# Rate-remultiplexing: An Optimum Bandwidth Utilization Technology

**Richard S. Prodan, Mukta Kar, and Majid Chelehmal**
**Cable Television Laboratories**

**ABSTRACT**

Compression technology, coupled with advances in digital modulation, has many advantages over its analog counterpart, most notably efficiency and flexibility in bandwidth utilization. MPEG standardization, MPEG-2 in particular, has been the key ingredient for interoperability and has been the catalyst in the widespread acceptance of digital audio/video (AV) technology. These factors have contributed to the transmission/broadcast of multiple standard definition television (SDTV) signals, or one high definition television (HDTV) signal, over a single 6-MHz channel. The advantages of digital technology are merging telecommunication services, computing, and digital AV industries into multimedia, where digital video will play a dominant role. New multimedia applications are evolving every day. Even though digital technology has expanded the transmission efficiency, the addition of new applications and services for delivery to homes and businesses will bring new challenges to the cable and broadcast industries. Most of these challenges can be facilitated by an efficient use of the transmission spectrum. We believe that rate-remultiplexing technology can address the issue of optimal utilization of available bandwidth using compressed digital video delivery.

This technology has been researched at CableLabs over the past two years. In this paper, rate-remultiplexing techniques will be analyzed, and their corresponding advantages and disadvantages will be discussed. The implementation of this technology in hybrid fiber coaxial (HFC) cable networks for efficient spectrum management will be discussed in detail. Finally, development activity and the current availability of equipment utilizing rate-remultiplexing will be discussed.

## INTRODUCTION

Multiplexing is the sharing of a single resource by more than one application. Multiplexing, such as frequency division multiplexing (FDM), has application in the analog world. However, multiplexing has become indispensable in digital and data communications. Such signals are placed in a time division slot sequentially. The multiplexed signals, along with the multiplexing information, form a serial bitstream, which is then transmitted over a link either as a baseband transport or then modulated over a carrier as shown in Figure 1. At the receiving end, the bitstream is demultiplexed (per multiplexing information) with the bitstream and all constituent signals retrieved. There are many advantages to multiplexing, the most important of which are flexibility and better utilization of the available spectrum. Without multiplexing, each signal will either require a separate physical link or a carrier frequency for transmission.

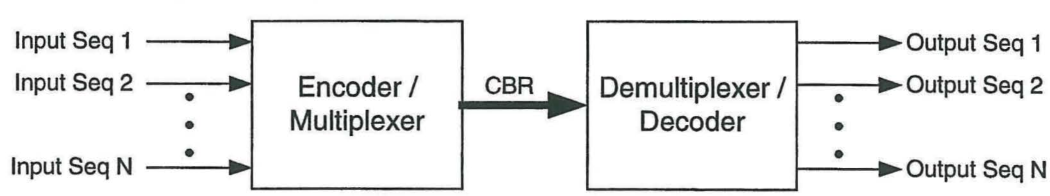


***Figure 1: System for Transmitting Multiple Digital Signals over a Single Channel***

Until a few years ago, multiplexing was used only for low-speed signals such as voice and data. Advances in compression technology and digital modulation have made digital video communication a reality. Although there are limited applications in the transmission of silent or still images, real-time video with synchronized audio make multiplexing essential. In the analog NTSC system, video and audio can be considered as frequency multiplexed. In a digital communication system, compressed video, audio, and private data are time multiplexed to form a single TV program stream. Simple encoding/multiplexing and demultiplexing/decoding block diagrams are shown in Figure 2 and Figure 3, respectively. In the same manner, multiple video, audio, and other data streams can be multiplexed to form a single serial stream containing multiple TV programs. This multiplexed stream may be transmitted over a short link in the baseband domain or may be modulated over a carrier and transmitted.

Until a few years ago, the use of compression technology and video, audio and data multiplexing was proprietary and was used in limited applications. The standardization effort, by ITU and by ISO/MPEG, was the catalyst in the widespread use of digital compressed AV technology. In particular, the MPEG-2 standardization and advances in digital modulation have contributed to the transmission/broadcast of multiple standard definition TV (SDTV) programs or high definition TV (HDTV) programs over a single 6-MHz channel. It is to be noted that using the analog technology, one 6-MHz channel can be used only to transmit one standard definition TV program. In effect, digital technology has the capability to expand the use of the available physical spectrum significantly.

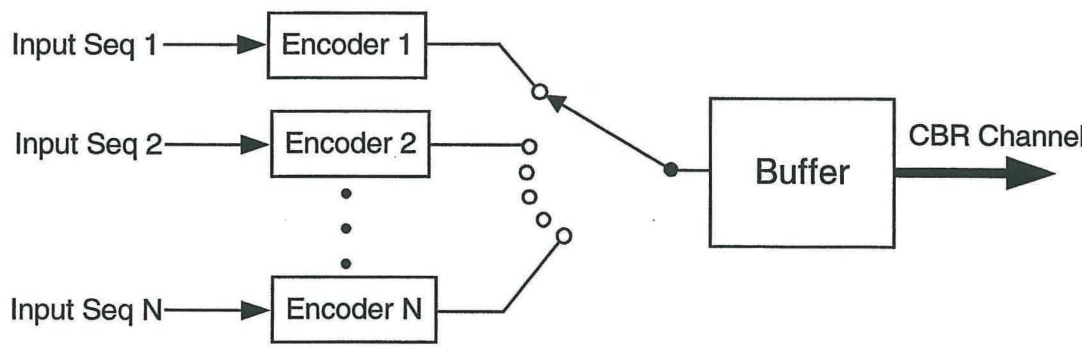


*Figure 2: Encoder/Multiplexer Block Diagram*

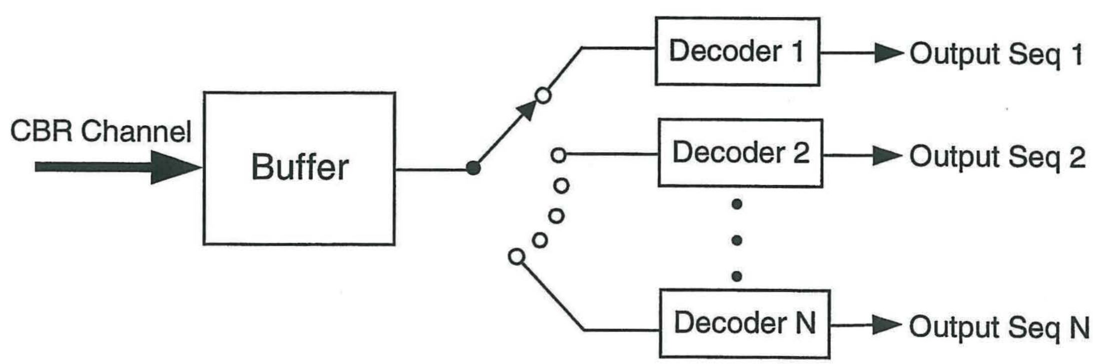


*Figure 3: Demultiplexer/Decoder Block Diagram*

Advances in compression technology and digital modulation have been merging the telecommunications services, computing and digital AV industries into the multimedia arena where digital video is an important ingredient. New multimedia applications are evolving every day and will compete for the available spectrum for delivery to the user/consumer.

Digital technology is complex and also is more expensive than analog technology. However, digital technology has the potential to add new services in addition to digital TV programming. To offset some of the cost of the investment for digital technology, as well as to increase the overall revenue stream, it will be prudent to add additional multimedia services. All of these services will require new channels, which implies that there will be the need for more spectrum. Using higher order digital modulation (64 QAM to 256 QAM in the case of cable) can expand the spectrum space. The use of a more efficient modulation technique will require upgrades to physical plants, including consumer premises equipment (CPE). An alternative to such upgrades is to use remultiplexing or "grooming" of the available spectrum so that new services may be added more efficiently.

## CBR AND VBR STREAMS

With constant bit rate (CBR), a sequence of video frames is compressed such that the output bitrate remains constant while maintaining a desired level of quality. Compressed bits used in each of the encoded frames may vary, but the average number of bits used per second is kept constant. In other words, the bitrate of the compressed stream is constant. Variable bit rate (VBR) allows an encoder to compress every frame to the best extent (with a minimum number of bits), while maintaining the desired quality level. The average output bitrate varies depending on the complexity of various scenes. VBR compression is particularly suitable for storage purposes and, for this reason, it is used in DVD technology. However, in transmitting a single VBR stream over a channel of fixed bandwidth, VBR provides no extra advantage over CBR. But, when VBR streams are created as a result of statistical multiplexing, a better bandwidth utilization is achieved compared to the straightforward multiplexing of CBR streams.

## STATISTICAL MULTIPLEXING

Figure 4 shows a block diagram of a statistical multiplexing system. In this system, a number of video sequences are compressed on the basis of what bits are allocated to each encoder. The bit allocation decision depends on the picture statistics of the current frames and on the coding statistics of the previous frames in the input sequences. Picture statistics are derived from picture complexity analysis data. Coding statistics indicate the in-use status of bits allocated for encoding the previous frame, and whether more bits or fewer bits are used than allocated. Encoders 1 through N act as VBR encoders. The video elementary streams (ES) are buffered in buffers 1 through N, and are multiplexed with other elementary streams and program-specific information (PSI). The multiplexer bitrate constraint is that the sum of all ES bitrates, which is less than, or equal to, the constant channel rate ($R_c$). Statistical multiplexing helps to utilize digital channels better than CBR-encoded streams, assuming that the peak demand for bits from all video encoders does not coincide. The important constraint here is that all the videos need to be encoded while multiplexing. A previously compressed stream typically had to be decompressed and re-encoded before it can be used in statistical multiplexing.

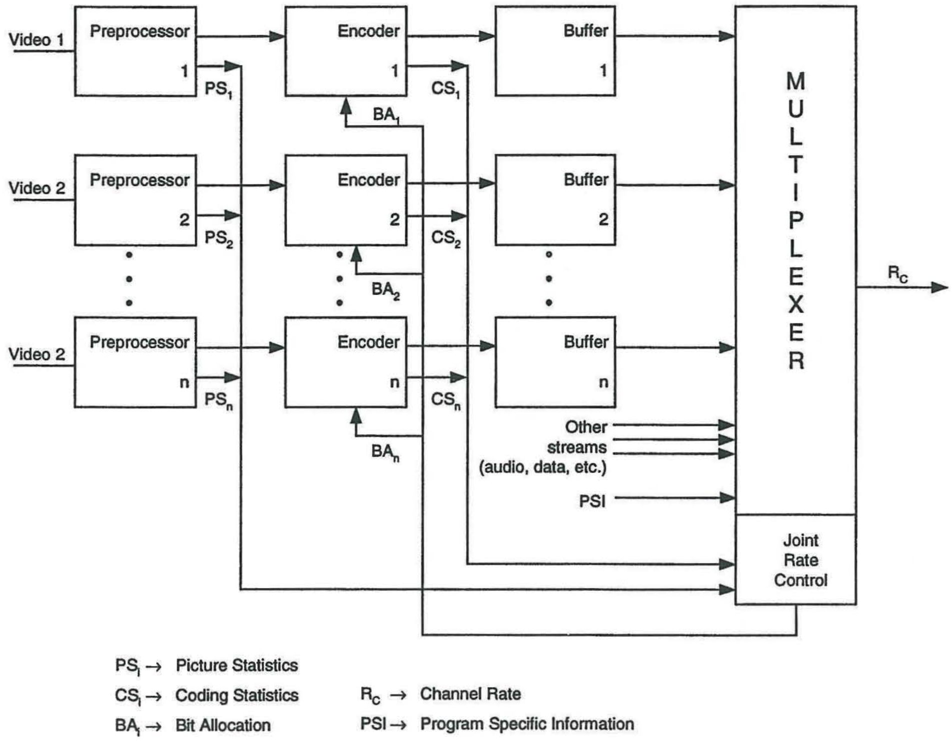


***Figure 4: Statistical Multiplexing System Block Diagram***

**DTV SIGNALS**

As is the case with analog TV programming distribution systems, digital television content providers will distribute programming using media such as satellite, off-air, or direct feed. These signals, when appropriately demodulated, will provide MPEG-2 multiplexed baseband transport streams. Each of these multiplexed streams will often contain multiple TV programs. All the programming received in a single multiplex may not be chosen at the headend for downstream delivery on the same 6-MHz channel. A *remultiplexer* receives one or more multiplexed streams as input and creates a new output multiplexed stream from local operator-selected programs. A remultiplexer is needed in the headend to interface multiplexes of previously compressed video, audio and program specific information (PSI) streams. Figure 5 shows a block diagram of a simple remultiplexer.

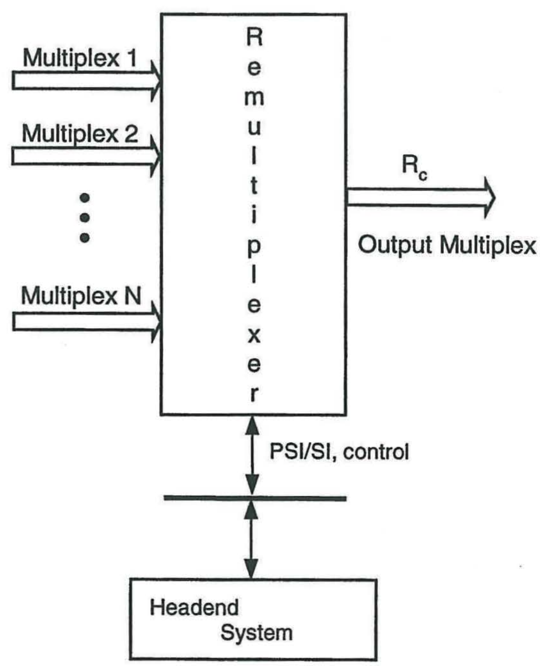


***Figure 5: Simple Remultiplexer Block Diagram***

Of course, both the input multiplexes and the new multiplex must be compliant to ISO/IEC

13818-1, MPEG-2 transport stream specifications. Additionally, the video elementary streams in the output multiplex must adhere to the Transport System Target Decoder (T-STD) buffer model to avoid overflow or underflow of the decoder buffer. A few of the important functions performed by a remultiplexer are:

1) Demultiplexes the input multiplexed streams (unbundles the individual programs);
2) Creates a new multiplex out of the operator-selected programs and includes PSI for the new multiplex;
3) Maintains the bitrate constraint such that sum of all elementary stream bitrates, including PSI does not exceed the transmission channel rate;
4) Removes jitter in Program Clock Reference (PCR) time stamp values and maintains AV synchronization within the programs;
5) Provides perceptually seamless switching capability from one program to the other without any audible or visual artifacts.

## RATE-REMULTIPLEXING

Nominally, a remultiplexer does not alter the ES bitrates while constructing a new multiplex out of the input multiplexed streams. The technology that deals with the multiplexing of compressed video streams along with other streams (audio and data), and trims the resulting multiplex to match an assigned constant total transmission channel bitrate, is known as rate-remultiplexing. Rate-remultiplexing may be thought of as an enhanced remultiplexing method. It meets the latter constraint by transcoding individual video ES within the output multiplex. The new functionality added to a standard remultiplexer to achieve bitrate control include: Variable Length (Entropy) Decoding (VLD) of the video elementary streams; examination of DCT coefficient quantization of each input video stream to determine the overall bitrate allocation; coding statistics determination across the multiplex; coded picture bitrate reallocation by altering (re-quantizing) the DCT coefficients; and Variable Length Coding (VLC) of the resultant re-quantized video elementary streams.

Transcoding together with joint rate control and statistical multiplex scheduling are applied to ensure that the output multiplex is an MPEG-2 compliant transport stream, and that each video ES in the multiplex adhere to T-STD buffer model—no overflow or underflow occurs at the decoder buffer. Degradation in picture quality is not noticeable with occasional or slight reductions in the average bitrate of individual video streams. However, significant reduction in average bitrate may cause noticeable degradation in perceived quality.

Currently, content producers create compressed content compliant to the MPEG-2 standard and distribute content to the broadcast affiliates or cable headends. However, headends and hubs may vary in quality (bitrate) based on the allocation of channel capacity for each program. For example, a small hub with limited availability of physical channels may try to pack in as many digital channels as possible with a corresponding compromise in quality. To meet varying needs, content producers can create compressed content at higher quality (i.e., higher bitrate). The affiliates and headends can lower the bitrate as needed before delivery over their systems. Similar situations may occur with digitally compressed commercials and content for video-on-demand (VOD). In creating compressed commercials, content producers can produce one high-quality version and store it in a server. But, based on the availability of digital bandwidth in the multiplex at various times and at various systems, the commercial's bitrate will have to be reduced during insertion. It is also possible to create different versions of commercials with different bitrates. However, storing different versions of the same commercial could be redundant if rate-remultiplexing is employed. Without rate-remultiplexing capability, no matter how many different versions are created, a close match between available channel bitrate and the stored compressed commercial can not be guaranteed. Similarly, in the case of video-on-demand based on the quality-of-service (QOS) requirement, the bitrate of the video stream can be reduced to a target different quality level (bitrate). Another case may arise when a compressed video stream is distributed over heterogeneous networks. It may be necessary to reduce the video stream bitrate for a section of the network due to the lack of channel bandwidth availability, or during times of congestion. In such a case, QOS will also degrade. In these cases, rate-remultiplexing compressed video provides a reasonable solution.

## TRANSCODING

Transcoding is the technique by which a compressed video stream is translated to a lower bitrate. Figure 6 is a block diagram of a simple transcoder. $R_i$ is the bitrate of the input compressed video, $R_o$, the rate of the output transcoded video and c(t) may be considered as the user's input constraints.

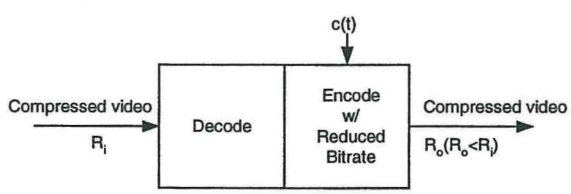


***Figure 6: Simple Transcoder***

In MPEG-2 compression, the majority of bits are used for representing the DCT coefficients of an 8 x 8 block of pixels (there are many 8 x 8 blocks in a picture). The main saving in bits is obtained by reducing the number of these non-zero DCT coefficients, or by making the value of the coefficients smaller. In the case of a compressed domain transcoder, rate reduction is achieved by representing coefficients up to a certain frequency threshold and setting a zero value for the coefficients above the threshold, or by coarsely quantizing the DCT coefficients. The latter not only causes reduction in the number of non-zero coefficients, but the values of the remaining coefficients also become smaller.

There are two transcoding techniques: open loop and closed loop. A typical open-loop transcoder is shown in Figure 7. It is easy to implement, and rate reduction is achieved in the compressed domain with minimal decoding and computation.

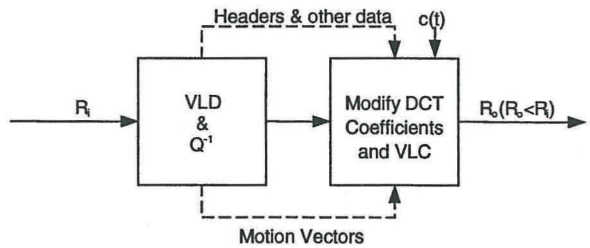


***Figure 7: Open-loop Transcoder***

Such a scheme provides little control over the output stream's picture quality. Another way to implement a transcoder is to decode the compressed video to uncompressed video and then re-encode it to a reduced bitrate. However, such a method will be highly complex to implement as it requires a decoder and an encoder for each video channel. It also adds more latency in transcoding.

Figure 8 shows a closed-loop transcoder where the re-encoded output is compared with the output of the first decoder. This provides a reasonable estimate of the error and the re-encoding decision may be made based on the estimated error. This is obviously better than an open-loop method where the bitrate is reduced without any computation of error resulting from the reduction in bitrate. Hybrid methods that estimate reconstructed (decompressed) errors in the compressed domain only can be used in a closed-loop system with significantly lower complexity.

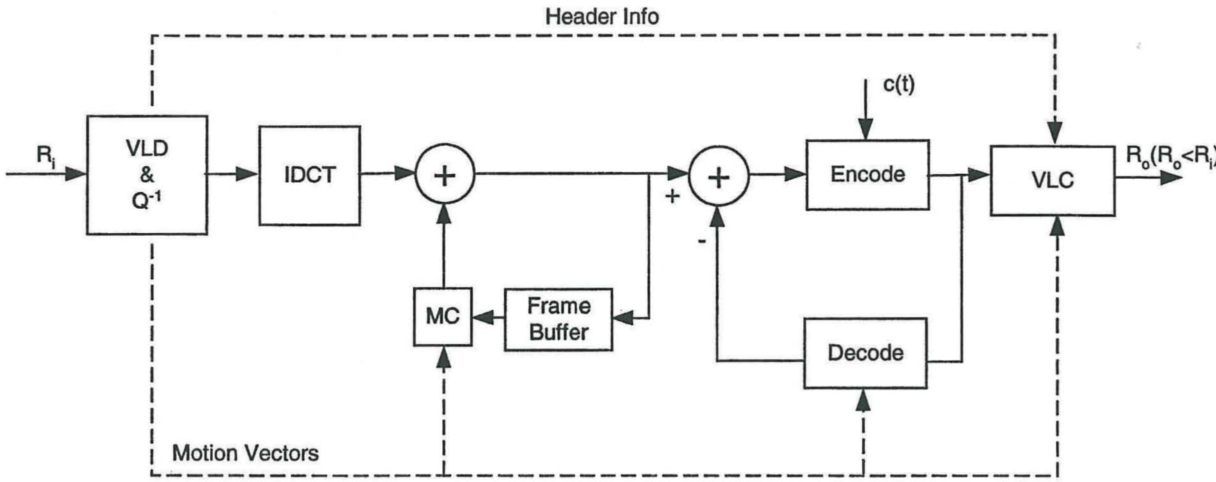


***Figure 8: A Typical Closed-loop Transcoder***

In MPEG-2 compression, motion vector (MV) computation is the most computationally intensive process. There are many ways to transcode a compressed video stream. In implementing any of these methods, a great deal of computation can be saved if one can reuse the MVs available with the input stream as much as possible. New prediction and MV computations may be needed in some local stream splicing situations such as ad insertion. It may be observed from Figures 7 and 8 that the computation of MVs has been avoided by utilizing the MVs available within the compressed stream. In open-loop transcoding, there could be drift in picture quality, particularly for a long group of pictures (GOP), as the P pictures are encoded and decoded with reference to either the I pictures or the previous P pictures. The error made in transcoding the initial I picture will be added with that of the following P pictures. In this way, the error accumulates in transcoding each consecutive P pictures until the next I picture. At every I picture, error accumulation resets. The problem of drifting in picture quality becomes worse as the number of iterations in transcoding increases. In general, in the open-loop method, the picture quality may degrade more than expected due to cascading transcoding operations on the same stream. In the closed-loop method, the degradation in picture quality due to cascading is deterministic and is reduced.

A rate-remultiplexer, shown in Figure 9, performs all of the functions of a remultiplexer, but has the following added capability. If the sum of the bitrates of all selected streams including PSI exceeds the channel transmission rate limit $R_c$, each video stream is trimmed or transcoded until the bitrate of the new multiplex is within that limit. This functionality will benefit headend operation in the following ways:

a) If some compromise in quality is acceptable, this later capability will allow the cable headend to pack more channels into a single multiplex.

b) Remultiplexing of multiplexed transport streams containing variable bitrate video elementary streams that have been statistically multiplexed when compressed at the source can be accommodated.

c) Only one bitrate version of a compressed commercial in the server need be stored, even though it will be remultiplexed in many different channels with different bitrates. It is assumed that most of the rate-remultiplexers will have the capability of digital program (local commercial) insertion (DPI). It was mentioned earlier that all remultiplexers should have smooth program switching capability. When the switching capability is already built in the device, it will be straightforward to add the program insertion capability.

d) The same thing will be true for video on demand (VOD) where only one high-quality version of the content will be stored. Then, based on the QOS requirement or available bandwidth, quality may be lowered if necessary.

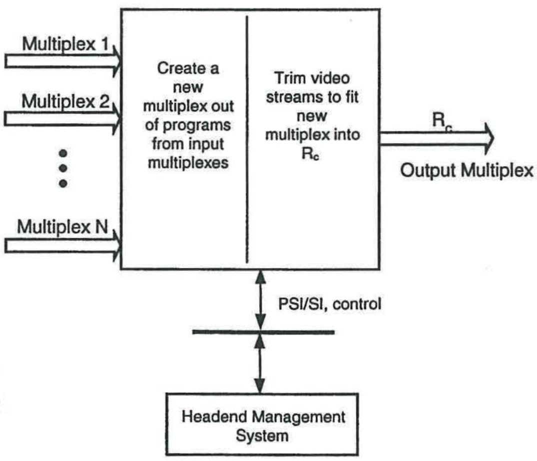


***Figure 9: Rate-remultiplexer Block Diagram***

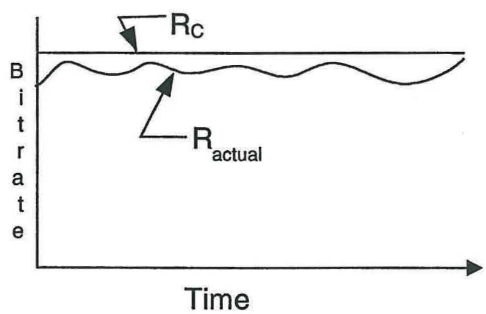


***Figure 10: Bitrate of the Output Multiplex from a Rate-remultiplexer***

In statistical multiplexing, encoding and multiplexing are performed at the same time and, as such, require all the input video streams to be in uncompressed format. The output bitrate of a statistical multiplexer is kept very close to the channel rate. The rate-remultiplexer can deal with previously encoded video streams, irrespective of constant or variable bit rate encoding. Even if the sum of instantaneous bitrates of all the selected streams for multiplexing is larger than $R_c$, it trims the video ES such that $R_{actual}$ fits within $R_c$ with minimal degradation in picture quality. The actual output bitrate ($R_{actual}$) of a rate-remultiplexer may vary (as shown in Figure 10) depending on the information content to the input video stream. Rate-remultiplexing may present an opportunity to deliver non-real-time data using the bits available.

The above advantages of rate-remultiplexing make it a very attractive choice over standard remultiplexing. It provides wider freedom to choose programs from various multiplexes and to pack them in a single output multiplex without having to worry about violating the constraint of fitting them together in a fixed rate channel. This freedom lends itself to greater flexibility by optimizing the use of the available 6 MHz channels in a specific market.

Local ad sales contribute significantly to the total revenue of the cable industry. The capability to insert compressed digital commercials into digital channels, at the headend, is a necessity for the support of local advertising inserted into regional compressed programming. Rate-remultiplexing technology provides that capability to a headend as it removes the need to match the bitrate of the local compressed commercial with that of the remotely transmitted program, or creating and storing different bitrate versions of the commercials. As mentioned above, in the case of VOD, it will be much easier to modify content bitrate to meet resource constraints or QOS requirements. Hence, rate-remultiplexing is an excellent tool for the optimal use of the digital channel capacity for digital video services.

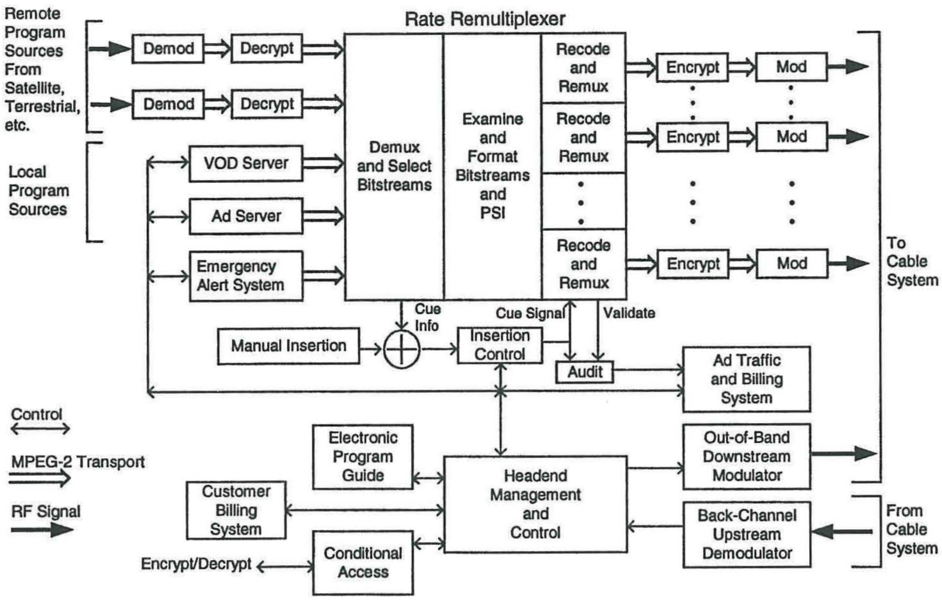


***Figure 11: Integrated Architecture of a Headend Using a Rate-remultiplexer***

Rate-remultiplexing will be an indispensable technology for most digital headends. A headend architecture where rate-remultiplexing technology has been integrated with the existing analog headends is shown in Figure 12. In this architecture, a number of multiplexes compliant to the MPEG-2 systems layer transport stream specifications (ISO/IEC 13818-1) have been interfaced to the rate remultiplexer. These multiplexes may originate from various sources, e.g., satellites (distributed by HBO, CNN, etc.), terrestrial (ABC, CBS, NBC, FOX, etc.), and direct feed (coaxial or fiber). They are appropriately demodulated and converted back to the baseband transport stream. The sources also include local servers such as VOD, ad, and other content servers. At the rate-remultiplexer, the input transport stream multiplexes are de-multiplexed into elementary streams, and a few of the programs are selected, per user choice, out of a number of programs available with input multiplexes. It also extracts PSI and SI streams associated with each input multiplex, and reformats and updates the information contained in these streams per the headend management system directives. The remultiplexer then remultiplexes the selected programs, including PSI and other data, into a new multiplex and recodes the video elementary streams, if necessary, to match the bitrate of the new multiplex with that of the available channel bitrate. DPI and VOD functions have also been integrated. By using transcoding, a major technical problem of matching stored bitrate with that of the channel bitrate becomes simplified. It is expected that the rate-remultiplexer will have the capability to detect network inserted cue-commands or a connector to interface externally detected cue-commands, including a local manual insertion mode. The output multiplexes from the rate-remultiplexer will be QAM-modulated. Each 6-MHz QAM modulated carrier is up-converted to the desired cable physical channel and is input to a combiner. The combiner sums analog channels with channels carrying digital multiplexes and channels carrying IP-based services. The output of the combiner is then transmitted over the cable system to subscribers. The out-of-band (OOB) channel for information and entitlement services and back channels for interaction on bi-directional systems have been included in this architecture.

## CONCLUSION

In summary, the need for rate-remultiplexing to support applications involving compressed video transmission have been explored. Statistical multiplexing at the source encoding level and rate-remultiplexing at the headend will help utilize the available digital bandwidth more efficiently.

Rate-remultiplexing combines existing remultiplexing technology with a new capability known as transcoding. Transcoding can reduce the bitrate of MPEG-2 compressed video without fully decoding and re-encoding a bitstream with the attendant loss of picture quality inherent in such cascaded compression. Transcoding can be divided into two major categories: open loop and closed loop. Open loop is simple to implement, but substantial picture drift may occur. It provides no control over errors made in transcoding a video elementary stream. Closed loop provides better control over errors and provides reasonable control over expected picture quality. Slight reductions in average bitrate may not cause any noticeable reduction in video quality. Substantial reductions in average bitrate may cause noticeable degradation in picture quality, which is expected in MPEG-2 compression.

Several advantages of rate-remultiplexing technology in a cable headend have been noted. A good degree of flexibility in packaging channels is provided. This will allow each headend to utilize their channel bandwidth resources in the system in an optimized way to deliver a selected number of services from multiple sources. Also, solutions to the problem of matching stored content bitrate with transmission channel bitrate in services such as DPI and VOD are accommodated. In other words, no bitrate match is required.

Finally, an integrated headend architecture was presented where rate-remultiplexing will play a major role in providing various digital television services and will coexist easily with existing analog/digital television and other services. Initially, rate-remultiplexing technology may be more complex than standard remultiplexing, but the advantages of rate-remultiplexing will outweigh the cost.

## REFERENCES

1. *Statistical multiplexing with look-ahead using MPEG-2 video encoding*, by Lilla Böröczky, Agnes Y. Ngai and Edward F. Westermann, presented at SMPTE 33rd conference on Advanced Motion Imaging, Orlando, Florida, February 25-27, 1999.
2. *A Frequency-Domain Video Transcoder for Dynamic Bit-Rate Reduction of MPEG-2 Bit Streams*, by Pedro A. A. Assuncão and Mohammed Ghanbari, published in IEEE Transactions on Circuits and Systems for Video Technology, Vol. 8, No. 8, December 1998.
3. *Video Transcoding for Matching Network Bandwidth Constraints*, by Pedro A. A. Assuncão, a Ph.D. thesis, Department of Electrical Engineering, University of Essex, U.K., 1998.
4. *Multiplexing VBR Video Sequences Onto a CBR Channel with Lexicographic Optimization*, by Dzung T. Hoang and Jeffrey Scott Vitter, submitted to ICIP '97.
5. CODING OF MOVING PICTURES AND ASSOCIATED AUDIO, ISO/IEC 13818-1 (Systems), ISO/IEC 13818-2 (Video).