OPTIMIZING BANDWIDTH EFFICIENCY THROUGH INTELLIGENT CHANNEL MULTIPLEX DEFINITIONS

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Abstract

The phenomenal expansion of high definition television (HDTV) programming is suddenly consuming large swaths of spectrum on recently upgraded cable plants, and necessitating consideration of techniques to improve bandwidth efficiency. As the easiest and most economical alternatives are utilized by cable operators, they are brought to more difficult considerations such as whether to commit to accelerated realization of all-digital cable, next generation encoding, further upgrades and other intensive undertakings.

Rate shaping bit rate adaptation of live video programs is a relatively inexpensive and easy bandwidth conservation technique, compatible with all digital video infrastructure already deployed throughout the cable plant. Emerging tools for smarter channel multiplexing further boost the effectiveness of rate shaping, by determining optimal combinations of programs based on their historical behaviors.

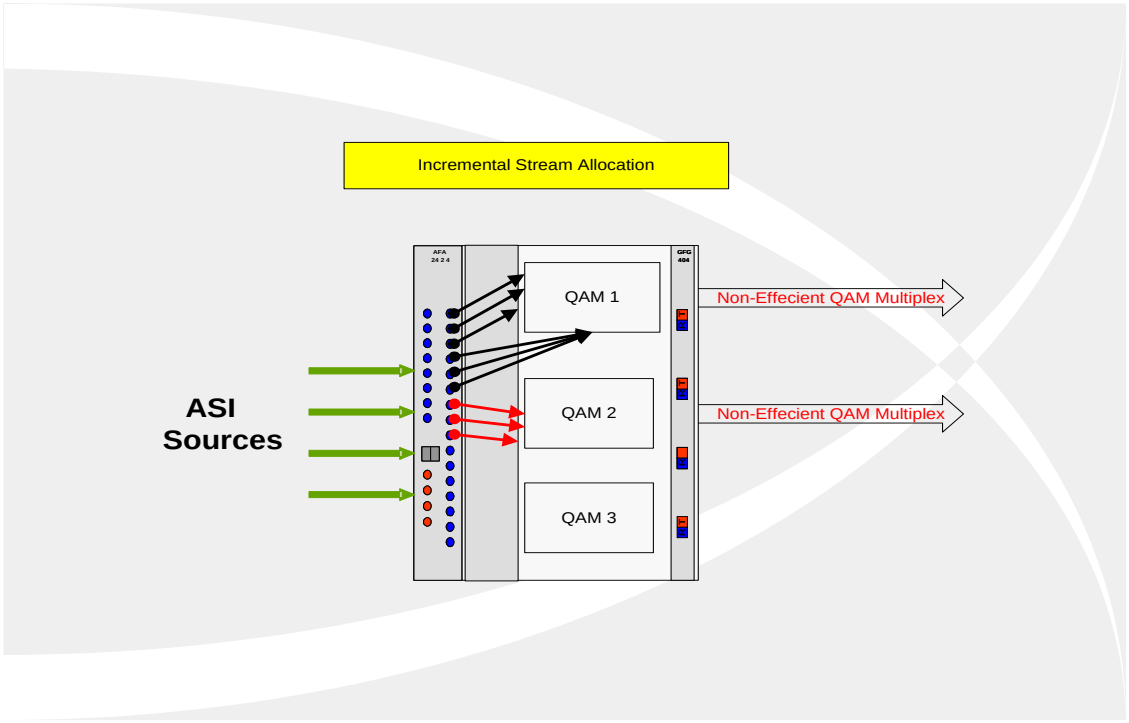
The channel multiplexing tools employ advanced algorithms to consider not only average bit rates of programs, but also their complexities, which are indications of the degrees to which they can be subjected to rate shaping with minimal compromise to their quality. Multiplexing together programs of varying complexity levels and of varying operator priorities, allows the most sensitive to be preserved with little processing while those of lower complexity or lower priority can receive more aggressive rate shaping without detrimental effects.

HISTORY OF CHANNEL MULTIPLEXING CONSIDERATIONS

The cable industry's evolution has progressively led towards increasing concern for which programs are placed where on the spectrum. In analog cable this consideration started with mimicking off-air channel placements, and as more cable-specific programming networks became available, there was jockeying for positioning based on popularity and negotiating leverage, leading to occasional modifications of the line-up, along with associated headend activity to accommodate.

As cable programming loads increased, so did spectral frequencies of plants and the occasional shuffling of line-ups continued. At one point, the program load relative to capacity according to current practices led to two profound shifts in cable techniques: the upgrades to hybrid fiber/coaxial (HFC) networks and the carriage of MPEG-2 digital content. As spectrums started to exceed half of 1 GHz and swaths of those spectrums were dedicated towards channels carrying multiple digital programs instead of a single analog one, the industry experienced a temporal lull in bandwidth pressures.

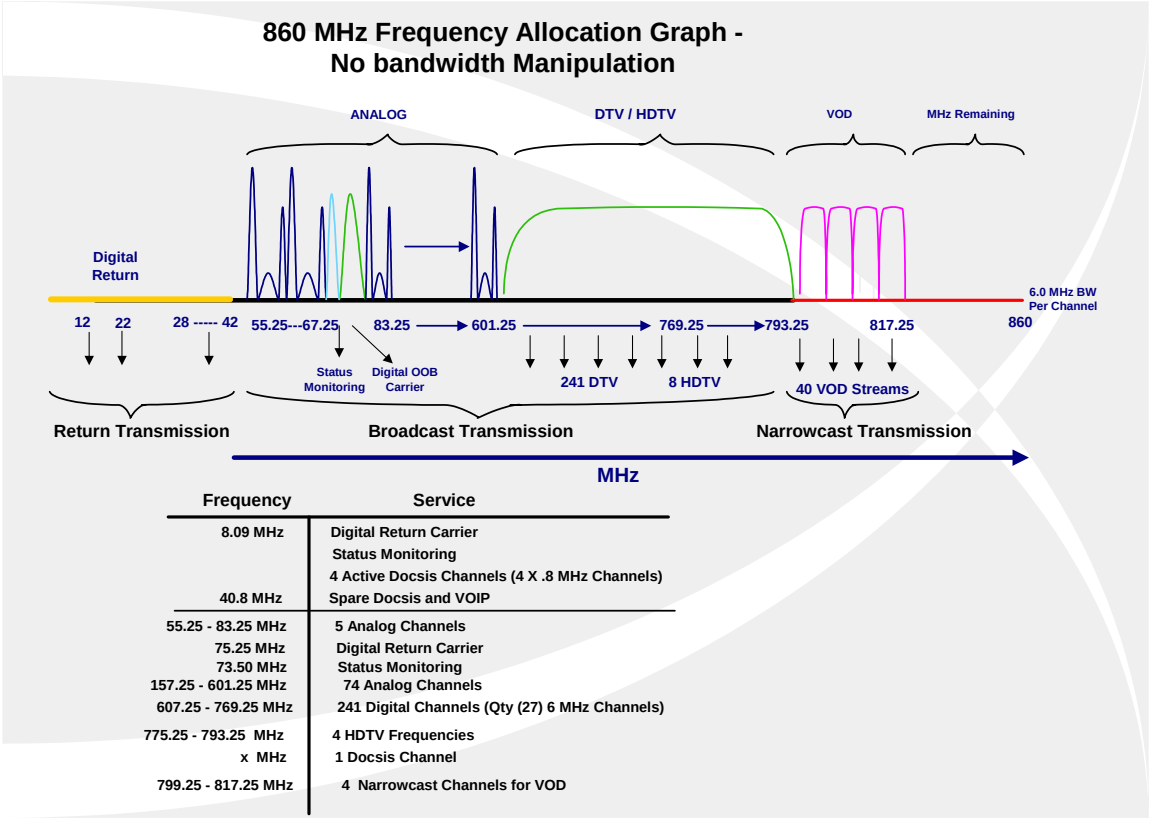
Planning channel multiplexes in the earliest digital cable plants was not a very strategic exercise. The first program to be carried would go into the first multiplex to be filled, and other programs would follow until that multiplex' channel was deemed full, after which the process would be repeated on the next channel. Upgraded plants tended to have ample bandwidth availability for their expanding programming, and digital techniques broke the correlation of spectral placement to the line-up experienced by subscribers, so determining multiplexes for purposes of subscriber accessibility became a less intensive engineering exercise.



Initial channel multiplexing allocated the first program under consideration to the first available QAM channel incrementally, rather than applying optimizing considerations.

Technology axioms hold that given enough bandwidth, people tend to find a way to fill it. The last several years have proven this true in cable video services, as the high capacities associated with HFC and digital content have led to the simultaneous launches and growth of multiple bandwidth-intensive services including HDTV and video on-demand (VOD). Current prospects are for bandwidth management to be further exacerbated by these two services converging such that rich content (i.e. high bandwidth sessions) is made available for personalized viewing (i.e. many simultaneous sessions contending for spectrum).

Spectral scarcity is rapidly setting in and operators must again consider their easiest and lowest cost means for alleviation. Smarter building of channel multiplexes for standard digital and HDTV programming can maximize the amount of content carried in each channel and presents an opportunity to optimally leverage the investments already made by the cable industry.



Launch and expansion of multiple emerging services has driven higher consumption of bandwidth on recently upgraded cable plants.

RATE SHAPING BIT RATE ADAPTATION

A key characteristic of digital video that facilitates improvements in bandwidth efficiency is the fact that the medium is inherently variable bit-rate in nature. MPEG-2's algorithmic structure concerns itself more with interpolating changes between frames than with depicting each complete frame in a sequence. As a result, a scene featuring static sets and talking heads can be maintained with little bandwidth required, whereas one with vibrant details and intensive action requires a lot. A video stream alternating between such sequences will have a progression of peaks and valleys in its bit rate.

Channel multiplexes for digital video broadcasting maintain legacy elements of cable's analog broadcast infrastructure. Specifically, the 6 MHz channel that can carry a complete analog broadcast signal is now allocated as a shared resource to a multiplex of digital video programs. This channel's capacity is 38.8 Mbps according to 256 quadrature amplitude modulation (QAM). With standard digital video typically consuming 3-4 Mbps per program, the earliest digital broadcast launches included approximately ten programs multiplexed in each channel for which 256QAM was the modulation technique.

Digital video's variable bit rate nature presents both a benefit and a dilemma for multiplexing. At a given interval in time, some programs will most certainly require capacity above their average bit rates, however it is equally likely that others will be below theirs, so that the multiplex in total should remain close to the sum of average bit rates. This coincidence of peaks for some programs with valleys for others is a

manifestation of the basic principles of statistical multiplexing. However, the multiplex' required bandwidth will not exactly equal the sum of average bit rates at all times, and will be as likely to exceed that sum as to be below it, so cable operators must consider how to plan and manage programming accordingly.

Rate shaping bit rate adaptation is a technique used increasingly for digital broadcasting, instead of planning channel multiplexes so that each one has some spare capacity to cope with moments when multiple programs require higher-than-average bandwidth availability. Rate shaping algorithms consider the programs in each multiplex, and at moments when particular multiplexes require excessive bandwidth, optimizing determinations are made of which programs can have their bit rates throttled back to an extent that improves the multieplex' bandwidth enough to fit within the 6 MHz channel, with video quality maintained as much as possible. Rate shaping's attractiveness includes the fact that it maintains content in MPEG-2 format, thus necessitating no change to program sourcing, the cable plant or equipment at subscriber premises.

Services	256QAM without Rate Shaping	256QAM with Rate Shaping	Bandwidth Gain
HD	≈ 2	Now in initial lab, field efforts	> 40%
SD	≈ 10	≈ 12	≈ 20%

Rate shaping enables substantial gains in bandwidth efficiencies without disrupting headend, plant or subscriber premises equipment.

Recent enhancements in rate shaping include capabilities for operators to determine priorities by program. For example, a live sporting event would be assigned high priority and would rarely be subjected to aggressive rate shaping, if it shares the same multiplex with lower priority programs such as re-run situation comedies. These factors drive emerging channel multiplex considerations, such as combining programs of varying priority levels, so that those with higher priority can be spared while rate shaping is applied to lower priority ones in the same multiplex.

Rate shaping is also beginning to be positioned for application to HDTV. The earliest cable carriage of HDTV brought the programming to 19.4 Mbps, allowing two programs to share a 6 MHz channel, which is at least five times more bandwidth consuming than common standard digital broadcasting, and even worse compared to standard digital broadcasting with rate shaping. Because high video quality is the essence of HDTV, the industry has been very conservative in its considerations of any form of processing the streams. Algorithmic improvements, being validated in multiple laboratory facilities and some of the earliest field deployments, indicate that in fact HDTV can experience bandwidth efficiency gains of 40% and more through rate shaping with no discernable impact on quality. HDTV and standard digital video can be multiplexed together in the same 6 MHz channels, with priorities set higher for the HDTV, in order to best assure that the highest standards are maintained.

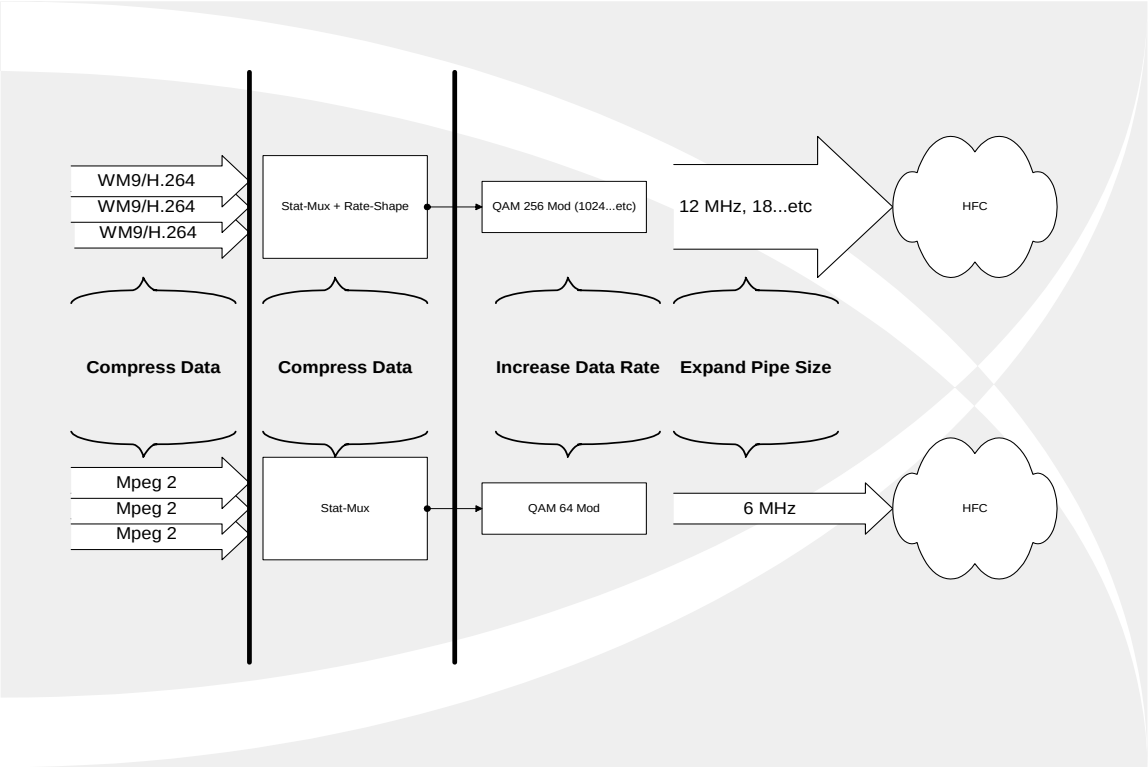
ALTERNATIVES FOR BANDWIDTH SCARCITY

The last few years' HDTV growth has been impressive. Programmers are rapidly expanding available content, consumers are enthusiastically buying compatible digital televisions, and competition from both the direct broadcast satellite (DBS) industry and off-air broadcasters assure that the cable industry will focus on participating in the phenomenon. Operators have rapidly eclipsed double-digit HDTV program carriage in many systems, and some are voicing expectations of carrying more than 20 during 2005.

The onset of HDTV carriage, simultaneous with the growth of VOD usage by subscribers, new tiered data service offerings by operators, and launches of voice over Internet Protocol (VoIP), increase the imperative of improving bandwidth efficiency immediately in order to maintain a technical competitive edge for cable versus DBS. A range of techniques are available to this effect that can be considered in light of their bandwidth efficiency gains relative to associated costs and efforts.

Several of the most available methods of achieving greater bandwidth efficiency are already being widely deployed by cable operators. Programs that were carried in analog but don't have to be for reasons of regulatory mandate, contractual obligation or sheer popularity are being converted to digital, which practically reclaims a full 6 MHz channel to carry digital programs. Systems still using 64QAM for some or all digital content can boost digital video carriage efficiency by 44% per channel by converting to 256QAM. Rate shaping on standard digital multiplexes tends to fairly easily support at least 12 programs each, providing a gain of at least 20% for channels carrying digital, before employing any of this paper's suggestions on intelligent channel multiplexes.

The methods of expanding bandwidth efficiency described above are attractive in terms of their capacity gains relative to the associated costs. Once they are implemented, some of the next considerations tend to be more intensive in terms of efforts and expenditures, including: further plant upgrades to expand spectrum, splitting nodes for more reuse of the same spectrum for personalized content, expanding frequency spacing from the long-standing standard of 6 MHz channels, and migrating to all-digital content, next-generation encoding techniques such as MPEG-4 or next generation modulation such as 1024QAM. Each of these requires extensive modification in the plant or subscriber premises, and operators should first consider any other alternatives to free required bandwidth.



Cable operators have a range of options that can be applied in isolation or jointly for cumulative gains in bandwidth efficiencies.

The authors propose that utilizing increasingly intelligent bandwidth planning techniques provide an intermediate opportunity for the cable operator that has already done analog reclamation, 256QAM upgrade and practice of rate shaping, but has yet to embark upon the more intensive techniques. Algorithms are being developed to perform more sophisticated analysis of bandwidth behavior of digital video programs, and the results can be used by intelligent tools to form multiplexes of programs in which rate shaping is likely to be optimally effective in order to yield several more programs per multiplex than those that can be achieved by rate shaping without planning.

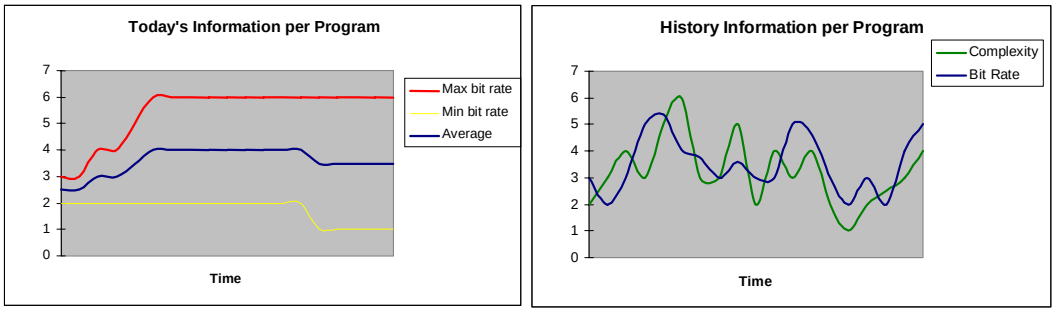
Current Rate Shaping Practice	Enhanced Performance	Bandwidth Efficiency Gain
12 SD	16 SD	33%
2 HD	2 HD + 4 SD	38%
2 HD	3 HD	50%

Rate shaping performance can be enhanced through practice improvements such as implementation of policies, with minimal effect on existing plant and equipment.

THE ROLE OF COMPLEXITY IN MULTIPLEXES

Because of considerations that vary by location, such as locally available programs, line-up histories and regional tastes, it is most sensible to plan channel multiplexes independently by system rather than uniformly for multiple systems of a single operator. Systems tended to this by trial-and-error multiplexing adjustments until bandwidth utilization reached an acceptable level, with subjective assessment of whether video quality could also be deemed sufficient. Increasingly, more intelligence is being applied through construction of multiplexes based on average bit rates measured over time so that there is greater predictability in the frequency and extent of rate shaping application. But since the process remains manual and localized, there is no assurance that best practices are maintained across all of an operator's systems.

While multiplexing practices by operators certainly represent improvements in fulfilling bandwidth efficiency and video quality goals to support more carriage of HDTV programming and other services, the practice of exclusively considering average bit rates does not optimally determine multiplexes, and subjective quality assessments are highly inexact. An emerging area of consideration in this regard is not only program bit rates but also program complexity. This concerns factors such as motion dynamics and pixilation detail that can be increasingly quantified and analyzed, rather than the subjective assessments of video quality currently practiced in most systems.



Complexity provides additional dynamics for analysis of digital video program behavior beyond historical bit rate considerations.

A program with a high degree of complexity is inherently more difficult to subject to rate shaping, because more information is required in the MPEG-2 stream to track it. Thus, a program with high complexity will have the greatest compromise to quality in rate shaping. Lower program complexity indicates the most relative potential for bandwidth efficiency gains by rate shaping. There tends to be some correlation between degree of complexity and bit rates, but there are programs with high average bit rates but low complexity, and these yield the greatest boost to bandwidth efficiency by rate shaping.

Considering the role of complexity in channel multiplexes can improve bandwidth efficiencies with assurance of video quality. Multiplexing programs of various complexity levels allows a higher sum of average bit rates that can be combined without impacting video quality. This is because when cumulative bit rates exceed capacity and rate shaping is enacted, the programs with the lowest complexity will receive the most

aggressive bit rate reduction, and those of higher complexity will be relatively spared to preserve their video quality. To place a premium on HDTV quality in particular, an operator can combine these programs, set at high priority, with low complexity ones, set at lower priority.

Content	Bit Rate	Complexity	Optimal Rate Shaping
NBA TV (Sports) 	6 Mbps	High	No to little bit rate reduction
HBO (Movie) 	6 Mbps	Medium	Medium reduction
C-SPAN (Info) 	6 Mbps	Low	High reduction

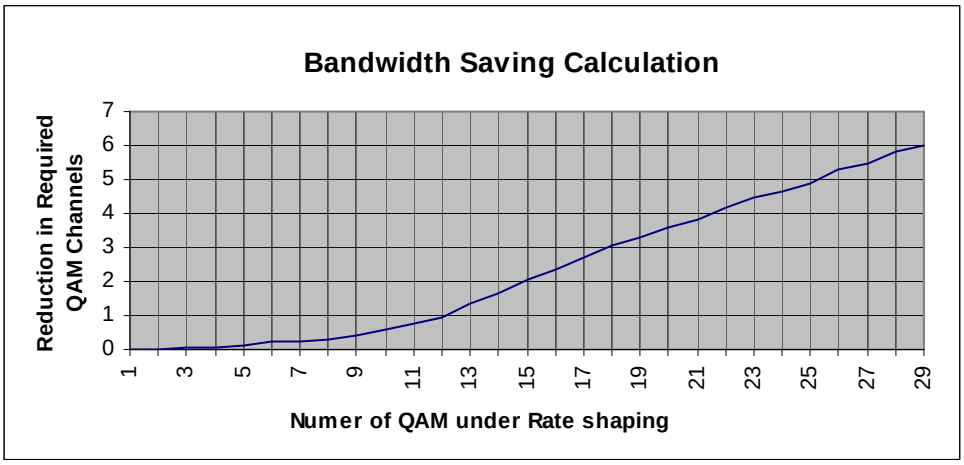
Complexity provides a more accurate indication of the eligibility of programs to be subjected to rate shaping while maintaining their video quality.

WORKING WITH A SMART CHANNEL MULTIPLEXING TOOL

As algorithms for analysis and monitoring of complexity improve, better tools are becoming available to recommend multiplexes that maximize the amount of standard digital and HDTV programming carried per channel, at the highest possible quality, without forcing adoption of expensive and intensive efforts for capacity expansion. These tools can explore both bit-rate and complexity characteristics of programs, over prolonged periods of time, and provide resulting suggestions of multiplexes to optimize for a system's objectives.

Brief moments do not provide sufficient data to determine program complexity, especially as most programmers provide varying content. Analysis of a week of programming can be used to capture a representative cycle of the nature of the video content, to set bit rates and complexity. These, along with priorities as set by the operator can then be used to determine the best multiplexes given the programs to be carried and the channels available for multiplexing. The more programs utilized the more effective

that the multiplexing is likely to be because of the higher statistical likelihood of achieving mixes of different complexity levels.

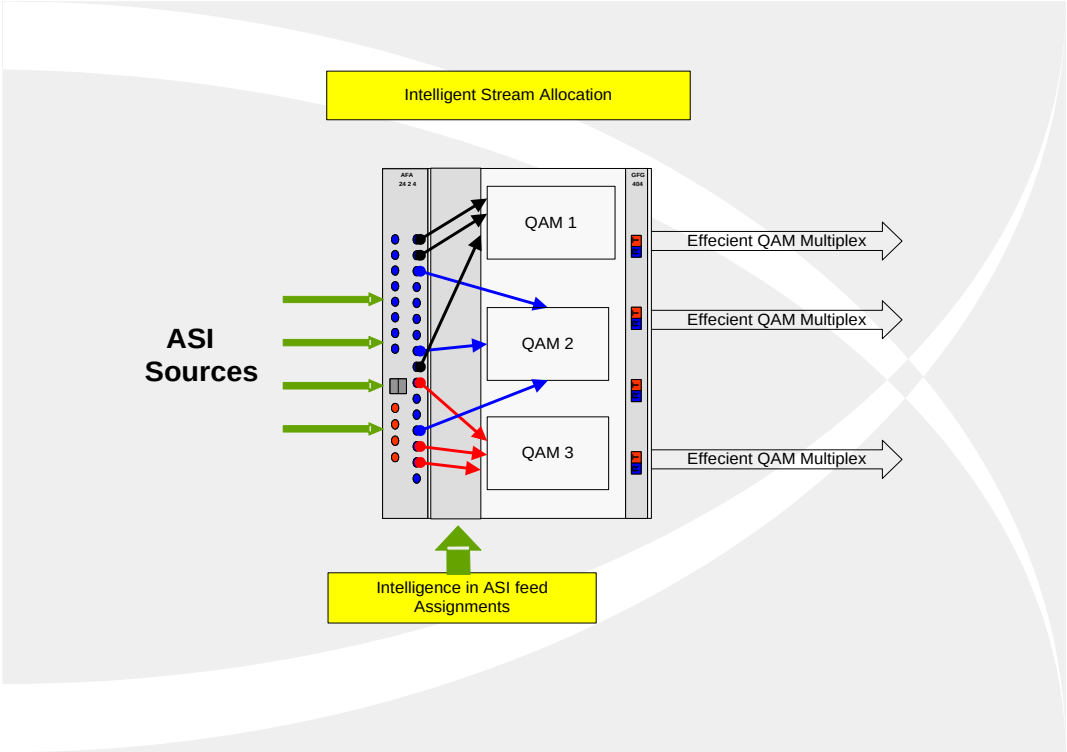


Rate shaping performed across more channels results in distributions of various program characteristics, which enhances efficiency and reduces total QAM allocation.

Because analytical algorithms constantly improve and programmers frequently change their offerings, it is important that an operator would re-apply those intelligent channel multiplexing techniques periodically. Adjustments in multiplexes over time assure that objectives are consistently met, whereas long-term maintenance of pre-determined multiplexes is likely to deteriorate performance, as optimal combinations of program complexities are unlikely to be static.

Besides gradual migrations in the nature of programming, operators could also consider planned seasonal adjustments. For example, historical analysis can be maintained for annual programming shifts, such as the onsets of seasons during which particular programmers tend to carry sports or movie content. These historical data can be reapplied, along with current data concerning other programs, at the starts of those seasons to rebalance multiplexes.

As channel multiplexing tools improve in their sophistication, there are other factors that operators can consider. Accommodating the frequency and bandwidth behavior of inserted advertisements in a program may be a characteristic that operators choose to overemphasize or underemphasize in multiplexes. Or periodic programming changes such as differences in day versus night or weekday versus weekend can be considered, so that combinations of programs tend to have offsetting complexities during different periods.



Smart channel multiplexing tools enable operators to strategically place programs in QAM channels according to results that optimize bandwidth efficiency and video quality.

Smart channel multiplexing tools provide an effective technique to accommodate the growth of HDTV and other bandwidth-intensive services without embarking upon more expensive plant and subscriber premises alterations. Applied alongside other techniques and services, the capabilities of smart multiplexing tools can eventually achieve even greater gains in efficiency and functionality. For example, complexity of different content could be dynamically considered in provisioning different VOD sessions to different channels. In the near term, smart channel multiplexing can be used to conserve capital, bandwidth efficiency and video quality, and over time its potency can be extended towards achievement of other cable operator objectives.