Digital Data In Analog Signals

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Abstract

The NTSC television system was designed primarily to make television receivers affordable in the era of vacuum tube circuits. In the age of digital and analog integrated circuits, much more aggressive signal processing is possible. This allows some of the signal inefficiencies accepted when NTSC was created to be overcome. It is now possible to add significant amounts of digital data into an analog signal in a compatible manner. The FCC has authorized the use of several of these systems and has encouraged the development of others.

Some of these systems simply use the Vertical Blanking Interval, VBI. Others add additional carriers. At least one system takes over portions of the video screen and adds digital data in its place.

This paper will review the methods proposed for compatible data insertion *into NTSC signals and explore possible applications of this approach.*

INTRODUCTION

Ancillary signals are additional signals which may or may not have anything to do with the video program content. Ancillary signals are a "bonus" which allows additional information and services to be provided. These signals were initially impractical due to the expense of early receiving circuits. Ancillary signals are possible because the spectrum utilization of the television signal is relatively inefficient. The goal of the designers of the television system, the National Television Systems Committee (NTSC) was to facilitate affordable consumer television receivers while maximizing the number of channels possible. This, of course, is a difficult trade off. A consequence of this difficult challenge is that there is spectrum capacity to harvest now that more complex electronics can be brought to bear.

The Data Application

Data transmission was the initial application for ancillary signals because data rates which fit into the under utilized spectrum spaces could produce useful results while not placing unrealistic demands on circuit design.

One of the first ancillary signal applications was Closed Captioning for the hearing impaired. The conservative design that characterized consumer electronics was extended to the captioning system. A very low data rate was employed. Fortunately, that is all that is required for this application.

Teletext is a more aggressive data application which puts text, graphics, and even photographs on the television screen. Additionally, Teletext can "download" software to computers either internal or external to the television receiver. While Teletext has failed in the U.S., it has enjoyed considerably greater reception in Europe.

The successors to Teletext are the systems currently becoming available for access to the Internet using television receivers or set top boxes. In other related applications, the signal directly feeds a computer. Because of the massive computing power available, much more interesting images can be delivered. Personal computers are now available with one or more tuners built in.

The Video Application

Recent developments in the television industries have focused upon the transmission of High Definition Television (HDTV) which requires a substantial increase in transmitted information and hence would greatly expand the required analog video signal bandwidth. This is unacceptable. Digital approaches are the solution. Great progress has been made in the area of digital TV bandwidth compression and a national standard has been selected by the Federal Communications Commission in December 1996. These HDTV developments have, by a combination of techniques, substantially reduced the bandwidth required for fully digital transmission of the video information. For instance, a single HDTV channel can be transmitted within the analog Broadcast TV channel assignment of 6 MHz rather than the tens of megahertz once thought necessary. In the case of cable's well-behaved spectrum, double the data transmission rate is possible. Two HDTV signals can be carried in 6 MHz.

This same technology which makes HDTV in 6 MHz possible allows multiple standard definition digital signals to be stuffed into 6 MHz. Movies have several advantages over video in this regard. Movies have twenty five frames per second versus video's thirty. This alone is a twenty five percent reduction in data requirements. Movies have the further significant advantage that they can be processed iteratively. That is, the movie is run through the processor several times with adjustment of the processor made to minimize the creation of artifacts on a scene by scene basis. Very good results have been obtained with movies at data rates of 3.0 Mbps. Quite acceptable results have been seen at 1.5 Mbps. When compared to the video obtained from a commercially recorded VHS cassette, the digital results have some advantages. Since the HDTV transmission rate is around 19 Mbps (in 6 MHz), six 3.0 Mbps movies can be carried in the same spectrum. At 1.5 Mbps, double that number is possible. Since cable has a more controlled spectrum, it can approximately further double these numbers leading to perhaps twenty four movies in 6 MHz. This is even more practical in systems that use statistical multiplexing.

The development of HDTV and its acceptance as a future broadcast standard has led to the requirement for a transition period between broadcasting the present analog TV to that of compressed digital HDTV.

It is quite likely that digital transmission of the current NTSC (standard definition) television signals will also become attractive for some applications, particularly in the transition period. Digitally compressed NTSC is now being delivered in several media with bandwidths much less than the traditional 6 MHz per channel. Since the transmission of standard analog NTSC will remain for many years before complete transition to digital high definition, the availability of a technique allowing simultaneous, non-interfering transmission of digitized NTSC-resolution signal(s) within the same spectrum as an analog NTSC signal could result in a two (or more) times expansion of channel capacity in the existing broadcast frequency assignments. If more efficient means of bandwidth compression emerge, even the transmission of HDTV simultaneously with analog NTSC is an attractive, though distant, possibility.

VBI TECHNIQUES

The original display device used in television receivers was the Cathode Ray Tube, CRT, which uses an electron beam to stimulate a phosphor coating on the inside face of a vacuum tube. This vacuum tube is appropriately called a picture tube. The electron beam is scanned horizontally to form lines and vertically to paint a complete image. The strength of the electron beam is in inverse proportion to the strength of the television transmitter power and regulates the amount of brightness in the picture. The deflection of the electron beam can be accomplished by electrostatic forces or magnetic forces. Most television display devices used magnetic deflection. Magnetic deflection circuits require time to move the electron beam back to the left side of the screen. During this time, the electron beam must be turned off or blanked to prevent unintended stimulation of the phosphor screen and the resulting interfering light. The period of time during which the electron beam is turned off is called the "horizontal blanking interval." When the electron beam reaches the bottom of the screen, it must be returned to the top of the screen to continue the process of making pictures. Just as in the horizontal case, the electron beam must be blanked to prevent disturbing light patterns on the screen. This period is called the Vertical Blanking Interval (VBI). The VBI is much longer than the horizontal blanking interval. The combination of the two blanking intervals constitutes around twenty five percent of the total time. This time cannot be used to convey pictures, but it can be applied for other useful purposes.

Closed Captioning

The first United States attempt to use the VBI for ancillary purposes was in 1970 when the National Bureau of Standards (NBS) proposed to use it for the distribution of precise time information nationwide. The ABC television network was a partner in that effort. While this initiative did not result in a service, ABC recommended a captioning service for the hearing impaired. The First National Conference on Television for the Hearing Impaired met in Nashville, Tennessee in 1971. This was followed with a demonstration by the NBS and ABC at Gallauded College in early 1972. In 1973, the engineering department of the Public Broadcasting System (PBS) initiated development funded by the department of Health, Education and Welfare (HEW). As a result of this work, the FCC reserved line 21 of field one of the television signal for the transmission of closed captions in the United States in 1976. In 1979, the National Captioning Institute (NCI) was founded to caption programming and to further the cause of captioning. In the early 1980s, Sears Roebuck stores carried a captioning decoder in set top box configuration selling for about \$250. In 1989, NCI contracted for ITT Semiconductor Corporation to develop a cost effective caption decoder microchip for use in television receivers. In 1990, Congress passed the Television Decoder Circuitry Act mandating new television receivers of thirteen inch diagonal display measure or greater to include caption decoding circuits after July 1, 1993. Approximately twenty million television receivers per year are covered by this requirement. 1992 saw NCI work with the FCC and the Electronic Industries Association (EIA) to develop captioning technical standards. The 1996 Telecommunications Act requires the FCC to institute rules requiring closed captioning on video programming but allowing exemptions for programming that would suffer an "undue burden".

The Closed Captioning (CC) system is called "closed" because it is turned "on" or "off" depending on who is using the television receiver. Those without hearing impairments and who understand the spoken words need not be disturbed by text on their screens. The CC system uses very low speed data in order to minimize the impact of transmission path problems such as reflections and interfering signals. The data rate for the CC systems is 503.5 Kbps of binary (two level) data. This allows only two eight bit characters to be transmitted per VBI line. If only field one is used, there will be thirty of these lines per second. This yields 480 bps or 3,600 characters per minute. If the average word is five characters long with a space, then 600 words can be conveyed per minute. The rest of the line is occupied with both a burst of seven sine wave cycles of 503.5 KHz clock run-in and a unique "start bits" pattern placed at the beginning of the line. These signals synchronize the detector circuitry. Since only Line 21 is protected for captioning by FCC rule, the rate of transmission is slow, but perfectly adequate for the purpose. The on-screen display consists of a maximum of fifteen rows of thirty two characters each. The captions usually appear only on rows one through four and rows twelve through fifteen. The middle rows are usually transparent to show the action. A text mode provides scrolling text. Further details can be found as part of the Electronic Industries Association (EIA) standard number EIA-608.

The closed captioning signal carries four components. There are two captioning "channels" and two text channels. The first captioning channel is synchronized to the video programming so that the words carefully match the video. The second captioning channel is not synchronized.

The EIA filed a petition with the FCC to expand the captioning standard EIA-608, to allow use of line 21 field 2. This adds two more captioning channels and two more text channels. A fifth channel has been added to carry Extended Data Services (EDS). EDS will carry a wide variety of additional information. Finally, the original intent of the NBS will be realized. Precise time information will be transmitted to set VCR clocks (and other clocks as well). The channel's name and call letters are included along with current program information such as title, length, rating, elapsed time, types of audio services and captioning services and intended aspect ratio. Also included is the data for the "V-chip" which is intended to control children's access to programming. Public service announcements such as weather and emergency advisories are also transmitted. Cable system channel layout information is provided so that the channel number indicator can use the more familiar channel identification number rather than the number associated with the frequency utilized. This facility will bring the same "channel mapping" benefits subscribers have enjoyed in their cable set top terminals to consumer electronic products.

Teletext

Teletext is a more aggressive form of data transmission which has been successful in Europe, but has failed to enjoy commercialization in the US. Teletext originated in Great Britain with experimental transmission commencing in 1972. The British Broadcasting Corporation (BBC) branded their service "Ceefax" while the Independent Broadcast Authority (IBA) called their service "Oracle". France developed a packet based Teletext system called Antiope based on a transmission system called Didon. Later Canada developed another system called "Telidon" which featured higher resolution graphics. The Japanese system, called "Captain" featured "photographic coding" to accommodate the Chinese Kanji characters and the Japanese Kana set.

There are a number of reasons for the difficulties in the US. Principle among these was the failure to find a strategy which made money. Without this, the system could not be supported. Additional difficulties included the high cost of memory at the time of implementation. While a Teletext page requires only about a kilobyte of storage, that small amount of memory was expensive then. Further problems centered around the quality of the graphics. The less expensive World System Teletext (WST) had crude "Lego-style" graphics in its basic form. The other contender, the North America Presentation Layer Protocol System (NAPLPS) used a higher resolution graphics system which painfully painted itself on the screen resulting in excessively long delays which tried the patience of the user. Still another complication was the FCC's 1983 decision to allow two standards and a marketplace resolution of the winner. One of the systems is based on the British approach and is called World System Teletext (WST) and the other is the NAPLPS evolution of Antiope, Telidon, and efforts by AT&T. A final problem was reliability of data reception. In a test in the Bay area of San Francisco, only about twenty five percent of installations of the NAPLPS system were trouble free. The remainder suffered from various degrees of multi-path impairment.

Both U.S. Teletext systems have a data rate of 5.727272 Mbps which is 364 times the horizontal rate and 8/5 of the color subcarrier. The data signal has a Non Return to Zero (NRZ) binary format. The WST data line consists of eight cycles of clock run-in (sixteen bits) followed by a unique eight bit "framing code" followed by sixteen bits of control codes and a payload of forty eight-bit display words. Since the page format is forty characters by twenty rows with an additional "header row", twenty one field lines are required per page of WST Teletext. The payload of 320 bits per line allocated means that if one VBI line in each field is allocated, a data rate of 320 x 2 x 30 = 19,200 bps is obtained. Ten lines of VBI are possible (Line 21 is reserved for captions and the first nine lines form the vertical synchronization pulses) yielding a maximum of 192 Kbps for full VBI utilization.

The WST system maps the data location in the VBI line to memory locations and to screen locations and always puts data in the same memory place. This allows for a very simple error protection scheme. Received data is compared with data already in memory. If it agrees, confidence builds that it is correct. It is possible to use a "voting" approach to obtain very robust transmission.

Packetized Teletext

The fundamental difference between the WST and the evolving set of Antiope, Telidon, and NAPLPS systems is that the latter systems all used a packet structure. They have been characterized as asynchronous because there is no mapping between the transmission scheme and memory and screen locations.

PBS has developed a packetized data delivery system based on Teletext called the "PBS National Datacast Network". The standard Teletext data rate of 5.72 Mbps is used yielding 9600 baud per VBI line allocated per field. The Datacast network distributes the same signal nationally. The goal is to generate revenue to help support the PBS network. There are a wide variety of commercial applications for this signal. Currently, the StarSight Electronic Program Guide (EPG) signal is distributed via PBS.

WavePhore

WavePhore utilizes lines 10 through 20 in each field for a data speed of up to 150 Kbps. WavePhore added substantial error detection and protection bits to its structure to protect against multipath and other transmission problems.

SUB-VIDEO TECHNIQUES

There are under-utilized portions of the NTSC spectrum which can be employed to "hide" data. In many cases, the process of hiding the data in incomplete and results in artifacts under certain conditions. In other cases, the preparation of the NTSC signal so that hiding is more effective, by itself reduces video quality. So the challenge is to both hide the data and not impair video quality while retaining signal robustness and the potential for an economic implementation.

The National Data Broadcasting Committee (NDBC) was formed in 1993 to establish a single standard for data transmission in video. It issued a request for proposals (RFP) and narrowed down the selection process to two contenders: WavePhore and Digideck. Laboratory tests were conducted by the Advanced Television Test Center (ATTC) in Alexandria Virginia in December 1994. In April of 1995, the NDBC selected Digideck for field testing. In June, WavePhore convinced the committee to re-test their system after improvements made based on the results of the lab tests.

Meanwhile, the FCC issued a Notice of Proposed Rulemaking (NPRM) in April of 1995. On June 28, 1996, the Federal Communications Commission (FCC or the Commission) approved digital data transmission in the video portion of broadcast television transmission in its Report & Order (R & O), "Digital Data Transmission Within the Video Portion of Television Broadcast Station Transmissions", in MM docket No. 95-42. This R & O amends FCC rules to allow ancillary data *within* the video portion of the NTSC signal in four formats. Two of the formats, by Yes! Entertainment Corporation and A. C. Nielsen Co. place low data rate signals in the overscan region of the picture. The other two systems, Digideck and WavePhore, embed the digital signal into the video signal. Both Digideck and WavePhore participate in the voluntary standards committee titled The National Data Broadcasting Committee (NDBC) sponsored by the National Association of Broadcasters (NAB) and the Consumer Electronics Manufacturers Association (CEMA). NDBC has conducted field tests of these systems in Washington, D. C. on WETA, channel 26 and WJLA, channel 7.

WavePhore

WavePhore encodes about 300 Kbps into the baseband portion of the video.

The WavePhore system begins by reducing video luminance and chrominance bandwidths. The "luminance" is reduced from its theoretical value of 4.2 MHz to 3.9 MHz and the upper sideband of the color signal is reduced by about 300 KHz. It is then possible to insert a data signal in this region at a carrier frequency of approximately 4.197 MHz above the video carrier and a strength approximately 20 dB above the noise floor of the video system. The data is synchronous with the video carrier and thus with the horizontal line frequency. As an odd multiple of one-quarter the horizontal scan frequency, it interleaves between the luminance and chrominance bundles of spectral energy. Data is not sent during the vertical and horizontal blanking intervals. Thirty bits of data are sent per video line. There are 240 available lines per field (not counting the VBI during which the signal is blanked). This yields a raw data rate of 431.6 Kbps. After error correction coding, the raw date rate is reduced to approximately the T1 rate divided by four or 384 kb/s. This one quarter the telephone T1 data rate and so WavePhore calls their system TVT1/4.

WavePhore shuffles the data before applying bi-phase modulation and filtering out the lower sideband. Shuffling the data reduces its visibility in the video. An adaptive equalizer is used in the receiver. A major advantage of the WavePhore approach is that once inserted into the video, it can be conveyed through and video path without giving it further attention. The WavePhore VBI system and the WavePhore sub-video system can be combined to provide over 500 Kbps.

There is some degradation of pictures using this system. However, it appears that the regulating body, the Federal Communications Commission, is willing to let the broadcaster determine what his individual marketplace values and to respond to that decision.

Digideck

The Digideck system adds a Differential Quadrature Phase Shift Key

(DQPSK) signal carrying about 500 Kbps. placed one MHz below the video carrier. In this regard, it is similar to the European NICAM system for adding digital audio to analog television broadcasts. This places the new carrier in the Vestigial Side Band (VSB) region of the signal. To accommodate this, the lower VSB slope is increased. Rather than starting at the traditional 750 KHz below picture carrier, in the Digideck system, it starts 500 KHz and drops more rapidly. The carrier is about 36 dB below peak power and has a raw capacity of 700 Kbps. Forward error correction and other overhead burdens reduce the data capacity to around 500 Kbps. Digideck calls the new carrier the "D-Channel". The data signal is clocked synchronously to the television signal for ease of recovery and for better hiding in the video.

The Digideck receiver also depends on an adaptive equalizer. A consequence of the D-Channel is that it must be inserted at the transmitter site and brought there by an alternate path.

Like the WavePhore system, Digideck introduces some artifacts. A marketplace approach will allow the Broadcaster to determine acceptability.

OVERSCAN TECHNIQUES

The Yes! Entertainment Corporation's system introduces a pulse in the video between 9.1 and 10.36 microseconds after the start of the horizontal synchronization pulse. The data rate is very low, about 14 Kbps. Its application is to deliver audio to a talking toy teddy bear! A.C. Nielsen uses line 22 of one field of the video for transmitting a program source identification. This ID is used to measure the viewing population for statistical purposes. A fifth system, by En Technology was denied permission at the time of the R & O. This system allowed data to extend from the VBI into all areas of the picture with the image being constrained to a variable size box surrounded by the "snow" caused by the data. This system was judged too intrusive.

APPLICATIONS

There are a variety of applications for data in analog signals. Data can be supplied as just data. Alternatively, if sufficient capacity is available, data can be used to deliver digital video or digital audio services. The data can be used with personal computers, special television sets or set top boxes or versions of the "net computer".

The January 1997 Winter Consumer Electronics Show in Las Vegas was dominated by two developments: the Digital Video Disk (DVD) and the World Wide Web on television set top boxes. This latter application has a great deal of equipment manufacturer excitement associated with it. Time will tell whether the marketplace catches the same degree of excitement.

A related application involves Datacasting. This is the inclusion of data in the broadcast television signal for use with a personal computer. The most aggressive such implementation is Intercast whose main partners include Intel and NBC. HyperText Markup Language (HTML) formatted Web pages are delivered in the VBI of the television signal. HTML is a method of linking information. Highlighted words or phrases can be "clicked on" and relevant information appears on the screen. In some cases, this is achieved by going to another location in the same document. In still other cases, data from another document is displayed. In other cases, locations on the World Wide Web are automatically accessed and information retrieved. A personal computer with a television tuner receives the signals and displays the video in a small window. The rest of the screen displays the HTML pages. The computer's hard disk can capture and store pages of interest. Since HTML pages are around 50 Kbytes each and most personal computers now come with at least a 1 GB hard drive, capacity is not a problem. In a major application of this technology, the pages downloaded pertain closely to the video programming. When several hundred pages are downloaded, the access speed is governed by the hard disk, not a modem. In affect, the server is built into the personal computer! The HTML nature of the pages makes accessing different parts of the data downloaded easy and familiar to any Web surfer. The HTML can include embedded links to related Web sites accessed with the computer's regular phone or cable modem. Access to these sites is automatic.

CABLE VS BROADCAST DATA

Since cable's spectrum is much more well behaved than the broadcast spectrum, several significant advantages accrue. A time domain equalizer may not be necessary. If one is included, it may have relaxed specifications leading to lower cost. There is no "airplane flutter", i.e. Doppler effect from approaching or receding aircraft. Because the spectrum is better behaved, less error detection and correction is required for a given level of performance. This was well demonstrated in the Advanced Television Grand Alliance's modulation scheme. While 8-VSB is used for broadcast, 16-VSB was developed for cable allowing two HDTV signals in 6 MHz on cable. 16-VSB does not have twice the data capacity of 8-VSB. The doubling of payload comes because 16-VSB requires significantly less data protection. If this same approach is applied to the techniques proposed for data carriage in analog television signals, more of the raw data capacity can be harvested for payload purposes. This approach has not been well explored and offers a significant opportunity. An additional advantage is cable's availability of multiple channels to carry data. The data carrying capacity of a cable system is just huge!

THE COMPATIBLE DIGITAL CABLE UPGRADE

Most plans to migrate to digital video do not include wholesale replacement of all channels because of the horrific expense of the digital set top boxes. Instead, there is the intention of converting a few of the channels to digital and leaving the remainder as analog. In this strategy, the channels converted to digital will have previously been occupied by low penetration services. Subscribers wishing to continue with those services will need a digital set top box. If these subscribers take no new services, just the ones they had previously taken, their costs go up considerably while there is no increase in revenue. Subscribers who do not wish the new advanced services will not receive a new digital set top box. However, they will lose programming previously carried on the analog channels which are converted to digital. This can be a proportionally serious loss for low capacity cable systems.

An alternative is to use techniques which hide the data in the video for carriage of digital signals. Since television tuners are relatively inexpensive, multiple tuners can be provided so that data can be collected from more than one channel. That data can then be assembled to provide the MPEG streams needed to create new synthetic channels. In this approach, all of the analog channels are preserved for those who are satisfied with the existing service. Only those willing to pay for more will incur the extra cost of the new set top box.

THE FUTURE

There is an effort underway by a new start-up company, EnCamera Sciences Corporation, to raise the capacity of data hidden in television signals to in excess of 3 Mbps per video channel. That capacity could support two MPEG video streams at 1.5 Mbps each or one higher quality stream at 3 Mbps.

Additionally, massive amounts of data can be carried for Web type applications.

While full digital television is on its way, the interim can see a lively and cost effective data service while continuing to serve the analog base of receivers.

THE AUTHOR

Dr. Ciciora is a technology consultant specializing in Cable Television, Consumer Electronics, and Telecommunications.

Most recently he was Vice President of Technology at Time Warner Cable. Walt joined American Television and Communications, the predecessor to Time Warner Cable, in December of 1982 as Vice President of Research and Development. Prior to that he was with Zenith Electronics Corporation, starting in 1965. He was Director of Sales and Marketing, Cable Products, from 1981 to 1982. Earlier at Zenith he was Manager, Electronic System Research and Development specializing in Teletext, Videotext and Video Signal Processing with emphasis on digital television technology and ghost canceling for television systems.

He has nine patents issued and several more pending. He has presented over one hundred papers and published about fifty, two of which have received awards from the Institute of Electrical and Electronic Engineers (IEEE). His papers have been translated into Japanese, Chinese, German and Spanish. Walt wrote a monthly columns for Communications Engineering and Design (CED) magazine and for Communications Technology (CT) magazine for three years each. He continues in alternate months for CED.

He currently serves on the Executive Committee of the Montreux Television Symposium. He was a member of the board of directors of the Society of Cable Television Engineers (SCTE) for six years. He was Chairman of the Technical Advisory Committee of CableLabs for four years and Chairman of the National Cable Television Association (NCTA) Engineering Committee also for four years. He was president of the IEEE Consumer Electronics Society for two years and is a past chairman of the IEEE International Conference on Consumer Electronics. He chaired the Joint Engineering Committee of the NCTA and the Electronic Industry Association (EIA) for eight years. He has served on several industry standard-setting committees. He currently co-chairs the Cable Consumer electronics Compatibility Advisory Group and its Decoder Interface subcommittee.

Walt is a Fellow of the IEEE, a Fellow of the Society of Motion Picture and Television Engineers (SMPTE), and a Senior Member of the SCTE. Other memberships include Tau Beta Pi, Etta Kappa Nu, and Beta Gamma Sigma.

Current interests center on competitive technology, the consumer electronics interface with cable, Digital Video Compression, Interactive Television, Multimedia, and High Definition Television.

Walt received the 1987 NCTA Vanguard Award for Science and Technology and was named "1990 Man of the Year" by CED magazine. CED also named him "1993 Man of the Year". He was the Fall 1994 Levenson Memorial Lecturer at the National Cable Television Center at Penn State.

Walt has a Ph.D. in Electrical Engineering from Illinois Institute of Technology (IIT) dated 1969. The BSEE and MSEE are also from IIT. He received an MBA from the University of Chicago in 1979. He has taught Electrical Engineering in the evening division of IIT for seven years.

Hobbies include helping his wife with her horses, reading, wood working, photography, skiing, and a hope to someday become more active in amateur radio (WB9FPW).

Optical Network Technology: Future Impact on CATV Networks

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Abstract

Future CATV networks may be able to transport video, data and voice services over large areas made possible by managing individual optical wavelengths within a single fiber, each wavelength carrying a different service type or going to a different location. The capability of optically routing, switching, provisioning and otherwise controlling various services without intermediate optical/electrical/optical conversion will enable creation of "All Optical Networks". This paper discusses the current state of optical technology required for these networks, where this technology is first appearing within existing CATV infrastructure, and how it may positively impact the capital, operations and maintenance costs of future CATV networks.

Introduction

Wave Division Multiplexing (WDM) is the ability to transmit two or more optical signals independently through the same fiber, utilizing different optical wavelengths. Although transmission of 1310 nm and 1550 nm wavelengths have been used for many years, it has been the advent of commercially available optical amplifiers which have made it is now technically feasible to transmit tens of optical signals simultaneously on the same fiber within a relatively narrow optical window of approximately 30 nm. This is referred to as Dense WDM Transmission, or simply dense WDM for short. Figure 1 illustrates a point to point dense WDM fiber link. Although the ability to transmit a dense WDM stream and amplify its multiple signals with a single optical amplifier is a key element of future All Optical Networks, commercial development of a number of new optical devices will be required in order to take full advantage of the potential benefits of All Optical Networks.

All Optical Networks may provide the following economic benefits to CATV service providers:

- Lower Fiber Plant Cost Through Significantly Reduced Fiber Counts
- Shared Signal Transmission and Switching Through Common Active Optical Components, Reducing Electronics Costs
- Improved System Reliability Through Reducing Overall Network Active Devices
- Faster Fiber Restoration After Cuts, Through Significantly Reduced Fiber Counts
- Reduced Future Costs For Network Capacity Expansion By Further Sharing Common Plant and Equipment

In addition to these benefits, technology improvements may allow each hub to economically serve significantly larger areas in terms of homes passed per hub, thereby allowing further consolidation and reducing operations costs.

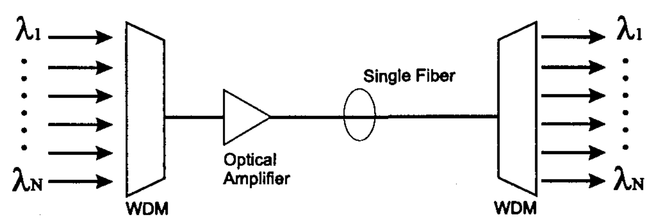

Figure 1. Dense WDM link. "N" can be 4-32 commercial applications today.

Elements of an All Optical Network

Dense WDM technology enables the creation of multiple optical circuit paths within a single fiber path (Figure 2). In relative terms, it is easy to compare an All Optical Network to a fiber network in the following way: An optical cable consisting of multiple fibers within a sheath becomes a "superset". An individual fiber within the cable can be thought of as a virtual fiber cable. An individual optical wavelength within the fiber can be thought of as a virtual fiber. Management, redundancy and routing can all be readily understood by translating requirements in conventional

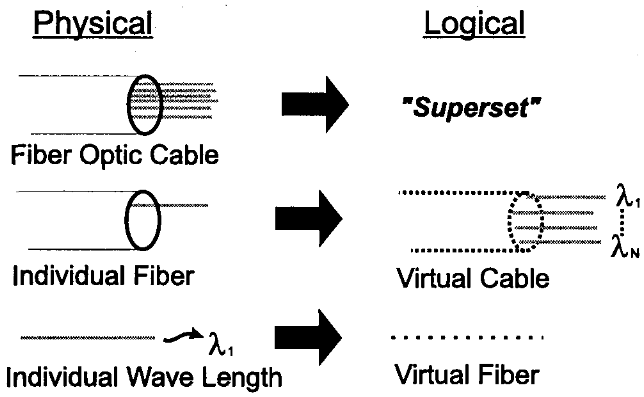

Figure 2. All optical network equivalents

networks between cables, fibers, and their virtual counterparts in an All Optical Network.

To attain the economic and operational benefits derived from implementing the future All Optical Network, a number of optical elements will be required which are currently not available in commercial quantities for wide scale deployment. Figure 3 is a compilation of these devices. From left to right shows progression in time of the anticipated evolution of these devices.

Dense WDM transmission is not without technical challenges. Operating at the 1550 nm window, attention must be paid to issues such as the dispersion performance of the optical fiber, the flatness of amplifier gain in the optical bandpass, and the optical stability of fiber devices. Recognizing these challenges, this paper is primarily focused on the potential application of All Optical Networks in CATV systems.

Large urban/suburban CATV networks consist of a series of hubs/subheadends (or video end offices) connected to one or two master headends (or video serving offices) usually via a redundant fiber optic ring, commonly referred to as the fiber backbone system. While most large backbones are exclusively digital, medium sized rings may be a combination of digital and high powered linear systems. A hybrid fiber/coax distribution architecture is used to distribute signals bidirectionally between the hub and the serving areas via linear optical transmission between the hub and optical nodes, and linear RF transmission within each serving area between the node and subscribers. Figure 4 illustrates a typical backbone system architecture while Figure 5 illustrates the distribution system architecture.

Dense WDM systems offer potential economic advantages in both digital and broadband linear (aka: analog) CATV transmission. The first area of anticipated use

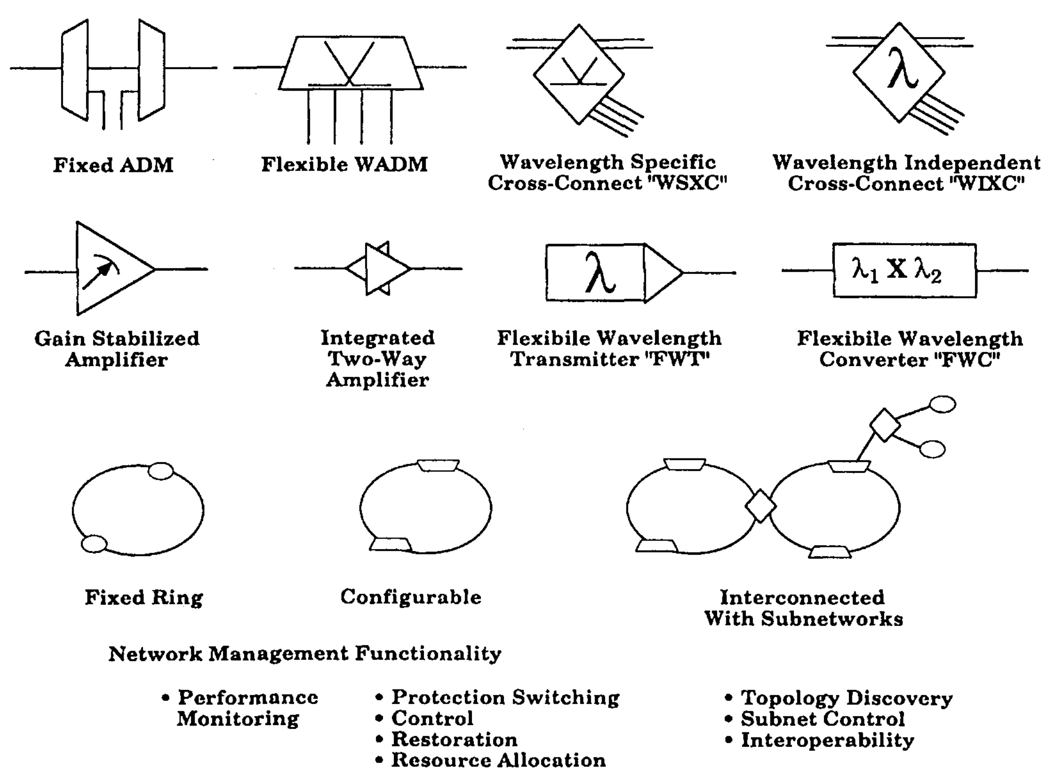

Figure 3. Current and future elements for All Optical Network: Source Bellcore

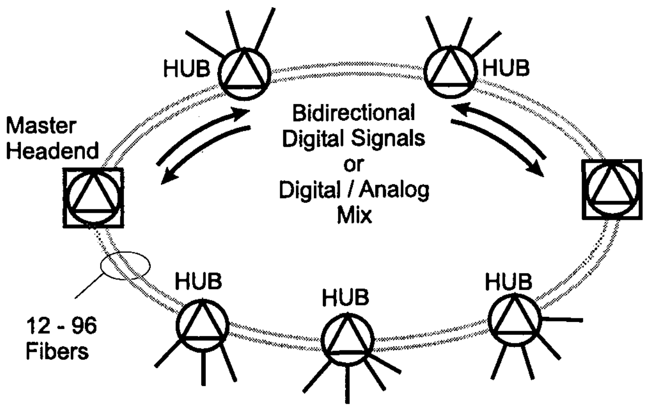

Figure 4. Backbone System. Fiber transmission is typically uncompressed digital for large networks, and a combination of digital and high power 1550 nm AM for smaller systems.

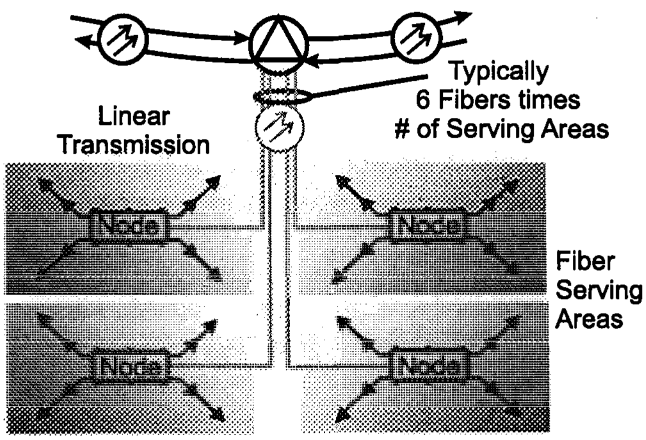

Figure 5. Distribution System. Fiber transmission is broadband linear between the hub and the optical nodes in the serving area.

of dense WDM technology in CATV networks is in fiber backbones, followed by potential implementation in the HFC distribution system.

Dense WDM in Backbone Systems

Fiber backbone systems generally cover long distances. The longest systems in the United States now cover over 500 kilometers. Given the expansion of CATV networks into the delivery of high speed data, telephony and other digital services, these systems usually employ uncompressed digital fiber systems to transport all video, data and voice services, or a combination of uncompressed digital and conventional telecommunications digital systems to transport and remultiplex various combinations of channels to create custom service delivery configurations at each sub-headend.

Shorter systems sometimes employ a combination of digital transmission systems (for voice and data services), and 1550 nm high power linear transmission systems (for broadcast video services) on separate fibers, which are then combined at the hubs.

Each fiber in backbone systems represents a significant capital cost because of the long distances traversed. The initial system may be even more expensive if requirements dictate leasing fiber(s) over a limited right of way such as a long bridge spanning a body of water. The ability of combining multiple digital signals using many optical wavelengths has already been demonstrated and commercial products are already available. For example, ADC Telecommunications demonstrated eight wavelengths of its DV6000 uncompressed digital system at the 1996 SCTE Expo as shown in Figure 6.

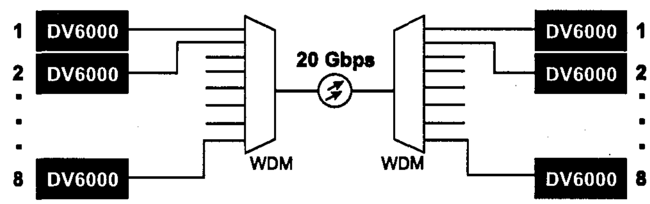

Figure 6. ADC Telecommunications' DV6000 Uncompressed Digital Transmission System employing DWDM for 20 Gbps transport.

This provides a single fiber capacity of 20 Gb/s, which translates to 128 analog CATV channels, 256 DS3 channels, 128 MPEG2 QAM multiplex signal streams (with up to 20 MPEG multiplex channels per stream) or a combination of these signal types. Other vendors currently provide systems which can transmit eight or more simultaneous wavelengths containing digital information, over the same fiber. A counter rotating ring can be implemented with no loss of capacity on 2 fibers, as shown in Figure 7. Alternatively, it is technically possible to implement a bidirectional WDM system with redundancy on a single fiber at 10 Gb/s.

Today, the application of WDM is primarily limited to point to point transmission between hubs on the ring. This is due to the fact that only "hard wired" fixed wavelength optical splitters are available. This provides the benefit of reduced fiber count, but not full optical add/drop capability. In order to dynamically drop or add a wavelength at any hub, a dynamically

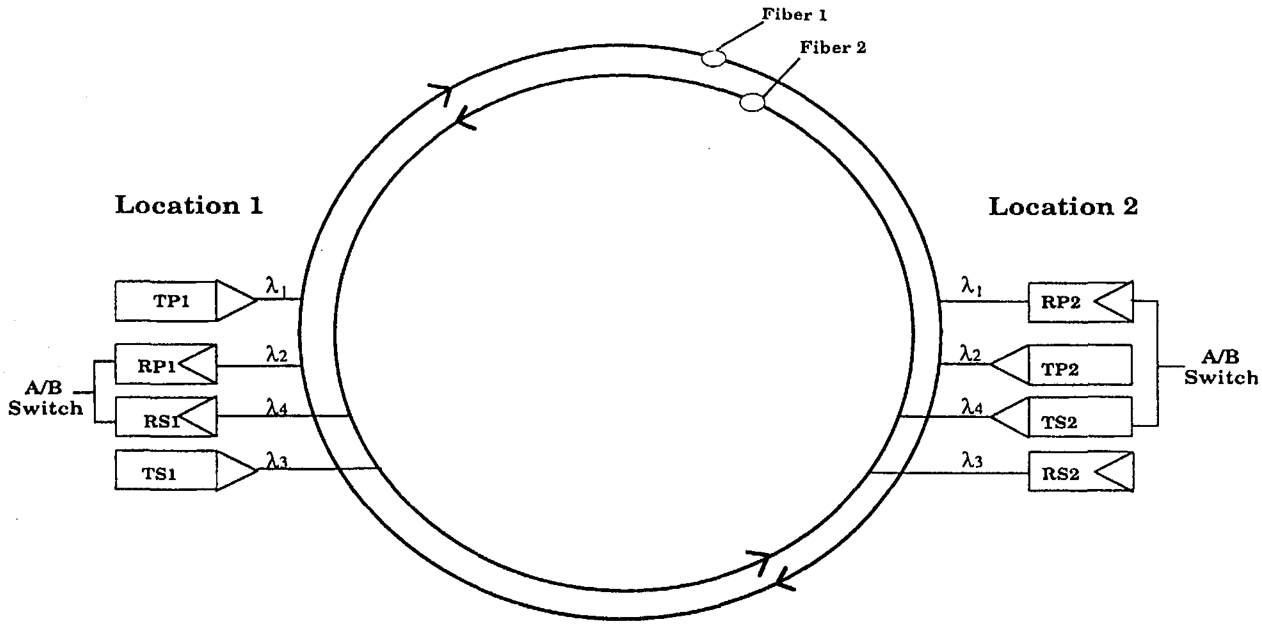

Figure 7. Counter rotating ring with full fiber and electronics protection

wavelength selective optical WDM device will be required. For high speed digital telephony systems, there may be a significant cost advantage in being able to do a drop and add function in optics versus electronically, due to the high cost of the digital add/drop multiplexor. Optical switching can perform virtually the same functions as TDM switching. The only optical limitation in multiplexor functionality s that there is not an easy way to make a drop *and pass* device.

The benefits of dense WDM are not as obvious in a smaller backbone system that employs 1550 nm high power linear transmission of CATV video channels. Although it has been demonstrated that digital and linear optical signals can be simultaneously passed through the same optical amplifier[1], the optical link budgets of high speed digital transmission systems are so dissimilar as to make this probably impractical in common implementation. For example, a 2.4 Gb/s operating at 1550 nm has a link budget of 29- 31 dB, translating to over 100 km in length, which is within the range of distance between 90% of all hubs. A typical high power linear system has a link budget of 12 - 14 dB. Therefore, the linear system will require amplifiers after a distance of 12- 14 dB which is less than half of the link budget for the digital system. Operating the digital system through these amplifiers will provide no advantage to the digital system, and therefore if digital and high power linear signals are mixed on the same fiber, extra cost must be incurred to provide splitters to the digital signals in order to bypass these optical amplifiers.

Dense WDM in HFC Distribution Systems

While there are clear capital and operational savings to be had today from building a new digital fiber backbone system employing dense WDM technology through saving of fibers and electro/optic repeaters, there are potentially larger future savings in the forward and reverse path of the HFC distribution system.

Consider that the average hub serves between 20 and 80 optical nodes. It is typical to provide 4-6 home run fibers between the hub and each node, since at least two fibers are normally required for bidirectional transmission, and extra fibers are installed to support future migration of nodes closer to the subscriber, or additional services close to the node. Multiplying the nodes times the fibers per node calculation means that as many as 480 fibers are required at the hub. Given that WDM would allow multiple linear signals to be transmitted on the same fiber, the number of fibers at the hub could be reduced by 67% while maintaining the ability for future expansion of nodes closer to the subscriber. Even greater savings are possible if fiber branching is allowed. For example, if 16 nodes could be served using 16 wavelengths originating on one fiber from the hub, then it is possible to serve 80 nodes two-way using only 10 fibers total. Figure 8 illustrates this concept. Note also, that in building a metropolitan system that there may easily be ten or more hubs, so that the savings realized is factored by the number of hubs (i.e. distribution networks) in the overall system. To accomplish this savings technically requires future development of both the lasers which can support 110 channel linear transmission at various wavelengths around 1550nm, as well as WDM optical devices which demonstrate excellent long term stability and performance while installed in an outdoor, unprotected environment.

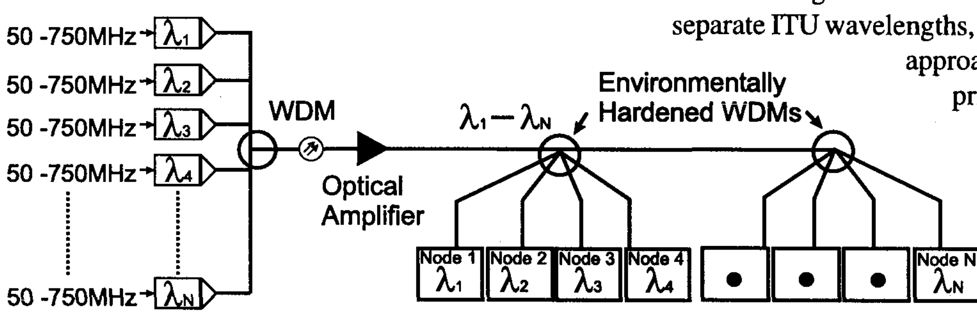

Figure 8. Potential Future Dense WDM in HFC Forward Path

Another alternative that has been postulated is to transmit in the forward path from the hub to nodes the common broadcast channels (typically from 50 - 550 MHz) at one common wavelength, and then to send the narrowcast signals to each node on a different wavelength where they are combined in the optical receiver. Although this is possible from an optical perspective, the combining of signals at the node receiver may be a more difficult approach in actual implementation. This is because it is difficult to combine the signals at each node with the correct RF level. Without going into a detailed technical explanation in the space of this paper, suffice to say that the RF output level of a signal out of an optical receiver is proportional to the input optical power of the received signal and the square of the depth of modulation. Trying to match two different optical transmitters' outputs coming into the node receiver with two power levels and two depths of modulation would probably be difficult.

Dense WDM may also hold future promise for return path expansion. Today, block upconversion is the most often proposed means of taking up to four 5-40 MHz return paths and transporting them across a single fiber back to the hub. In the future it may be possible to optically multiplex the return paths instead of frequency multiplexing these signals. Of course this will require both the multiple optical wavelength transmitters which are cost effective, and the WDMs which meet the environmental rigors required to be installed in a strand mounted unprotected optical node.

All Optical Network Challenges

The current barriers to All Optical Networks center around devices and availability. The ITU has suggested standardized channel spacing based on specified optical wavelengths in the 1550nm bandpass region of optical amplifiers. In the digital realm, high speed 1550 nm wavelength lasers are becoming available for 40 separate ITU wavelengths, at prices which are rapidly approaching standard 1550nm pricing. Work is being done by some vendors on creating multi-wavelength laser arrays to further drive down pricing. However, using 40 different channels brings up the real world problem of transmitter sparing. Currently, this limits the flexibility. The ideal solution is a tunable wavelength laser, if not for all transmitters, then at least as a universal spare. This is a comparable problem to that which the CATV industry had in the 1980's, when VSB/AM modulators were fixed channel. The advent of tunable lasers will significantly accelerate the implementation of WDM systems. Correspondingly, similar breakthroughs are required in broadband linear optical devices.

Another key requirement is the availability of low cost/highly efficient WDM devices, both fixed wavelength and tunable, suitable for indoor and outdoor installation. In this area, technology is moving forward very quickly, and the emergence of these devices appears on the horizon.

Conclusions

Dense WDM technology and the ability to create All Optical Networks will allow further improvements in the cost, flexibility and reliability of CATV networks.

Availability of the optical components necessary to create these networks will occur within 2-3 years, giving network providers additional means of providing better service and additional capacity to their customers.

References

[1] Chinlon Lin, Keang-Po Ho, Hongxing Dai, Janyi Pani, Hermann Gysel, Mani Ramachandran, "Hybrid WDM Systems for High Capacity Video Trunking Applications", National Fiber Optics Engineers Conference Proceedings, September 1996, p. 261.