ABSTRACT

During the past decade, cable television (CATV) systems have evolved from one-way broadcast of analog video transmission to two-way hybrid fiber/coaxial (HFC) networks delivering both analog and broadband services. The broadband services include high speed internet access, cable telephony, video-on-demand, and digital video. In this talk, we describe HFC transmission systems including the infrastructure, transmission formats, enabling technologies, system performance and impairments. The performance results of some typical HFC/CATV transmission systems are discussed along with the impact of fiber nonlinear effects. The fiber nonlinear effects include stimulated Brillouin scattering, self phase modulation, stimulated Raman scattering, and cross phase modulation. The methods to minimize the effects of fiber nonlinear impairments are also presented.

Keywords: Hybrid fiber coaxial, cable television, fiber nonlinear effects, high speed internet access, digital video
1. INTRODUCTION

During the recent years, cable television (CATV) systems have evolved from one-way broadcast of analog video transmission to two-way hybrid fiber/coax (HFC) networks delivering both analog and digital services [1-4]. The traditional one-way broadcast utilized the tree-and-branch coaxial network, where signals from the headend were transported using radio frequency (RF) subcarriers to multiple users with the use of RF amplifiers and power splitters. These systems utilized several cascades of RF amplifiers to overcome the high losses of coaxial cables and splitters. But, the cascaded RF amplifiers affected the quality of the received signals due to significant levels of noise and intermodulation distortion. The use of fiber optic technology in cable TV transmission systems has resulted in a significant reduction of the number of cascaded RF amplifiers, leading to robust transmission of signals. The HFC network utilizes an optical fiber to transport signals from the headend to a fiber node, which is located in a specific serving area. The converted RF signals from a fiber node are sent to different subscribers over a coaxial cable. In addition to the transmission of analog video signals, a variety of broadband services such as high speed internet access, cable telephony, and digital video are also offered over a HFC/CATV network [5].

In this paper, we describe HFC/CATV transport systems which include fundamentals, transmission formats, enabling technologies, and system performance & impairments. The infrastructure of a HFC/CATV network including its evolution and the fundamentals are presented in Section 2. Section 3 describes the enabling technologies for HFC/CATV transport systems. The system performance including different impairments are discussed in Section 4. Finally, Section 5 gives the conclusion.

2. HFC/CATV INFRASTRUCTURE

Prior to the mid 1980’s, the hybrid fiber coaxial video transmission systems operated in the 800 nm wavelength over a multimode fiber. The capacity of these systems were limited due to high fiber loss and intermodal dispersion. The rapid increase in system capacity occurred during late 1980’s by the deployment of 1300 nm lightwave systems over a conventional single mode fiber. During the 1990’s, the development transitioned to 1550 nm wavelength window that took advantage of low fiber loss and erbium doped fiber amplifiers (EDFAs), leading to long distance transmission systems [6-10]. In addition, the dense wavelength division multiplexing (DWDM) technology was also utilized in HFC/CATV networks, which enabled a two-way broadband transmission. Figure 1 shows a typical HFC/CATV network infrastructure utilized in a large metropolitan environment.

![Figure 1](image-url) A typical HFC/CATV network infrastructure. Source for Figure [33]. © 1998 IEEE.

In Figure 1, the signals from the master headend are transmitted over a SMF using 1550 nm DFB laser transmitters and EDFAs to the primary and secondary hubs. At the master headend, the analog or digital video signals from various sources such as satellite transponders, terrestrial broadcast, and video servers are combined using a subcarrier multiplexing (SCM) technique [11]. A master headend typically supports four or five primary hubs and each primary hub supports about 100,000 homes. Each primary hub feeds into three or four secondary hubs, each supporting about 25,000 homes in the serving area. The signals from the secondary hubs are transmitted to the fiber nodes using a tree-and-branch architecture. The size of a fiber node is measured by the number of homes passed (HP) and it can vary from a small node size of 100 to a large node size of 2000 HP. At each fiber node, the received optical signal is converted into a RF signal for downstream transmission over separate fibers. The RF signal is transmitted over a coaxial cable to different subscribers using RF amplifiers and taps. Conversely, a fiber node also converts the user RF signals into optical signals for return path or upstream transmission. The frequency
spectrum in a two-way HFC/CATV network is divided between the forward and return paths. Figure 2 depicts a HFC/CATV transmission spectrum for both forward and return paths across many parts of the world.

For example, the downstream analog system in U.S. supports the transmission of several analog video channels in the 50-550 MHz band using amplitude modulated -vestigial sideband (AM-VSB) signaling scheme, whereas the digital video and data services occupy 550-750 MHz band. These digital services utilize M-ary QAM (quadrature amplitude modulation) scheme for transmission. The frequency band 5-42 MHz is reserved for the transmission of digital services in the return path. The transmission in the return path is accomplished by either using M-QAM or quadrature phase shift keying (QPSK) modulation schemes.

The broadband HFC/CATV network provide simultaneous transmission of both multichannel analog video and digital video/data channels using AM-VSB and M-QAM schemes respectively. The RF QAM digital transmitters and receivers, also commonly known as QAM modems are the critical elements of a broadband HFC/CATV networks to transport digital video and audio compression are set by the Motion Pictures Expert group (MPEG) [12]. The high speed internet access digital data are transmitted using cable modems based on Data Over Cable Interface Specifications (DOCSIS) [13]. Other different standards for broadband digital data services include Digital Audio-Visual Council (DAVIC) or Digital Video Broadcasting (DVB) [14].

In a broadband HFC/CATV transport system, the broadcast AM-VSB optical signal at 1550 nm or 1310 nm is amplified and then combined with the broadband optical M-QAM signal for forward transmission. The broadband optical M-QAM signal carries the digital video and data, which are transmitted over different wavelengths $\lambda_1, \lambda_2, \ldots, \lambda_N$ using a (DWDM) dense wavelength division multiplexing (MUX) device. This hybrid optical signal is transmitted over a SMF to the respective fiber nodes. Today, these systems carry about eighty analog video channels and thirty 64/256 QAM channels. In the return path, each subscriber is connected to the closest fiber node via a coaxial cable. The MUX device located in the hub multiplexes the received return signals for transmission towards the headend. Finally, the wavelength demultiplex device (DMUX) located in the headend demultiplexes the wavelength stream into individual wavelengths for further processing.

3. ENABLING TECHNOLOGIES

Unlike the metro and long-haul lightwave systems, the HFC/CATV transport systems have different requirements in terms of system performance due to the simultaneous transmission of both analog and digital signals. The key lightwave technologies involved in a broadband HFC/CATV transport system are: analog DFB lasers, external modulators, optical amplifiers, analog optical receivers, and digital return technology. The analog CATV transmission must provide a high carrier to noise ratio (CNR) to achieve an acceptable signal quality at the receiver. Hence, requirements for DFB lasers are high output power, low RIN, high linearity, and low distortion. The signal distortion in analog transmission systems is determined by the nonlinearity of the power versus current characteristics of a DFB laser and measured in terms of CSO and CTB levels. The CSO refers to composite second order distortions due to 2nd order nonlinearity, whereas CTB is the composite triple beat, also known as composite third order distortion, which occurs due to third order nonlinearity.

The use of directly modulated DFB lasers in the 1550 nm wavelength region causes severe signal distortions due to fiber dispersion and hence limits the transmission distance to a few kilometers [15]. Therefore, external modulators such as MZ modulators are essential to minimize these signal distortions. The main design
requirement for an external modulator is that it should provide high linearity for analog transmission. The MZ modulators which were used for digital transmission cannot be readily used for analog applications and hence require some corrective design measures. Several linearization techniques or pre-distortion circuitry have been incorporated into the design of these external modulators to minimize the signal distortions [16-17]. In addition, suppression of stimulated Brillouin scattering (SBS) effects and interferometric noise were also achieved in these modulators [18]. The analog optical receivers located at the fiber nodes, hubs or headends are designed to detect and process the SCM analog video (AM-VSB) signals. Hence, the performance requirements of these receivers are different from those of digital receivers. These receivers must provide a flat frequency response in the downstream and upstream frequency bands.

The performance of optical amplifiers play a key role in the development of long trunk HFC/CATV transport systems [19-22]. The amplifiers are required at the master headend or hub locations to boost the signal levels. The major requirements for optical amplifiers are: high output power, low noise, low distortion, low gain tilt, and polarization insensitivity. These requirements warrant the use of doped fiber amplifiers such as PDFAs or EDFAs, instead of semiconductor based amplifiers. The PDFAs amplify the 1310 nm CATV transmission signals and EDFAs are commonly utilized in many of the today’s 1550 nm HFC/CATV long distance transmission systems. Some of the recent developments include high power ytterbium-erbium doped fiber amplifiers (YEDFAs), which provide an output power of 25 dBm. In addition to the higher power requirements, the amplifier noise figure should be low to maintain a required CNR in a cascaded amplifier link. The low noise figure between 3 and 4 dB has been achieved by using the 980 nm laser pumps. Another requirement is that gain equalization in EDFAs is required to suppress the CSO distortions induced by gain tilt. The Er-Al codoped fiber amplifiers have proven to be beneficial towards minimizing the gain tilt [22].

One of the problems in a two-way HFC network is that the performance of a return path is severely limited by noise, ingress, and low bandwidth. The digitization of RF signals leads to efficient and improved performance of the return path in HFC/CATV systems [23-24]. The performance of the digital return is characterized by the noise-power-ratio (NPR) and dynamic range. The NPR is defined as ratio of signal-to-noise plus nonlinear distortion. The NPR is limited by the Gaussian noise at lower input power levels and the clipping and nonlinear distortions limit the NPR at higher signal power levels. The dynamic range is the difference between high and low power signal levels, which maintain a desired NPR. In practice, an overall NPR of about 37 dB along with a dynamic range of 11 dB is typically required for satisfactory operation of the digital return link.

4. SYSTEM PERFORMANCE & IMPAIRMENTS

The performance of HFC/CATV transmission systems are limited by many degradation mechanisms or impairments. The primary degradation mechanisms in short trunk (< 30 km) AM-VSB/M-QAM lightwave systems include clipping-induced distortion, multiple optical reflections, and dispersion induced distortions. On the other hand, the long trunk (> 50 km) AM-VSB/M-QAM lightwave systems incur penalties due amplifier spontaneous emission noise (ASE) and fiber nonlinearities such as self phase modulation (SPM), Stimulated Brillouin Scattering (SBS), cross phase modulation (XPM) and Stimulated Raman Scattering (SRS). The impact of all these impairments on the performance of AM-VSB/M-QAM is discussed in the following paragraphs.

Clipping-Induced Distortion

The clipping-induced distortion occurs when the laser is driven below the threshold current by the composite AM/QAM signal, resulting in clipping the modulated waveform. The experimental results indicate that the clipping induced distortion combined with receiver shot noise, thermal noise, and laser RIN sets a practical limit on capacity for a given laser power level [25]. In the case of M-QAM transmission systems [26], the BER is significantly degraded forming a BER floor due to laser clipping. Figure 3 shows the BER performance of a 64-QAM signal based on the BER model and measurements. The BER results presented in Figure 3 are based on the transmission of 60 simulated AM-VSB NTSC channels along with a single 64-QAM channel at 601.25 MHz using a directly modulated DFB laser transmitter. It can be seen that the BER of the QAM channel degrades significantly with a higher AM modulation index of 6% and BER floor occurs as the optical modulation index (OMI) is increased.

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Several methods have been proposed and demonstrated during the recent years to minimize the clipping distortion in AM/QAM transmission systems [27-28]. The popular methods are based on pre-clipping the composite AM-VSB signal before modulation. In this method, the SCM AM-VSB signal is pre-clipped by a limiter in order to avoid the below threshold operation of the laser. The pre-clipped AM signals are passed through a bandpass filter and then they are multiplexed with QAM signals before driving the laser diode.

Multiple Optical Reflections

The signals in a lightwave link are reflected towards the transmitter through discrete reflections from splices, connectors, and couplers or by double Rayleigh backscattering (DRBS) [29-30]. These multiple reflections convert the laser phase noise fluctuations to intensity noise through the interference of the scattered and original signals. The noise resulting due to the interference between two or more reflections is called interference intensity noise (IIN). The total relative intensity noise (RIN) along the link is significantly increased due to multiple reflections. Figure 4 depicts the effect of multiple reflections on the performance of a 16-QAM channel using a directly modulated DFB laser transmitter.

It can be seen from Figure 4 that the BER degrades significantly as the reflection level is increased to -40 dB or higher. The effect of these multiple discrete reflections can be minimized by using isolators, fusion splices, and angle polished (APC) connectors.
Dispersion-Induced Nonlinear Distortions

The dispersion induced nonlinear distortions occur due to the interaction of laser chirp with fiber dispersion [31-32]. This happens in the case of a directly modulated 1550 nm DFB laser transmission over a standard SMF, leading to the second order distortions. Figure 5 shows the calculated CSO distortion (dBc) versus fiber span length for different AM-VSB channels using a 1550 nm DM-DFB laser transmitter.

![Figure 5](image)

**Figure 5** Calculated CSO distortion (dBc) versus fiber span length for different AM-VSB channels. The calculations assume 42 AM-VSB channels with a frequency chirp of 720 MHz/mA over a standard SMF. Source for Figure: [31]. © 1994 IEEE.

It can be seen that the CSO levels increase with the increase in fiber length. The CSO distortion of < -55 dBc limits the fiber length to only a few kilometers. Therefore, the directly modulated DFB laser transmitters operating at 1550 nm over a standard SMF can not be used for long-distance transmission over a standard SMF. However, the CSO distortions can be minimized if a 1550 nm externally modulated DFB laser transmitter is used. The other option is to utilize dispersion compensating fibers to compensate for the fiber dispersion, thus reducing the CSO distortions to the acceptable levels [42].

ASE NOISE

In the case of long trunks, although the in-line amplifiers compensate for the fiber span losses, but add ASE noise, thus degrading the CNR of the transmitted signal. Figure 6 shows the measured CNR of a 547.25 MHz channel versus the AM modulation index with in-line EDFAs over a 120 km SMF.

![Figure 6](image)

**Figure 6** The measured CNR of 547.25 MHz versus the AM modulation index with and without in-line EDFAs over a SMF. Fiber length: 50 km (without in-inline EDFAs) and 120 km (with two-inline EDFAs). Source for Figure: [33]. © 1998 IEEE.
It can be seen that the in-line EDFAs affect the CNR of the transmitted signal significantly due to the signal-spontaneous and ASE-ASE beat noise components. Notice that the measured CNR is decreased by 4.5 dB due to the in-line EDFAs. Similarly, the experimental results indicate that the BER performance of 256-QAM signals incurred a power penalty of about 2.5 dB due to the line EDFAs as a result of ASE noise [33].

Self Phase Modulation

Self phase modulation (SPM) arises due to the power dependence of the refractive index of the core, resulting in frequency chirping or phase modulation of the signal. In AM-VSB transmission systems, the interaction of frequency chirping of the signal with fiber dispersion leads to significant nonlinear CSO and CTB distortions at the receiver [34-35]. The magnitude of CTB distortion due to SPM is much smaller than the CSO distortions. Figure 7 depicts the calculated CSO distortion induced by SPM in a long distance HFC/CATV link.

![Graph showing CSO distortion vs fiber length](image)

**Figure 7** Calculated CSO distortions in an AM-VSB transmission system over a 3×50 km SMF at 480 MHz. The calculations assume a modulation index of 5% and a channel power = 16 dBm. Source for Figure: [35]. © 1999 IEEE.

As can be seen from Figure 7, the CSO levels increase significantly with the transmission distance and reach an unacceptable level of about -45 dBc at 150 km. Therefore, the minimization of SPM induced CSO distortions is particularly important in long distance amplified CATV transmission links. An effective technique to minimize SPM effect in a standard SMF is to employ dispersion compensating modules, at each fiber span, which reduces the fiber dispersion [42]. The effects of SPM are expected to be smaller over other fibers such as Allwave, NZDSFs or DSFs.

Stimulated Brillouin Scattering (SBS)

The Stimulated Brillouin Scattering (SBS) arises due to the interaction of light with the vibrational modes (acoustic phonons) of the fiber and the fiber launch power is limited by the SBS power threshold. This power threshold becomes smaller for signals operating at 1550 nm wavelengths over longer distances. Also, it is important to note that the SBS power threshold also depends on the linewidth of an optical source. Higher linewidths give rise to higher SBS thresholds. In practice, the SBS power threshold is increased by using SBS suppression techniques. First, the effect of SBS can be countered by broadening the laser optical spectrum above the Brillouin linewidth. This method has been applied in [34] to obtain higher spectral linewidths by directly modulating a laser with a sinusoid at a frequency (called dither frequency) much lower than the lower-frequency cutoff of the receiver. This will cause the laser to be FM modulated at a frequency that is outside the receiver bandwidth, but will result in a large effective linewidth. Another popular way to broaden the source linewidth is to phase dither the output of an external modulator [55]. In this case, a single tone phase modulation around 1.8 GHz (twice the maximum channel frequency) is used to increase the SBS power threshold. Using this method, the SBS threshold power of 17 dBm has been obtained for 1550 nm long-haul HFC/CATV transmission systems [36].

Stimulated Raman Scattering (SRS)

Stimulated Raman Scattering is an interaction between the light and vibration of silica molecules. The incident light wave scattered by molecules undergoes a shift in the frequency, called the Stokes frequency. Thus, if two optical waves separated by the Stokes frequency are co-injected into a Raman active medium, then the lower frequency wave (called the probe wave) gets amplified at the expense of the higher frequency wave (called the pump
wave). The process of this amplification is known as Stimulated Raman Scattering phenomena and affects the performance of multi wavelength HFC/CATV transmission systems [39, 41]. SRS causes the power transfer from the shorter wavelength channels to longer wavelength channels, thus leading to crosstalk at the subcarrier frequencies of AM-DSB signals. In WDM-SCM systems, each wavelength is modulated by a set of RF subcarrier frequencies. Hence, the SRS crosstalk terms at the subcarrier frequencies are generated through SRS interaction between the subcarriers and optical carriers through modulated gain. Figure 8 shows the SRS crosstalk versus channel optical power for different wavelength spacings in the case of 1300 nm transmission over a 20 km standard SMF.

![Figure 8](image)

**Figure 8** Calculated SRS crosstalk versus channel optical power for different wavelength spacing with two WDM-SCM channels for 1300 nm transmission over a 20 km standard SMF. Source for Figure: [39]. ©1995 IEEE.

The SRS crosstalk increases with the number of channels and higher channel power levels. For WDM-SCM systems operating in the 1550 nm wavelengths, the SRS crosstalk will be significantly lower at higher subcarrier frequencies (≥ 400 MHz), because of higher fiber dispersion and causes walk-off between RF subcarriers at different wavelengths [39]. Hence, the non zero dispersion fibers such as SMF results in lower SRS crosstalk than DSF. Also, decreasing the channel spacing and/or the channel power will decrease the effects of SRS, but system design should adopt a trade-off between the channel spacing and power.

**Cross Phase Modulation (XPM)**

XPM arises, when the phase of one optical carrier is modulated by other WDM channels. The phase modulation is converted to intensity noise due to fiber dispersion leading to nonlinear interaction between the optical carriers that is referred to as XPM crosstalk [40-41]. The calculated XPM crosstalk at 500 MHz is shown in Figure 9 as a function of channel spacing in a 1550 nm SCM-WDM transmission over a 20 km SMF.

![Figure 9](image)

**Figure 9** XPM crosstalk at 500 MHz versus channel spacing in a 1550 nm SCM-WDM transmission (2 channels) over a 30 km SMF at a channel power of 10 dBm. Source for Figure [42].
It can be seen that the XPM crosstalk decreases with increase in channel spacing as a result of walk-off due to fiber dispersion. The channel spacing of less than 5 nm yields a higher XPM crosstalk. The XPM crosstalk also increases with the number of channels and channel power as similar to SRS crosstalk. But, XPM crosstalk is smaller for larger channel spacing and increases with higher subcarrier frequencies. Therefore, the combined effects of XPM and SRS must be optimized with respect to subcarrier frequencies and channel spacing in a SCM-WDM system design [41].

5. CONCLUSION

This paper gave an overview of HFC/CATV transmission systems in terms of infrastructure, transmission formats, enabling technologies, system performance and impairments. The performance of some typical HFC/CATV transmission systems were discussed due to many impairments. A careful system design is essential to optimize the performance of a hybrid AM-VSB and M-QAM system with respect to system impairments such as clipping and dispersion induced distortions, optical reflections, ASE noise and fiber nonlinearities. Some of the optimized results pertaining to the minimization of fiber nonlinear effects [42] will be outlined during the presentation.

ACKNOWLEDGEMENT

The authors would like to thank Bryant Isaacs, President of ARRIS New Business Ventures Unit for supporting the consulting project towards the investigation of the impact of fiber nonlinearities in SCM/WDM long distance 1550 nm transmission systems as well as Purdue University (North Central) for supporting this consulting activity [42]. In addition, the authors would like to acknowledge several researchers [2-41] who contributed their work in the field of HFC/CATV transmission systems.

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