associated with SBS suppression and resulting higher launch powers are not adequately offset by the greater number of subscribers supported on a short-reach PON. Furthermore, a higher split ratio in a PON also means more bandwidth sharing, so launching more power into shorter-reach PONs actually results in higher cost and lower performance (bandwidth) per subscriber. From this we conclude that, in real networks, SBS will have a simple parametric impact on cost (by limiting the power that can be transmitted over a 20 km PON and increasing RIN at low frequencies), but that there is currently no cost advantage to be gained by exploiting the more complex reach dependence of this effect.
In-Band IP Packet Video Transmission

Compared to the complexity and subtlety of the RF video overlay on a PON (Figure 1), IP packet video transmission is conceptually simple and straightforward to understand (Figure 6). In essence, video channels are MPEG-2 encoded (currently), as for digital CATV systems, but instead of transmitting this stream as part of a broadcast multiplex on a QAM-modulated RF carrier, it is encapsulated in an IP packet stream and sent as multicast packets on the data network (1,490 nm on a PON). MPEG encoders in the video head-end and MPEG decoders (STBs) in the home are required, just as for digital cable; however, unlike digital RF systems, no other specialized video equipment is required (i.e., no CATV lasers and no EDFAs in the network, nor special 1,550 nm receivers with good isolation from 1,490 nm in the home). The only network video cost is the cost of the additional data bandwidth required to provide the necessary video service to all users. On first inspection, this seems trivial to quantify—if one knows the number of attached users, the number of channels per user, and the bandwidth per channel, the total bandwidth required is simply the product of these three factors. The network cost would then be the cost of the additional bandwidth required in the access (e.g., PON) equipment in the CO.

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Figure 6.
A typical IP packet video transmission system.
The above analysis would be an acceptable zeroth order approximation to quantifying IP video network costs, but it would significantly overestimate the bandwidth needed, and therefore the cost. The reason is that multicast protocols are employed in IP video deployments to allow the number of active channels to be dynamically configurable based on the current requests seen from the attached users. If no one is watching a given channel in the lineup, it is not requested and no bandwidth is utilized. In contrast, if everyone is watching the same channel, only one copy is requested and made available to everyone, similar to broadcast. Thus, multicast is really just self-limiting broadcast, with lower bandwidth requirements, on average. The bandwidth savings can be significant, however; if one considers a lineup of 250 channels offered, where only 1 channel is watched by all users as suggested above, a savings of 249/250 or 99.6% in bandwidth would be achieved. Clearly, an accurate understanding of typical viewer behavior is vital to estimating the real cost of supplying multicast video with a low probability of channel blocking. In this section, we describe methods we have developed that allow such an accurate estimation to be made for a wide variety of different multicast deployment scenarios.

The central uncertainty in calculating the efficiency of multicast over broadcast transmission is quantifying how many users watch the same channel at any given point in time. This question has recently been addressed in part by Weber and Gong [21], who employed statistical methods to the bandwidth savings CATV networks could realistically achieve by allowing the less popular channels to be offered as “switched broadcast” options, rather than as fixed “always on” broadcast channels. The authors point out that a channel’s status is a Bernoulli process with two outcomes (“on” or “off”) and that, for N users, the probability of a given channel being “off” was \((1 - s)^N\) and the probability of it being “on” was \((1 - (1 - s)^N)\), where \(s\) is the channel “share” (= number of viewers/total number of active viewers for all channels). The total number of channels watched can then be equated to the sum of the probabilities for all channels which, by the Central Limit Theorem, approximates a normal distribution. As such, properties such as the blocking probability (the probability that the number of channels requested, which is derived from the normal distribution function, exceeds the number of channels supported by the available bandwidth) can be readily estimated. Conversely, for a specified blocking probability, the number of channels, \(C\), supported can be calculated. Importantly, the preceding analysis requires quantitative knowledge of \(s\) for each channel; due to the absence of such a priori knowledge of \(s\) (and for the sake of computational simplicity), the authors assume that all channels are watched with equal probability, stating that this will represent the upper bound (overestimate) to the true number of channels.

Our approach overcomes this limitation by defining a function that accurately describes \(s\) for each channel, for any number of channels, \(C\). The function selected is known as a Zipf function, named for Harvard linguistic professor George Kingsley Zipf [23]. Zipf’s Law states that the popularity of an event (= program on a given channel, in our case) is proportional to \(1/n^\alpha\), where \(n\) is the ordinal rank of the event (1st, 2nd, 3rd . . . nth) and \(\alpha\) is close to unity. This law has been shown to describe a wide variety of different events such as the popularity of words in the English language, the populations of cities, or the income of companies. The key factor in the applicability of Zipf’s Law is that the objects in question have a property that follows an exponential or similar skewed distribution that limits how often items will occur. Invariably this means that the objects must be competitive in some way—e.g., the efficiency of communication placing value (= greater popularity) on shorter words, economies of scale resulting in exponentially increased income for the largest corporations. Zipf’s Law has also been shown to apply to streaming video [14] and movie rentals from a video store [7] with, in these cases, a mixture of societal forces (increased desire to see the top movies), market forces (e.g., investment in the movie, marketing) and consumers’ available movie-watching time/money, all conspiring to result in Zipf-like popularity distributions.

The application of Zipf’s Law to TV-watching has not previously been investigated, despite there
being a clear self-limiting behavior—the audience for a particular program depends on societal factors and the accessibility of the program. The latter is a strong function of the number of stations that carry the program nationally, as well as the placement of the station in the channel lineup and the marketing/advertising of the program. These factors result in the “big 4” networks’ shows (which have national coverage on stations with low channel numbers and strong marketing) attracting the largest audiences, with the audiences decreasing markedly for the cable channels.

In order to establish the appropriateness of a Zipf-type function to describe broadcast viewership, we have used data obtained from Nielsen Media Research for different programming. Ratings data for a sample taken at 9:00 p.m. from 540 viewers in Philadelphia watching a total lineup of 128 channels (of which only 64 channels were being watched at that time) are shown in Figure 7. It is clear that there is a marked decline in rating (= share * fraction of possible TV-owning households currently watching TV) with channel rank, with the fifth most popular channel/program having only 20% of the viewers of the most popular channel. Also shown in Figure 7 is a fit of the data to a Zipf-type function; we see that there is a remarkably good fit when the exponent \( a \) is close to unity (0.95). We have investigated the applicability to other Nielsen data sets from a variety of different timeslots and find that although the quality of the fit varies, the exponent for the best fit always fell in the range of 0.8 to 1.1. We therefore conclude that for the purposes of this study, a Zipf-type function provides an acceptable description of TV channel demand at each point in time.

In the remainder of our methodology, we use a Monte Carlo approach to assess the number of channels required on a given network node (e.g., per PON). We generate a variable-size array of users (viewers) and assign each a random number that is mapped into a specific channel the viewer is watching, using a Zipf function. We perform this mapping for \( N \) users and for a distribution of \( C \) channels and then sum the number of channels actually watched (\( >0 \) users) at that instant. In essence, this Monte Carlo approach can be regarded as akin to users randomly “channel surfing”, starting at any point in the channel lineup and for an arbitrary (random) duration, but with the endpoint (the channel selected to view) not being chosen randomly but by viewer preference—described by the Zipf function mapping in our case. We repeat this entire process 1,000 times, at which point convergence in the statistics has essentially occurred, resulting in a distribution of the number of channels watched by this group of viewers with a well-defined mean and standard deviation. We favor this Monte Carlo approach to the invocation of the Central Limit Theorem and consequent reduction to normal statistical methods with tabulated solutions (the approach taken by Weber and Gong [21]), as it better represents small video deployments (such as video deployed on a 32-user PON). In the limit of large \( N \), we find the two approaches produce very similar results.

Sample results of our calculations under a variety of different conditions are shown in Figure 8. It is apparent that all three variables in this model—the number of channels, the number of users, and the Zipf exponent \( a \)—have an effect on the resulting channel count. Clearly, the largest single effect on the mean number of channels required is the number of users watching TV, in accordance with intuition. The value of \( a \) appears to have a secondary effect on channel count, as does the number of

![Figure 7. Comparison of TV program popularity (channel rating) in rank order to a Zipf functional form.](image-url)
channels available in the lineup. The full effect of these variables is more completely explored in the data presented in Figure 9.

From Figure 9, we see that indeed the number of channels required ($C_{\text{reqd}}$) depends on the number of users/viewers for all $\alpha$ and $C_{\text{avail}}$, with 1,800 users watching 13x as many channels from the same 500-channel lineup as a group of 38 viewers. These data also highlight the fact that the number of channels required is non-linear in $N$: 13x as many channels were required for 47x more users. In contrast, we see that changing the number of channels available has a very different effect—the number of channels required does not depend strongly on the number of channels available for small number of users (e.g., increasing the number of channels available by 5x only results in a 50% increase in the number of channels required for 128 users). In contrast, there is a near linear dependence for large $N$, with a 500% increase in $C_{\text{reqd}}$ observed as $C_{\text{avail}}$ increases by 5x for 1,800 users.

Lastly, varying user channel preferences (expressed through the Zipf exponent $\alpha$) has a relatively weak effect on the channel count: for any given number of users, varying $\alpha$ from 0 to 1 changes the number of channels required by at most ~1.7 (e.g., 720 users, 500 channel lineup), with the effect being much smaller for fewer users and channel counts.

These observations ideally must be translated into a bandwidth requirement in order to estimate the cost associated with delivering in-band video to a given number of users. To this end, we introduce the concept of multicast efficiency, $E_{MC}$, which we define as

$$E_{MC} = 1 - \frac{C_{\text{reqd}}}{C_{\text{avail}}}. \quad (6)$$

$E_{MC}$ is a measure of the bandwidth saved relative to that required in an analogous broadcast network and is plotted under different conditions in Figure 10. From these plots, we see that the greatest bandwidth savings (largest $E_{MC}$) occur when $N$ is small (<720 users), and when $\alpha$ is close to unity, and when $C_{\text{avail}}$ is large (>200 channels). These results are intuitive: as the number of channels approaches the number of users, with each user showing a strong tendency to watch the same limited subset of channels, the fraction of available channels needed decreases markedly and the multicast bandwidth savings is maximal.

Using these results, it is now possible to accurately estimate the actual multicast bandwidth necessary to provide video services under any combination of $N$, $C_{\text{avail}}$, and $\alpha$; and to compare the price and performance of such an in-band video delivery schema to
that using RF carriers, described previously. In the following section we provide one such example of a comparative analysis for a likely combination of parameters in order to illustrate the tradeoffs that can markedly influence the choice of in-band versus out-of-band video delivery.

**Evaluating Relative Costs**

We conclude by undertaking a direct comparison of the cost of providing video services using an RF video overlay with the analogous costs for providing the same video services in-band as IP video. In order to aid in the comparison of the two approaches, we make the following assumptions:

- Video services are deployed over a PON:
  - For the RF overlay video, a 622 Mb/s/1,490 nm BPON is assumed for data and voice services only, and the RF video is deployed on a separate wavelength (1,550 nm), using separate components. As such, only the excess costs of the video components are attributed as “video costs.” We assume these excess video costs comprise network costs associated with a CATV laser ($13,750 with 4 output ports) and 2 stages of EDFAs with cost points of $7,000 ($+10$ dBm with 10 output ports) and $13,500 ($+18.5$ dBm with 8 output ports), respectively, as well as triplexer optics (and associated video
receiver circuitry), with a cost premium of $95 relative to the simpler diplexer (1,490 nm only) optics.

—For in-band video, a 1.2 Gb/s/1,490 nm BPON is assumed, with the in-band video services paying for the extra in-band bandwidth they consume and the higher data rate customer premises equipment (CPE) required.

—No costs associated with the baseline 622 Mb/s 1,490 nm data BPON are included in either case, only the excess cost for video services.

• The PON has a reach of 20 km and a maximum of 32 households attached. Each household can, however, have multiple users, so that up to between 50 and 300 video channels may be required.

• Digital video services require a STB for QAM demodulation and/or MPEG decoding and channel selection. The cost of STB is the same for both RF digital video and IP digital video. The total assumed cost is $200 for a STB(s) that can handle up to three simultaneous streams.

• A Zipf exponent of 0.95 is assumed for IP video services, which effectively reduces the bandwidth required to provide in-band video services as described previously.

• Four QAM carriers are assumed to be CNR-equivalent to one analog RF carrier (e.g., CNR_{QAM} = 42 dB and CNR_{analog} = 48 dB) and each QAM carrier can carry 8 SDTV channels or 2 HDTV channels.

• The ratio of HDTV:SDTV content is 1:10. The bandwidth per SDTV stream is 4 Mb/s and HDTV is 19.8 Mb/s per stream.

The results of our total cost calculations are shown in Figure 11. One of the most immediately obvious results of this analysis is that the RF overlay is a very economical way to deliver pure analog TV services up to the maximum of 80 analog channels that can be accommodated by the allocated RF spectrum. This is true for take rates of 30% and above, with the savings being particularly apparent at take rates approaching 100%. The relative economy of a pure analog RF service, compared to either digital service, results from the absence of a need for a $200 STB for analog services, as TVs are already equipped with the necessary tuning equipment. This finding rationalizes the RBOC request for an RF video system for deployment in an environment with a preponderance of analog video subscribers.

Interestingly, when one considers digital video systems, or systems with greater than 80-channel capacity, the RF video overlay becomes much less attractive: in-band IP video services are as much as $90 more economical to deploy per household than digital RF video services at 100% take rate. At lower
take rates (30%), the same trend that is observed for 100% take rate is apparent at low channel counts; however, as the channel counts increase, the bandwidth required increases and this extra cost is no longer optimally shared due to the low take rate. The poor sharing of this infrastructure cost is felt more strongly for IP video than for RF video (recall that 8 SDTV channels fit in a single QAM-256-modulated 6 MHz RF carrier in our simulated network, whereas 1 SDTV channel consumes 4 Mb/s of in-band data bandwidth), resulting in a crossover at around 200 channels, after which digital RF video is the more economical solution, albeit marginally so.

There are several other elements that contribute to the relative cost of the two approaches, such as the efficiency of multicast relative to broadcast and the relative CPE costs. We can discern the following key factors from the plot. First, the multicast efficiency, $E_{MC}$ (described earlier), results in the asymptotic behavior shown for the in-band video approach; the approximate results in the absence of this effect are shown by the associated dashed lines. Clearly, this is an important differential cost factor, which underscores the importance of the analyses of multicast viewing behavior such as that presented herein. Second, the net cost difference between the digital RF approach and the IP video approach ($65–90) is of the same order of
magnitude as the additional cost of the CPE triplexer optics and video circuitry (assumed $95 in our model), which suggests that aggressive cost reduction in this element would increase the relative merit of the overlay approach. Sample results obtained using the same assumptions as for the data plotted in Figure 11a, but with a $50 triplexer premium assumed, are plotted in Figure 11b to illustrate this point. Clearly, the relative price difference between digital RF video overlay and IP video has decreased at 100% take rate, and the RF overlay approach is more economical at any channel count at 30% take rate.

The preceding comparison of RF video overlay versus in-band IP video delivery options is based on only a limited combination of parameters (using a $95 and a $50 triplexer cost premium), yet the prior analysis has shown that there are many factors that may adversely affect the price/performance metrics associated with one approach. For example, clearly longer reach PONs (>20 km) with a substantial number of analog channels or with higher split ratios (>32) will be less favored relative to IP video solutions. Conversely, if, for example, the bandwidth demands per user increase significantly because the particular deployment scenario does not afford a high value of $E_{MC}$ or the bandwidth per channel increases due to increased (>10%) HDTV content, IP video solutions will suffer in comparison to digital RF video solutions due to the increased multiplexing efficiency of the latter. Alternatively, if more advanced compression schemes (e.g., MPEG-4 Part 10/H.264 or Windows Media 9) become commonplace and reduce the average bandwidth per channel by a factor of 2 or more, IP video approaches will become even more economical. The results of this latter effect are illustrated in Figure 11c, for which the same assumptions are used as for the data in Figure 11a, but the bandwidths per SDTV and HDTV channel are halved. Under these circumstances, IP video is favored relative to the digital RF video overlay for the entire range of channels available and at all take rates considered.

Overall, we find that IP video approaches seem to be favored in the majority of likely deployment scenarios, and have the additional advantage of offering the end user a truly converged multimedia solution (with all that implies in terms of additional revenue and reduced churn), although there are a number of circumstances for which the RF video overlay is more economical. Consequently, the specifics of a given deployment scenario need to be examined on a case-by-case basis, considering both initial capital expenditure (CAPEX) and ongoing OPEX, as well as revenue expectations, in order to optimize the choice of video technology.

A last point worthy of mention is that we have only explicitly considered one PON technology in this analysis, namely, BPON (either as 622 Mb/s with RF video overlay, or as a 1.2 Gb/s BPON with in-band video). While it is clear that there are different cost points associated with GPON and EPON, as well as other active FTTH technologies, those different costs are often associated with non-video related services (such as voice quality of service [QoS] and operations, administration, maintenance and provisioning [OAM&P] features) and attributes. Therefore, to a good approximation the principal conclusions presented regarding video-specific costs will be unchanged, regardless of the particular access technology under consideration.

Conclusions

Our comprehensive analysis of the two main fiber video technologies and the resultant summary cost results illustrate the sensitivity of the preferred (lowest cost) solution for video services to a number of factors; in particular take rate, analog versus digital needs, and channel counts. We have also elucidated many other sensitivities that exist for the different video delivery systems and how they modify these cost results. These results provide new insight into the essential merits of the different approaches and, in combination with the full analysis presented of each technology, should allow an accurate estimation of the optimal solution for a given deployment scenario. As such, this work should provide an invaluable template for aiding in the selection of the appropriate video delivery mechanism for a wide variety of different scenarios with different topographical or technological/services needs.
Looking ahead, the additional cost associated with providing VoD services must also be accounted for. It is likely that large-scale deployment of VoD services using an RF overlay approach is not as economical as using in-band delivery, due to the need for QAM modulators and additional CATV lasers and EDFAs close to the end user. Evaluating the additional price/performance tradeoffs associated with these “premium” future networks is the subject of our ongoing work. These studies, when combined with the comprehensive models of broadcast-like services described herein and good models of demand for such premium services, will allow a complete picture of the costs of multimedia networks to emerge.

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