Capacity Trends in Direct Broadcast Satellite and Cable Television Services

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by

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EXECUTIVE SUMMARY

Direct broadcast satellite (DBS) and cable television services have experienced continual growth in program-carrying capacity since their beginnings. This growth has been enabled by several core technologies, the capabilities of which increase over time.

The development of, and improvements in, the following technologies and techniques have contributed to increased DBS program-carrying capacity:

- Video compression
- Digital modulation and forward error correction
- Satellite platforms
- Satellite frequency reuse

The efficiency of video compression technology doubles about every 10 years. Improved digital modulation and forward error correction techniques permit improved bandwidth efficiency and operation closer to theoretical limits. Satellite platforms have increased their electrical power generation. Increased satellite frequency reuse provides greater spectrum efficiency. Patented innovations in the DBS industry point to additional potential sources of capacity increases.

Regarding cable, continual improvements in the following technologies have contributed to program-carrying capacity increases:

- Amplifiers and cable
- System architecture
- Video compression
- Digital modulation and forward error correction

Increasing frequency limits in amplifiers and coaxial cable raise the number of channels that can be carried. System architecture has evolved such that redundant transmission of all programs to all customers can be lessened or eliminated, increasing capacity for other uses. Video compression raises program-carrying capacity. Digital modulation and forward error correction increases cable system capacity beyond that available with analog systems; the transition from analog to digital is continuing today.

Advances in digital compression, modulation and error correction, along with new satellite platforms, increased reuse of DBS spectrum, continued deployment of fiber, and transition to new distribution architectures all can enable the continuing growth of program-carrying capacity for DBS and cable systems.

DBS and cable companies also can deploy such upgrades relatively quickly, since they control their distribution architecture "end-to-end." This allows them to implement more efficient network technologies faster than terrestrial broadcasters, for example, whose distribution evolution relies on consumers acquiring new hardware from third-party manufacturers, and typically involves the time-consuming development of open industry standards.

No current technical barriers to further program-carrying capacity increases exist in the DBS or cable television industry for the foreseeable future.

Therefore, any suggestions of technology-based capacity constraints that allegedly limit cable and satellite companies' ability to continue offering existing and new TV program channels lack credibility. On the contrary, the advances described in this report indicate that the vast majority of pay television services will encounter few technical obstacles to increasing their program-carrying capacity for the foreseeable future. Capacity constraints that may have hampered growth previously yield to evolved technologies and techniques in today's digital multichannel TV world.

Capacity Trends in Direct Broadcast Satellite and Cable Television Services

1. INTRODUCTION

Direct broadcast satellite (DBS) and cable television services have experienced continual growth in capacity since their beginnings. This growth has been enabled by several core technologies, the capabilities of which increase over time. This paper looks at DBS and cable television services in the U.S., examines how system capacity has changed over time, and looks at how some core technologies will likely evolve. It is found that there is no technical barrier to further capacity increases being implemented over time in the DBS and cable television services.

2. DIRECT BROADCAST SATELLITE

The start of direct-to-home satellite television in the U.S. can be placed at 1979, preceding DBS, when the FCC decided that receive-only satellite terminal licensing would no longer be mandatory. Some consumers started installing relative-large (2-3 meters diameter) dish antennas and analog receivers to pick up video programming intended for use by cable headends. Twenty-four standard-definition channels were available, more if the antenna were repositioned. This programming was available freely at first, but encryption added to some channels in 1986 restricted their access. Penetration of this initial large-dish technology grew slowly, peaking at about 3.9 million homes in 1994. There were several early direct-to-home service startup attempts that would use smaller antennas, but these were not successful.[1]

In 1994, DBS services using digital technology began. Household penetration grew to 13% in 1999 and 22% in 2004. Digital technology made the service practical, allowing a smaller consumer antenna size (less than one-meter diameter), the ability to tune to dozens of channels without repointing the antenna, and enabling more channels in a given radio-frequency bandwidth.[2]

DBS program-carrying capacity has increased over time, in terms of number or resolution of channels. The first DBS systems in 1994 provided over 200 standard-definition (SD) channels. In 2004, program-carrying capacity increased to where over 10 high-definition (HD) channels could be added to the 200-plus SD channels.[3] Recently, DIRECTV reported having over 185 HD channels and five 3D channels.[4] Since HD channels require

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[1] S. Dulac and J. Godwin, "Satellite Direct-to-Home," *Proceedings of the IEEE*, vol. 94, no. 1, pp. 158-172, Jan. 2006.
[2] Id.
[3] Id.
[4] DIRECTV Annual Report, 2012.

several times the bit rate of SD channels, this is a significant increase in capacity. As discussed below, the prospects are good for further capacity gains, should DBS operators take the necessary steps to advance their systems.

The development of, and improvements in, the following technologies and techniques have contributed increased DBS capacity over time:

- Video compression
- Digital modulation and forward error correction
- Satellite platforms
- Satellite frequency reuse

Each of these factors is discussed below.[5]

2.1 Video compression

Video compression uses digital technology to reduce the number of bits needed to send a video program. The more efficient the video compression technology, the fewer bits needed for each channel, and the more channels that can be sent using a satellite transponder’s fixed bandwidth. Alternatively, more efficient video compression allows the same bit rate to be used to send higher-resolution video.

At its most basic, video compression works by removing redundancy within a video frame and between video frames while maintaining quality as perceived by the viewer. The more computationally complex the compression algorithm, the more the video can be compressed. Practically, implementation of more advanced algorithms is limited by the state of the art in Very Large Scale Integrated (VLSI) circuit technology. Over time, video compression algorithms, and the microelectronics needed to implement them, improve in parallel and occasionally reach a point when the improved algorithms become practical to implement.

Evolution of video compression technology has resulted in continual improvement of compression efficiency. About every 10 years, video compression doubles in efficiency as shown in Figure 1 below.

[5] In this paper, “channels” refers to linear television channels by which streams of programming are offered on a specific channel at a specific time of day.

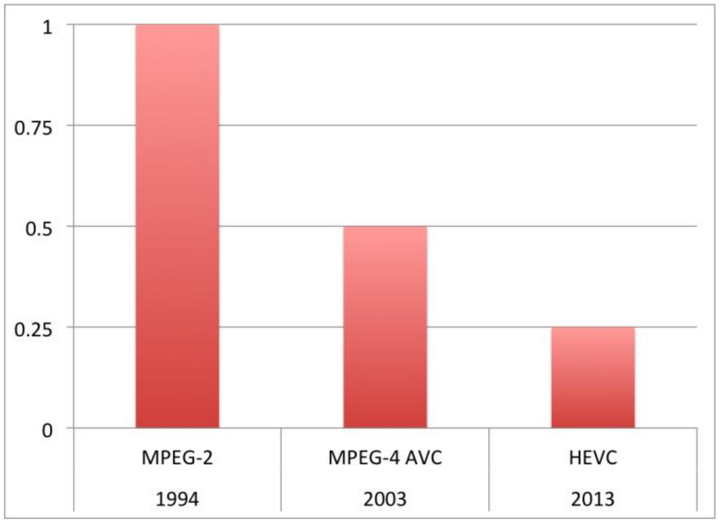

Figure 1. Relative bitrate of video compression standards for a given video quality.

Early direct-to-home systems, by their analog nature, could not benefit from digital video compression. The introduction of digital DBS systems in 1994 saw the application of the MPEG-2 standard for video and audio coding, which was developed jointly by ITU and the Moving Picture Experts Group (MPEG). DBS systems were one of the major target applications of MPEG-2, and the DBS industry actively participated in the MPEG-2 standards process.[6]

MPEG-2 was developed under enormous schedule pressure, including from the DBS industry.[7] It was apparent during its completion that further improvements could have been made had the work plan permitted. MPEG-2 was completed in 1994 and MPEG-4 was approved as an MPEG work item that same year. MPEG-4 was first standardized as MPEG-4 Visual in 1999.

In 2001, ITU and MPEG formed a joint team to prepare a standard enabling video compression better than MPEG-4 Visual; this standard was finalized in its first edition in 2003, and is commonly known as MPEG-4 Advanced Video Coding (AVC). In 2004 the DBS industry started deploying video compression technology comporting with MPEG-4 AVC, which reduced by half the bit rate needed to represent video compared to MPEG-2.[8]

Having a more efficient standard does not necessarily mean it is deployed. DISH Networks says that, even though it has been deploying receivers that utilize MPEG-4 compression technology for "several years," "many" of its customers still have receivers

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[6] D. C. Mead, *Direct Broadcast Satellite Communications*. Upper Saddle River, NJ: Addison-Wesley, 2000, 114.

[7] Id., 232.

[8] Dulac and Godwin, "Satellite Direct-to-Home."

that use less efficient MPEG-2. DISH Networks says that MPEG-4, when fully deployed, will allow an increase in the number of channels that can be carried over its existing satellites. [9]

The latest video compression standard, High Efficiency Video Coding (HEVC), was developed by MPEG and ITU and approved in early 2013. If it is deployed, it would allow today's program-carrying capacity to double compared to MPEG-4 AVC, and quadruple compared to MPEG-2.[10] DIRECTV currently reports over 185 HD channels.[11] With HEVC, this could be increased to over 370 HD channels. Or, anticipating the introduction of 4K Ultra HD (UHD) television, the channels of which use the capacity of about four HD channels, capacity could be increased to, say, 330 HD channels and 10 4K UHD channels.

Continuing this trend, NTT recently announced further video compression advances saying that, through use of proprietary technology, it has demonstrated a 2.5-times bandwidth saving over MPEG-4 AVC, improving on the 2-times gain of HEVC. Put another way, the company says it can cut the MPEG-4 AVC bit rate by 60% without any loss of picture quality.[12]

There is no sign that video compression will stop improving in efficiency. It will continue to be an enabler of increased capacity for the foreseeable future. It should also be noted that similar advances in audio compression technologies continue to emerge, and that these contribute, albeit to a lesser extent, to the ongoing increase in efficiency of spectrum use by direct satellite services, for both television audio and audio-only content.

With changes in video compression, or in other core technologies, there is concern about getting updated hardware into the hands of consumers. DIRECTV says, however, that it assigns a useful life to its existing set-top receivers of three to four years, depending on their capability.[13]

2.2 Digital modulation and forward error correction

Modulation and error-control coding by DBS operators in the U.S. is influenced by standards developed by the Digital Video Broadcasting Project, a standards development organization made up of about 200 members. DVB-S2 is the Project's latest digital satellite transmission system, and is intended to gradually replace the former standard,

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[9] DISH Networks Annual Report, 2012.
[10] Next Generation Video Compression, Ericsson Review, April 24, 2013.
[11] DIRECTV Annual Report, 2012.
[12] NTT press release, *NTT Develops World's Highest-level Compression Software Encoding Engine Fully Compliant with Next-gen "HEVC /H.265" Video Coding Standard, Rolls Out "HEVC-1000 SDK" Codec Development Kit,* August 8, 2013, at http://www.ntt.co.jp/news2013/1308e/130808a.html (last visited September 20, 2013).
[13] DIRECTV Annual Report, 2012.

DVB-S. The DVB-S2 standard is used by DIRECTV in conjunction with MPEG-4 AVC video compression for delivery of HDTV services.[14] Both the DVB-S and DVB-S2 standards specify digital modulation and forward error correction for DBS systems.

2.2.1 Digital modulation

Modulation refers to the way the satellite's radio signal is varied to convey digital video to the viewer. Early pre-digital direct-to-home technology used frequency modulation (FM). Digital DBS system introduction in 1994 saw the use of digital modulation in the form of Quadrature Phase Shift Keying (QPSK), which is able to represent two digital bits at once, in a symbol, through phase shifting. In 2005, 8PSK was added, which can represent three bits per symbol and is thus more bandwidth efficient.

DISH Networks reports that a "significant number" of its subscribers don't have receivers that utilize the more bandwidth-efficient 8PSK modulation. It says it is in the process of deploying receivers compatible with 8PSK. It is not clear what the timetable is for replacement.[15]

The DVB-S2 standard provides for even more bandwidth-efficient modulations schemes, 16APSK and 32APSK, capable of representing four and five bits per symbol.[16] Typically, however, DBS transponders are operated in a nonlinear mode that is good for QPSK and 8PSK but not good for 16APSK and 32APSK, which are intended for more linear-modes.[17] Higher-order modulation schemes in DBS also require a higher carrier-to-noise ratio at the receiver; as discussed below, satellite platform evolution has been toward higher power-generation capabilities.

Related to modulation, in 2012, DIRECTV was issued a U.S. patent on a method of combining transponder bandwidths to achieve a bandwidth-efficiency improvement of 21%.[18] The patent notes that there are guard bands between adjacent transponders of the same polarization. Such guard bands are a holdover from legacy FM, which required a higher carrier-to-noise ratio than digital modulation. DIRECTV's patent discloses a method of combining transponders into a wideband "virtual" transponder that is able to transmit on existing guard bands so the satellite has greater bandwidth efficiency. The

[14] *2nd Generation Satellite – DVB-S2,* DVB Project Office fact sheet, August 2012.
[15] DISH Network Annual Report, 2012.
[16] ETSI EN 302 307 V1.3.1 (2013-03): "Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications (DVB-S2)"
[17] Dulac and Godwin, "Satellite Direct-to-Home."
[18] E. C. Chen, "Combining transponder bandwidths for source and forward error correction coding efficiency," U.S. Patent 8,200,149, June 12, 2012.

patent says guard bands "represent an attractive source of bandwidth that is still available."[19]

2.2.2 Forward error correction

All digital modulation techniques are subject to errors during demodulation by the receiver. These errors can be caused by noise and interference. A digital bit intended to be a "1" can instead be decoded as a "0," and vice versa, especially when the signal-to-noise ratio is relatively low. Forward error correction systematically adds bits to a transmission so a receiver, through a similar systematic process, can detect and correct many errors.

Early DBS systems used Reed-Solomon and convolutional codes together. Newer DBS systems based on DVB-S2 uses a more efficient combination of Bose-Chaudhuri-Hcquengham (BCH) with Low Density Parity Check (LDPC) codes. The major benefit of the BCH/LDPC codes is that link performance is closer (within 0.7 dB) to the theoretical Shannon limit, increasing bandwidth efficiency. The codes also allow DVB-S2 to be approximately 30% more bandwidth efficient compared with DVB-S, the previous standard.[20]

In 2012, DIRECTV was issued a patent for adaptive error correction, which would allow error correction to be optimized based on varying conditions, such as weather, the value of the content being transmitted, and local conditions for individual spot beams.[21] The patent notes that, typically, DBS error correction is chosen based on a worst-case error rate, making it overly robust for most situations and resulting in inefficient use of bandwidth. The method disclosed in the patent would allow error-control optimizations to be applied with finer granularity at the spot-beam level. Different spot beams could have different optimizations depending on local conditions. Bandwidth that is no longer needed for worst-case forward error correction could be devoted to increasing program-carrying capacity.

2.3 Satellite platforms

The start of digital DBS service in 1994 included new Boeing 601 satellite platforms developed specifically that application.[22] Solar panels on these satellites, using single-

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[19] The FCC recently launched an inquiry to examine whether satellite operators are "warehousing" capacity excessively, including through not using the latest available technology. Issues Related to Allegations of Warehousing and Vertical Foreclosure in the Satellite Space Segment, FCC IB Docket No. 13-147, adopted June 5, 2013.
[20] Dulac and Godwin, "Satellite Direct-to-Home."
[21] L. J. O'Donnell, H. M. Hagberg, and M. A. Gorman, "Adaptive Error Correction," U.S. Patent No. 8,136,007, March 13, 2012.
[22] Dulac and Godwin, "Satellite Direct-to-Home."

junction (single layer) silicon solar cells, could generate over 4 kilowatts of direct-current power. Traveling-wave-tube amplifiers were phase-combined in pairs to provide greater reliability over traditional single-tube implementations. The conversion efficiency of direct-current to radio-frequency energy was about 50%. These early satellites could support eight 240-watt travelling-wave-tube transponders providing coverage to the 48 contiguous United States.

DBS satellite platforms evolved over a decade to provide more bandwidth per satellite without proportionately-greater cost, with the Boeing 701 platform representative of 2005 technology. Solar panels increased in size and used more efficient triple-junction (triple-layer) gallium arsenide solar cells. Direct-current power increased four-times to 16 kilowatts, compared to the earlier Boeing 601 platform.[23] Traveling-wave tube efficiency had increased to 65% by the year 2000.[24]

It is expected that the efficiency of satellite platforms will continue to improve, making more power available for broadcast services, and allowing for more efficient operation.

2.4 Satellite frequency reuse

If satellite orbital locations are sufficiently apart to avoid interference and maintain coverage, satellites at those locations can operate on the same frequencies, reusing that spectrum and increasing program-carrying capacity. Generally, Ku-band frequencies can be reused down to at least nine-degree separation without objectionable interference. Ka-band frequencies can be reused down to at least four-degree separation without objectionable interference.

DIRECTV uses a fleet of twelve satellites, with eleven owned and one leased. It has seven Ku-band satellites at the following orbital locations: 101° West Longitude (W.L.) (three), 110° W.L. (one), 119° W.L. (one), 95° W.L. (one-leased), and one spare satellite that is currently being leased by a third party and operating at 56° East Longitude. It also has five Ka-band satellites at 99° W.L. (two) and 103° W.L. (three). DIRECTV plans to add capacity with the launch of two new satellites in 2014. DIRECTV reports unused capacity, in the form of in-orbit spare satellites and excess transponder capacity, that is kept as backup in the case of a satellite failure.[25]

Similarly, DISH Networks owns, or leases capacity on, 15 satellites in seven orbital locations. It has entered into a contract for construction of a new satellite to provide additional HD capacity. That satellite is expected to be launched in 2015.[26]

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[23] C. W. Bostian, W. T. Brandon, A. U. Mac Rae, C. E. Mahle, and S. A. Townes, “Key technology trends – Satellite systems, “Space Communications, vol. 16, 97-124, 2000.
[24] Mead, *Direct Broadcast*, 50.
[25] DIRECTV Annual Report, 2012.
[26] DISH Network Annual Report, 2012.

The FCC has adopted a Notice of Proposed Rulemaking regarding operation of Ku-band DBS satellites at less than the nominal nine-degree separation. If such rules are approved, it would allow for increased capacity by DBS providers.[27] In the meantime, the FCC has, on occasion, granted a few applications requesting Ku-band DBS operation at less than nine-degree separation.[28]

In addition to frequency reuse through multiple orbital locations, satellite spot beams for local markets permit frequency reuse from the same satellite between non-contiguous beams.

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[27] Notice of Proposed Rulemaking in the matter of Amendment of the Commission's Policies and Rules for Processing Applications in the Direct Broadcast Satellite Service (FCC IB Docket No. 06-160) and Feasibility of Reduced Orbital Spacing for Provision of Direct Broadcast Satellite Service in the United States (FCC Report No. SPB-196), adopted August 14, 2006.

[28] See, e.g., the FCC's Order in the matter of SES Americom, Inc., Petition for Declaratory Ruling Regarding Direct Broadcast Satellite Service to the U.S. Market from the 105.5° W.L. Orbital Location, IBFS File No. SAT-PDR-20070129-00024, Call Sign S2731, adopted January 16, 2013. This orbital location is between the 101° and 110° orbital locations used by DIRECTV on the same band.

2.5 Summary of DBS Capacity Increases

Table 1 collects the above concepts.[29]

Table 1. Technical characteristics of DBS systems over time.

	1984-1986	**1994-1996**	**2004-2006**	**2013**	**Next Generation (potential)**
Primary application	Delivery to cable head-ends	Direct-to-home	Direct-to-home	Direct-to-home	Direct-to-home
National viewable TV channels per home	24 national SD (per antenna position)	>200 SD	>200 SD and >10 HD	>185 HD and five 3D	>330 HD plus 10 4K UHD
Downlink beam shape	Single 48-states beam plus some Alaska and Hawaii coverage	Single 48-states beam plus some Alaska and Hawaii coverage	48-states beam, Alaska and Hawaii coverage, plus spot beams for local markets	48-states beam, Alaska and Hawaii coverage, plus spot beams for local markets	48-states beam, Alaska and Hawaii coverage, plus spot beams for local markets
Number of orbital slots per system	>10	1	>3	5	>5
Total satellites per system (maximum)	N/A	Up to 3	>10	15	16
Video compression	None	MPEG-2	MPEG-2 plus MPEG-4 AVC for certain services	MPEG-2 and MPEG-4 AVC	HEVC
Modulation	FM	QPSK, Reed-Solomon and convolutional codes	QPSK plus 8PSK for certain new services	QPSK and 8PSK	8PSK
Forward error correction	None	Reed-Solomon and convolutional codes	Reed-Solomon and convolutional codes	Prior solution plus BCH and LDPC codes	BCH and LDPC codes

29 Table adapted from Dulac and Godwin, "Satellite Direct-to-Home," Table 4. Dulac and Goodwin have been associated with DIRECTV, and their Table 4 tends to follow the evolution of the DIRECTV system.

3. CABLE TELEVISION

Cable television began in 1948 when Ed Parson of Astoria, Oregon connected homes to an antenna using twin-lead transmission wire.[30] The purpose was to receive distant or obstructed broadcast signals that were not easily obtained with a home antenna. Among the early operators of these systems were TV retailers, who were looking to boost TV sales with a better signal. The number of channels received corresponded to those "in-the-air." The first systems just carried all or part of the 12 VHF television channels (2-13).[31] Growth in these systems continued in the U.S. until the late 1960s, when almost all of the areas in the U.S. that could benefit had service.

Early cable television systems, those built in the mid-1950s to the mid-1970s, generally used 170 MHz of bandwidth from 50 MHz to 220 MHz, and provided from 12 to 22 television channels.[32]

The mid-1970s saw satellite delivery of television programs to cable headends, enabling channels beyond those from area broadcasters. These new channels included local stations that are distributed nationally, movie channels, and specialized channels for news, weather and sports. The number of channels increased to where some capacity could be devoted to pay-per-view programs using conditional access technology.

Medium-channel-count cable systems, constructed in the late 1970s, operated with bandwidths of 280 MHz and 350 MHz, providing 40 channels and 52 channels, respectively.[33]

Higher channel-count systems were constructed beginning in 1981. These included 60-channel, 450 MHz systems. These were followed by dual-cable, 400 MHz and 450 MHz systems carrying 108 channels and 120 channels, respectively.[34] Dual-cable systems declined in popularity, with single-cable systems constructed that used 450-750 MHz bandwidth. These large-capacity systems were capable of two-way operation, with signals to the consumer occupying radio frequencies 50 MHz and higher, and signals from the consumer to the cable headend occupying the 5-30 MHz or 5-40 MHz bands.[35]

DIRECTV and DISH Network began offering service in the 1990s offering greater channel counts compared to analog cable systems. In response, cable operators upgraded

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[30] W. S. Ciciora, "Cable Television in the Unites States – An Overview," Cable Television Labs, Inc., 1995, revised second edition.
[31] W. Ciciora, J. Farmer, D. Large, M. Adams, *Modern Cable Television Technology*, San Francisco, CA: Morgan Kaufman – Elsevier, 2004, 12.
[32] Ciciora, "Cable Television."
[33] Id. at 22.
[34] These dual cable systems are an example of increasing capacity through frequency reuse, analogous to satellite frequency reuse discussed in Section 2.4 above.
[35] Ciciora, "Cable Television."

their systems by incorporating more optic fiber into coaxial networks and starting the transition to digital technology from analog.[36]

Today, the largest cable operators in the U.S., Comcast, Time Warner Cable, and Charter, use hybrid fiber optic and coaxial cable networks (discussed below) that provide two-way transmission. Comcast and Time Warner Cable systems provide 750 MHz capacity or higher. RF bandwidths of 870 MHz have been common for new construction.[37]

Comcast provides various levels of service ranging from a basic service with 20-40 channels to a full digital service with access to over 300 channels. Comcast's digital video services also include its On Demand service, which offers more than 30,000 standard-definition and high-definition programming choices. Comcast plans to continue to increase the number of On Demand choices available, including HD programming.[38]

Time Warner Cable (TWC) similarly offers tiers of video programing as well as other services. The channels in these tiers range from approximately 25 channels to approximately 400 channels. Approximately 165 HD channels are offered. There is also a "large selection" of video-on-demand programming in HD.[39]

In addition to channels, the cable industry has also evolved data services from simple text content to today's high-speed broadband. This, in turn, has enabled program delivery using Internet Protocol (IP) technology.

Continual improvements in the following technologies, discussed below, have contributed to this increase:

- Amplifiers and cable
- System architecture
- Video compression
- Digital modulation and forward error correction

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[36] Annual Assessment of the Status of Competition in the Market for the Delivery of Video Programming, FCC MB Docket No. 12-203, Fifteenth Report, adopted July 19, 2013 (hereinafter, *15th Report*), para. 84.
[37] Ciciora, *Modern Cable*, 752.
[38] Comcast Annual Report, 2012.
[39] Time Warner Cable Annual Report, 2012.

3.1 Amplifiers and cable

The primary medium of cable television is coaxial cable. It conducts and contains the radio-frequency energy used to carry programs. Amplifiers are installed periodically along coaxial cable paths such that the gain of an amplifier compensates for loss along an intervening cable, with limits on the number of amplifiers along one path due to accumulating distortion of the signal caused by the amplifiers.[40]

Amplifiers and cables have a practical upper-frequency limit. The trend has been for these technologies to improve, with the upper-frequency limit increasing. This has allowed for increased bandwidth and corresponding increases in program-carrying capacity.

3.2 System architecture

The early days of the cable industry saw coaxial cable used along all parts of the system and deployed in a tree-and-branch architecture. From the cable headend (the origination point), trunk cables would connect to feeder cables. From the feeder cables, drop cables would connect to the home.[41] While this architecture was economical at the time, the relationship between signal levels and quality, number of amplifiers, and bandwidth limited the size of purely coaxial systems. In addition, the bidirectional services later envisioned by the industry, including data services and telephony, were impractical to implement with purely coaxial technology.

In the 1990's, the cable industry moved toward a hybrid fiber coax (HFC) architecture that relieved these concerns. In this configuration, optical fiber extends from the headend to neighborhood nodes. These nodes are connected to customers using coaxial cable. This relieves coaxial cable constraints in much of the system. Since different signals can be sent to each node, this is a form of frequency reuse. In a common hybrid fiber coax configuration, approximately 500 customers are connected to a node using 870 MHz of bandwidth.[42]

TWC's cable systems use a hybrid fiber coaxial cable architecture. TWC is transitioning from the use of traditional local headends to two national centers connected to TWC's nationwide fiber backbone, which interconnects with regional and metro rings.[43]

Comcast currently uses a hybrid fiber-optic and coaxial cable network that, Comcast says, is sufficiently flexible and scalable to support its future technology requirements. Comcast says it continues to develop and launch new technology initiatives, "deploying

[40] Ciciora, *Modern Cable*, 442, 495, 507.
[41] Ciciora, "Cable Television."
[42] Ciciora, *Modern Cable*, 752.
[43] Time Warner Cable Annual Report, 2012.

multiple tools to recapture bandwidth and optimize our network, including using advanced video encoding and digital compression technologies."[44]

A newer architecture that can further increase cable system capacity includes switched digital video (SDV). SDV increases capacity by sending to a group of homes only those channels that are being watched. The remaining capacity is freed for other uses, such as high-speed broadband.[45] The FCC says that, at the end of 2012, SDV served approximately 43% of digital cable customers in the top-eight cable systems.[46]

Several "fiber-deep" architectures exist to extend fiber deeper in the network, as far as to the home, but they are not yet common.[47] It is expected, however, that use of fiber distribution will continue to generally increase, including a growing number of installations that take fiber all the way to the customer's premises.

To the extent that fiber is used today, coaxial cable attenuation and accumulating coaxial cable amplifier noise is not an issue. Fiber optic systems have their own practical limitations, including distance and the number of times a signal can be split before amplification.[48] Generally, though, bandwidth and path-length limitations of fiber optic systems are improved over those of coaxial cable systems, and the additional bandwidth can be used to increase program-carrying capacity.

3.3 Video compression

Similar to the DBS industry, the conversion of cable systems from analog to digital enables them to take advantage of the efficiencies of video compression. More channels can be sent in a given bandwidth. Video and audio compression are discussed with regard to DBS in Section 2.1 above; the same concepts apply to cable systems.

MPEG-2 is the dominant video compression technology in cable. Perhaps because the cable industry has fewer program-carrying-capacity constraints, it is not moving quickly toward more efficient video compression such as MPEG-4 AVC. This delay means it could conceivably wait longer, skip MPEG-4, and move directly to HEVC. The advent of more efficient architectures, however, such as those using SDV, could further reduce the urgency in adopting newer video compression technology.

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[44] Comcast Annual Report, 2012.
[45] Time Warner Cable Annual Report, 2012.
[46] *15th Report*, para. 5.
[47] Ciciora, *Modern Cable*, 775.
[48] Id., 780.

3.4 Digital modulation and forward error correction

At the end of 2012, slightly more than half of the collective footprints of the top eight cable operators had been converted to all digital.[49] This makes more efficient use of cable system bandwidth. TWC expects, over the next few years, to continue to reclaim spectrum currently dedicated to the delivery of analog video signals, thereby freeing additional capacity for other uses.[50]

Digital modulation and forward error correction for cable systems is standardized by the Society of Cable Telecommunications Engineers SCTE.[51] The main form of digital modulation on cable systems today is quadrature amplitude modulation (QAM). QAM varies the signal amplitude and phase depending on the information to be sent. QAM can appear as 64 QAM and 256 QAM, which can send 6 or 8 bits at once, respectively.

Though not yet standardized, there is the potential to use 1024 QAM, which can send 10 bits at once, for higher bandwidth efficiency, thereby further increasing program-carrying capacity.[52]

The standardized forward error correction is a four-layer process consisting of Reed-Solomon coding, interleaving, randomization, and Trellis encoding.

The future of cable system modulation looks to be disrupted by migration of linear video content from MPEG/QAM to IP.[53] If this occurs, only the channels being viewed need be sent, freeing remaining cable system bandwidth, and making traditional cable program-carrying-capacity notions irrelevant. Comcast is expected to introduce an all IP set-top box in 2013. It is expected to use a cloud based interface to get linear video that has been transcoded from QAM video to IP streams that can be delivered to the home.[54]

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[49] *15th Report*, para. 5.
[50] Time Warner Cable Annual Report, 2012.
[51] Society of Cable Telecommunications Engineers SCTE 07 2011: Digital Transmission Standard For Cable Television.
[52] Notice of Proposed Rulemaking in the matter of Cable Television Technical and Operational Requirements, FCC MM Docket No. 12-217, adopted August 3, 2012, para. 9.
[53] *15th Report*, para. 90.
[54] Id., para. 358.

3.5 Summary of Cable Channel-Count Increases

Table 2 collects the above concepts.

Table 2. Technical characteristics of cable systems over time.

	Mid-1950s to mid-1970s	Late 1970s	1980s	2012	Next Generation (potential)
Available channels per home	12-22	40-52	120	300-400	>1000
Video/audio encoding	None	None	None	MPEG-2 (linear) MPEG-4 (IPTV)	HEVC
Modulation	Analog	Analog	Analog	Analog and Digital	Digital/IP

4. CONCLUSION

Program-carrying capacity in DBS and cable television systems has consistently increased since the start of those industries, and the prospects for continuation of such growth remain high.

DBS is taking advantage of improved video compression techniques to increase system capacity. Improved digital modulation and forward error correction techniques make more efficient use of radio-frequency bandwidth. Current satellite platforms operate with several times the DC power of earlier models. Frequency reuse has allowed the same frequencies to be used to deliver additional channels.

Cable television has increased its program-carrying capacity through use of higher-capability amplifiers and coaxial cable. It has also increased capacity through ongoing conversion from analog to digital systems, which make use of video compression, digital modulation, and forward error correction. New network architectures have made more efficient use of cable system bandwidth.

Current advances in video and audio compression, digital modulation and error correction techniques, new satellite platforms, increased reuse of DBS spectrum, continued deployment of fiber, transition to switched digital video, and IP-based distribution architectures all can enable the continuing growth of program-carrying capacity for DBS and cable systems.

Note that DBS and cable companies also possess significant agility to deploy these upgrades relatively quickly, since they exercise substantial control over their distribution architecture "end-to-end"—all the way to consumers' set-top receivers. This allows those companies to implement evolved and more efficient network technologies faster than terrestrial broadcasters, whose distribution evolution relies on consumers acquiring evolved hardware from third-party manufacturers, a process that often involves the time-consuming development of open industry standards.

It may therefore be concluded that no technical barriers to further program-carrying capacity increases currently exist in the DBS or cable television industries. Any suggestions of technology-based capacity constraints that limit cable and satellite companies' ability to continue offering existing and new TV program channels lack credibility. On the contrary, the advances described in this report indicate that the vast majority of pay television services will encounter few technical obstacles to increasing their program-carrying capacity for the foreseeable future. Capacity constraints that may have hampered growth previously yield to evolved technologies and techniques in today's digital multichannel TV world.

About Steven J. Crowley, P.E.

Steve Crowley helps organizations with technology analysis, R&D activities, regulatory proceedings, standardization, and patent portfolio management. Crowley's background includes work in mobile broadband, broadcasting, satellite, unlicensed services, cable television, and device performance measurement. Clients have included manufacturers, service providers, trade associations, government agencies, entrepreneurs, and law firms.

Crowley has participated in many industry and government activities dealing with standardization and technology assessment, including APCO, 3GPP, 3GPP2, IEEE 802, CEA, CTIA, and TIA. He has published many articles on technology in industry and popular publications and contributed to a book on due-diligence review of broadcast stations. He has spoken before industry groups on subjects such as digital audio broadcasting, human exposure to radio-frequency energy, spectrum policy, and new business opportunities in technology.

Crowley holds a Bachelor of Science in Electrical Engineering (BSEE) from Bradley University and a Master of Business Administration (MBA) from Duke University. He is the co-inventor of several wireless communications technologies, each of which has been awarded a United States patent. He is licensed as a Professional Engineer by the District of Columbia.

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