AN EVALUATION OF ALTERNATIVE TECHNOLOGIES FOR INCREASING NETWORK INFORMATION CAPACITY

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Abstract

HDTV, VOD, ITV and other applications are placing ever-greater pressure on operators to transport more information – that which is widely distributed as well as communications with individual customers. Choosing how to create adequate capacity is difficult; driven by financial and regulatory constraints, capital costs and ongoing operating considerations.

This paper will evaluate some of the technical options against those factors. Evaluated technologies will include bandwidth expansion to 1 GHz, more efficient modulation, more efficient video encoding, elimination of analog video carriage, splitting of existing nodes, switched digital video and a proposed use of frequencies above 1 GHz that offers the greatest bi-directional bandwidth expansion and the greatest benefit/cost ratio.

INTRODUCTION

Bandwidth Pressures

The history of cable television is one of ever-increasing need for information capacity, initially driven by the expansion of over-air broadcasting, then premium and ad-supported satellite networks, followed by pay-per-view and high-speed data services. Today, operators are launching bandwidth-intensive high-definition television (HDTV) channels, various flavors of video on demand (VOD), higher Internet access data rates, and telephone services. Each of these increases the need for an increase in system information capacity (for purposes of this paper, unless otherwise specified, "bandwidth" will by used interchangeably with "information capacity" and "RF bandwidth" will be used when the historical meaning is intended). The increasing bandwidth demands fall into three broad categories:

1) Common downstream ("broadcast") bandwidth; that is, bandwidth occupied by signals that are transmitted throughout the network (irrespective of whether or not individual customers are enabled to receive them). An example of common signals would be a high-definition stream from HBO that would be continuously transmitted system-wide, but for which only certain subscribers would be authorized.

2) Interactive downstream ("unicast") bandwidth; that is, bandwidth occupied by signals that are transmitted to individual customers. VOD, Internet communications and telephone are all examples of such signals.

3) Upstream bandwidth; that is, bandwidth occupied by signals that are transmitted from individual customers towards the headend. With the exception of a small amount of bandwidth occupied by network element management systems (NEMS), all upstream signals fall in the same category as interactive downstream bandwidth.

The Case for Dramatic Bandwidth Increase

Historically, manufacturers have offered cable operators increases in upper downstream RF bandwidth limits in steps of 50 MHz or so from an upper frequency limit of 220 MHz to 860 MHz, with the upstream bandwidth remaining fixed, except for one step from 30 to 42 MHz. By contrast, in the data world, speeds have increased exponentially over several orders of magnitude. As more content carried over cable systems is digital in nature, more communications are directed to and from individuals, and competitors greatly increase both video and non-video capacity, the question is whether operators will need to significantly increase bandwidth, especially upstream bandwidth, to take advantage of opportunities and meet competition.

A few points to consider:

1) On the competitive data front, SBC and Verizon, among other telcos, have launched a major fiber-to-the-curb/home push. Typical of the technology to be deployed is Wave7's equipment which provides 500 Mb/s symmetrical data, shared among 16 passings, in addition to 860 MHz of RF downstream bandwidth.[i] Verizon is offering data rates to 30 Mb/s downstream/5 Mb/s upstream in its fibered markets, with the capability to offer rates of hundreds of megabits per second.[ii] Some overbuild competitors in the US have already offered 100 Mb/s service options to customers and speeds of between 10 and 100 Mb/s are commonly available in Asia. Finally, the capability of copper plant continues to improve and now supports high-definition digital video.

2) Cable operators are already being pushed to significantly increase rates – Comcast announced a standard rate of 4 Mb/s and an available 6-Mb/s downstream/768-kb/s upstream rate; Cox increased its standard rate to 4 Mb/s[iii] and RCN has upgraded its rates to 10 Mb/s.

3) On the telephone side, the number of VoIP residential and small business lines is predicted to hit almost 11 million by 2008, with a significant amount of that traffic carried over cable systems.

4) Direct broadcast satellite operators will be taking advantage of new spectrum, closer satellite spacing, higher power and spot beam technology to realize greatly increased throughput – as much as 18,000 MB, or enough to carry 2800 high-definition programs at 6.5 Mb/s/program using advanced codecs.[iv]

5) In general, television is moving from pre-scheduled broadcast of standard-resolution programs to on-demand presentation of high-definition, with a 4X increase in bits per stream and the need to send programming to (and receive communications from) individual subscribers. Competitively, one satellite operator expects to offer its customers 150 national and 500 local HDTV channels by 2007

6) Finally, upstream data communications rates from subscribers are increasing rapidly. VoIP is a symmetrical service; file sharing can be symmetrical or even asymmetrical in the upstream direction; and near-future services such as video telephony will require multiples of the bandwidth required for voice. Comcast recently announced plans to offer video instant messaging. RCN now offers a video surveillance service that allows customers to stream video from up to four cameras through their broadband connection.[v]

In summary, there is significant evidence that cable operators will need major increases in bi-directional information capacity in the near future, and that the upstream in particular, with a current capacity of only about 100 Mb/s/node, is a major bottleneck that will need to be addressed.

Operators can realize this increased information capacity through an increase in RF bandwidth, through more efficient use of existing bandwidth, or through more efficient sharing of existing bandwidth. Additionally, increased interactive bandwidth can be realized by sharing of the bandwidth devoted to interactive services among fewer customers. The various upgrade technologies that will be considered differ in their effects on broadcast verses interactive and downstream verses upstream information capacity, as will be seen.

Candidate Technologies

There are many approaches to generating more information capacity in a cable system. This paper will evaluate the following possibilities:

1) An increase in downstream upper RF bandwidth limit from 550, 750 or 870 MHz to 1 GHz.
2) An increase in digital modulation density from 256 QAM to 1024 QAM.
3) Utilization of more effective digital video compression technologies, such as MPEG-4.
4) Subdivision of existing optical nodes.
5) Elimination of analog video carriage, with the formerly-analog signals transmitted only in digital form.
6) Use of switched digital video to avoid sending low-usage channels to subscriber groups except when requested.
7) Use of RF bandwidth above 1 GHz to expand both downstream and upstream capacity.

This is obviously not a comprehensive list, and the choices are not mutually exclusive. For example, an operator may choose to simultaneously increase modulation density and also use advanced digital compression algorithms. For keep the matrix manageable, however, we evaluated each option separately.

When it comes to discussing quantitative results, we used what we felt were reasonable assumptions for an average cable system. For every possible upgrade scenario, however, the results will vary depending on the assumed condition of the unmodified plant. For example, a marginal system may not be able to take advantage of 1024 QAM without fixing basic problems, while other systems may require little incidental preparation.

Methodology

For ease of comparison, each technology was evaluated as a candidate for upgrading a hypothetical 100,000 home cable system which currently has 500-home nodes and an average density of 100 homes per plant mile. It is assumed to be 80% aerial plant. The connected household penetration is assumed to be 70%, with 35% of connected homes equipped for digital video reception. The system is assumed to currently carry 80 channels of analog video, 136 total standard-resolution broadcast digital video streams, 12 high-definition broadcast digital video streams, VOD, high-speed data, and VoIP. Unless otherwise stated, the system is assumed to have been upgraded to 750 MHz within the previous ten years. Other assumptions regarding the system will be discussed when relevant to each individual candidate technology.

Technologies were evaluated with respect to their effect on both downstream and upstream capacities and with respect to both commonly delivered (broadcast) and interactive services. In each case, the technologies were also evaluated qualitatively with respect to future enhancement options. Finally, conformance of each alternative to current regulatory requirements is noted.

INCREASE TO 1 GHz BANDWIDTH

An increase in the upper downstream frequency limit to 1 GHz follows the traditional pattern of cable RF bandwidth expansion. While it offers additional downstream capacity, it does not address the upstream bottleneck and does not offer a straightforward path to future increases, as discussed below.

Distribution Network Issues

The cost of coaxial equipment upgrade will depend on the starting bandwidth and on the condition of the original plant. Variables include: the percentage of passive devices which are already rated at 1 GHz, whether upgrade modules are available for actives, whether the gain of the new actives will be sufficient to avoid re-spacing, the condition and type of original coaxial cable and connectors, and whether the increase in drop cable loss is such as to require replacement.

The tradeoffs in a bandwidth increase are well known. If the amplifier spacing does not change, each amplifier must have higher gain and either the input levels will be lower (degrading C/N), the output levels must be higher (degrading distortions), or the amplifier must have higher power output hybrids (increasing power consumption and heat). Furthermore, the number of signals carried will presumably increase, further increasing intermodulation products. Alternately, amplifier spacing can be decreased, but then the number of cascaded amplifiers increases, degrading both noise and distortion. Thus, this technology is self-limiting and does not offer a solution to future expansion.

Our estimates are based on figures developed by a major MSO for their current mix of cable systems of various bandwidths, conditions and original parentage. Added to these costs are estimates of the replacement optical equipment required at headend or hub and node to feed the upgraded plant.

Consumer Premises Equipment (CPE) and Regulatory Issues

The entire cost is not in the distribution system upgrade – the bandwidth must be used for something. No existing CPE tunes above 870 MHz, nor is it required to do so to meet current DOCSIS (data) or SCTE 40 (video) standards. Furthermore, since the FCC has adopted SCTE 40 into its rules, operators are forbidden from offering one-way digital video services above 864 MHz.

We therefore assumed that, while the upgrade would create additional capacity between the existing upper limit and 864 MHz, the space above that would be limited to services that need be received only on CPE provided by cable operators. Of the available choices, the most logical seemed to be simulcasting of the existing analog programming (the first step to an eventual all-digital plant and recovery of the spectrum now used for analog transmission) to digital-only converters. We estimated the cost of simulcasting from a report on Charter's Long Beach, CA conversion[vi] and estimated the cost of the digital-only converters at $85[vii], the recovery value of the old converters at $25, and the labor cost to make the change at $10. Thus, the estimated cost includes the CPE changes necessary before the expanded bandwidth can be used, but not the cost of adding any new services.

Using these assumptions, the total cost and gained downstream bandwidth (in equivalent 6-MHz channels) is as follows:

Original Bandwidth	550	750	860
Cost/HP	$274	$116	$81
Added DS Chans	75	42	23

This upgrade, of course, does nothing to address the upstream issue.

UPGRADE TO 1024 QAM

The highest existing digital modulation is 256 QAM, which transmits 8 bits of information per symbol, for an effective transmission rate of about 38 Mb/s in a 6-MHz RF channel. One proposal for increasing information capacity is to use the next logical increment of modulation density, 1024 QAM, to increase the bandwidth efficiency of networks by transmitting 10 bits per symbol, a theoretical increase of 25%.

The practical network issue with this upgrade is existing network noise and distortion performance. SCTE 40 mandates end-of-line C/(noise + interference) of 33 dB for 256 QAM.[viii] To maintain the same headroom, a 1024 QAM signals would need to be received with a C/(noise+interference) of 39 dB.

In most cable systems, data signals are carried at the same average power level as analog video signals (typically referred to as 6 dB lower only because analog video signals are referenced to sync peak level and digital signals to average power level). Thus, raising the power level of 1024 QAM signals is probably not a practical option.

Typical cable systems are designed for an end-of-line ideal analog video C/N (thermal noise only) of 48 dB. With normal variations, aging and maintenance tolerance, 46 dB is about all that can practically be assured – just enough to pass the FCC's 43 dB requirement after passing through a typical converter (with 0 dBmV input and a 13 dB noise figure).

Taking into account the difference in noise susceptibility bandwidth between video (4 MHz) and data (5.3 MHz) and the 6 dB difference in how their levels are referenced, the expected carrier-to-thermal-noise of a received data signal may be as low as 38.8 dB, to which must be added the effects of composite beat products among analog signals, composite intermodulation products among digital signals and crosstalk in multi-wavelength optical links.[ix] Otherwise stated, a system that just meets FCC specifications for analog video will not be adequate to carry 1024 QAM signals.

Distribution Network Costs

To account for solving the inevitable system problems and increasing performance slightly, we estimated a cost of $850/mile in distribution system "fixes".

Headend Costs

Existing headend modulators must be replaced to prepare the system to utilize the expanded throughput. To minimize the cost, we assumed that only digital video modulators are replaced (leaving data and VoIP unchanged). Additionally, we added the cost of re-multiplexers for those signals currently received from satellite and passed through the headend unchanged. This prepares the system for adding 2-3 additional video streams per multiplex in the future.

Customer Premises Equipment Costs and Regulatory Issues

No existing CPE is capable of receiving 1024 QAM signals. Furthermore, current FCC rules mandate that one-way digital video services use only 64 QAM or 256 QAM. Although operators may approach the technical issue in various ways, we assumed that existing converters would be replaced with hybrid analog/digital converters enhanced to receive 1024 QAM that would cost $175, with a value of $25 assigned to the retrieved converters they replace. We have assumed that all existing converters are replaced, which enables the efficiency improvement to be applied across all digital video channels, but means that converter replacement dominates the other costs.

Using these assumptions, the total cost of an upgrade to 1024 QAM is $60 per home passed for an effective downstream bandwidth increase of 6.75 6-MHz RF channels. As with the 1 GHz upgrade, converting to 1024 QAM does not address the upstream bandwidth constraint, nor provide a path for future upgrades. Unlike, a 1 GHz upgrade, our 1024 QAM scenario is in conflict with current FCC regulations, however applying it to only interactive services would greatly reduce the throughput gain.

ADVANCED VIDEO COMPRESSION

All cable digital video services today are compressed using MPEG-2. While this was a breakthrough technology when introduced, more efficient algorithms have since been introduced, of which the dominant contenders are MPEG-4 AVC and Windows Media (SMPTE VC-1). Either offers roughly a 2:1 increase in streams/channel compared with MPEG-2. Since a large use of downstream bandwidth in a typical cable system is for digital video, adopting a more efficient compression algorithm will increase overall effective throughput.

Because no new modulation is involved, the upgrade imposes no increased demand on the distribution network.

Headend Costs

The cost of adopting advanced compression is dependent on how widely it is adopted. We assumed that most digital video would arrive at the upconverted system in the new format, either from the original program source or from the MSO's regional center.

Customer Equipment Costs and Regulatory Issues

The CPE situation for advanced encoding is essentially the same as for use of 1024 QAM – existing boxes do not receive and cannot be upgraded to receive the new-format signals, and thus require replacement.

The regulatory issues are also similar, as the FCC limits one-way digital services to MPEG-2 encoding. As with 1024 QAM, we calculated the efficiency gain across all digital video channels and did not address the regulatory issues.

In summary, an upgrade to advanced video encoding is less expensive than an upgrade to 1024 QAM because no plant changes are required, and results in a larger effective capacity increase. Specifically, the estimated cost, using our assumptions, is $53 per home passed and results in an effective bandwidth increase of 12.2 downstream RF channels. It does not address the upstream bottleneck.

NODE SUBDIVISION

Subdividing optical node serving areas does not increase the instantaneous system information capacity to any network segment, but does share that capacity among fewer customers. Thus, to the extent that the sub-areas are fed separately, an effective capacity increase is realized for those services which are delivered to individual customers. To be precise, the capacity is increased in proportion to the bandwidth allocated to those services and multiplied by the number of downstream or upstream segments created. Furthermore, since nothing is changed except for effective node size, no regulatory or CPE technical issues are created.

Plant Costs

We assumed that the previous upgrade was not a total rebuild – that is, it utilized as much of the then-existing plant as possible -- and that the cost was further minimized by "dropping" non-scaleable nodes into the coaxial distribution system to create the required 500-home serving areas. Thus, the cost of node subdivision included the cost of replacing the node itself with a segmented model (2:1 downstream and 4:1 upstream) and re-routing the coaxial distribution plant to create four roughly-equal-sized segments (requiring, on average, 1,000 ft of new cable plus splicing). It does not include any service-specific hardware.

Headend Costs

In order to activate the expanded bandwidth, we included the cost of one additional downstream transmitter and three additional upstream receivers to communicate with the new sub-nodes and thus activate the additional capacity.

In summary, we estimated that the division of 500-home nodes into two downstream segments and four upstream segments, would cost approximately $30 per home passed. We assumed that eight downstream channels were used for individual subscriber, interactive services, resulting in a net effective bandwidth gain of four channels in each of the two downstream sub-nodes, equivalent to a doubling of the downstream interactive service throughput capability. We assumed that 30 MHz of the upstream bandwidth was usable for interactive services and therefore the 4:1 split creates an effective bandwidth gain 22.5 MHz in each of the four upstream sub-nodes, equivalent to a quadrupling of upstream interactive service throughput capability.

CONVERSION TO ALL-DIGITAL

In the future, all television, whether over-air broadcast, satellite or locally originated, will be in digital form. One option for operators is to accelerate that process by converting all current analog video signals to digital form and providing digital converters at every connected television receiver.

The advantages include at least a 10:1 increased usage of former-analog bandwidth, lower cost receivers, uniform transport protocols across all services and breaking DBS operators claim to be the only "all digital" network. Disadvantages include the cost of providing converters to current analog subscribers and defeating the features of some basic subscriber's video equipment. Additionally, current FCC regulations require carriage of at least Basic channels in analog format absent individually-granted exceptions, though that requirement will cease when broadcasting transitions to digital[x].

We evaluated two versions of an all-digital conversion – a downstream-only version and a further option in which a portion of the formerly-downstream bandwidth is allocated to upstream usage.

Plant Costs

Since standard 256 QAM signals are assumed, analog channels are converted to digital at approximately the same total RF power per channel, and thus no additional loading is placed on the distribution system. As discussed above, end-of-line digital signal C/N should be slightly below 39 dB at worst, and thus have a significant margin above the SCTE 40 and FCC minimum of 33 dB, even when distortion parameters are included. Thus, no plant changes are required to make the analog to video conversion in the downstream-only option.

Expanding the upstream bandwidth, however, requires changing every diplex filter in the system, the upstream amplifiers (wider bandwidth and higher gain), upstream optical transmitter modules in nodes, and optical receivers in the headend. We assumed that the new upstream spectrum would extend from 10 to 85 MHz and that the downstream spectrum would start at 105 MHz to preserve use of equipment that operates in or near the FM band. We estimated the total of plant and optical headend cost to make the frequency change to be $10,180 per 500 HP node, including the cost to realign the plant.

Headend Processing Costs

As with advanced compression techniques, we assumed that most (75%) of signals would arrive at the headend in digital form from broadcasters, cable networks or MSO regional centers, but that the remainder would require conversion at the headend. We scaled Charter's reported cost to upgrade their California system[xi] by the required number of locally-converted channels and estimated the total headend cost to be $250,000.

Consumer Premise Costs

We assumed the same $75 digital-only converter cost for this option as for the 1024 QAM case. The difference is that, rather than replacing existing digital converters because of incompatibility, additional converters are required for every television outlet in the system what did not previously have one.

The cost of the downstream-only ("low-split") version and the version that includes expanding the upstream spectrum ("mid-split") is summarized in the table below. The mid-split version more than doubles upstream capacity.

Option	DS Only	DS + US
Cost/HP	$157	$175
Added DS Chans	72	63
Added US MHz	0	38

SWITCHED DIGITAL VIDEO

With the exception of server-based on-demand programming, cable operators currently transmit all available programming choices simultaneously and continuously throughout their networks. However, given the widely different popularity of different programming among any given group of subscribers, viewing is concentrated among a few channels and many of the hundreds offered are not simultaneously viewed. Thus, even though there are good reasons for offering a wide choice of programming, it is an inefficient use of bandwidth to send signals to sections of the network except when at least one subscriber wishes to access them.

Switched digital video (SDV) gains effective network throughput by offering less popular programs to service groups only on demand, using technology that is transparent to users – that is, the viewer should ideally be unaware when selecting a program that it might not be delivered until the virtual channel is selected. Use of SDV does not increase the information capacity of the network, but rather shares it more efficiently.

When a switched channel is selected, a small resident application in the user's box sends a request to the headend SDV server, which, if the requested stream is not already being viewed in the service group, adds it to an appropriate multiplex. Then it directs the box to the correct channel and program identifier. When the channel is no longer being viewed within the group, the stream is dropped.[xii]

Trials of SDV are still in an early stage, with widely varying results. One operator estimated a potential savings of 26% of total video channels[xiii], while a larger and more recent trial conducted in a Cox system suggests that as many as 41 programs can share an RF channel on a switched basis and that trials with 28 programs per channel resulted in no instances of blocked access[xiv].

The regulatory problem with switched video is that operators are required to deliver all non-interactive digital video services in a way that is compatible with one-way digital cable-ready receivers. Those receivers are obviously not capable of sending message to the headend to request streams. Thus, until that hurdle is overcome, only interactive video services can be offered on a switched basis.

Given the state of development of SDV and regulatory constraints that limit which channels can be offered on a switched basis, we assumed that 100 current two-way digital program offerings (premium and pay-per-view) would be delivered over five statistically-shared RF channels – a savings of 50% over the spectrum formerly required. In other words, we assumed that an operator would choose in this option to comply with current regulations.

Headend Costs

There are no distribution plant costs associated with the addition of SDV, since the distributed signals are identical to non-switched signals. In the headend, a SDV manager is required to manage the addition and deletion of streams and an MPEG switch/mux is required to create the required multiplexes feeding each service group. We assumed that bandwidth, multiplexers and modulators were dedicated to the SDV service, rather than being shared with on-demand services. The cost estimate assumes 4 nodes and 5 RF channels (80 streams total) per service group.

Customer Premise Costs

SDV is completely compatible with current-generation digital two-way boxes. The required software module is much smaller than that required to implement VOD. Therefore, there is no cost to implement SDV among existing digital video subscribers.

With the above assumptions, implementation of a limited SDV service to existing digital video customers is estimated to cost only $5175 per node, but to free up only the equivalent of 5 downstream RF channels. It has no effect, of course, on upstream congestion and, in fact, adds traffic from video set-top boxes for which low latency is very important. Much greater gains are possible, of course, but only if the regulatory issues are resolved.

EXTENDED BANDWIDTH (> 1 GHz)

A final choice is to activate the spectrum above 1 GHz for bi-direction bandwidth expansion. While various proposals for use of this spectrum have been proposed for many years, none have been widely deployed as an upgrade strategy. The system described below, however, has been successfully used to implement selective overlays to service commercial customers[xv], so the viability of the technology was not at question, but rather its applicability to a system-wide upgrade to serve the entire customer base.

The version we evaluated is based on the creation of two sub-octave transmission bands -- 1250-1950 MHz downstream and 2250-2750 MHz upstream -- with nodes and amplification equipment paralleling legacy equipment in the field, as shown in Figure 1. Splitting amplification between legacy and extended amplifiers greatly simplifies amplifier design. Passives are replaced by equivalent units passing the entire 5-2750 MHz band. Tests have shown that current-generation hard cables used by the industry will support these frequencies, while the first non-TEM mode does not occur until about 4.6 GHz for the largest cable sizes in use today.[xvi]

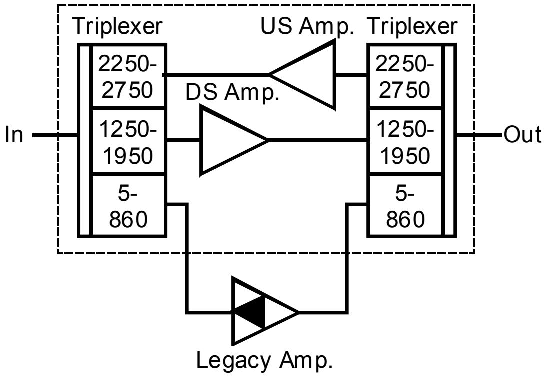

Figure 1: Extended Frequency Amplifier

In order to assure compatibility with existing headend and CPE and to ensure compliance with FCC regulations, the extended downstream frequency band is converted to/from 100-800 MHz and, for residential applications, each upstream sub-block of 12-42 MHz could be converted to one of ten “slots” in the 2250-2750 upstream distribution band and back in the headend.

This scheme would allow both headend RF equipment and consumer premises equipment to operate at normal levels and frequencies. Since the entire 500 MHz upstream spectrum is transported to the headend without any channelization, it is also possible to allocate a wider portion of the spectrum to applications which require greater data rates than can be transported through a standard cable television upstream path. Only a terminal equipment change would be required to re-allocate the spectrum for such applications. As with any block segment conversion scheme (such as those used for years for upstream node segmentation) low phase noise, frequency accurate converters are required. The premise equipment diagram is shown in Figure 2.

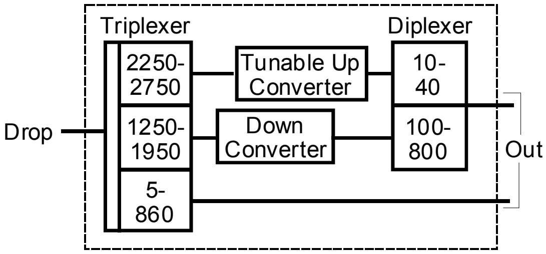

Figure 2: Premises Terminal

In addition to a 2:1 downstream and up to 17:1 upstream bandwidth increase (11:1 if all channelized in 30-MHz sub-bands), a significant advantage of this scheme is that the expanded upstream communications capacity is not “locked” to a sub-node group (as in node subdivision), but rather can be assigned on a subscriber-by-subscriber basis anywhere in the node serving area, simply by assigning which slot upstream frequencies are converted to. A second significant advantage is that the ingress into any upstream slot is limited to that occurring in the residences (or businesses) whose upstream communications are converted to that slot, thus improving the usability of the added spectrum. Ingress in the drop has no effect on the extended spectrum.

Plant Costs

The plant upgrade effort is comparable to a typical rebuild effort. Because the required techniques to parallel active equipment are different, we based our estimated labor costs on actual field trials and on evaluations by experienced contractors in cable construction. The material costs include powering upgrades required for the additional actives. As with node subdivision, we assumed that the required two fibers (or at least one wavelength on each of two fibers) between headend or hub and node were available.

Headend Costs

Headend costs include the equipment required to activate the additional bandwidth, including frequency conversion and optical transmitters and receivers.

Premise Costs

As with other options, the cost of activating frequencies above 1 GHz is dependent on how those frequencies are utilized. For purposes of this study, we assumed that analog video, cable modem and VoIP signals remained on the legacy bandwidth, while digital video and a digital simulcast of analog video signals were placed on the expanded downstream band, with STB upstream signals on one of the expanded upstream slots. This scenario is compatible with all existing digital and analog equipment, including subscriber-owned modems and television receivers, while allowing the cable operator to purchase digital-only STBs going forward and freeing bandwidth for advanced video and data services. The model included the cost of installing residential block converters for every customer who subscribes to digital video services. We estimated the labor cost of this to be comparable to installing a standard drop amplifier.

We evaluated the cost of such an upgrade under two scenarios -- activation of two or eight of the ten possible upstream slots – in order to determine how sensitive the technology is to the degree of upstream bandwidth expansion. The results are summarized in the following table.

Option	2 Blocks	8 Blocks
Cost/HP	$121	$129
Added DS Chans	117	117
Added US MHz	60	240

In summary, the use of frequencies above 1 GHz for expansion of both down and upstream bandwidth offers the greatest information capacity of any of the evaluated options, with the possibility of further expansion of the upstream at very low cost.

SUMMARY

Quantitative comparisons will depend on assumptions and intended use the expanded capacity. This summary is based on the assumptions stated previously.

Regulatory Issues

The use of frequencies above 862 MHz, 1024 QAM or advanced encoding for digital video all violate provisions of Paragraph 76.640 of the FCC's rules, if applied to one-way digital video services. Until and unless those provisions are modified, the gain from use of these techniques will be constrained because of that. Our summary results take those restrictions into account.

Secondly, the FCC requires that basic television service be carried in an analog form. Thus, the conversion to all-digital video is dependent on obtaining a waiver or waiting until all VHF over-air transmission ceases.

Instantaneous vs Virtual Capacity Increases

Some evaluated technologies increase the peak information-carrying capacity of the network, while others realize the effective throughput increase by other means. Both are important: Peak capacity limits the amount of information that can be transmitted to any given subscriber group, while virtual capacity increases are dependent on how services are divided between those which are broadcast and those which are directed to specific customers or customer groups. Today, peak upstream capacity, using 16 QAM, is limited to about 100 Mb/s (ten 3.2 Mb/s channels, each with a capacity of 10 Mb/s). Even if 64 QAM were usable across the entire 9-41 MHz band, the potential increase would only be about 25% to 125 Mb/s.

All the evaluated technologies increase downstream effective capacity. The following table shows which also increase peak downstream information rates and which increase upstream effective and/or peak rates.

Technology	DS	Upstream	
	Peak	Peak	Virtual
1 GHz	Yes	No	No
1024 QAM	Yes	No	No
AVC*	Yes	No	No
Node Split	No	No	Yes
All digital	Yes	No	No
+ US expand	Yes	Yes	Yes
Switched	No	No	No
Extended BW	Yes	Yes	Yes

*Advanced video compression

Only the elimination of analog video combined with expansion of the upstream band or the use of two-way extended bandwidths provides an increase in both upstream and downstream effective and instantaneous information rates.

Comparisons of Capacity and Cost

Figure 3 illustrates the increase in effective downstream channels for each of the technologies, while Figure 4 shows the increase in effective upstream bandwidth. Figure 5 shows the cost effectiveness of each, which we calculated by taking the ratio of per-node capital cost to the total downstream-plus upstream effective bandwidth increase.

Assuming our assumptions are reasonable, it appears that the most efficient 1 GHz upgrade is from a 750 MHz system. While a 550 MHz system will gain more DS bandwidth, it will also require much more cable, passive and drop replacement work. On the other hand, while an 860 to 1 GHz upgrade is the least costly of the three, the lower incremental bandwidth makes it less efficient.

As expected, converting to all-digital video gains a lot of DS bandwidth due to the 10:1 improvement in program streams per channel. Looking at Figure 5, however, it is not one of the most capital-efficient upgrades simply because of the cost of placing one or more digital converters in every Basic subscriber's house. Converting to a mid-split configuration is slightly less cost-efficient but is one of only three options to improve the critical upstream throughput bottleneck.

1024 QAM, advanced video compression and switched video offer only moderate throughput gains for a couple of reasons. 1024QAM, which carries 10 bits per symbol, only offers a theoretical 25% gain over 256 QAM. Additionally, all three technologies are currently constrained the FCC regulations and which are derived from SCTE40. Of the three, SDV is the most efficient because it is compatible with existing set-tops. Absent regulatory restrictions, SDV holds the promise for major downstream effective throughput gain.

Splitting of existing nodes offers significant gains in effective downstream and upstream bandwidth for moderate cost and without causing any regulatory problems or equipment compatibility issues. It is second only to extended bandwidth in cost efficiency.

Use of extended bandwidths, as described earlier, is comparable in cost to a 1 GHz upgrade and less expensive than an all-digital conversion. It offers the greatest incremental bandwidth improvement -- effective and instantaneous; upstream as well as downstream -- of any of the options. As a result its cost effectiveness is greater than any of the alternatives. Furthermore, the incremental cost to activate 8 upstream blocks is slight compared with activating just two, so that it is very economically scalable to future expansion needs. We suggest that it should be seriously considered for future major throughput upgrades.

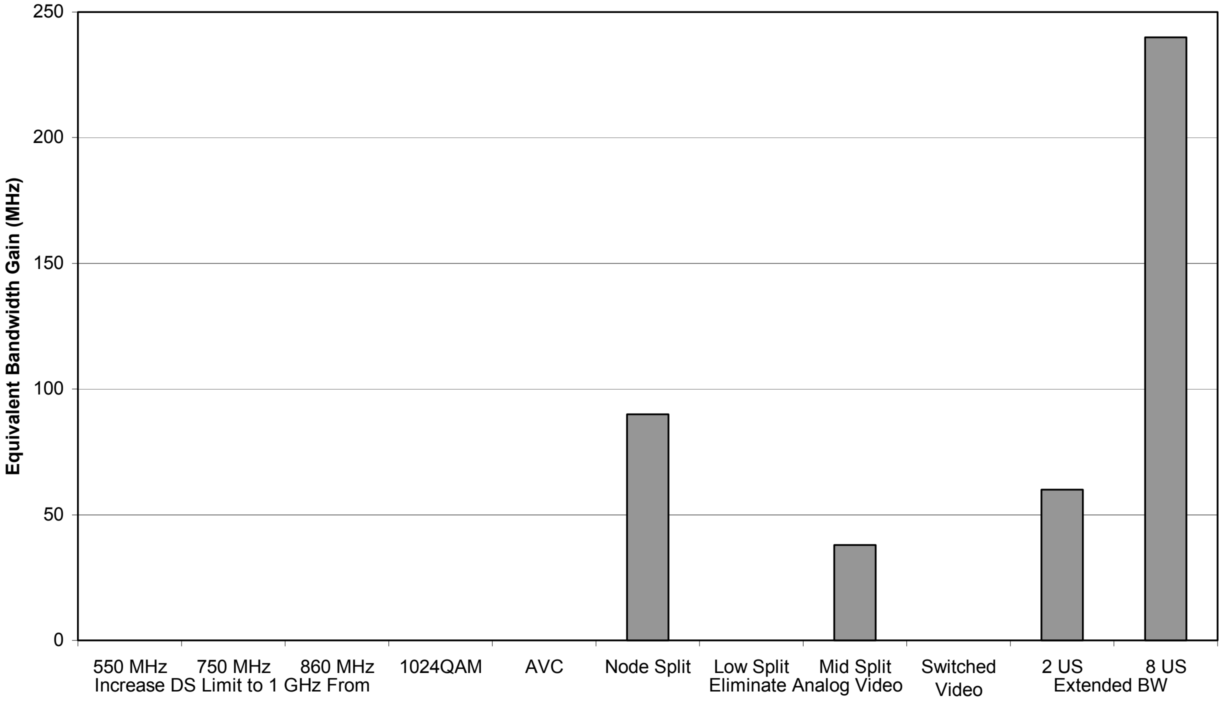

Figure 4: Effective Upstream Bandwidth Gain

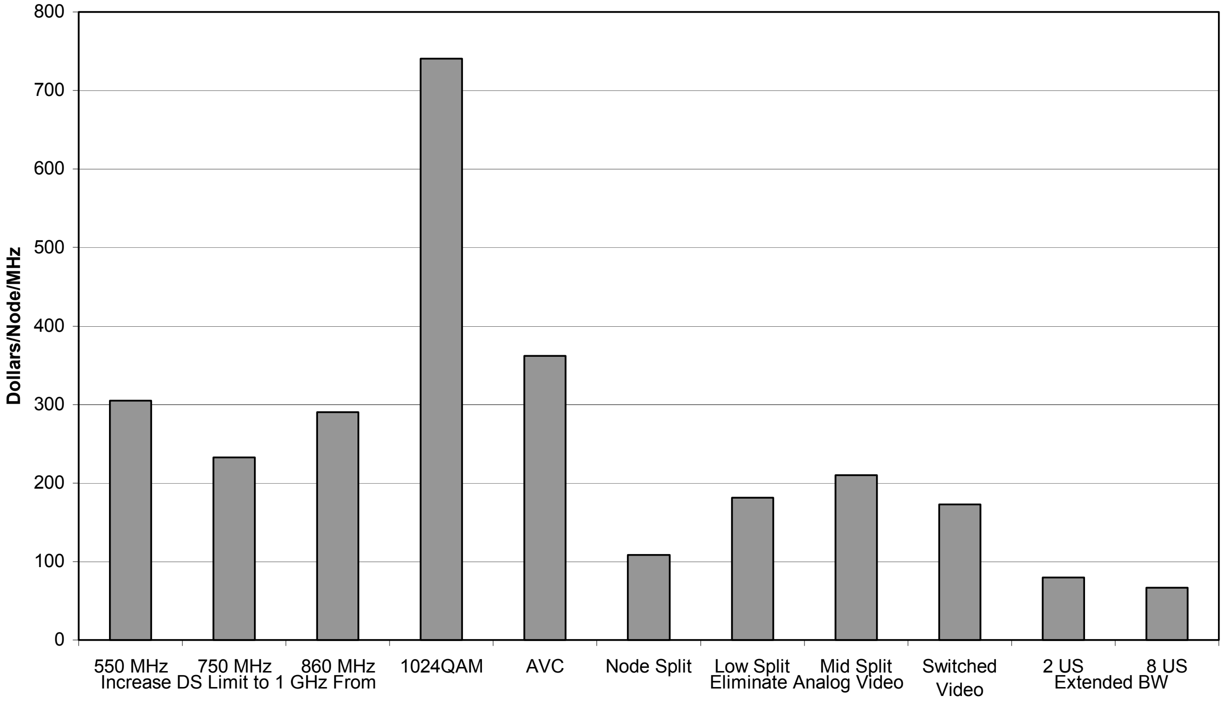

Figure 5: Cost-Benefit Ratio

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