Broadband Capacity Growth Models

Will the end of Exponential Growth eliminate the need for DOCSIS 4.0?

A Technical Paper prepared for SCTE by

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1. Introduction

Internet consumption grew exponentially last decade, doubling every other year. Several years ago, the growth rate began slowing, but COVID turned the world on its head with everyone living, working, and playing from home. This created a bandwidth (BW) bubble, especially upstream. Will this bubble continue, signaling a new paradigm, or return to our previous path?

ARRIS/CommScope has the most extensive broadband capacity monitoring history in the industry. Data collection started in 2010; done every year since; and covers 10's of millions of modems from numerous multiple system operators (MSOs). The 2022 data is in: this paper analyzes the new normal, quantifies the '21 COVID bump, and shows our recent consumption or average bandwidth per sub (Tavg) growth rates.

The real multi-billion-dollar question is what's the BW growth for coming decades? This drives our network investment strategies. Has Tavg growth slowed to a lower rate (e.g., doubling every 3-4 years) or is it no longer exponential? Some folks claim exponential growth is dead, and that BW growth is linear or following the Adoption S-curve. [S-curves have exponential growth in early years, linear growth during middle years, and flattens out in later years.] E.g., will Tavg reach a limit of 2½ ultra high-definition (UHD) streams per home (~25Mbps) and stay there? Or will another S-curve, potentially driven by virtual reality (VR) / augmented reality (AR), start a new era of high growth?

The paper highlights research on all alternatives; creates trendlines for each; and measures how accurately it matches last decade's data. These BW growth trajectories are mapped out for 5/10/15 years. The resultant spaghetti plots show a cone of uncertainty that grows over time, roughly doubling every 5 yrs.

The 2nd half of the paper plugs various Tavg growth trendlines into the CommScope network capacity modeling tool to analyze 1218/204 megahertz (MHz) & Data Over Cable Service Interface Specifications (DOCSIS®) 4.0 plant. It shows their useful lifetime using various growth models and explores whether low growth might eliminate the need for 4.0, or just delay it, giving precious time to transition.

Our wrap up recommends some migration strategies to minimize up front investments while maintaining flexibility to increase network capacity and manage uncertainty risks.

2. Network Capacity Planning Overview

Determining the capacity requirements for a service group (SG) is critical for providing customers with the appropriate quality of experience (QoE). Figure 1 shows an example of a SG upstream (US) capacity usage over a 16-minute window sampled at 1-second intervals. If an operator samples the BW usage once every 16-minutes, then it determines the average BW over that interval as shown by the purple line. This is a very useful datapoint but insufficient to determine the required capacity for the SG.

Sampling at 1-minute intervals would capture some of the variations, or ripples in the system but would still miss the many spikes which are individual modems bursting on top of the average BW. The gray line in the figure shows the high-water mark from 1-minute samples.

If an operator could sample at 1-second intervals or faster, then they could more closely determine the required SG capacity. The 1-second high-water mark is shown by the orange line. But sampling at these rates is not feasible in real systems, so another method is needed.

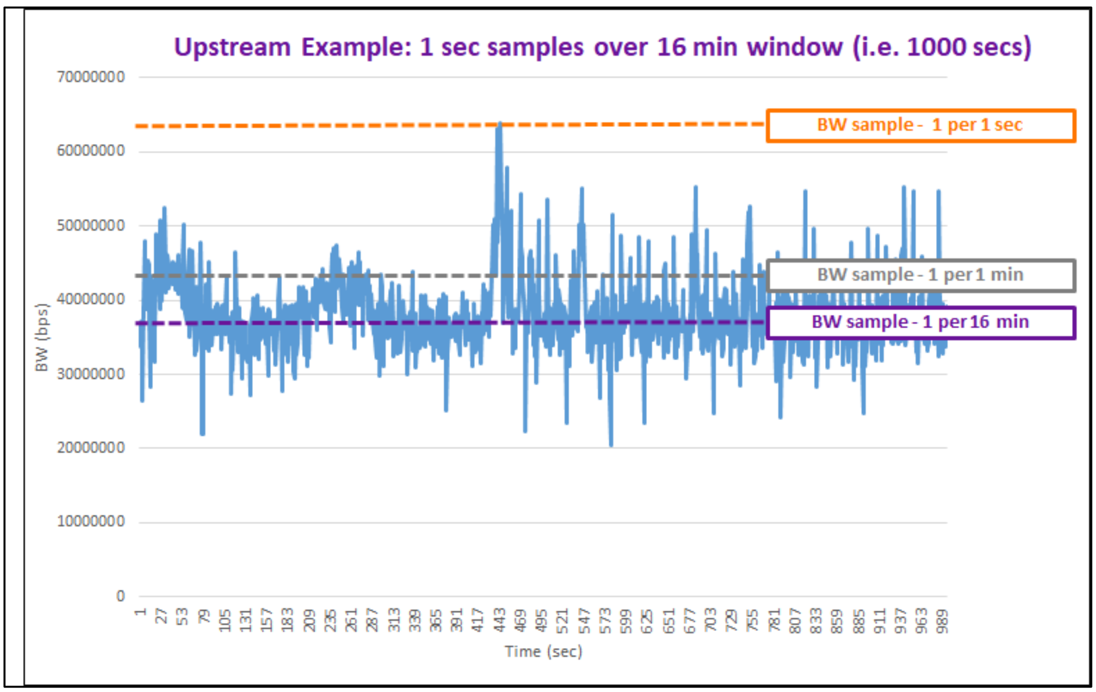


Figure 1 – Example of Upstream Capacity Usage

2.1. The "Basic" Traffic Engineering Formula

The CommScope (formerly ARRIS) team has provided industry leading traffic engineering research for over a decade. Originally, [CLO_2014] introduced QoE for broadband networks and developed a relatively simple SG traffic engineering formula that's easy to understand and useful for demonstrating basic network capacity components. Over time, this evolved and a network capacity analysis [ULM_2019] gave an updated insight into calculating the SG capacity requirements. Some additional references of note include [EMM_2014], [ULM_2014], [CLO_2016], [ULM_2016], [CLO_2017], [ULM_2017] and [HOWALD_2022].

The "Basic" formula shown below is a simple two-term equation. The first term (Nsub*Tavg) allocates bandwidth capacity to ensure that the aggregate average bandwidth consumption generated by the number of subscribers (Nsub) can be adequately carried by the service group's bandwidth capacity. The first term is viewed as the "Direct Current (DC) component" of traffic that tends to exist as a continuous flow of traffic during the peak busy period. The growth rate of Tavg has seen much research.

"COMMSCOPE/CLOONAN'S CAPACITY EQUATION" Traffic Engineering Formula:

$$C \geq (Nsub * Tavg) + (K * Tmax\_max) \quad (1)$$

where:

C is the required bandwidth capacity for the service group
Nsub is the total number of subscribers within the service group
Tavg is the average bandwidth consumed by a subscriber during the busy period
K is the QoE constant (larger values of K yield higher QoE levels)…
where $0 \leq K \leq$ infinity, but typically $1.0 \leq K \leq 1.2$
Tmax_max is the highest Service Tier (i.e., Tmax) offered by the MSO

Figure 1 shows there are obviously fluctuations that occur (i.e., the "alternating current (AC) component" of traffic) which can force the instantaneous traffic levels to both fall below and rise above the DC traffic level. The second term (K*Tmax_max) is added to increase the probability that all subscribers experience good QoE levels for most of the fluctuations that go above the DC traffic level.

The second term in the formula (K*Tmax_max) has an adjustable parameter defined by the K value. This parameter allows MSOs to increase the K value and add bandwidth capacity headroom that provides better QoE to their subscribers within a service group. In addition, the entire second term is scaled to be proportional to the Tmax_max value, which is the maximum service tier being offered to subscribers.

In previous papers [CLOONAN_2013, CLOONAN_2014, EMM_2014], found that a K value between 1.0 to 1.2 provides good QoE results for a 250 subscriber SG. Larger SGs need even larger values of K while very small SGs might use a K value ≤ 1.0.

2.2. The "Modified" Traffic Engineering Formula

Over time, it was discovered that the optimum K value varies based on all the inputs: Nsub, Tavg and Tmax_max. [ULM_2017] noted some of these limitations along with some refinements to the basic formula above. This resulted in the following which is still algebraically equivalent to the basic formula:

Modified "COMMSCOPE/CLOONAN'S CAPACITY EQUATION" Traffic Eng Formula:

$$C \geq (Nsub * Tavg) + (K-1) * Tmax\_max + Tmax\_max \quad (2)$$

The subtle change is that there are now three main components to the traffic engineering formula:

1. Peak Busy Period Average Consumption (i.e., Nsub * Tavg)
2. Peak Busy Period Ripple for managing QoE (i.e. (K-1) * Tmax_max)
3. Headroom for maximum Service Tier Burst (i.e., 1 * Tmax_max)

Figure 2 shows how the modified formula maps to the US capacity usage example given in Figure 1. The basic formula might have used a value of K=1.2 in this example. This is now broken into a burst component equal to Tmax_max plus a ripple component that is estimated by 20% * Tmax_max.

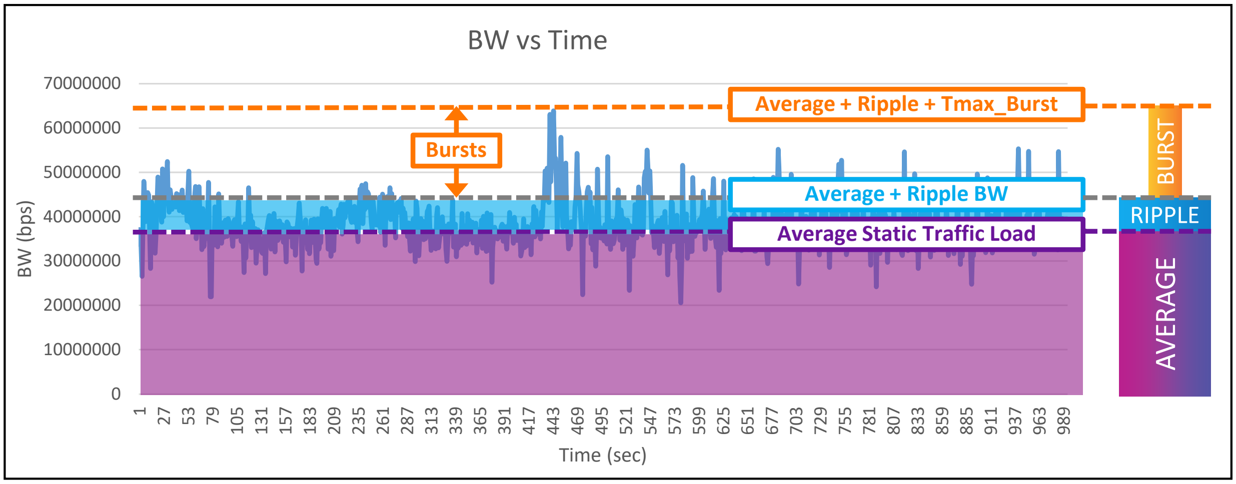


Figure 2 – Mapping Traffic Eng Formula to US Capacity Usage Example

Figure 3 shows a network capacity example for a 1 Gbps downstream (DS) service tier; 150 subs in the SG; and Tavg = 3 Mbps/sub. This requires SG capacity ≥1500 Mbps. This includes a ripple component of 5% * Tmax_max = 50 Mbps. Note that in this example, the ripple component as a function of Tmax_max is much smaller than the initial K=1.2 values because Tmax_max is significantly higher.

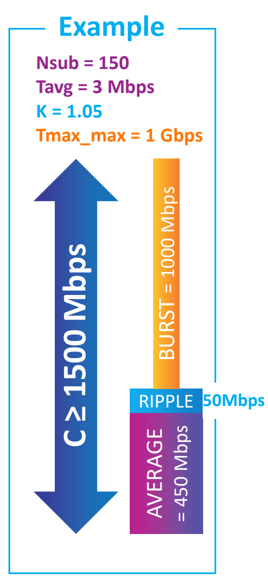


Figure 3 – Network Capacity Example for 1G Service Tier

2.3. Max Service Tiers in 10G Era

So, what kind of service tiers will subscribers enjoy in this new 10G bandwidth era? These tend to be marketing driven. The Tmax value from the traffic engineering formula helps define the Service Level Agreement (SLA) that the operator can potentially offer to their customers.

First, 10G passive optical network (PON) provides a net downstream capacity of ~8.5 gigabits (Gbps) to the consumer. Using the traffic engineering formula, this capacity might support a downstream SLA of 7.5 Gbps. The SG utilization (i.e., Nsub * Tavg) for a 64 subscriber PON might grow to a 1+ Gbps over the next decade. That means a consumer with a 7.5 Gbps SLA will have a QoE coefficient of K= ~1.0 which is reasonable for this relatively small SG size.

The 7.5 Gbps SLA from 10G PON sets a bar that Hybrid Fiber Coax (HFC) systems must match with their DOCSIS 4.0 upgrades. Some network capacity modeling results are shown in a later section to show how many subscribers the HFC can support per SG at this SLA.

HFC does have an advantage because it can incrementally add capacity with additional spectrum to achieve a true 10 Gbps SLA that is equivalent to 10G Ethernet. Getting to a true 10 Gbps downstream SLA will mean providing greater than 10 Gbps network capacity. This will push the PON networks into next generation PON technology (e.g., 20+ Gbps). Some future technologies such as 1.8 and 3.0 GHz HFC plants are discussed further in [CLO_2019].

Choosing the upstream SLA is more complicated. As will be seen later in Figure 7 with the DS:US consumption ratio, there might be a 12:1 ratio between the two. However, in the new 10G era, a gigabit US SLA tier with high burst rates may be needed, even if the US consumption is much lower than downstream.

Looking at PON systems, they offer both symmetric and asymmetric data rates. A gigabit passive optical network (GPON) provides 2.5 Gbps downstream data rates with 1.2 Gbps upstream data rates for a 2:1 ratio. The Institute of Electrical and Electronics Engineers (IEEE) 10G ethernet passive optical network (EPON) downstream might be paired with either a 1G or 10G upstream for 10:1 or 1:1 ratio. In the International Telecommunication Union (ITU) world, XG-PON pairs 10 Gbps downstream with 2.5 Gbps upstream (i.e., 4:1 ratio) while XGS-PON provides a symmetric 10 Gbps in both directions for 1:1 ratio.

HFC systems have traditionally been extremely asymmetric, but these trends are changing. In the upcoming network capacity modeling section, a 2.5 Gbps upstream SLAs is paired with the 7.5 Gbps DS SLA on a 1794/396 MHz plant.

2.4. Determining Service Group QoE based on Probabilities

The Peak Busy Period Average Consumption and maximum Service Tier Burst components are well known and easily obtained. Much traffic engineering research has since focused on quantifying the Peak Busy Period Ripple component for QoE as it is impacted by all inputs, not just Tmax_max.

It became apparent that quantifying the SG subscribers QoE needed to focus on the probabilities for SG capacity. And to predict behavior across different SG with different parameters, a network capacity transmit model for individual subscribers was necessary.

Our research found that there is a massive amount of data and many complicated variables at play here. It turns out that providing sufficient QoE for traffic engineering is a problem that is suited to Big Data Analytics. Our goal is that Big Data Analytics can be leveraged to not only select optimum QoE margins in existing networks but become a tool to predict how networks will morph and the QoE margins of the future. It is important to note that the operator can choose how much margin they would like to build in.

Once single subscriber BW probability distribution functions (PDF) were in place, it is then possible to create a SG BW PDF to analyze the behavior at the SG level. An example of the SG BW DS probabilities is shown in Figure 4. This is the output of a Monte Carlo simulation with 100K trials. It is a SG that consists of 128 subs, all of which have a 1G DS service tier. The DS Tavg = 15 Mbps which represents a time in the future.

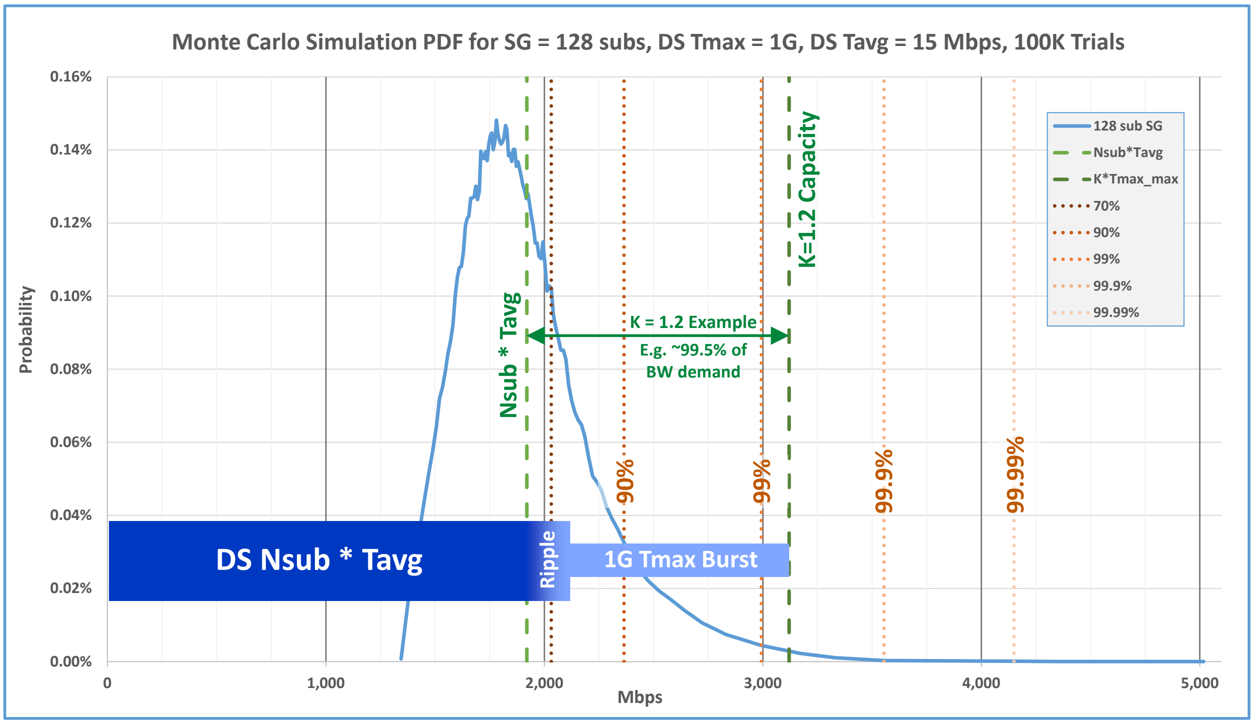


Figure 4 – Mapping Traffic Eng formula unto SG Probabilities

Note the asymmetry in the curve – there is a much longer tail to the right. Various cumulative distribution function (CDF) probability thresholds are shown (i.e., 90%, 99%, 99.9%, 99.99%) to provide an insight as to the probability the SG BW reaches different capacities.

The blue candlestick in Figure 4 shows how the traffic engineering formula overlays the SG PDF. In this instance, the formula forecasts 3,120 Mbps is required. Note that this is sufficient for ~99.5% of the peak busy period time. For the remaining 0.5% of the time, the buffers may be temporarily filled, and some latencies introduced. Note that 0.5% represents ~50 seconds out of every evening. For most of those 50 seconds, the delays should be insignificant and not noticed by users. This is normal network behavior and why many users can share a single network pipe. Please keep in mind how low the probabilities are for the Tmax_max burst regions as shown above.

Some new revelations of CommScope's probability research are discussed further in [HOWALD_2022].

3. Broadband Subscriber Traffic Consumption – 2022 Update

ARRIS/CommScope has the most extensive broadband capacity usage monitoring history in the industry. Data collection started in 2010; done at the start of every year since; and covers 10's of millions of modems from multiple MSOs. Subscriber usage has been monitored from the same group of MSOs for consistency. This dataset has been compared and maps closely to many other MSOs globally.

3.1. Downstream Peak Period Average Bandwidth per Subscriber, DS Tavg

Figure 5 shows the average subscriber downstream consumption, DS Tavg, during peak busy period for several MSOs over a ten-year period. At the start of 2022, DS Tavg was 3.5 Mbps per sub averaged across all the MSOs.

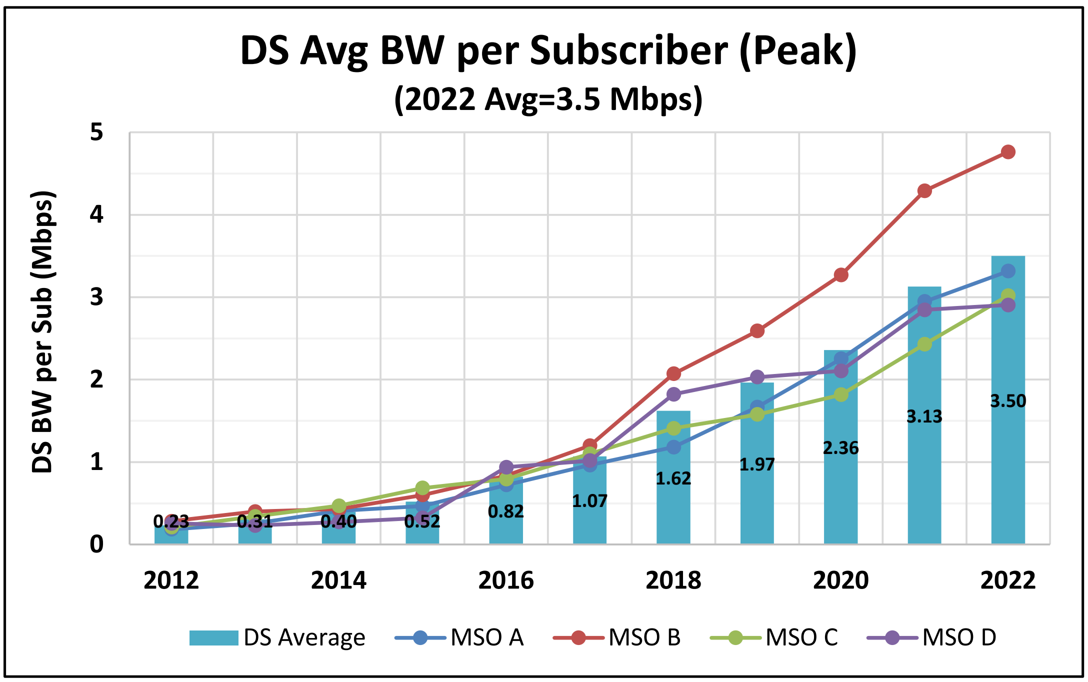


Figure 5 – DS Tavg, Average Subscriber Downstream Consumption

It turns out that the DS Tavg growth rate was much higher last decade and continues to tail off in recent years. The DS Tavg is up only 12% from 2021. Looking across a 3-year window, the DS Tavg has grown roughly 21% per year. That is half the compounded annual growth rate (CAGR) from five years ago.

3.2. Upstream Peak Period Average Bandwidth per Subscriber, US Tavg

The 2022 US Tavg is almost 300 Kbps as shown in Figure 6. This is up 14.5% from the 2021 COVID inflated numbers. The 3-year CAGR for US Tavg is 28%, which is higher than DS Tavg CAGR for the first time and up from five years ago.

3.3. Downstream to Upstream Peak Period Average Bandwidth Ratio

The DS:US ratio as shown in Figure 7 peaked at 14.4 to 1 ratio in 2020. As of 2022, the average DS:US ratio in this post-COVID new normal seems to have stabilized around 12:1. There was significant variation between the different MSOs with a range of 8:1 to 18:1 ratio.

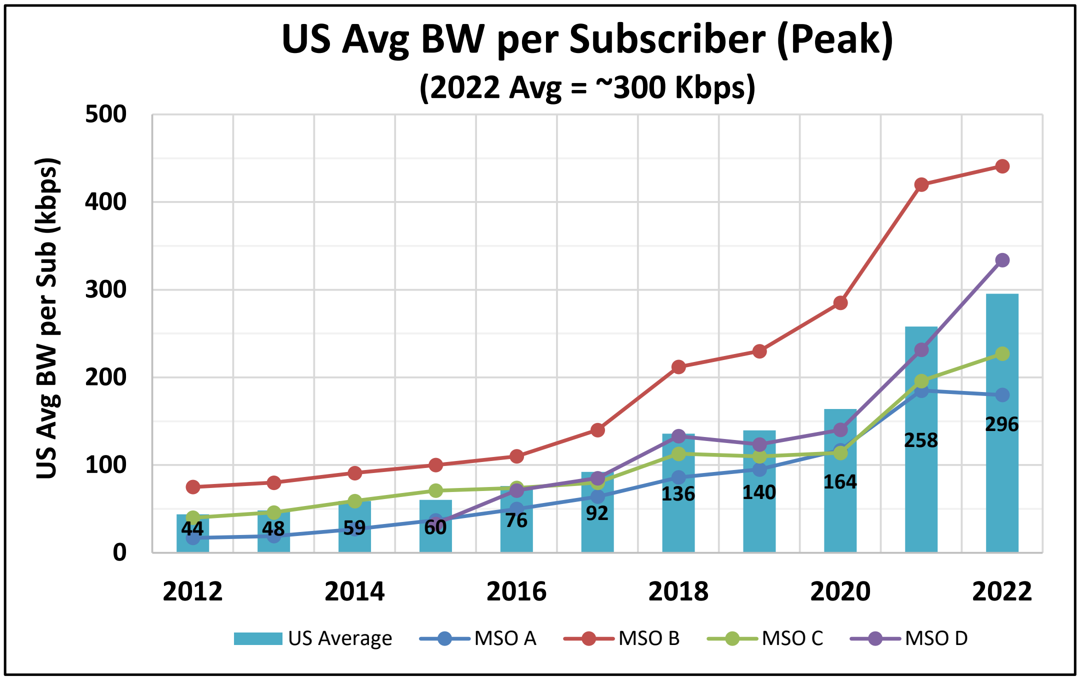


Figure 6 – US Tavg, Average Subscriber Uptream Consumption

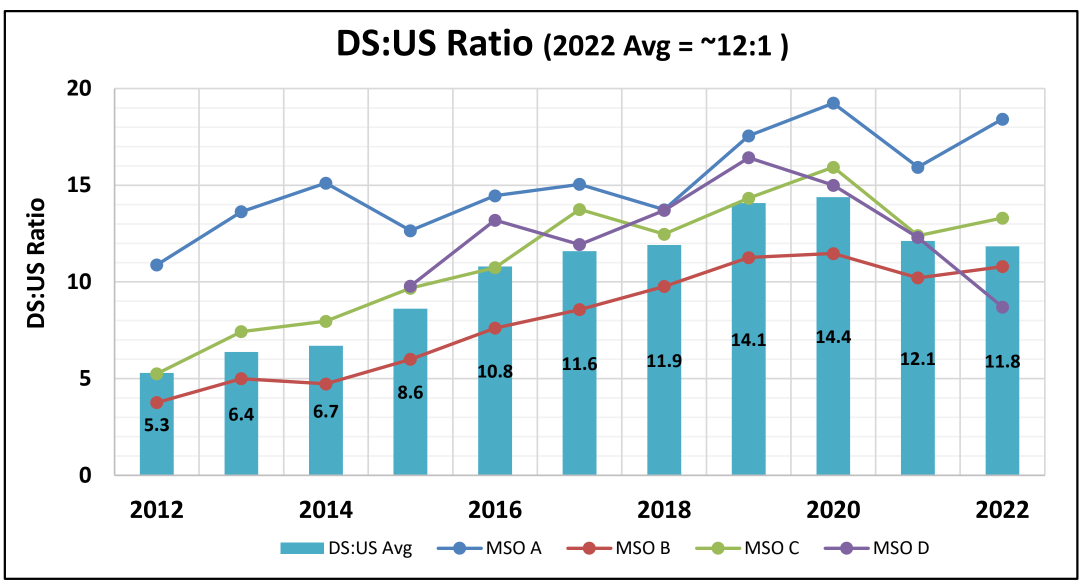


Figure 7 – Tavg, Downstream to Upstream DS:US Ratio

4. Broadband Traffic Growth Trendlines

As operators plan their network migration for the next decade or two, Tavg growth becomes a critical component in that planning. This drives our network investment strategies. Growth rates appear to be changing dramatically of late and have cast a lot of uncertainty around future consumption growth rates.

The real multi-billion-dollar question is what will be the BW consumption growth for coming decades? Has Tavg growth slowed to a lower CAGR (e.g., doubling every 3-4 years) or is it no longer exponential? Some folks claim exponential growth is dead, and that BW growth is linear or following the Adoption S-curve. S-curves have exponential growth in early years, linear growth during middle years, and flattens out in later years. E.g., will Tavg reach a limit of 2½ UHD streams per home (~25Mbps) and stay there? Or will another S-curve (e.g., VR/AR driven) start a new era of high growth?

Before looking at each possible growth trendlines, it is useful to review last decade's growth patterns.

4.1. Broadband Traffic Growth in retrospect

4.1.1. DS Tavg Growth – 2010-22

The year-over-year (YoY) changes in DS Tavg are shown as the blue candlesticks in Figure 8. Through 2018, there were many years with ~30% YoY change and then a couple years with larger 50%-70% YoY change. The giant spurts in DS Tavg often coincided with new DOCSIS technology improvements (e.g., going from 8 to 16 or 16 to 32 bonded 3.0 single carrier quadrature amplitude modulation (SC-QAM) channels).

After 2018, things started to change. The 2019 and 2020 YoY changes were only ~20%. During the COVID lockdown of 2021, DS Tavg only went up ~32%. Then 2022 DS YoY clocked in at only 12%.

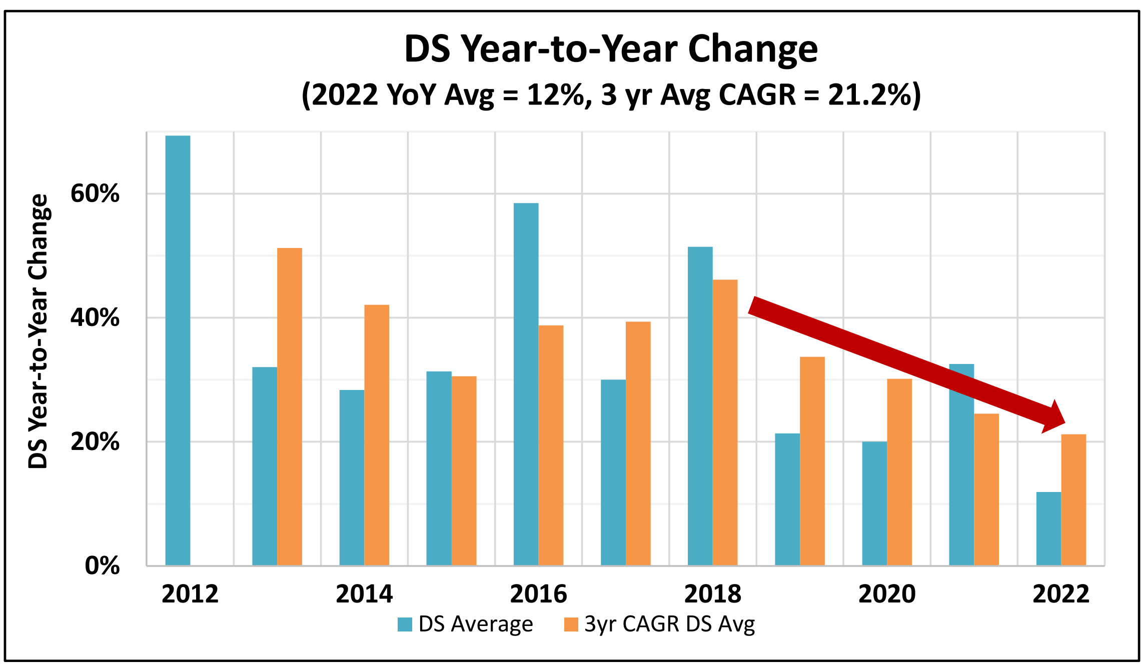


Figure 8 – DS Tavg YoY & 3-yr CAGR for 2010-22

Given the volatility of the YoY data, the CAGR for a sliding 3-year window was investigated. This is shown by the orange candlesticks in Figure 8. The 3-year CAGR hovered around 40% last decade, but then started dropping noticeably after 2018 as shown by the red arrow. The fact that the 3-year window is constantly dropping implies that the DS Tavg growth rate is either dropping to a much lower percent or it is no longer exponential. The next section looks at these possibilities.

In any respect, 2018 appears to be an inflection point for DS Tavg growth. There is no known obvious reason as to what caused this change. It started well before COVID and appears to be continuing in our new normal post-lockdown world.

Using the powers of Excel, multiple types of trendline were matched against DS Tavg data from 2010 to 2018. For each trendline, Excel's R^2 (R-squared) metric is also shown, as an estimate of trendline's "goodness of fit". R-squared quantifies a trendline's percentage of variation compared to the actual subscriber consumption, Tavg, over the given length of time [Investopedia R2], [Wiki R2], [Exceltip R2]. In cases where R-squared was not an available option on the graph, excel "RSQ" function was used to produce the R-squared value shown. (An alternative way to calculate it is to use the squared value of the correlation coefficient [CORREL], which is a covariance of the trendline with data, divided into the product of standard deviation of trendline times standard deviation of data).

The value of R-squared varies between 0 and 1, and closer to 1 it gets, better the trendline explains the data. A line fit with R-squared = 0.9959, for example, means that 99.59% of the variation is explained by the trendline, and this is valid in the time interval considered. However, projecting these trendlines outside of the time where data exists is best done with a "caveat emptor" (buyer beware!) warning – there are no guarantees the adherence to the trendline will continue in the future. This is analogous to the stock market adage of "past performance not indicative of future results"!

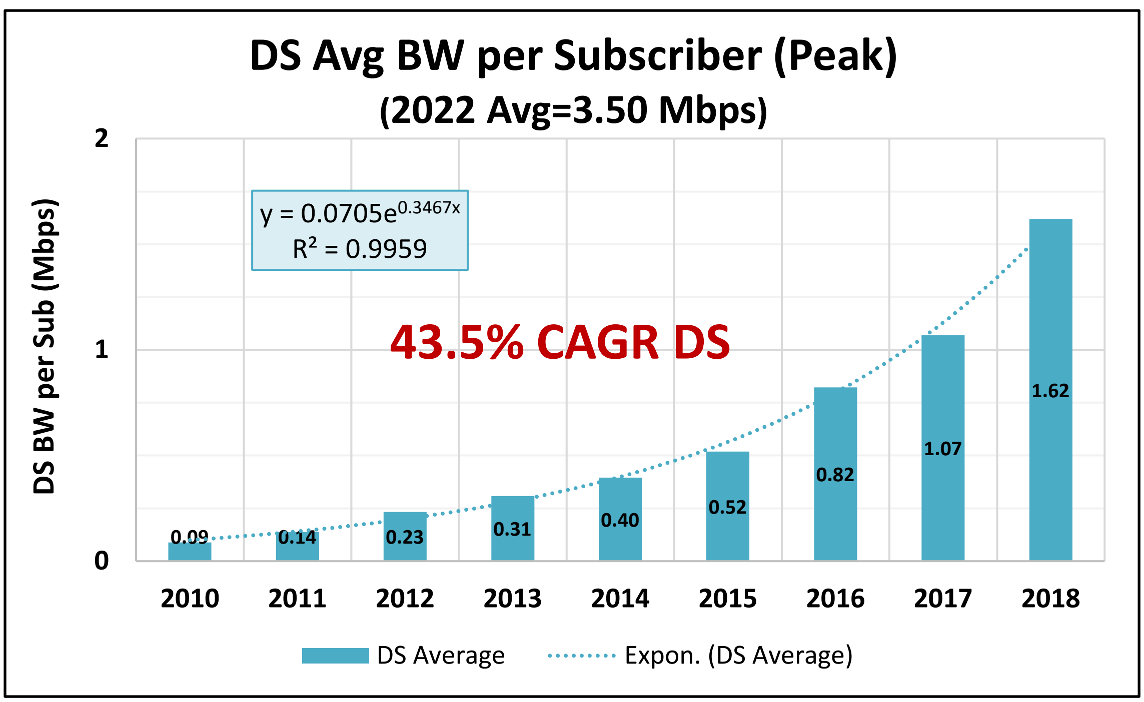


Figure 9 – DS Tavg Growth Trendline – 2010-2018

Analyzing the 2010-2018 DS Tavg data creates an exponential trendline that resulted in a 43.5% CAGR DS over that 8-year window. That equates to doubling in slightly less than every other year. This is shown in Figure 9. For the 2010-2018 DS data in Figure 9, R-squared (R^2) = 0.9959 which is an excellent match of better than two 9's of accuracy. So, in 2018, the DS Tavg growth projection would have been:

- 2018 DS Growth projection => DS Tavg = **100 Mbps/sub by 2030**

At this consumption growth rate, many people thought that operators would need Fiber to the Premise (FTTP) for all their subscribers by then.

4.1.2. US Tavg Growth – 2010-22

The YoY changes in US Tavg are shown as the purple candlesticks in Figure 10. The 3-year sliding window CAGR is shown with the pink candlesticks.

Up until 2018, the US YoY would bounce from 10% or less to the 20%-25% range. The 3-year sliding window smooths out some of that YoY variation and showed an US CAGR around 17%. The US data saw some large YoY spikes >40% in 2018 and then again during the 2021 COVID lockdown. However, the other years (i.e., 2019, 2020, 2022) showed less than 20% US growth. The US 3-year sliding window has shown a definite uptick and has been in the 20% to 30% range since 2018.

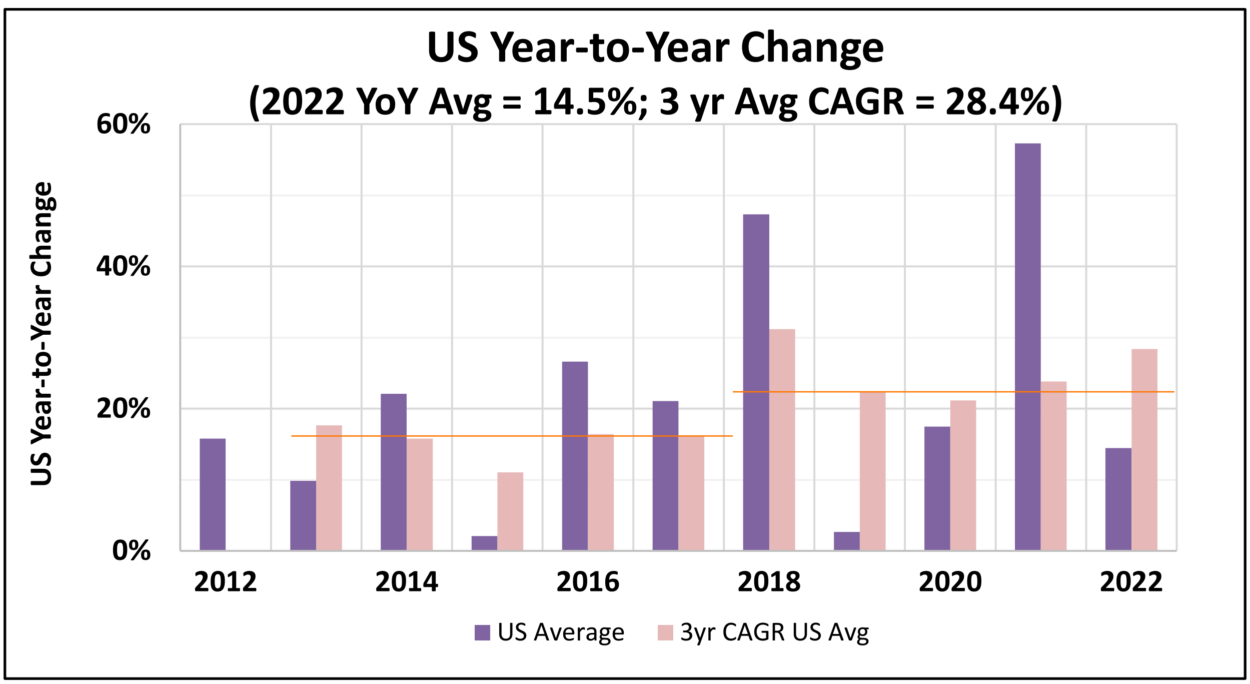


Figure 10 – US Tavg YoY & 3-yr CAGR for 2010-22

The 2010-2017 US Tavg growth trendline was 17.3% CAGR as shown in Figure 11. There is much more volatility in the US data, so US $R^2 = 0.9805$ is not nearly well matched as the DS. If the 2018 spike is introduced into this data, then R-squared became significantly worse.

At this point in time, the US Tavg growth projection was:

- 2017 US Growth projection => US Tavg = **<u><1 Mbps/sub by 2030</u>**

The US Tavg consumption was not on anyone's radar in 2017. However, this projection also implied that the DS:US ratio would exceed 100:1. [ULM_2017] speculated whether the DS:US ratio would "stabilize" around 15:1, but it wasn't clear if that would happen due to DS growth slowing or US growth increasing. It turns out that both happened.

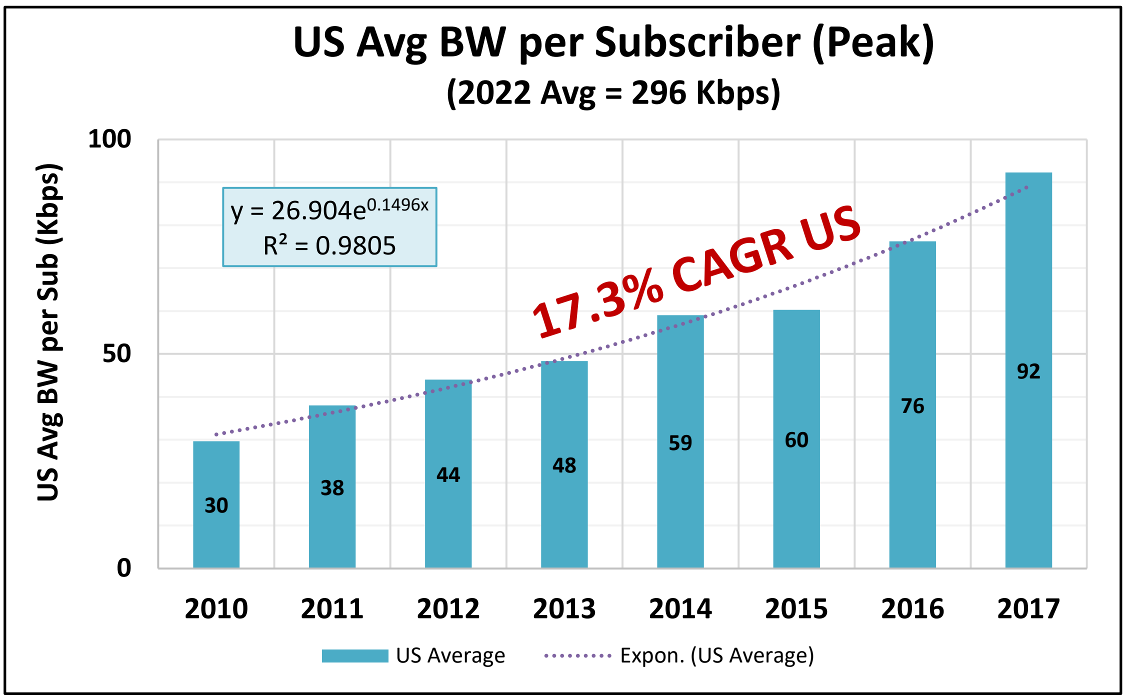


Figure 11 – US Tavg Growth Trendline – 2010-2017

4.2. Correcting for the COVID Bump

The Coronavirus Bandwidth Surge wreaked havoc on our long-term consumption growth planning. Growth patterns started shifting pre-COVID in 2019 and early 2020, but then things were turned upside down during lockdown with our January 2021 Tavg numbers. [ULM_2021] spelled out this impact on cable networks.

The 2022 Tavg numbers represents the first data points being seen since a return to the "new normal". Some of the Tavg impacts from the COVID lockdown were anomalies that need to be disregarded while other impacts appear to be a permanent shift. To calculate our current growth trendlines requires the anomalies to be factored out.

Ignoring the 2021 data for a second, DS Tavg increased 48% from pre-COVID Jan '20 to post-lockdown new normal in Jan '22. That maps to a 21.8% growth each year if not for the COVID bump. The blue candlestick in Figure 12 shows the estimated 2021 DS Tavg without the COVID bump. The pink candlestick on top of the 2021 data shows the size of DS anomalies estimated during the lockdown. Note that this was less than 10% additional DS traffic. For our growth trendline analysis, the blue candlesticks are used, and the COVID bump anomalies shown in pink will be ignored.

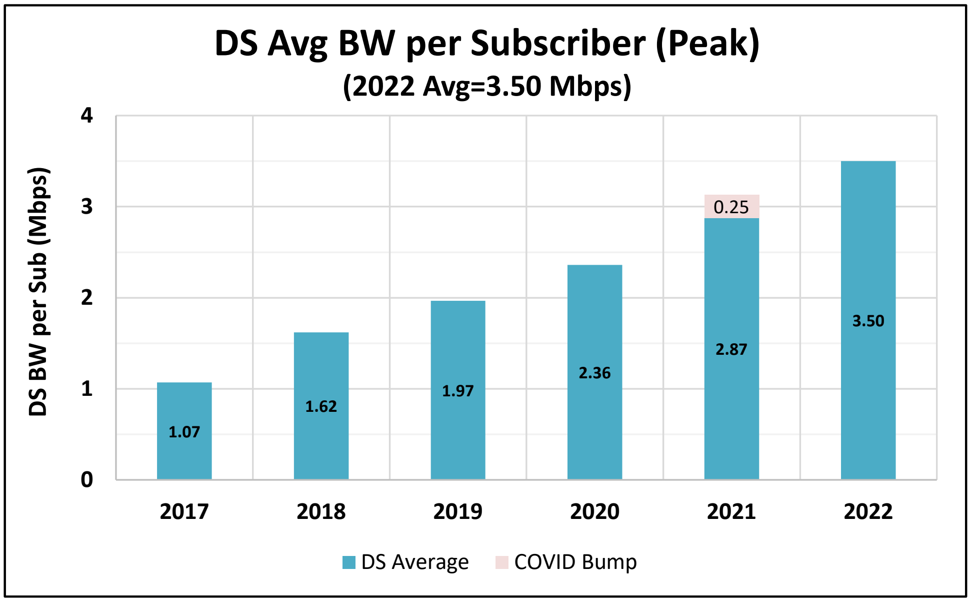


Figure 12 – DS Tavg – Estimating COVID bump in '21

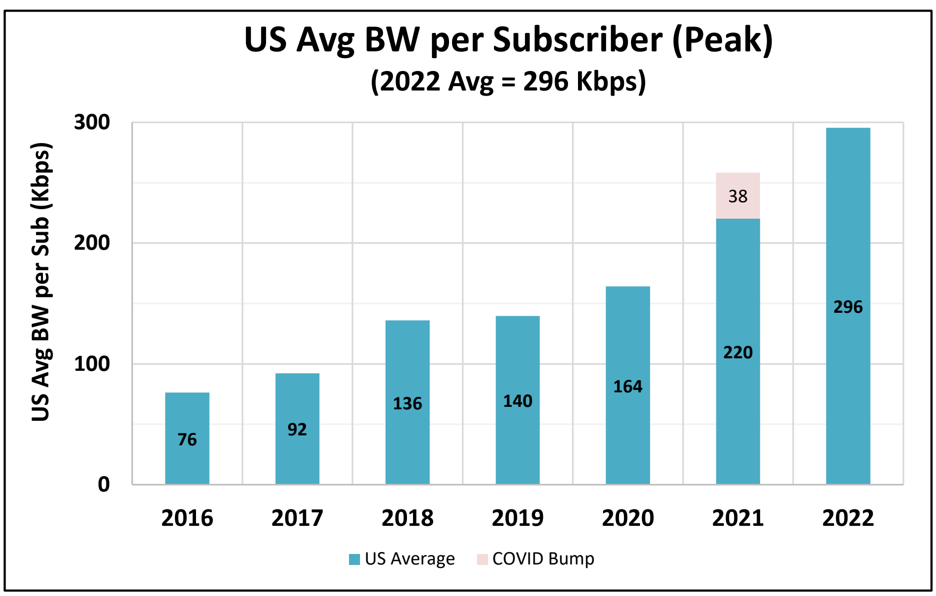


Figure 13 – US Tavg – Estimating COVID bump in '21

Figure 13 shows that the US Tavg grew 80.5% from pre-COVID Jan '20 to post-lockdown new normal in Jan '22. That maps to a 34.35% growth each year if not for the COVID bump. The blue candlestick in Figure 13 shows the estimated 2021 US Tavg without the COVID bump. The pink candlestick on top of the 2021 data shows the size of US anomalies estimated during the lockdown. Note that this was almost 20% additional US traffic, much higher than the DS. For our growth trendline analysis, the blue candlesticks are used, and the COVID bump anomalies shown in pink will be ignored.

4.3. Various Downstream Growth Trendlines

4.3.1. DS Exponential Growth Trendline

Conventional wisdom for the last couple decades was that broadband traffic grows exponentially. That is the first growth trendline considered. Since 2018 appears to be an inflection point, Figure 14 shows the exponential growth trendline from 2018 to 2022. This accurately maps to a 21.1% CAGR DS, which is Tavg doubling roughly every 3.75 years. The data was extremely well matched with DS $R^2 = 0.9998$, almost four 9's accuracy.

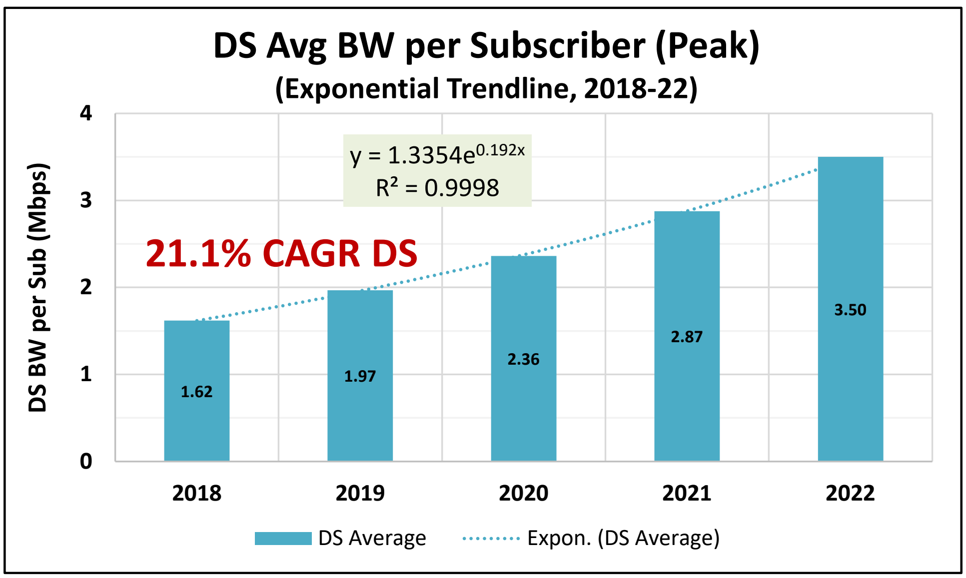


Figure 14 – DS Tavg Exponential Trendline – 2018-2022

By comparison, Figure 15 looks at the DS Tavg exponential for the 2016-22 span. Including the 2018 spike certainly skews the data. This results in a 27.6% CAGR but DS $R^2 = 0.9789$ shows a much poorer fit than the 2018-2022 trendline in Figure 14. Visual inspection of Figure 15 also shows how the trendline is obviously pulling away from the actual 2022 datapoint. Another reason why the 2018-2022 CAGR is the exponential trendline of choice for our DS Tavg growth projections.

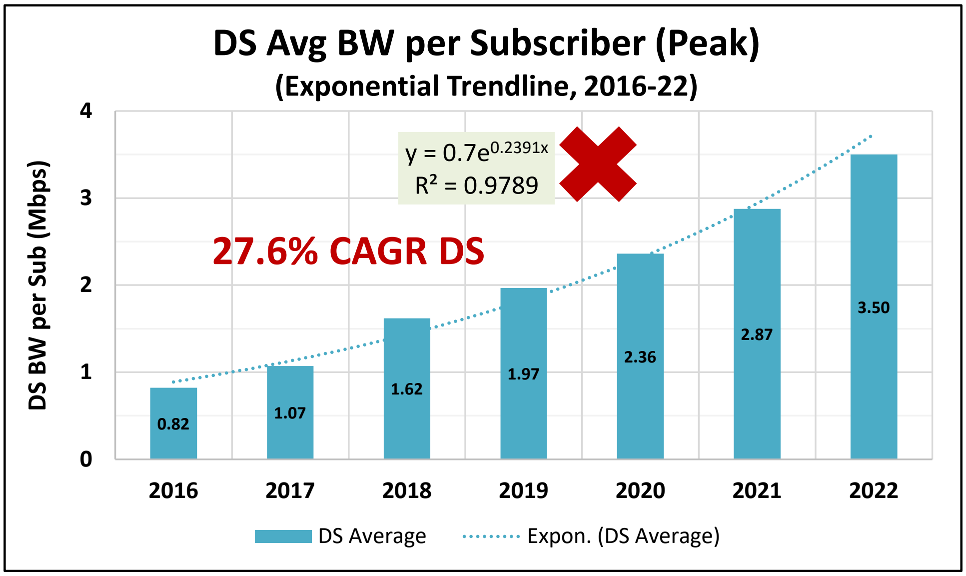


Figure 15 – DS Tavg Exponential Trendline – 2016-2022

4.3.2. DS Linear Growth Trendline

Recent discussions have speculated whether the DS Tavg has entered a phase of linear growth rather than exponential growth. The 2017-2022 linear trendline analysis is shown in Figure 16. Various time windows were considered starting in 2016, 2017 and 2018. The 2017-2022 had the best linear match with the DS $R^2 = 0.9912$. While this is not as close as the exponential match above, it is still better than two 9's of accuracy. This is a viable contender and should be considered as one of the possible DS Tavg growth projections.

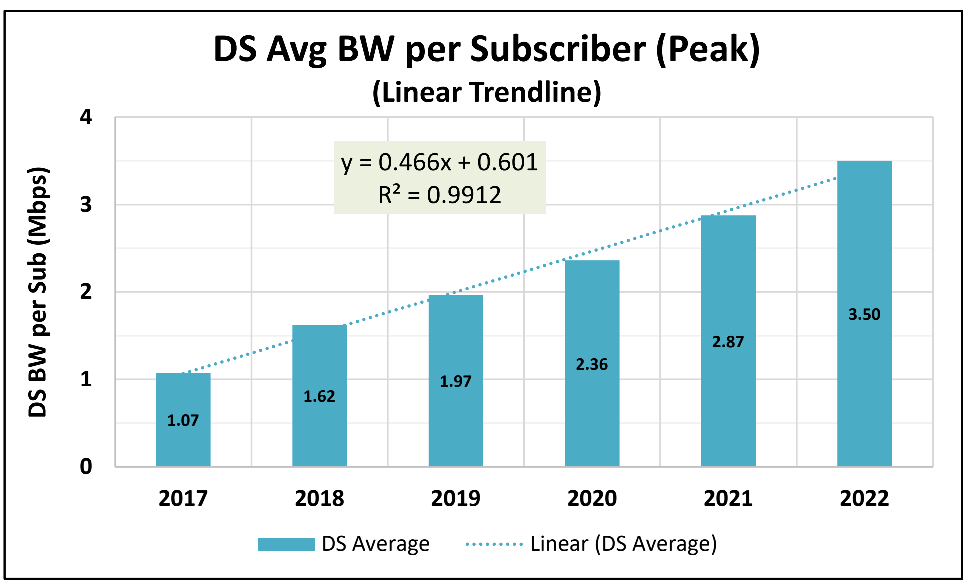


Figure 16 – DS Tavg Linear Trendline – 2017-2022

4.3.3. Other DS Growth Trendlines

Since the door was opened to look at trendlines other than exponential, our research also looked at polynomial, power and logarithmic trendlines to see how well those might match.

The 2016-22 order of 2 polynomial trendline is shown in Figure 17. It had a very good match with DS $R^2 = 0.997$. This was better than linear but not as good as exponential trendlines. For polynomial trendlines, starting in 2016 had a better match than 2017 or 2018. This is another option to consider for our long-term growth projections.

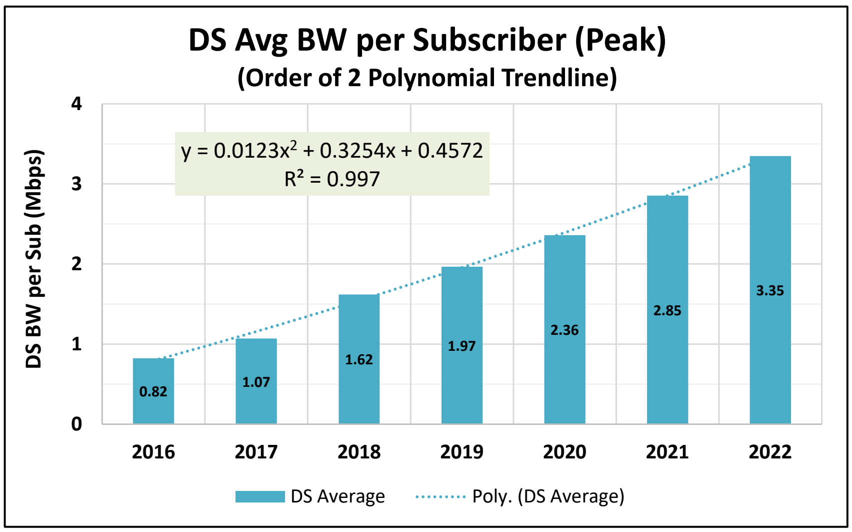


Figure 17 – DS Tavg Order of 2 Polynomial Trendline – 2016-2022

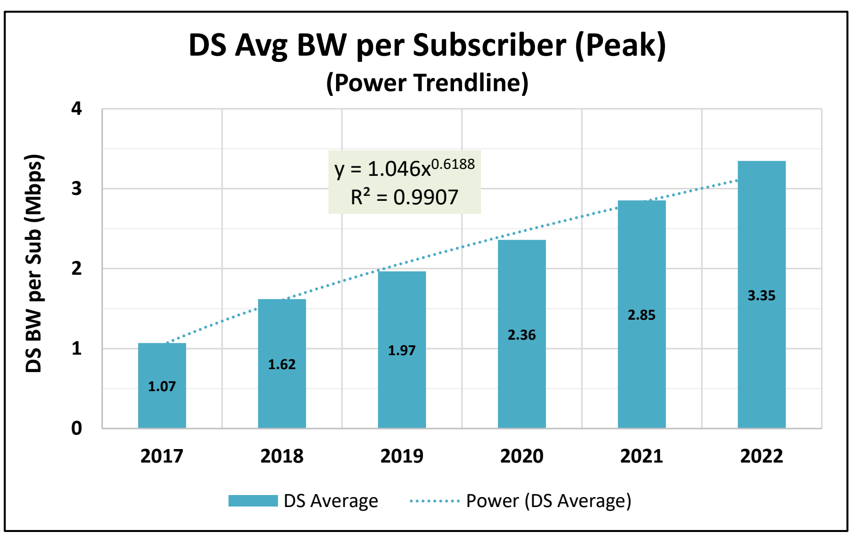


Figure 18 – DS Tavg Power Trendline – 2017-2022

The 2017-2022 power trendline is shown in Figure 18. It had a very good match with DS $R^2 = 0.9907$. This match tracked the linear trendlines and is another option for consideration. For power trendlines, a starting window of 2017 provided the best results.

The logarithmic trendline is shown in Figure 19. This was a relatively poor match with DS $R^2 = 0.9322$. This trendline is not a candidate for our long-term growth projections.

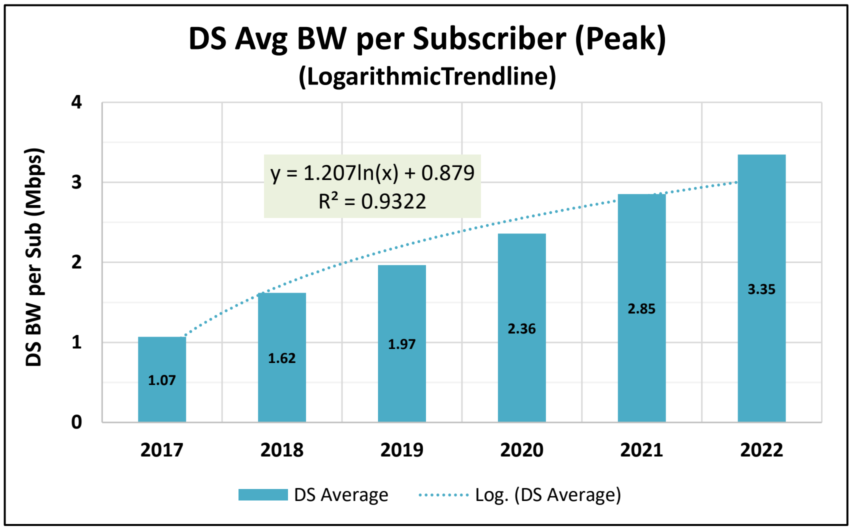


Figure 19 – DS Tavg Logarithmic Trendline – 2017-2022

4.3.4. DS Adoption Curve (S-curve) Growth Trendline

One recent school of thought is that broadband consumption is following an Adoption Curve, a.k.a. S-curve, that other technologies have followed. The S-curve theory has been around for multiple decades. Some overviews are given in [CHR_1992] and [ARK_BLOG].

In S-curve theory, there is a period of exponential growth rate in the early years. This then levels off to linear growth rates in the middle years which is followed by slowing to zero growth in the latter years. Figure 20 shows this form in a chart from [CHR_1992] with the basic S-curve equation below it. We inserted the red arrow to show where the DS Tavg might currently sit on a S-curve.

The rational for broadband traffic following an S-curve goes like this:

1. From 2010 to 2018 – video usage over the internet grew rapidly due to applications like Netflix and YouTube. Video penetration and video bit rates increased extensively resulting in exponential growth year to year.
2. From 2018 to present – video use on the internet approaches 80%, so slowing increase in video streams results in slower growth rates. The net result is linear growth.
3. From present to late 2020's – video bit rates continue a slow shift towards 4K Ultra-HD resolution; operators migrate to IP video. Growth rates continue to decline.
4. From late 2020'2 into 2030's – video penetration reaches saturation with no more growth. Growth rates are very slow to zero.

As an example, the DS Tavg might peak once operators deliver 2½ unique 4K streams to every home, so every customer has their own private UHD video stream. This might lead to the DS Tavg point being ~25 Mbps/sub in 10-20 years.

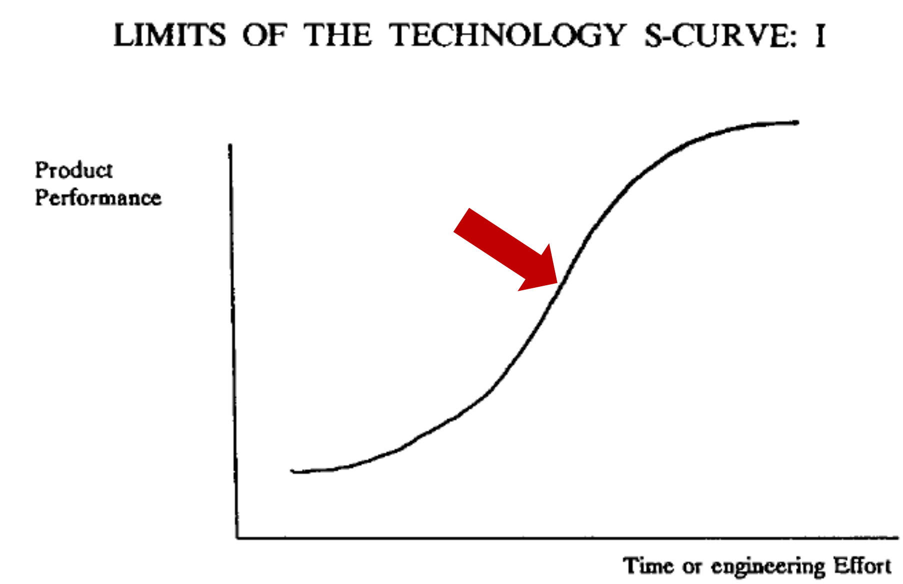


FIGURE 1. The Technology S-Curve

$$f(x) = \frac{L}{1 + e^{-k(x - x_0)}}$$

$f(x)$ = output of the function

L = the curve's maximum value

k = logistic growth rate or steepness of the curve

x_0 = the x value of the sigmoid midpoint

x = real number

Figure 20 – The Technology S-Curve and Equation

In reality, one technology wave may be followed by another wave, and then another. [CHR_1992] showed this possibility in a chart that is copied in Figure 21. As an example, maybe Netflix + YouTube adoption was part of the 1st S-curve which has reached maturity. A second S-curve is underway that is a migration to managed IP video delivery with 4K UHD streams. A third S-curve based on Augmented Reality (AR) and Virtual Reality (VR) is in the early stages and goes mainstream in another decade.

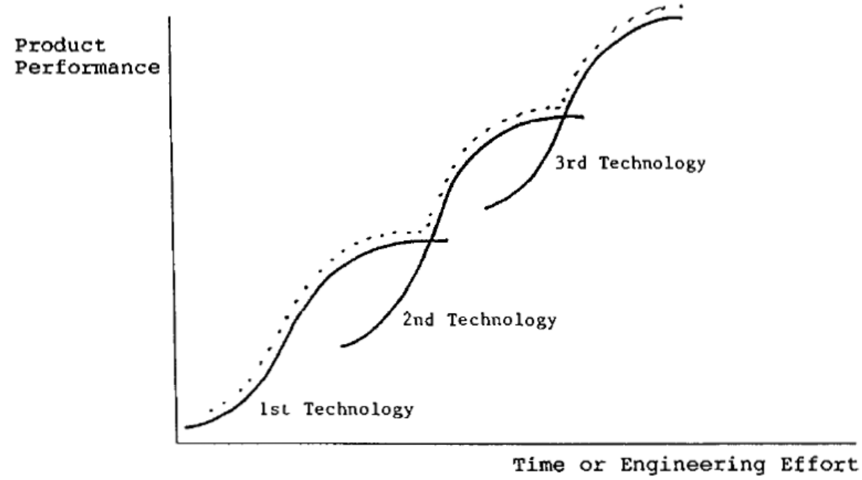
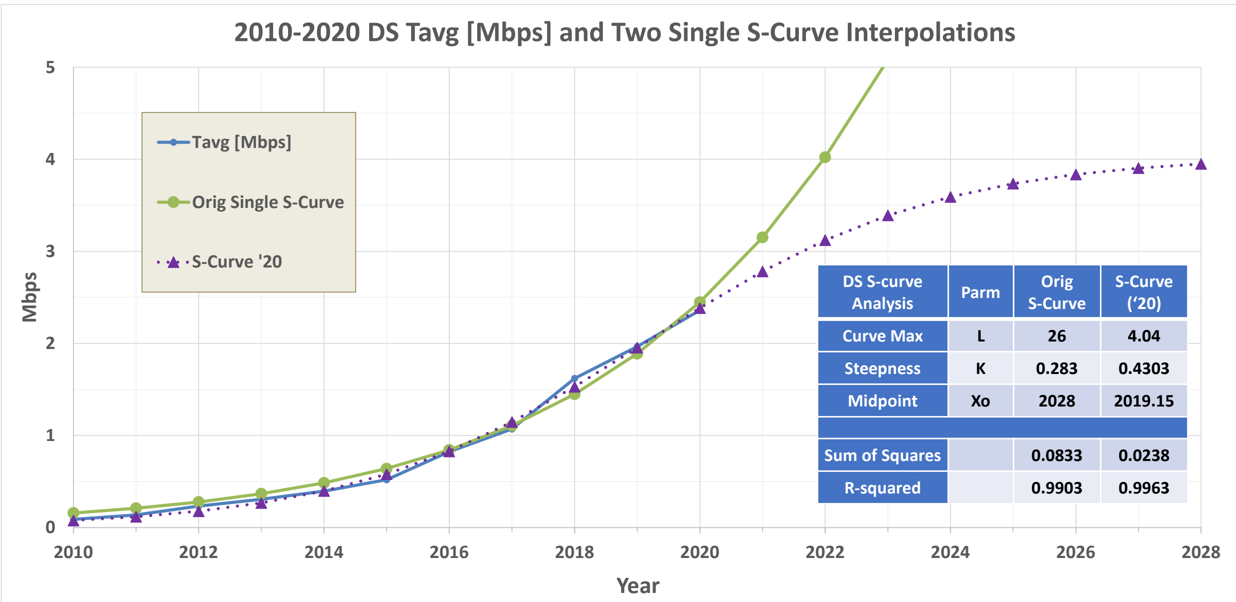


FIGURE 3. Prescriptive S-Curve Strategy

Figure 21 – Prescriptive S-Curve Strategy

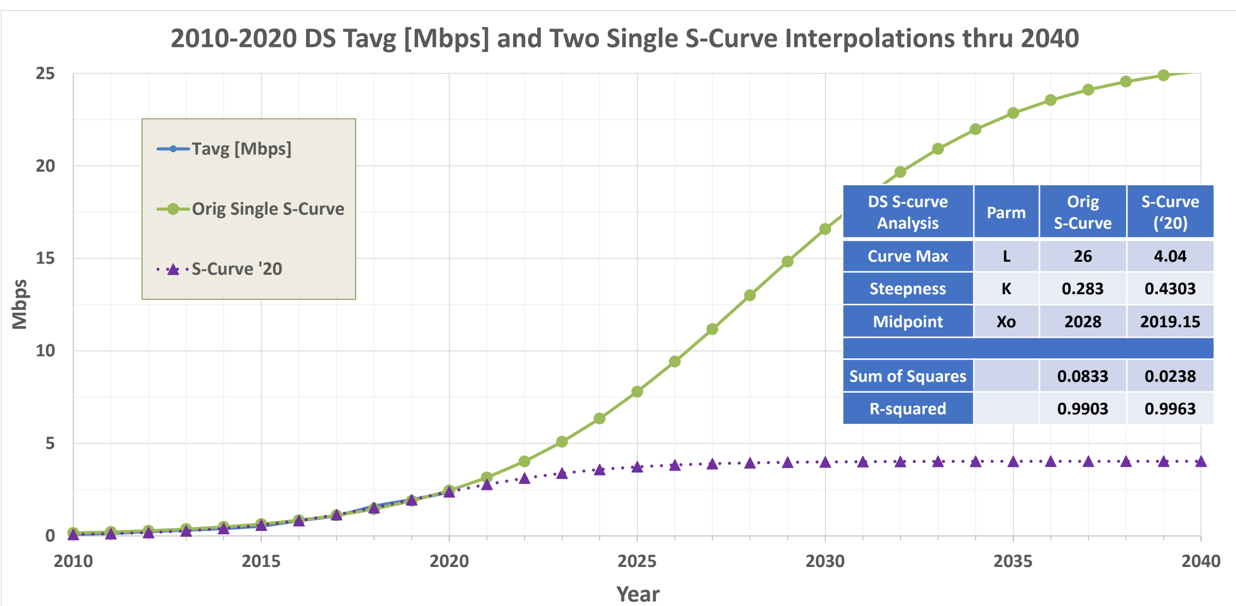
For our research, models were created for a single, double and triple S-curves. A best-fit algorithm was then run to match these curves to the 2010-2022 DS Tavg datapoints. Figure 22 shows two possible single S-curve growth trendlines mapped to the 2010-2020 DS Tavg (i.e., before COVID). The actual DS Tavg is the blue curve. The green single S-curve was our original S-curve model that assumed an upper asymptote of 26 Mbps/sub. In 2020, it had a reasonably good match with DS $R^2 = 0.9903$.

The purple dotted curve in Figure 22 shows another single S-curve fit. This one did not make any initial assumptions about the upper limit and used a best-fit algorithm to optimize DS R-squared values. This resulted in an even better DS $R^2 = 0.9963$. But notice in Figure 23 how much both S-curves diverge even though both have pretty good matches. One hits a limit of 26 Mbps and the other 4 Mbps. This illustrates the sensitivity in making these projections.



DS S-curve Analysis	Parm	Orig S-Curve	S-Curve ('20)
Curve Max	L	26	4.04
Steepness	K	0.283	0.4303
Midpoint	Xo	2028	2019.15
Sum of Squares		0.0833	0.0238
R-squared		0.9903	0.9963

Figure 22 – Mapping a Single S-curve to 2010-2020 DS Tavg



DS S-curve Analysis	Parm	Orig S-Curve	S-Curve ('20)
Curve Max	L	26	4.04
Steepness	K	0.283	0.4303
Midpoint	Xo	2028	2019.15
Sum of Squares		0.0833	0.0238
R-squared		0.9903	0.9963

Figure 23 – Mapping a Single S-curve to 2010-2020 DS Tavg thru 2040

As the 2021 and 2022 datapoints are added to the blue curve, it plots a path that is right in between these two 2020 single S-curve projections. The best-fit single S-curve was run again with 2010-2022 data and the results are shown as the light blue dotted curve in Figure 24. S-curve '22 DS R^2 improved further to 0.9975, while the two '20 projections got worse. With this update, the upper limit increased 33% to ~5.4 Mbps/sub. This is still significantly lower than the original green single S-curve trendline in Figure 25.

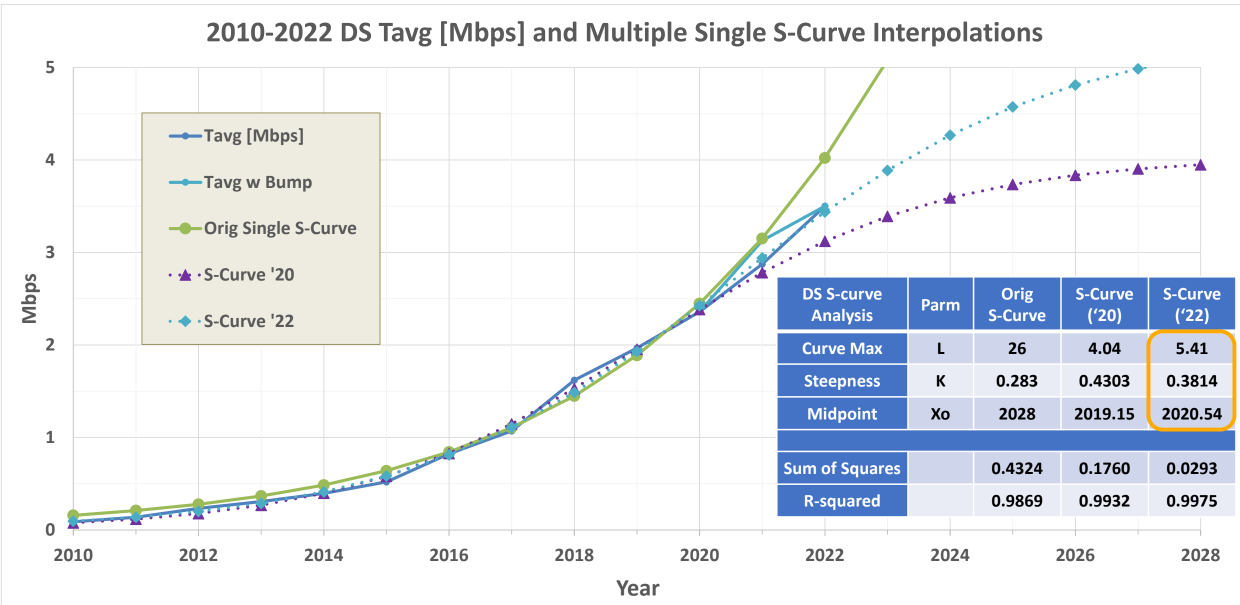


Figure 24 – Mapping a Single S-curve to 2010-2022 DS Tavg

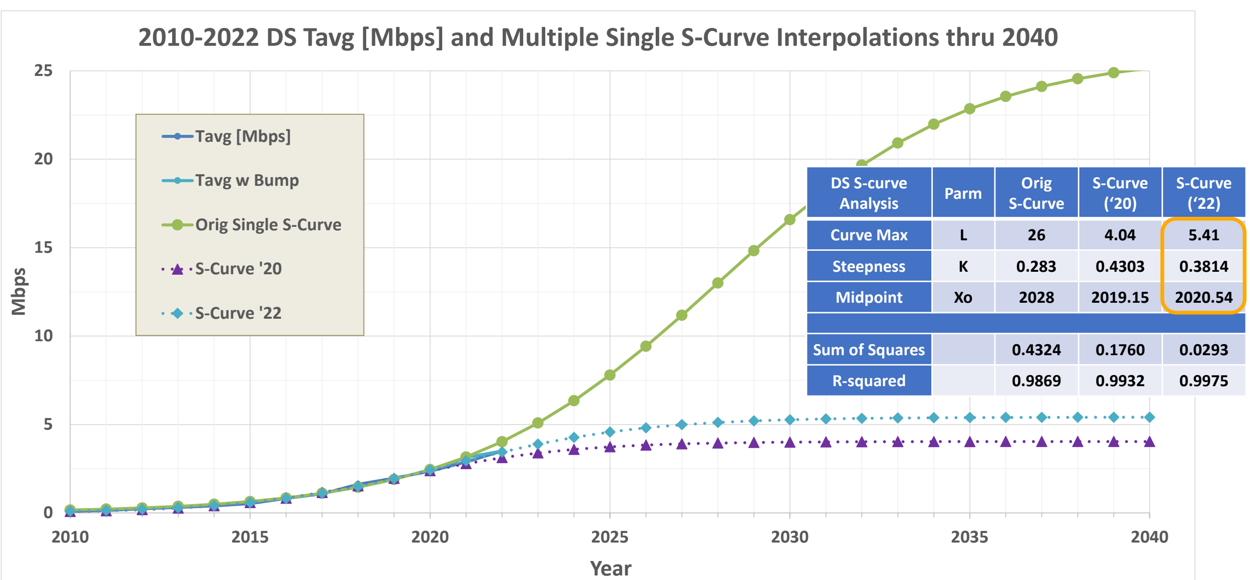


Figure 25 – Mapping a Single S-curve to 2010-2022 DS Tavg thru 2040

The next step makes a best-fit growth trendline combining two S-curves as shown in Figure 26. The mid-point of each S-curve is the year 2018 and 2028 respectively while the other parameters are optimized. There is an excellent fit with DS $R^2 = 0.9982$. The individual S-curves are dotted lines with the sum of the two represented by the dashed dark blue curve. The double S-curve reaches an upper limit of ~28 Mbps, very close to the original green single S-curve which is also in Figure 26 and Figure 27.

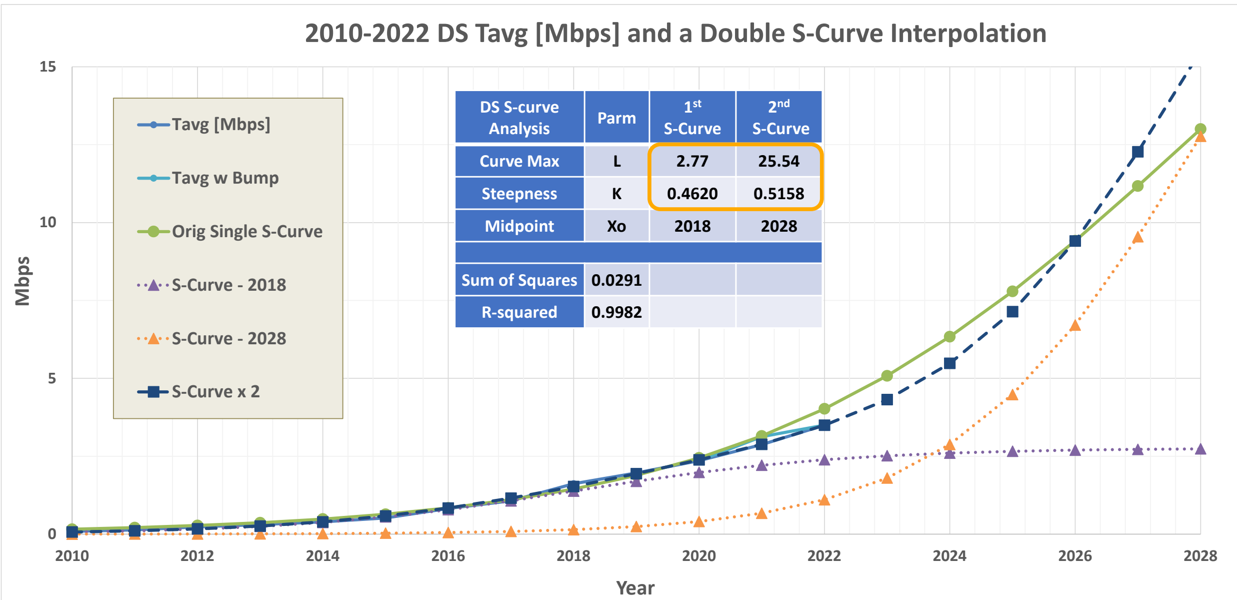


Figure 26 – Mapping two S-curves to 2010-2022 DS Tavg

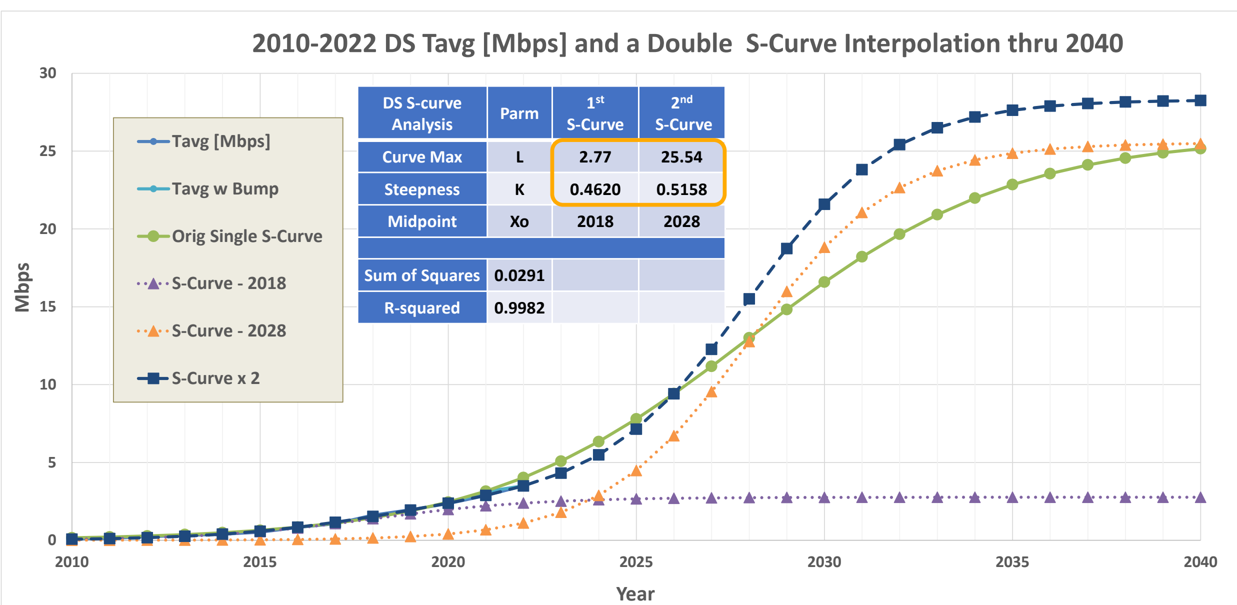


Figure 27 – Mapping two S-curves to 2010-2022 DS Tavg thru 2040

Figure 28 and Figure 29shows the best-fit results for a trendline using three S-curves. The mid-point is set for years ‘18, ‘28 and ‘38 respectively and the other parameters are optimized. There is a good fit again with DS $R^2 = 0.9982$. The individual S-curves are dotted lines with the sum being the dashed dark blue curve. Figure 28 zooms in on the triple S-curve scenario to give a better look at how it matches the 2010-22 data. It also clearly shows the contribution of each of the three individual S-curves over time.

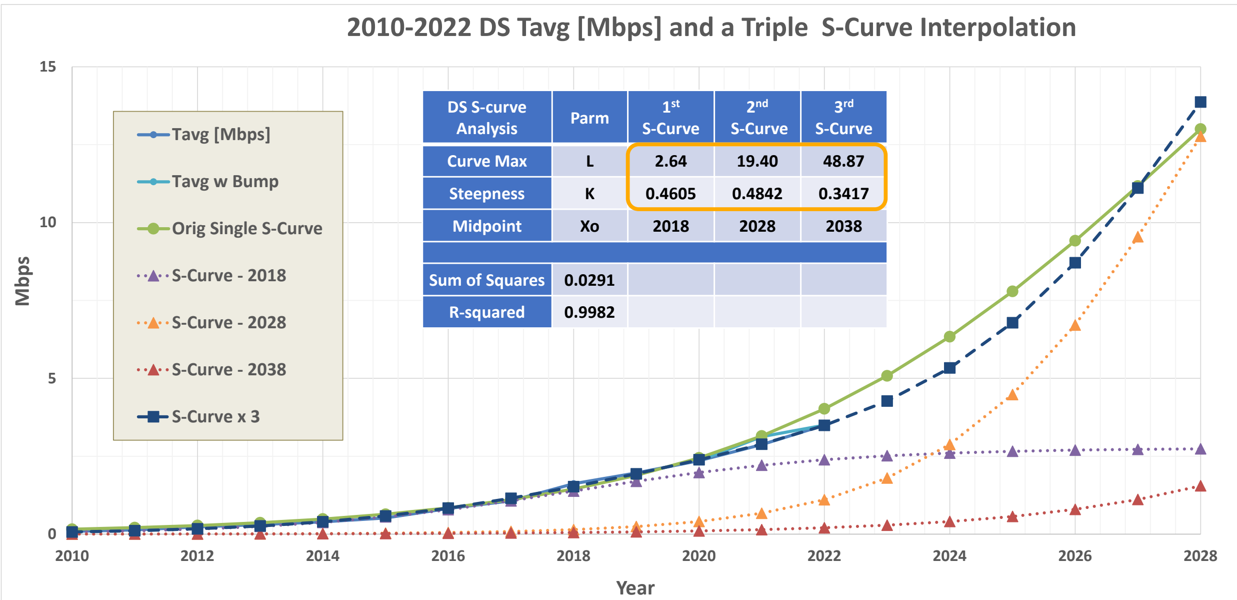


Figure 28 – Mapping three S-curves to 2010-2022 DS Tavg

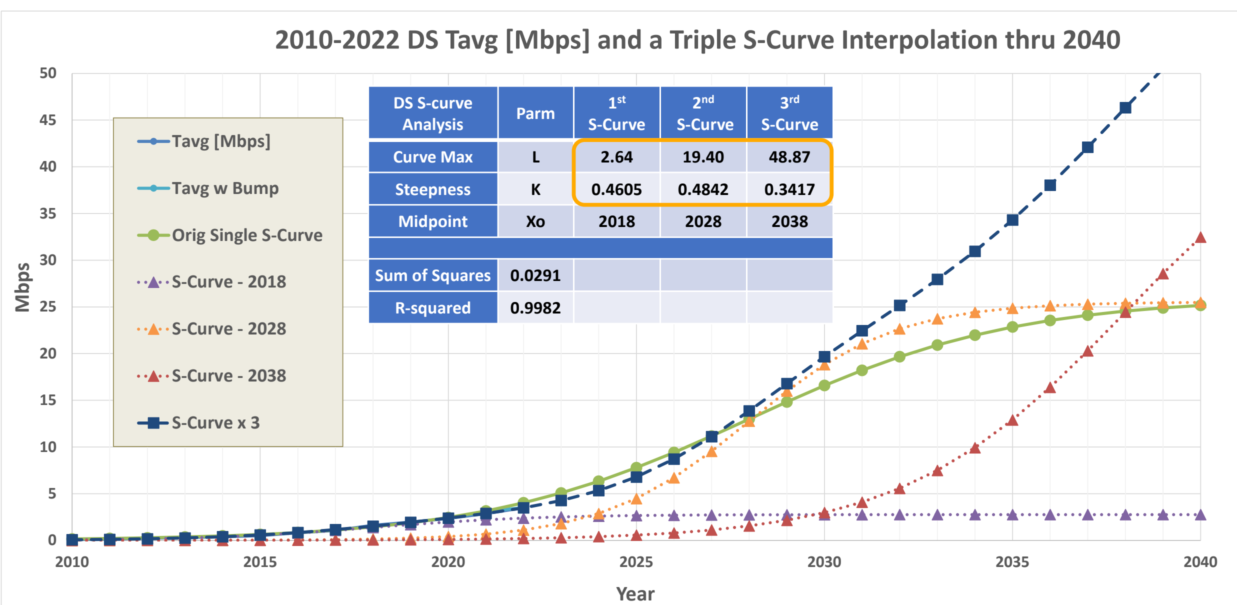


Figure 29 – Mapping three S-curves to 2010-2022 DS Tavg (Zoomed In)

The original green single S-curve is also included. The triple S-curve remains close to it through 2030 as seen in Figure 28, but then the two diverge significantly during that next decade as shown in Figure 29. This divergence is caused by the third S-curve ramping up. This might represent the adoption of VR/AR technology that takes off in the 2030's. The triple S-curve eventually reaches an upper limit of ~70 Mbps in 20+ years.

4.4. Mapping DS Tavg Growth Projections over a 10-15 Year Span

Now it is time to pull all these growth projections together to see how they compare. At this stage, there is not enough evidence to warrant one option over another. A handful of the trendlines at the extremes with a poor fit have been disregarded (i.e., 2016 exponential, power, log trendlines). All the DS Tavg growth trendlines for years 2017-2032 are plotted in Figure 30. The red circles show the growth trendlines of interest and represent the amount of uncertainty between the different projections.

In five years, 2027, DS Tavg is expected to be in 5-12 Mbps/sub range. A decade from now, 2032, that increases to a 7-25 Mbps/sub range. By considering these multiple potential growth trendlines, there is now a "cone of uncertainty" that grows over time. Notice that the window of uncertainty has almost doubled from five to ten-year window.

Figure 31 now extends the growth trendlines out 15 years to 2037. It resembles a spaghetti plot for a hurricane path! By 2037, the DS Tavg is 8-65 Mbps and the cone of uncertainty has doubled once again.

In an earlier section, it was noted that in 2018 with 43.5% CAGR, the expected DS Tavg would reach 100 Mbps by 2030. Looking at our current growth projections, the high growth projection (21% CAGR) hits 100 Mbps in 2040; while the low growth linear projection takes 200+ years to reach that!!!

From a network capacity planning perspective, our conclusions on considering multiple growth trendline options are:

- the 5-year window gives us reasonably high confidence for near-term planning
- the 10-year window gives us a range of high, moderate, and slow growth scenarios for longer term planning
- the 15-year window shows too much variance to be used for network capacity planning and is more of an academic exercise.

The authors view these growth trendline projections as an on-going process that gets updated and adjusted every year.

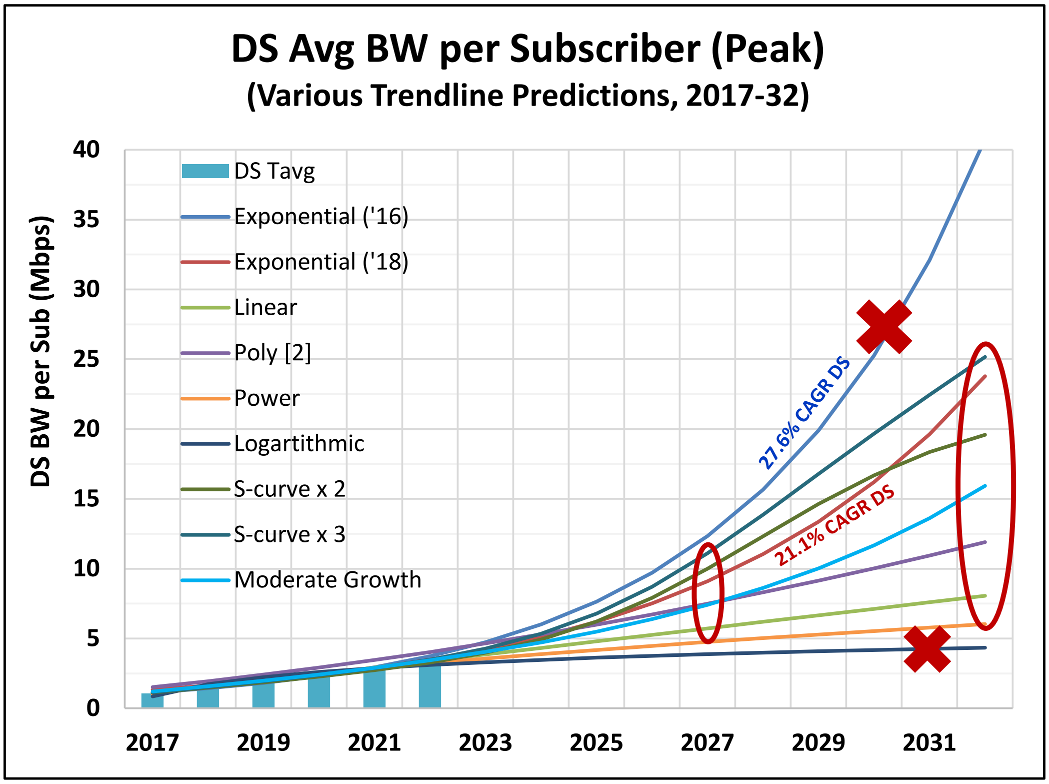


Figure 30 – DS Tavg Growth Projections for 2022 to 2032

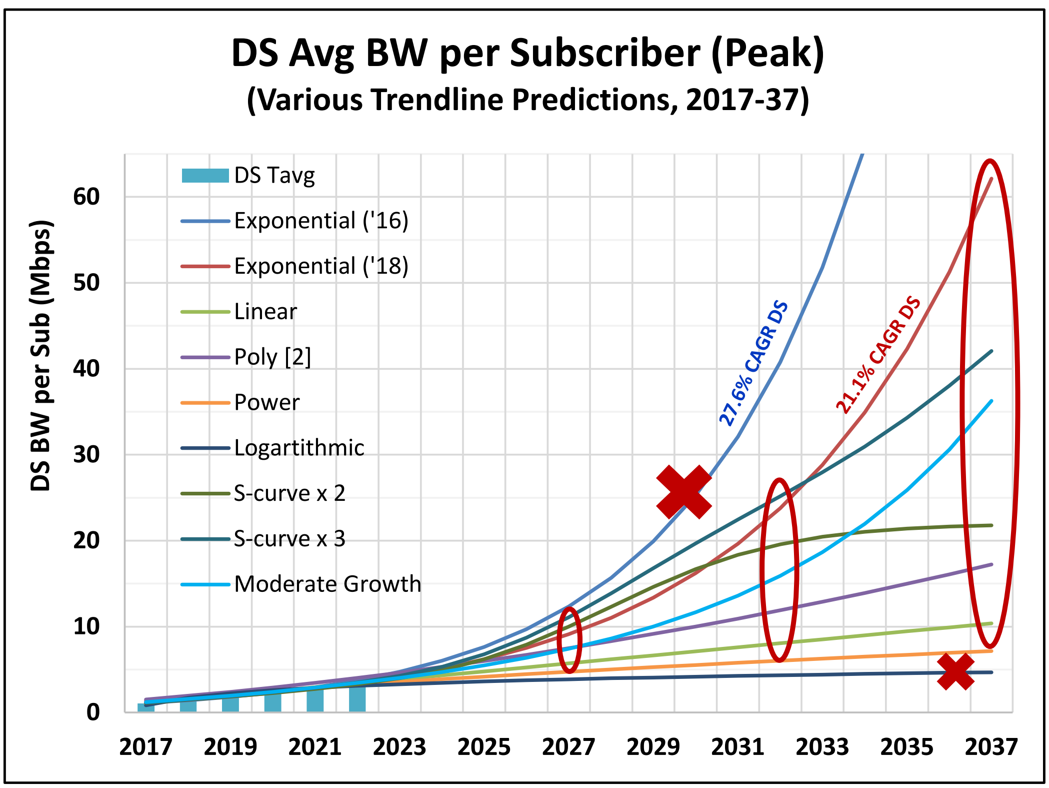


Figure 31 – DS Tavg Growth Projections for 2022 to 2037

4.5. Various Upstream Growth Trendlines

Upstream consumption growth over the last 4-6 years has been very different from DS growth. US growth rates have increased while DS growth has declined considerably. Upstream consumption has also been more volatile than DS, with very large spikes in 2018 and again with the 2021 COVID lockdown.

4.5.1. US Exponential Growth Trendline

The 2016-22 US exponential trendline is shown in Figure 32 while the 2018-22 period is in Figure 33.

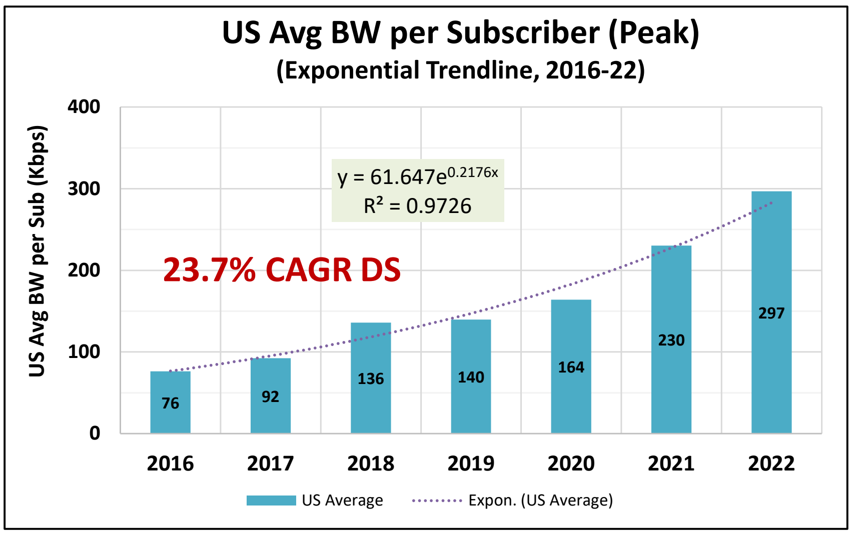


Figure 32 – US Tavg Exponential Trendline – 2016-2022

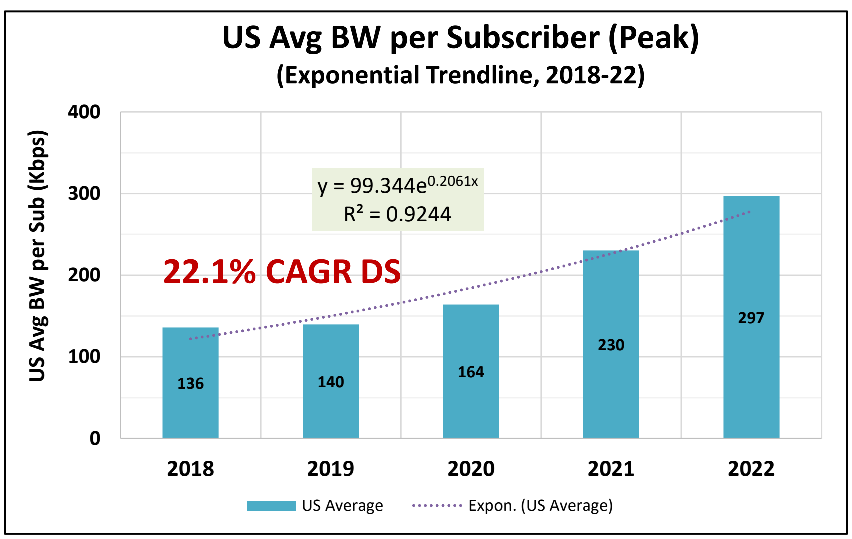


Figure 33 – US Tavg Exponential Trendline – 2018-2022

The 2016-22 exponential growth trendline has a 23.7% CAGR with US $R^2 = 0.9726$. The 2018-22 exponential growth trendline has a 22.1% CAGR with US $R^2 = 0.9244$. The 2016-22 trendline is a much better fit and the one that will be used as our high growth exponential scenario. Including the extra two years made for a better fit this time.

4.5.2. US Linear Growth Trendline

Figure 34 shows the US linear growth trendline. The US $R^2 = 0.9195$ which is a relatively poor fit. Linear growth assumes a slowing growth rate, but the upstream has seen an increased growth rate. As such, this trendline is not a candidate for consideration at this time.

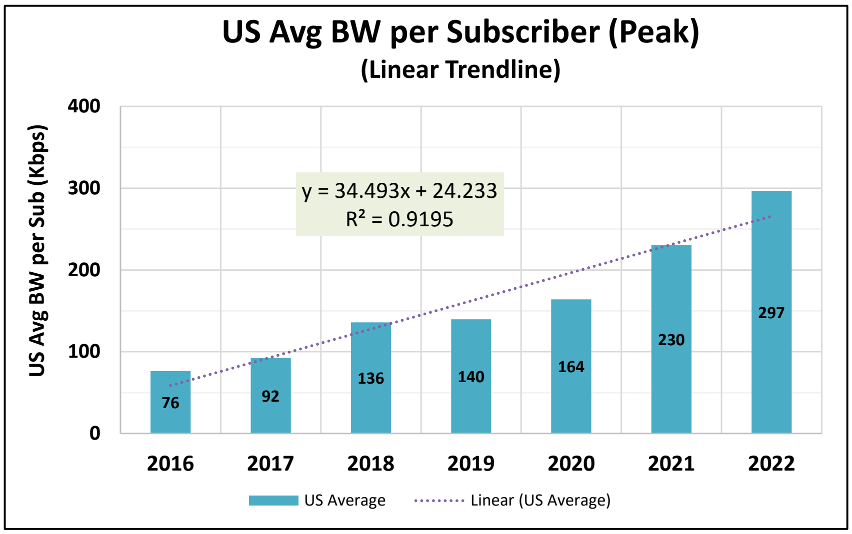


Figure 34 – US Tavg Linear Trendline – 2017-2022

4.5.3. Other US Growth Trendlines

The order of 2 polynomial growth trendline does provide a good fit. The 2016-22 trendline is shown in Figure 35 with the 2018-22 trendline in Figure 36. The 2018-22 trendline has the better fit with US $R^2 = 0.9948$ compared to US $R^2 = 0.9737$. It is even a better fit than the 2016-22 exponential trendline.

The 2016-2022 US power trendline is shown in Figure 37. It had a very poor match with US $R^2 = 0.8984$. The logarithmic trendline was even worse and is not even shown. These trendlines are not candidates for our long-term growth projections.

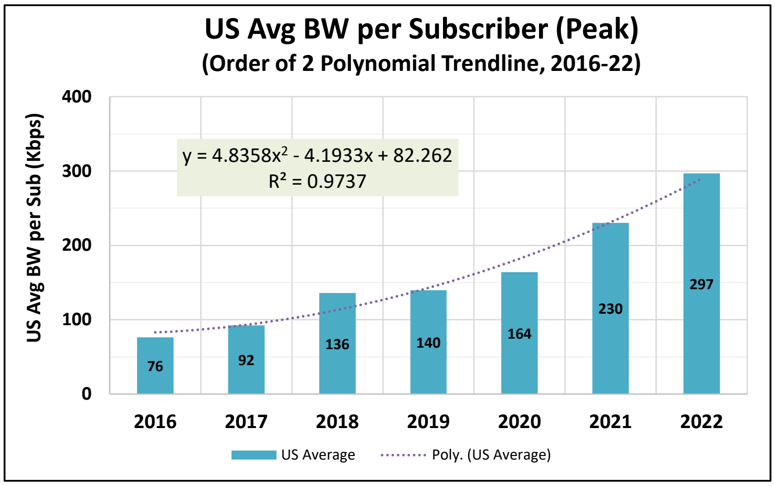


Figure 35 – US Tavg Order of 2 Polynomial Trendline – 2016-2022

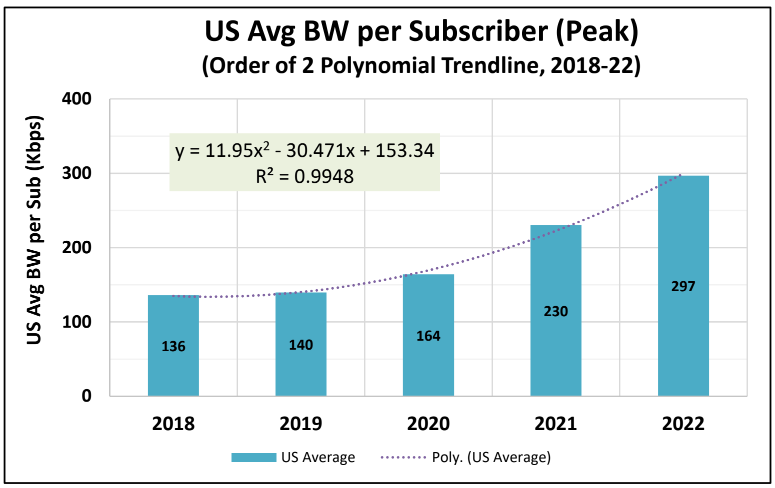


Figure 36 – US Tavg Order of 2 Polynomial Trendline – 2018-2022

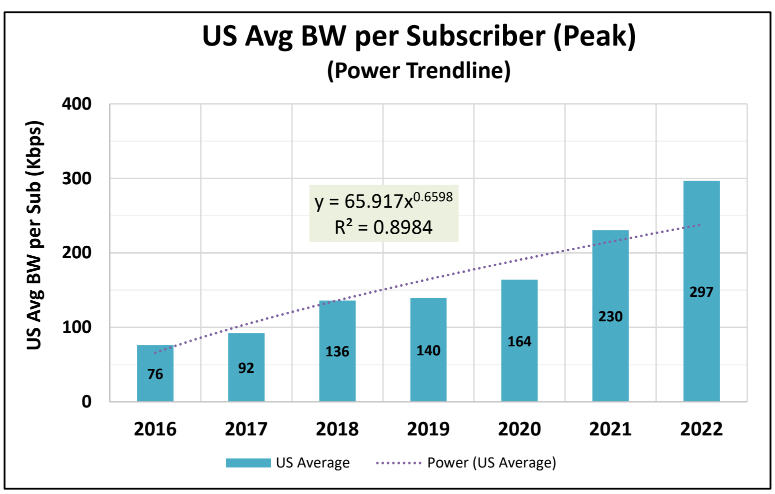


Figure 37 – US Tavg Power Trendline – 2017-2022

4.5.4. US Adoption Cure (S-curve) Growth Trendline

As noted above, the upstream growth behavior is very different than downstream one. The 10G initiative will be opening up a world of new applications. Many of these could start driving upstream bandwidth consumption further. This may come from a plethora of IOT devices in the home, or maybe more affordable HD resolution video cameras pushing content to the cloud.

Figure 38 and Figure 39 show the mapping of a single S-curve to the 2010-22 US Tavg data. The first figure is a view up until 2028, while the next figure zooms out to 2040. The US Tavg data is shown both with and without the COVID bump. The trendline without the COVID bump provides the best results with US $R^2 = 0.9815$, a relatively good fit for the upstream.

The upper bound on the US S-curve is 3.71 Mbps/sub. Note that the single S-curve midpoint is the year 2033. From an S-curve perspective, the US consumption is still in its early years of exponential growth.

Our modeling then calculated a best fit for two S-curves shown in Figure 40. The second curve ended up with a midpoint that was 20 years into the future and has minimal impact on the present day (i.e. <0.1 Kbps). The result is that the single and double S-curve scenarios are nearly identical for the next 12 years. It is almost 15 years before a separation between the two becomes obvious. Again, this shows that mapping out to 15+ years is more of an academic exercise.

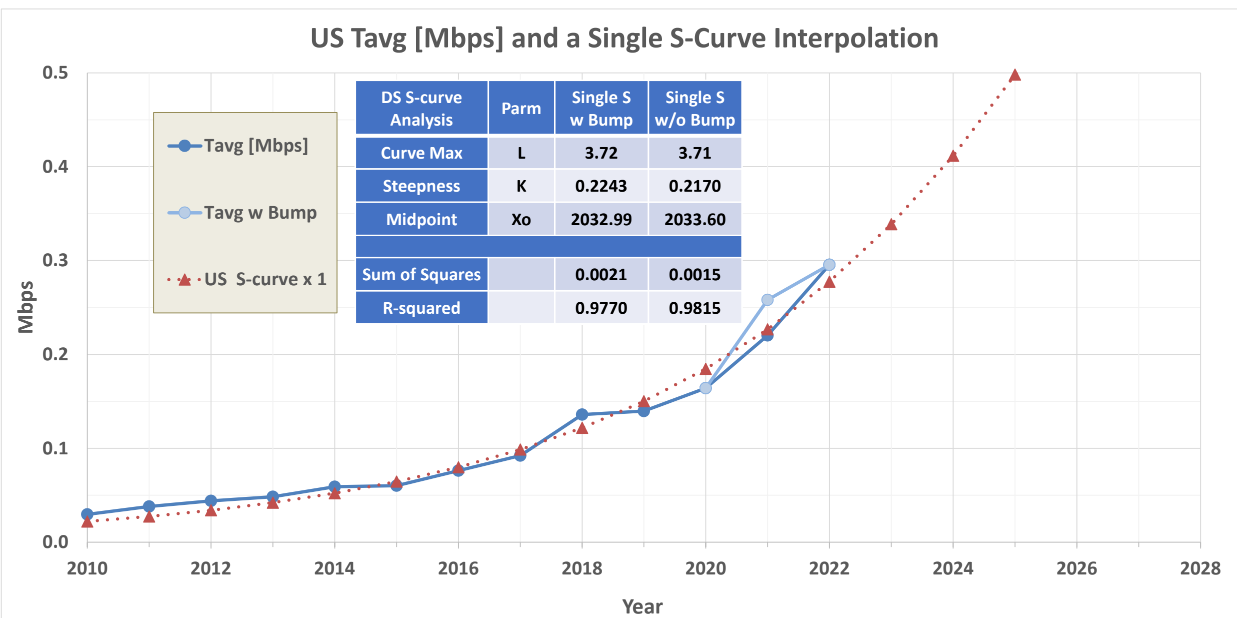


Figure 38 – Mapping a Single S-curve to 2010-2022 US Tavg

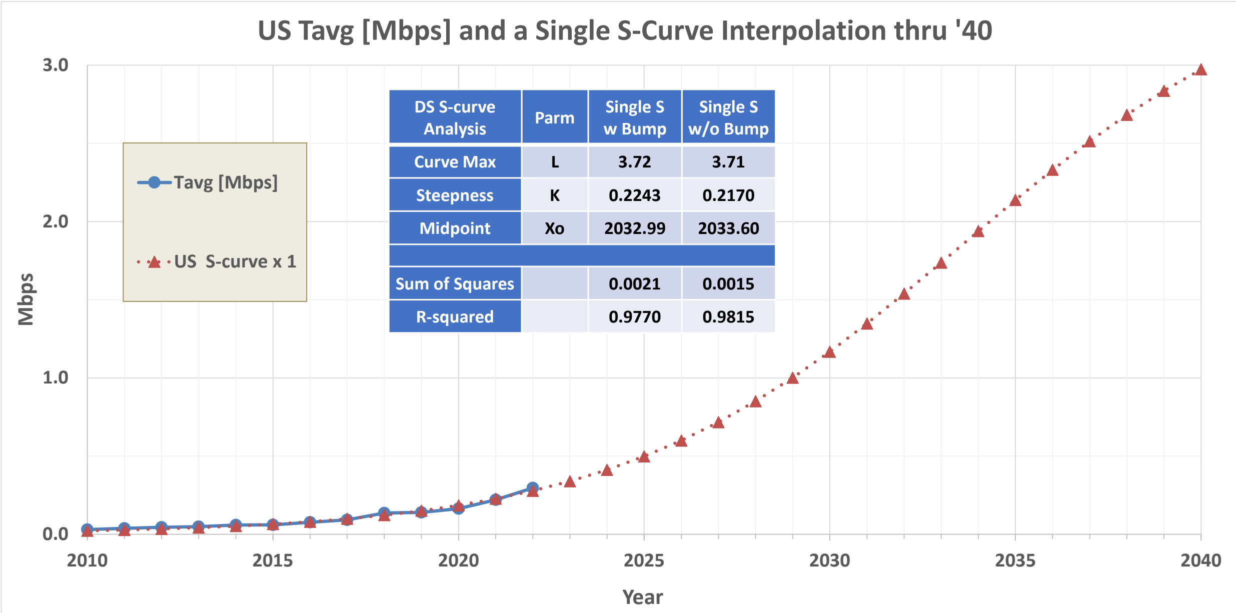


Figure 39 – Mapping a Single S-curve to 2010-2022 US Tavg (Zoomed Out to 2040)

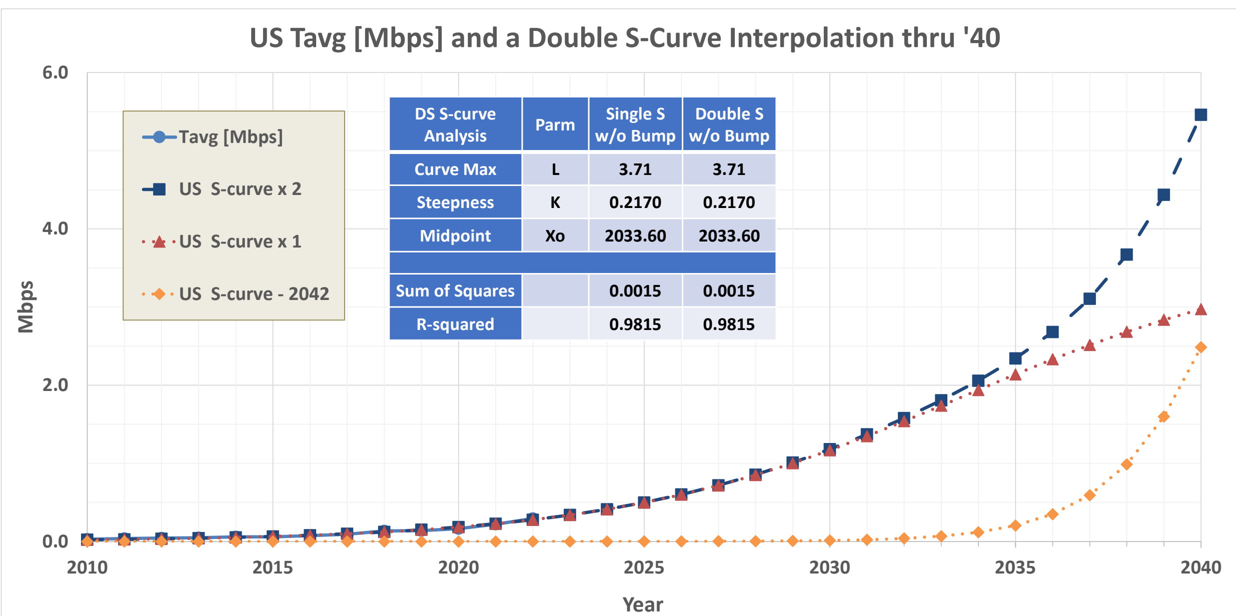


Figure 40 – Mapping a Double S-curve to 2010-2022 US Tavg (Zoomed Out to 2040)

4.6. Mapping US Tavg Growth Projections over a 10-15 Year Span

The upstream traffic growth projections have fewer options since the slower growth trendlines like linear are not currently under consideration. This obviously could change in the future as more Tavg data is collected and there is a better understanding of the "new normal" in this post-COVID lockdown world.

Figure 41 shows the US Tavg growth projections for the next decade. The trendlines at the lower extremes with a poor fit have been disregarded (i.e., linear, power, log trendlines). The red circles show the growth trendlines of interest and represent the amount of uncertainty between the different projections.

In five years, 2027, US Tavg is expected to be in 0.7-1.1 Mbps/sub range. A decade from now, 2032, that increases to a 1.2-2.5 Mbps/sub range. Notice that the upstream "cone of uncertainty" is smaller than the downstream, but it still has almost doubled as it goes from the five to ten-year window.

Figure 42 now extends the growth trendlines out 15 years to 2037. By 2037, the US Tavg is now 2-7 Mbps/sub, and the cone of uncertainty has roughly doubled once again.

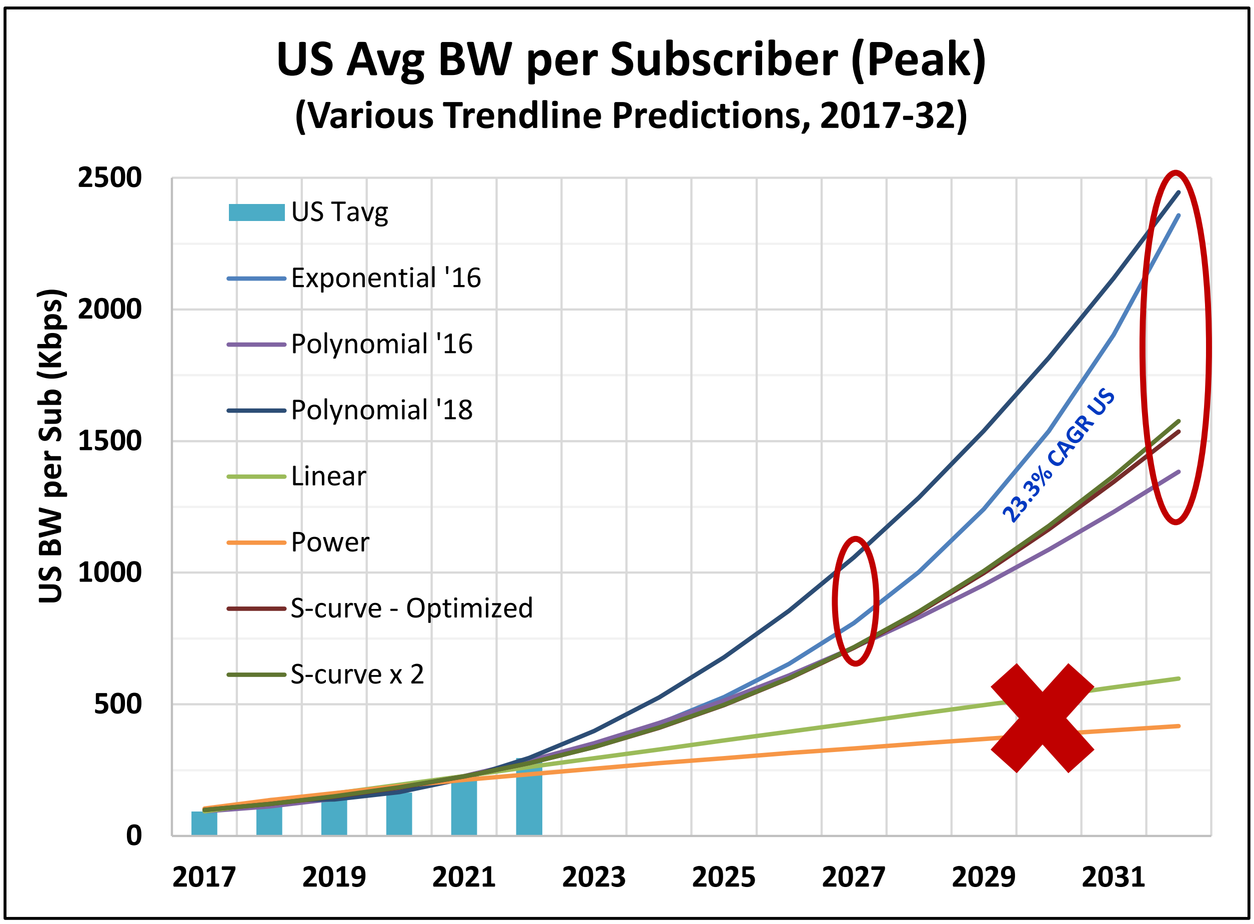


Figure 41 – US Tavg Growth Projections for 2022 to 2032

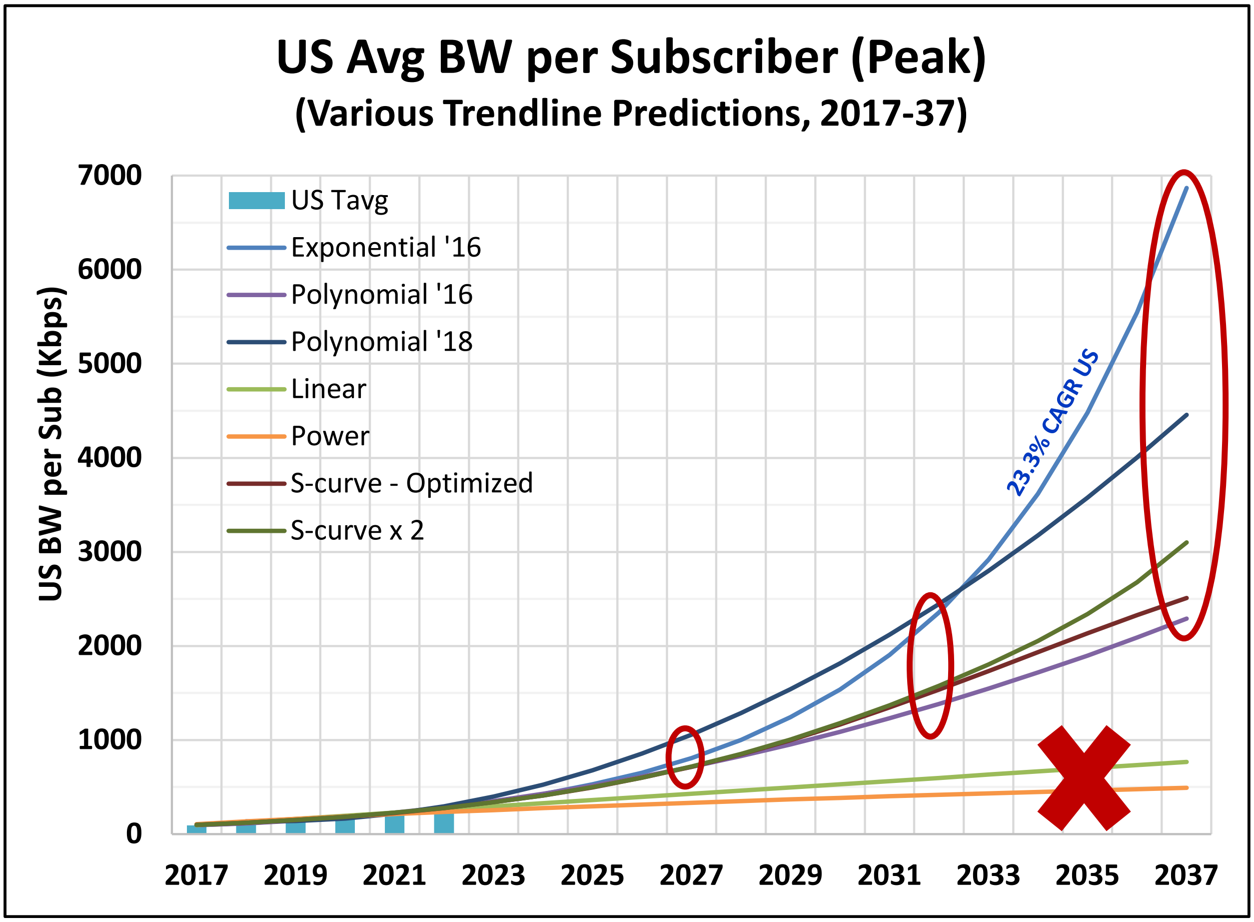


Figure 42 – US Tavg Growth Projections for 2022 to 2037

4.7. DS:US Tavg Ratio projections

Now let's put the DS and US Tavg growth projections side-by-side. This is shown in Table 1. From here, an estimate for the DS:US ratio can be made over time. The authors believe that there is some interdependence between the DS and US Tavg consumption growth, so it is highly unlikely that the DS and US will hit opposite ends of their low and high projections. The low and high ratio range in the table is slightly tempered from these extremes.

With the upstream showing a slightly higher growth trajectory, the mid-range of the DS:US ratio is expected to ease from the current 12:1 down to something closer to 10:1. Over the longer term, there is no evidence that the mid-range of the DS:US ratio will vary much from 10:1.

Table 1 – Tavg Growth Projections: DS, US & DS:US

Tavg Growth Projections	DS Tavg Range		US Tavg Range		DS:US Ratio Range		
Year	Low	High	Low	High	Low	Mid	High
2022	3.5		0.3		12:1		
2027	5	12	0.7	1.1	6:1	10:1	15:1
2032	7	25	1.2	2.5	5:1	10:1	18:1
2037	8	65	2	7	4:1	10:1	20:1

5. Network Capacity Modeling for Low to High Growth Projections

So, how do these BW growth projections drive our network investment strategies? Our next step plugs various Tavg growth trendlines into the CommScope network capacity modeling tool to analyze 1218/204 MHz and DOCSIS 4.0 plant. It shows their useful plant lifetime using various growth projections and explores whether low growth might eliminate the need for 4.0; or just delay it, giving precious time for the operator to transition.

Over recent years, there has been a slowing in the downstream usage growth rate (i.e., DS Tavg) compared to the service tier growth rate (i.e., DS Tmax_max). This has a number of consequences including the network becomes more “bursty”. It also means that the overall utilization of the network is lower. In this respect, it is important to try and maximize subscribers per service group (SG) to take advantage of statistical multiplexing and to get better economics. This analysis focuses on the number of subscribers that a service group can support over time for a given configuration.

5.1. Network Capacity Modeling Assumptions

The CommScope network capacity model contains 100’s of different inputs that can vary from year to year. The paper uses a relatively good to best case scenario that was taken from modeling work done for several operators based on their current network migration plans.

Many HFC plants today are still 870 MHz, 750 MHz or even lower. The model assumes that the HFC plant is upgraded to at least 1218/204 MHz plant by 2024 (and as needed to extended spectrum DOCSIS (ESD) by 2025). The modeling starts with 400 subs per SG as the maximum, then reduces max subs per SG as needed over time. Note that this is an extremely large SG that could represent a node in the 600 to 1,000 homes passed region.

From DOCSIS perspective, it assumes that up to 400 typical data subs per cable modem termination system (CMTS) Service Group (SG) as the starting point. And from a DOCSIS combining perspective – 1 node per CMTS SG for both DS & US to start (e.g., 1x1 Remote MAC-PHY device, RMD). If the upstream ever becomes the limiting factor, then the upstream will be split (e.g., 1x2 RMD). If an operator starts with a 1x1 RMD, then a migration to 2x2 RMD enables SG splits down the road.

Legacy video begins with 60 total quadrature amplitude modulation (QAM) electronic industries association (EIA) channels today. But a rapid migration to 100% IPTV in 2024 reduces that to zero QAM EIA channels. These scenarios assume there are no video on demand (VOD) QAM channels, no Analog video spectrum, and no switched digital video (SDV) QAM channels.

For DOCSIS Services, the beginning includes 32 DOCSIS 3.0 SC-QAM channels. DOCSIS 3.1 (D3.1) modems are used for all the top tiers. Older DOCSIS 2.0/3.0 modems are phased out over time until there is 100% D3.1/4.0 modems by 2025.

The model uses the broadband consumption numbers from this paper. DS Tavg = 3.5 Mbps in 2022. Modeling runs were then done from 2022 to 2032 for high growth (i.e., 21% CAGR), moderate growth (i.e., 16% CAGR) and low growth (i.e., linear) scenarios. US Tavg = 300 Kbps in 2022; with 23% CAGR growth from 2022 to 2032. Our findings show that the plant tends to be downstream BW limit so there was no need to consider low to moderate growth upstream scenarios. These result in:

- DS Tavg High Growth: 21% DS CAGR = 24 Mbps by ‘32;
- 23% US CAGR = ~2.4 Mbps by ’32
- Note that this is still a 10:1 DS:US ratio

The CommScope network capacity model has a lot of flexibility and allows us to adjust Tavg per service tier (e.g., Top Billboard tier is 2X Flagship tier). The DS Tavg and US Tavg listed are the weighted average across all subscribers in the SG.

For the DOCSIS Physical (PHY) layer, the model assumes:

- D3.1 orthogonal frequency-division multiple access (OFDMA) US = 7.58 bps/Hz (1024 QAM, 4K fast fourier transform (FFT), 1.875us cyclic prefix (CP))
- D3.1 orthogonal frequency-division multiplex (OFDM) DS = 9.7 bps/Hz (4096-QAM, 8K FFT, 1.25us CP) up to 1218MHz
- 1794 MHz plant drops to 8.58 bps/Hz on average (2048-QAM, 4K FFT, 1.25us CP)
- ‘Normal’ amp spacing = ~9.0 bps/Hz; ‘Stretch’ amp spacing = ~8 bps/Hz

The service tier mix is shown in Table 2. The Top Billboard tier jumps to 5 Gbps DS with a 1 Gbps US in 2024 for the 1218/204 MHz plant. Note that a 5G DS Tier requires four bonded OFDM channels on a D3.1 plant. This can easily be handled with DOCSIS 4.0 modems operating in D3.1 environment. The 1794/396 MHz plant has a Top Billboard tier of 7.5G DS X 2.5G US. Any tiers 500/50 or higher are assumed to be immediately moved to D3.1 modems only.

Table 2 – Network Capacity Model – Service Tier mix and 3.0/3.1 mix

Service Tier	Mix %	2022	2024	2026	2028
Top Billboard	2%	2G/400	5G/1G or 7.5G/2.5G		
Performance	13%	1G/100	2G/200	5G/1G	5G/1G
Flagship	50%	200/20	500/50	1G/100	2G/200
Economy	35%	100/10	200/20	200/20	500/50
% D3.1 modems		50%	75%	100%	100%

Regarding video services, the managed IPTV bundle grows to 100% penetration by 2024 replacing all Legacy Video subs. It assumes 50% of high-speed data (HSD) subs take IPTV bundle (e.g. 150 IPTV subs out of 300 HSD subs). The IPTV service is 100% Unicast delivery with the following mix of video bit rates:

- HD streams: 5 Mbps per today; dropping to 3 Mbps by 2030
- 4K UHD streams: 5% @ 20 Mbps in ‘23 growing to 50% @ 8 Mbps in 2032

5.2. Making the Most of 1218/204 MHz HFC Plant

With so much interest in slowing DS Tavg growth rates, the first case study considered standard D3.1 1218/204 MHz plant offering a 5G DS tier with a 1G US tier. What is the maximum sized SG that can be supported over the next decade?

The model was run for high (21% CAGR), moderate (16% CAGR) and low (linear) DS Tavg growth rates. That leaves DS Tavg a decade from now at 24, 15 and 8 Mbps/sub respectively. The US Tavg with a 23% CAGR reaches 2.4 Mbps/sub while the lower growth projections are just above 1.5 Mbps in 2032.

Figure 43 shows the max number of subs per SG for low, moderate, and high DS Tavg growth projections. All projections can support 400+ subs through 2025. In 2026, the high growth scenario needs to gradually reduce the max subs/SG each subsequent year. It is still supporting 300 subs/SG until 2028, 200 subs/SG through the end of the decade and 150 subs/SG in ten years. The moderate growth rate follows a similar curve only delayed about two years. The slow linear growth is still supporting 400 subs/SG at the end of the decade and 350 subs/SG in 2032, a decade from now.

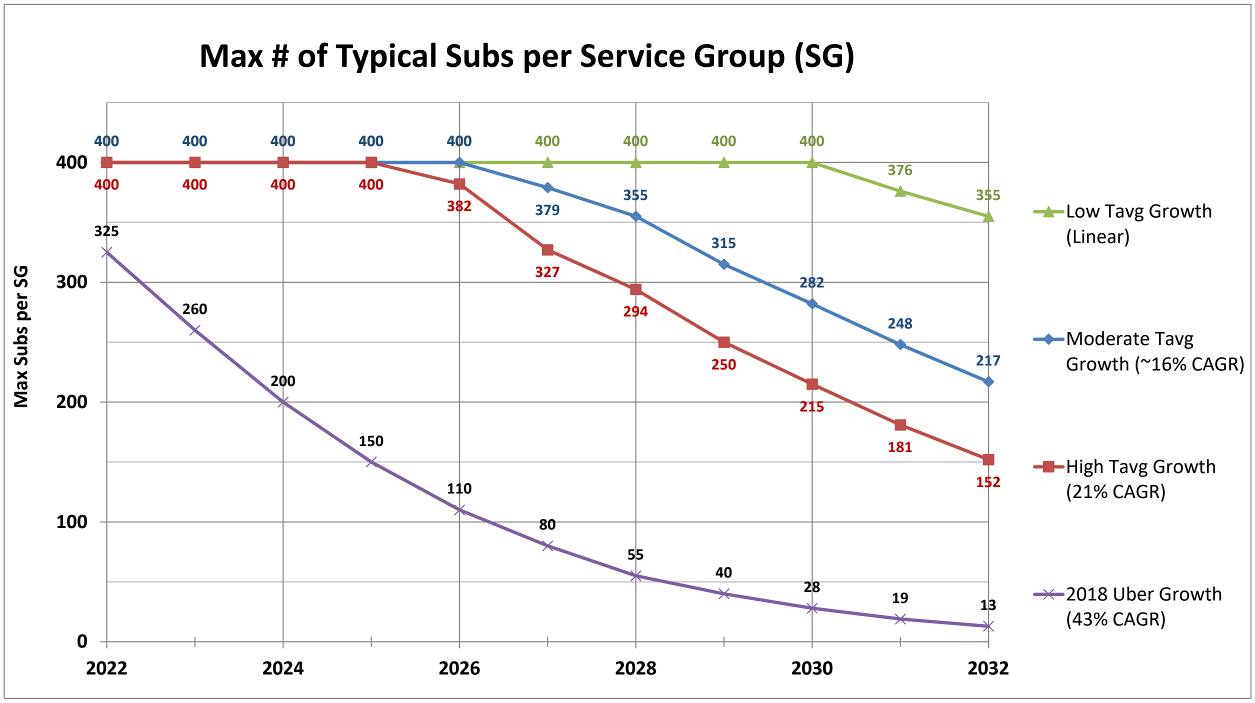


Figure 43 – Max Subs per SG for Low, Moderate & High DS Tavg growth, 1218/204 MHz

For comparison purposes, Figure 43 also shows the 2018 projections using the 43% CAGR uber growth. It had projected that max subs per SG would drop to 28 subs by 2030. This drove many people to think that FTTP would be required by then. The reality is that a 1218/204 MHz plant supporting 5G x 1G tiers can easily last into the next decade, maybe even further if the slower growth projections hold.

Figure 44 maps two max subs/SG scenarios onto the DS Tavg trendline charts from Figure 28. When DS Tavg = ~11 Mbps, the max subs/SG supported is ~300 subs. This is the lower horizontal red dashed line. When DS Tavg = ~23 Mbps, the max subs/SG supported is ~150 subs. This is the upper horizontal red dashed line. For a given trendline, it can support that SG size until it crosses that dashed line. Looking at the 150 max subs/SG as an example, the highest growth projections show it lasting until the end of this decade while multiple slower projections don't even reach the mark in 15 years. The slow linear growth takes multiple decades. If an operator is at 150 subs/SG today, they will stay there for a very long time (provided the 5Gx1G tier is sufficient!). This might be true for markets where there is limited demand or need for multi-gig upload speeds.

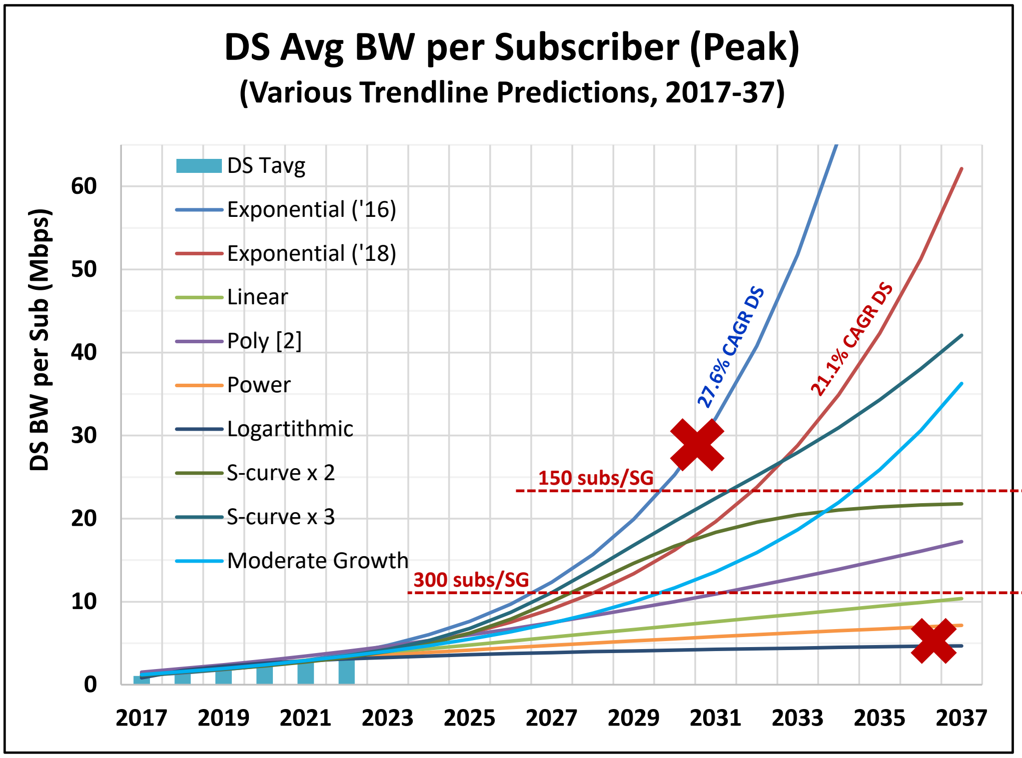


Figure 44 – 1218/204 MHz Max subs / SG vs. various DS Tavg projection trendlines

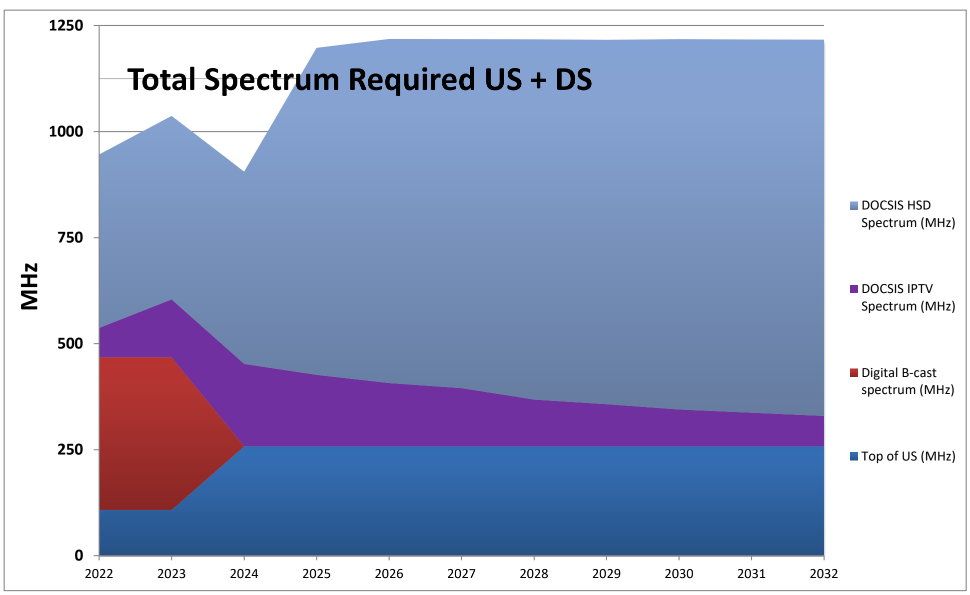


Figure 45 – 1218/204 MHz System – Spectrum Utilization

Figure 45 shows the spectrum utilization for the 1218/204 MHz plant scenario. The 204 MHz high split is introduced in 2024. The US spectrum is on the bottom of the chart. In that same year, the operator has finished the IPTV migration and the legacy video spectrum (in red) is reduced to zero. The overall spectrum requirements are reduced with these savings, even though the IPTV spectrum (in purple) had increased slightly. Note – there are many inputs that impact IPTV BW consumption, so savings may vary from operator to operator depending on their particular situation.

In 2025, the 5G DS tier is introduced which fills up most of the available 1218 MHz of spectrum. Note that the SG size is still at 400 subs. After 2025, the SG size is reduced as needed to keep within the allotted 1218 MHz. Note that the IPTV spectrum is shrinking over time. This is due to both fewer subs and the video bit rate reductions, despite higher UHD %.

Figure 46 shows the models outputs for DOCSIS usage in Mbps broken out into three components:

- QoE Delta (i.e. K*Tmax), Nsub*Tavg and IP Video

It shows these three components for both D3.1 modems and 3.0 modems (which are removed by 2025). The redline on the top is the total available system capacity. Note that the 1218/204 MHz plant is providing a total of >9 Gbps usable capacity. That is higher than a 10G PON at 8.6 Gbps.

Figure 46 gives a good visual of the proportion of capacity needed for each component. The sum of the three components needs to be below the total available capacity. Note that this scenario is reasonably balanced between the consumption and burst components. Cutting the SG size in half would only provide an extra 1.5 Gbps of capacity, not enough to drastically change the 5G DS tier.

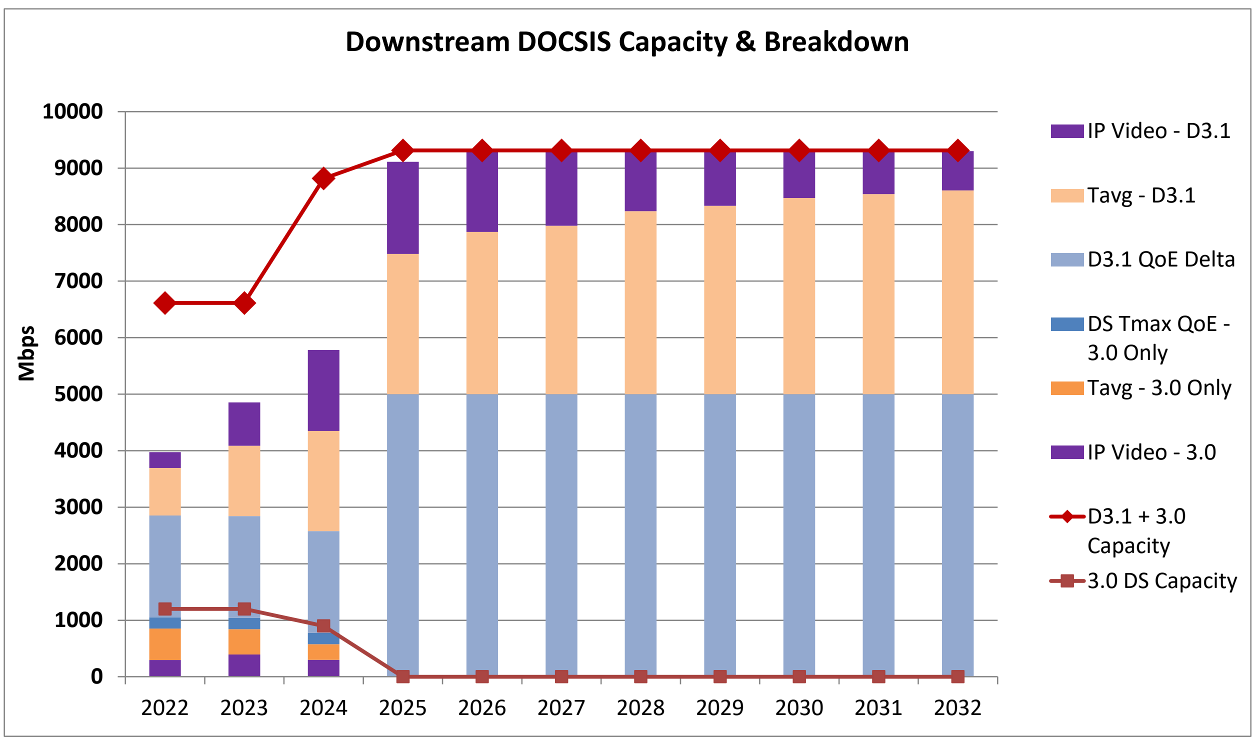


Figure 46 – 1218/204 MHz System – DOCSIS DS Usage: Tmax, Tavg, IP Video

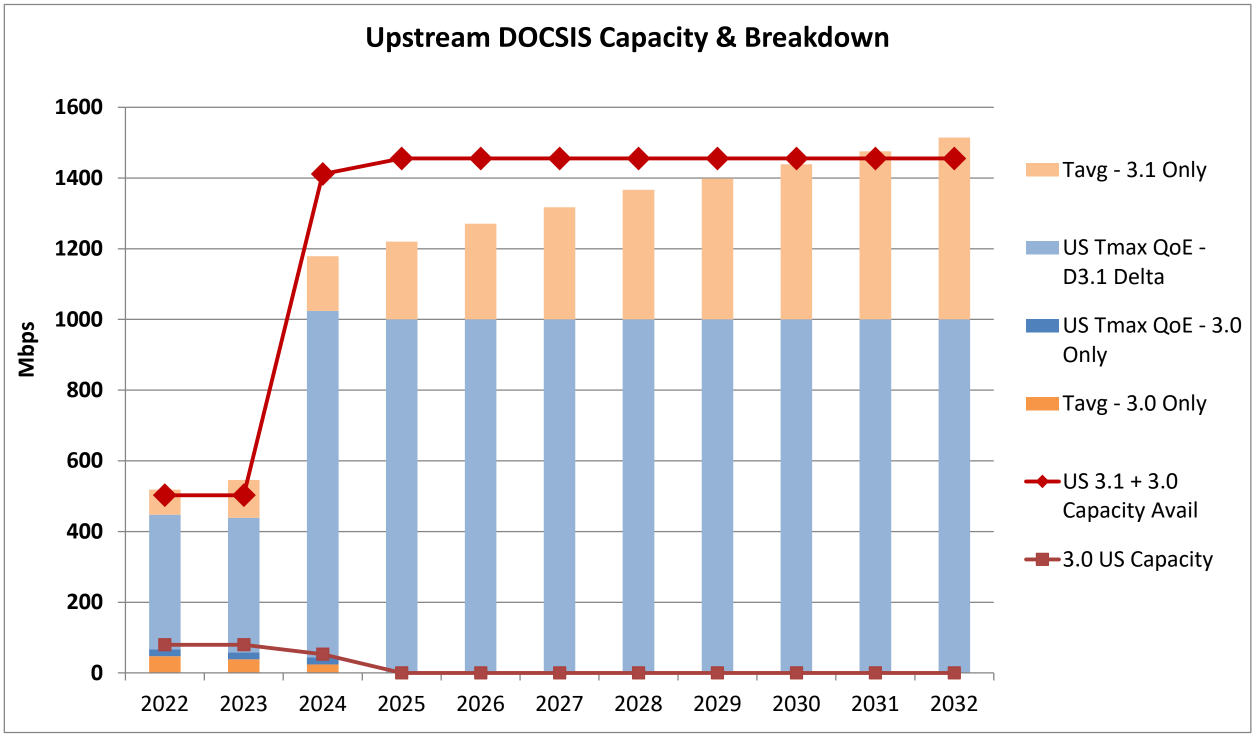


Figure 47 – 1218/204 MHz System – DOCSIS US Usage: Tmax, Tavg, IP Video

The US DOCSIS capacity usage is broken out in Figure 47. Supporting a 400 Mbps US tier in 85 MHz during 2022-23 is a bit tight, but there is plenty of capacity after the 204 MHz high split upgrade. As can be seen, the Tmax component dominates over time. Figure 47 assumes the SG size is being set based on a moderate DS Tavg growth projection of 16% CAGR while the US Tavg is on a high growth 23% CAGR. See that the US has sufficient capacity until 2032. At this point, the operator might consider switching from 1x1 to 1x2 RMD configuration. Also, the DS:US ratio has dropped all the way to 6:1.

Perhaps the key point of this 1218/204 MHz case study is that a node with 150+ subs can be upgraded to 1218/204 MHz and support a service tier of 5 Gbps x 1 Gbps for the next decade and beyond. There is no pressing near term need to push the HFC to very small (and inefficient!) SG sizes, that could be, for example, achieved in N+0 systems.

5.3. Matching 10G PON on a 1794 / 396 MHz ESD Plant

The next case study focused on a DOCSIS ESD 1794/396 MHz plant offering a 7.5G DS tier with a 2.5G US tier. The primary goal here is to match the 10G PON DS service tier level. As before, the model was run for high (21% CAGR), moderate (16% CAGR) and low (linear) DS Tavg growth rates. The DS Tavg and US Tavg both hit the same numbers in 2032 as the previous case study.

Figure 48 shows the max number of subs per SG for low, moderate, and high DS Tavg growth projections. All projections can support 400+ subs through 2024. In 2025, slightly earlier than the previous case study, the high growth scenario gradually reduces the max subs/SG each subsequent year. It is still supporting 250 subs/SG until 2028 and ~130 subs/SG in ten years. The moderate growth rate follows a similar curve only delayed about two years. The slow linear growth supports 400 subs/SG through 2026 and 300 subs/SG in 2032, a decade from now. For comparison purposes, Figure 48 also shows the 2018 projections using the 43% CAGR uber growth.

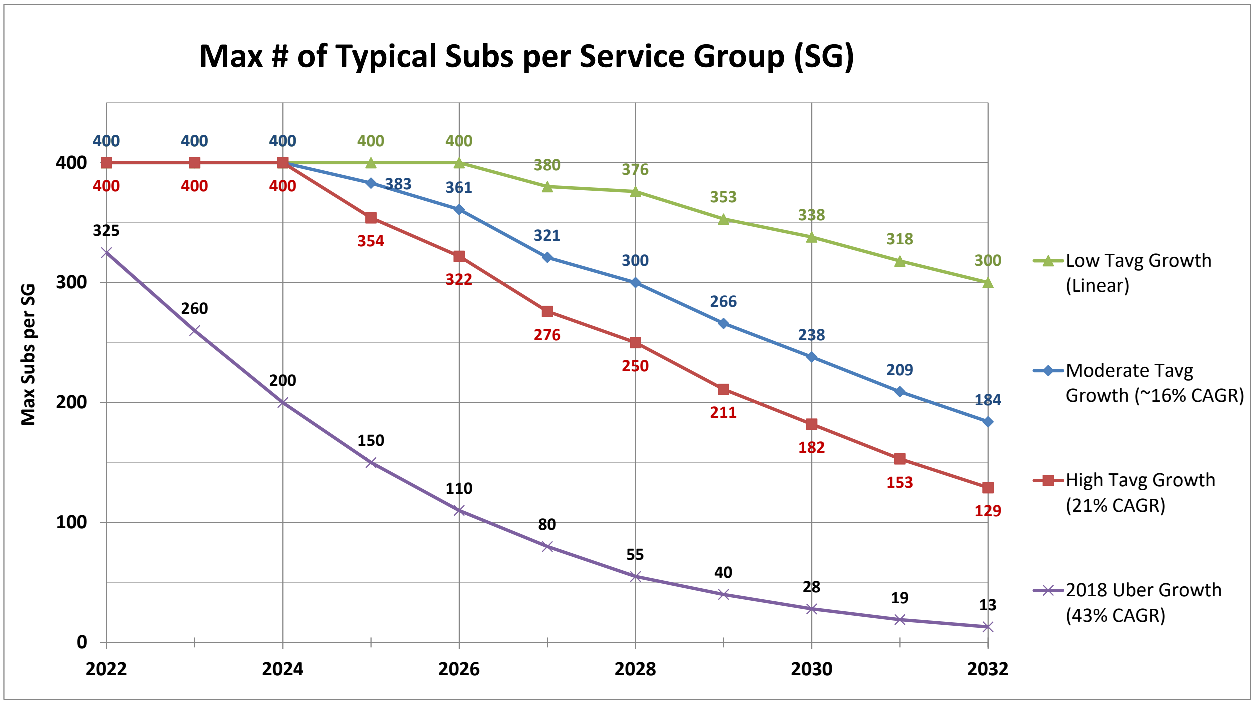


Figure 48 – Max Subs per SG for Low, Moderate & High DS Tavg growth, 1794/396 MHz

Figure 49 maps two max subs/SG scenarios unto the DS Tavg trendline charts from Figure 28. When DS Tavg = ~8 Mbps, the max subs/SG supported is ~300 subs. This is the lower horizontal red dashed line. When DS Tavg = ~19 Mbps, the max subs/SG supported is ~150 subs. This is the upper horizontal red dashed line. For a given trendline, it can support that SG size until it crosses that dashed line. Looking at the 150 max subs/SG as an example, the highest growth projections show it lasting until 2027 while the slow linear growth will take multiple decades. For a 150 subs/SG today that is upgrade to1794/396 MHz ESD plant, it can stay there until 2029 with high growth but for a very long time with slow linear growth. Thus, node splits on the ESD plant become very sensitive to which DS Tavg growth trendline it tracks. A proactive operator might want to deploy a 2x2 RMD in that location even though 1x1 may be adequate for many years.

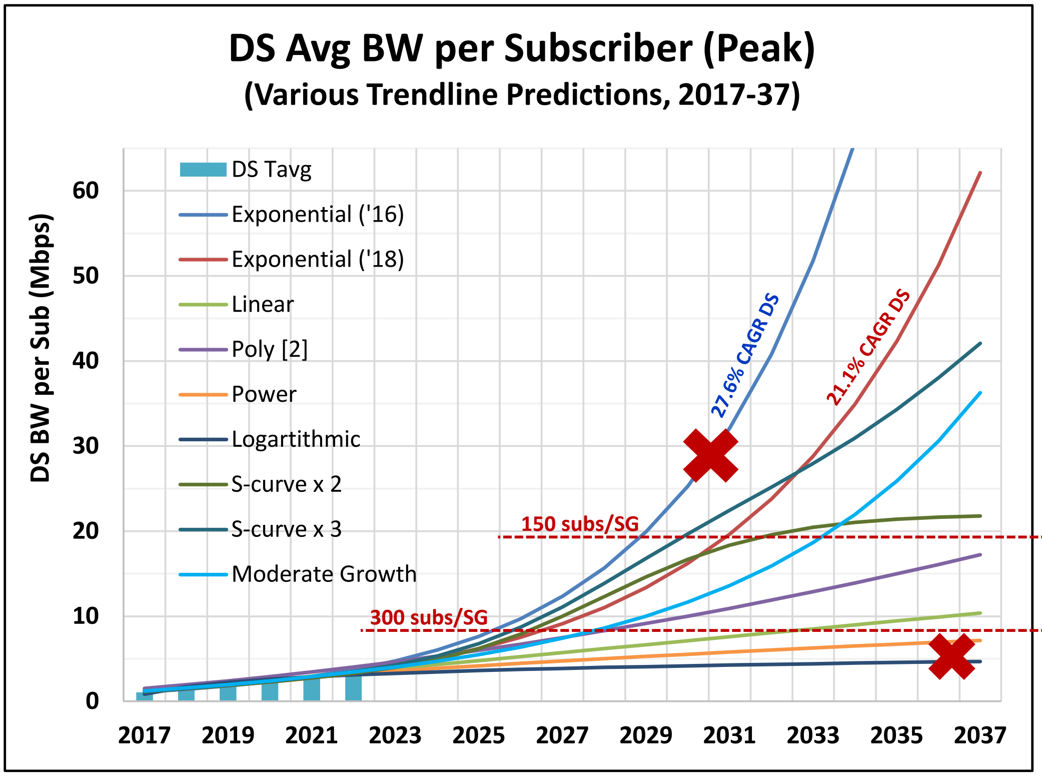


Figure 49 – 1794/396 MHz Max subs / SG vs. various DS Tavg projection trendlines

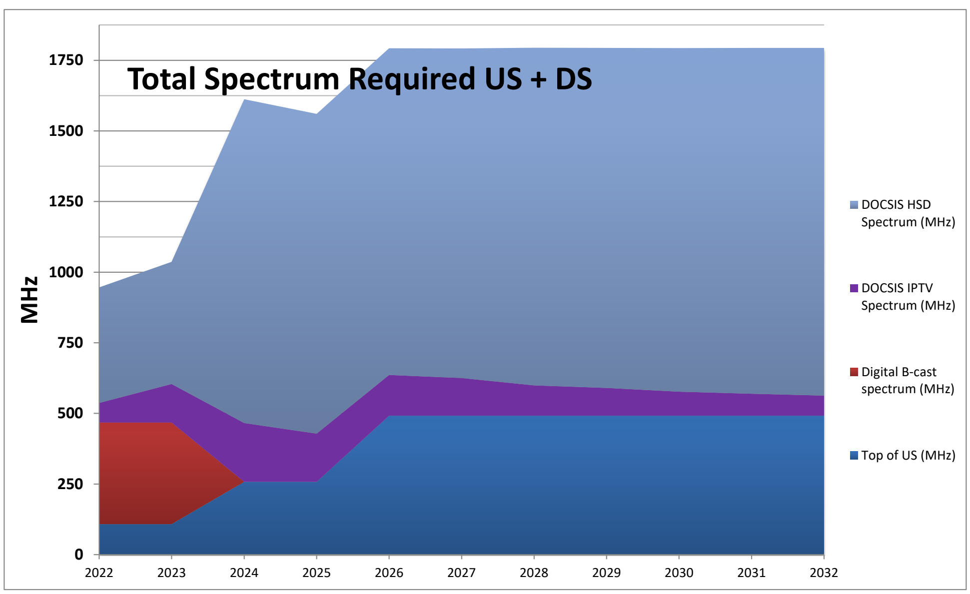


Figure 50 – 1794/396 MHz System – Spectrum Utilization

Figure 50 shows the spectrum utilization for the 1794/396 MHz plant scenario. The 204 MHz high split is introduced in 2024 at the same time the DS expands to 1794 MHz. Then the US split is reconfigured for 396 MHz in 2026. The legacy video and IPTV spectrum follow the same trajectory as before. The first big spectrum jump in 2024 is the 5G DS introduction. The 2nd jump in 2026 is the 7.5G DS tier introduction.

Note that the SG size is at 400+ subs until 2024, then the SG size is reduced as needed to keep within the allotted 1794 MHz. As before, the IPTV spectrum is shrinking over time due to both fewer subs and the video bit rate reductions, despite higher UHD %.

Figure 51 shows the 1794/396 MHz model outputs for DOCSIS usage in Mbps broken out into three components:

- QoE Delta (i.e. K*Tmax), Nsub*Tavg and IP Video

The redline on the top is the total available system capacity. Note that it is initially 1794/204 MHz plant with >13 Gbps usable capacity, but then settles back to ~11 Gbps for the 1794/396 MHz plant configuration. This is significantly higher than a 10G PON at 8.6 Gbps.

Figure 51 gives a good visual of the proportion of capacity needed for each component. The sum of the three components needs to be below the total available capacity. Note the Tmax burst component is starting to dominate the usage. Cutting the SG size in half provides minimal benefit, ~ 1 Gbps of additional capacity. If an operator would prefer additional plant life, they might consider backing down the DS Tmax to 5 or 6 Gbps.

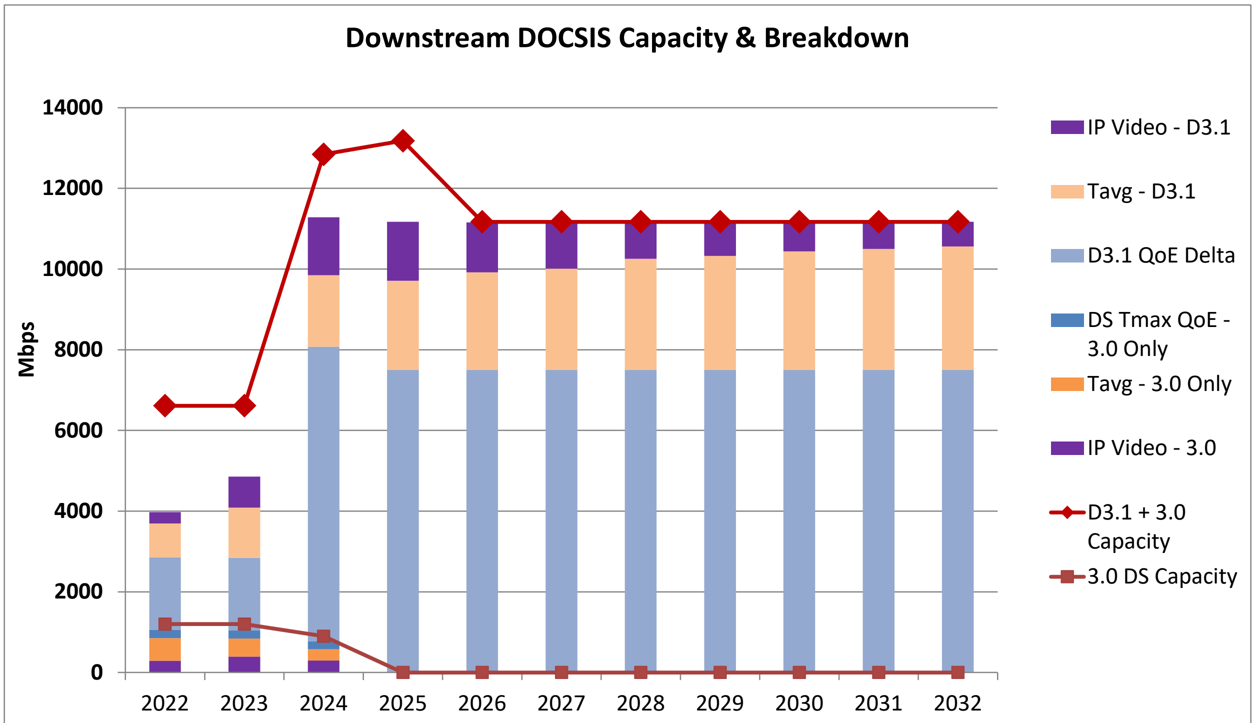


Figure 51 – 1794/396 MHz System – DOCSIS DS Usage: Tmax, Tavg, IP Video

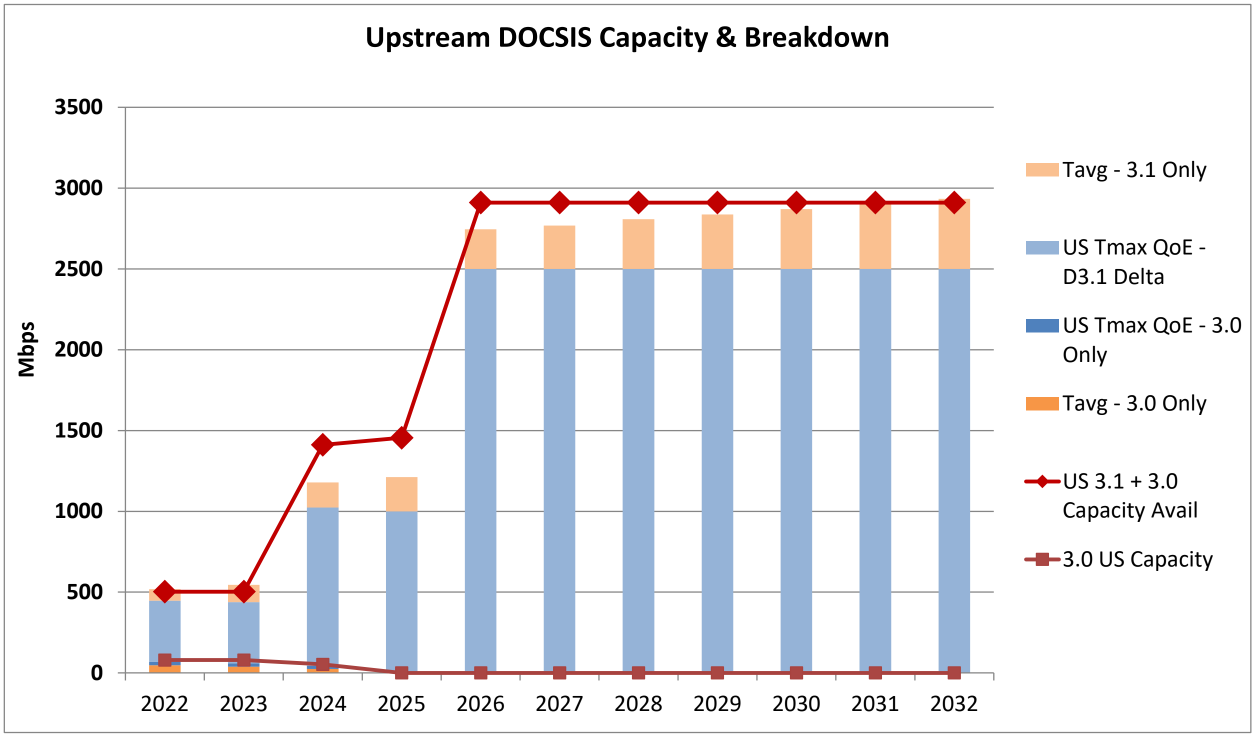


Figure 52 – 1794/396 MHz System – DOCSIS US Usage: Tmax, Tavg, IP Video

The US DOCSIS capacity usage is broken out in Figure 52. As can be seen, the Tmax component dominates over time. Figure 52 assumes the SG size is being set based on a moderate DS Tavg growth projection of 16% CAGR while the US Tavg is on a high growth 23% CAGR. See that the US has sufficient capacity through 2032. It remains a fairly balanced 1x1 RMD configuration despite the DS:US ratio dropping to 6:1.

Perhaps the key point of this 1794/396 MHz case study is that a node with 150+ subs can be upgraded to 1794/396 MHz, but the timing of additional node splits on the ESD plant becomes very sensitive to which DS Tavg growth trendline it tracks. A proactive operator might want to deploy a 2x2 RMD in that location even though 1x1 may be adequate for many years. As with the previous case study, there still seems to be no pressing near term need to push the HFC to very small (but inefficient!) SG sizes such as those found in N+0 systems.

5.4. Other 1794 MHz ESD and FDX Options

The D4.0 specification [DOCSIS_4.0_PHY] provides operators with lots of different choices and options. From the highest level, D4.0 offers both Extended Spectrum DOCSIS (ESD) and Full Duplex DOCSIS (FDX). ESD DS spectrum goes up to 1794 MHz, a.k.a. 1.8 GHz. The specification offers five different upstream split options going from 204 MHz up to 684 MHz. The DS spectrum starts after a guard band above the US. The size of the guard band increases proportionately with the US split.

FDX shares US + DS spectrum in the FDX Band. This is variable width. The FDX Band starts at 108 MHz and can go as high as 684 MHz. While the top of the DS spectrum is nominally 1218 MHz, many operators considering FDX do not want to replace their taps, so they may be limited to 1002 MHz of DS spectrum, at least initially.

Table 1 shows the maximum DS + US service tiers supported by the various ESD and FDX options. The table also provides the max number of subs per SG for two different DS Tavg – 7 and 15 Mbps/sub. The 7 Mbps DS Tavg might occur 3-8 years from now depending on high, medium or low growth rates; while the 15 Mbps DS Tavg happens in a much longer window that is 8-20+ years from now.

The max tier calculation uses mostly best-case assumptions including:

- 100% IPTV, no Legacy Video spectrum
- 100% DOCSIS 3.1/4.0 modems
- DS Tavg = 7 or 15 Mbps/sub
- 4096-QAM for dedicated DS below 1218 MHz and 1024-QAM US for dedicated US
- A range from 1024-QAM to 4096-QAM for ESD DS > 1218 MHz and FDX DS in FDX Band
    - Previous network capacity modeling used an average of 2048-QAM

Most of the max tiers are shown in Gbps except for '2G' = 2 x 940 Mbps and '5G' = 5 x 940 Mbps.

As a reference point, the final row of the table provides the max tier and SG sizes for a 10G PON network. This includes the symmetric versions: 10G EPON, 10G XGS-PON and NG-PON2. It does not include XG-PON which only has 2.5G US optics and is limited to a 2G US tier. Note the 10G PON SG size limits as DS Tavg increases.

Table 3 – DOCSIS 4.0 Maximum Service Tiers and Max Subs per SG

<table>
<tr><th colspan="2" rowspan="3">DOCSIS 4.0 Max Service Tiers</th><th rowspan="3">Max DS Tier</th><th rowspan="3">Max US Tier</th><th colspan="4">Max Subs per DOCSIS/PON SG</th></tr>
<tr><th colspan="2">DS Tavg = 7Mbps</th><th colspan="2">DS Tavg = 15Mbps</th></tr>
<tr><th>1K-QAM</th><th>4K-QAM</th><th>1K-QAM</th><th>4K-QAM</th></tr>
<tr><td rowspan="5">ESD 1.8GHz</td><td>204 / 258</td><td>12G</td><td>1.25G</td><td>194</td><td>371</td><td>90</td><td>173</td></tr>
<tr><td>300 / 372</td><td>11G</td><td>'2G'</td><td>182</td><td>360</td><td>85</td><td>168</td></tr>
<tr><td>396 / 492</td><td>10G</td><td>2.5G</td><td>162</td><td>340</td><td>76</td><td>159</td></tr>
<tr><td>492 / 606</td><td>9G</td><td>3G</td><td>151</td><td>328</td><td>70</td><td>153</td></tr>
<tr><td>684 / 834</td><td>7.5G</td><td>'5G'</td><td>54</td><td>232</td><td>25</td><td>108</td></tr>
<tr><td rowspan="2">FDX</td><td>1002 / 108-684</td><td>6G</td><td>'5G'</td><td>220</td><td>353</td><td>114</td><td>176</td></tr>
<tr><td>1218 / 108-684</td><td>7.5G</td><td>'5G'</td><td>305</td><td>400+</td><td>154</td><td>216</td></tr>
<tr><td colspan="2">10G PON</td><td>7.5G</td><td>7.5G</td><td colspan="2">128</td><td colspan="2">64</td></tr>
</table>

With the ESD options, an operator can choose how symmetric or asymmetric to make their system. For this analysis, the service tiers were maximized at the expense of SG size. This is yet another trade-off the operator can make. Note – by reducing max DS tiers, the ESD SG size can be significantly increased as our case study showed.

With the asymmetric 204 MHz split, the operator could offer a 12 Gbps DS tier, far eclipsing the 7.5G DS tier with 10G PON. This system is roughly 10:1 DS:US ratio as a 1.25 Gbps US tier pairs with it. Even with DS Tavg = 15 Mbps, the SG size is still a reasonable 173 subs at 4096-QAM.

The most symmetric ESD option is the 684 MHz split. This can achieve 7.5G DS with '5G' US, but SG sizes start to get squeezed.

The middle of the road 1794/396 MHz ESD case study previously considered can be optimized a bit further. Going with smaller SG, improving HFC plant for even better QAM modulations and eliminating the managed IPTV service can buy enough capacity to push the DS tier to a true 10 Gbps. This is paired with a 2.5 Gbps US tier. If an operator can't make these improvements, they could drop to a 300 MHz split to still get the true 10 Gbps, but now the US tier is reduced to '2G' (i.e., 2 x 940 Mbps).
In the FDX camp, a 1002 MHz system can support up to 6G DS with a '5G' US with reasonably large SG sizes. If the operator pushes this plant up to a true 1218 MHz system, then the DS tier goes up to match 10G PON at 7.5 Gbps DS tier.

6. Conclusion

The CommScope (formerly ARRIS) team has led industry traffic engineering research for over a decade. [CLO_2014] introduced broadband QoE using a simple formula with basic network capacity components. This evolved and [ULM_2019] gave an updated insight into calculating the SG capacity requirements:

Modified "COMMSCOPE/CLOONAN'S CAPACITY EQUATION" Traffic Eng Formula:

$$C \geq (Nsub * Tavg) + (K-1) * Tmax\_max + Tmax\_max \qquad (2)$$

The subtle change is that there are now three main components to the traffic engineering formula:

1. Peak Busy Period Average Consumption (i.e., Nsub * Tavg)
2. Peak Busy Period Ripple for managing QoE (i.e. (K-1) * Tmax_max)
3. Headroom for maximum Service Tier Burst (i.e., 1 * Tmax_max)

While burst and ripple components manage a subscriber's QoE, the consumption component is key to SG sizing. The Tavg growth rate has seen much research and is the focus of this paper. ARRIS/CommScope has the most extensive broadband capacity monitoring history in the industry, collecting continuously since 2010 from the same MSOs. The 2022 data is in and DS Tavg growth continues to slow.

The paper looks at the consumption growth so operators can drive their network investment strategies for coming decades. Has Tavg growth slowed to a lower CAGR or is it no longer exponential? Several possible growth trendlines were investigated including exponential, linear, Adoption S-curve and others. Our research measures how accurately each trendline matches last decade's data. These BW growth trajectories are mapped out for 5/10/15 years. The resultant spaghetti plots in Figure 53 show a cone of uncertainty that grows over time, roughly doubling every 5 yrs. To understand the impact of these slowing growth rates, consider the following comparison to projections from just four years ago:

- 2018 DS Growth (43% CAGR) projection => DS Tavg = 100 Mbps/sub **by 2030**
- 2022 DS High Growth (21% CAGR) projection => DS Tavg = 100 Mbps/sub **by 2040**
- 2022 DS Low Growth (Linear) projection => DS Tavg = 100 Mbps/sub **in 200+ years**

The implication is that *the need for FTTP to all subscribers may be pushed back multiple decades*. From a network capacity planning perspective, our conclusions on multiple growth trendline options are:

- the 5-year window provides a reasonably high confidence for near-term planning
- 10-yr window provides high, moderate, and slow growth ranges for longer term planning
- the 15-yr window shows too much variance and is more of an academic exercise.

The CommScope network capacity model studies raise several key points. The 1218 MHz case study shows a 500HP node with 2x2 RMD and 150+ subs/SG upgraded to 1218/204 MHz supports 5G x 1G service tier for the next decade and beyond. This may work for markets where there is limited demand or need for multi-gig upload speeds. The 1794/396 MHz case study in Figure 54 shows that a node with 150+ subs can offer 7.5G x 2.5G tiers; but the timing of additional node splits on the ESD plant is sensitive to which DS Tavg growth trendline it tracks. In either case, there is no pressing need to push the HFC to very small (but inefficient!) N+0 SG sizes.

Operators need to consider the low/medium/high growth scenarios when formulating their network migration strategy. A companion paper to this, [ZORAN_2022], looks at the economic impacts of these different growth scenarios for different cable and FTTP architectures. The goal is to minimize up front investments while maintaining flexibility to increase network capacity and manage uncertainty risks.

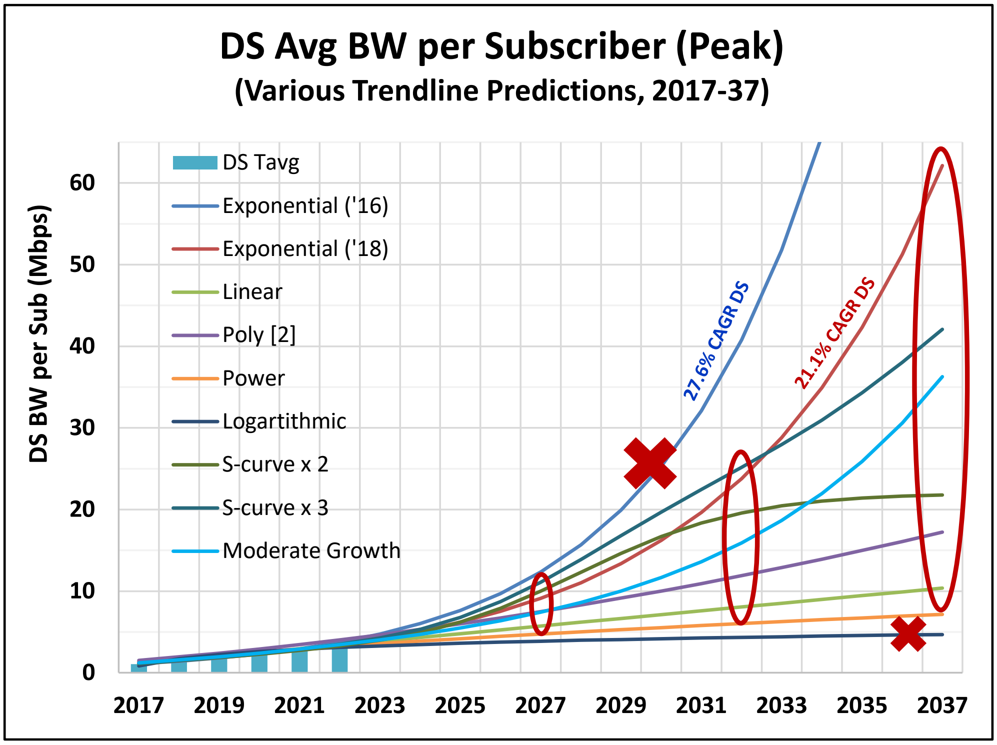


Figure 53 – DS Tavg Growth Projections for 2022 to 2037

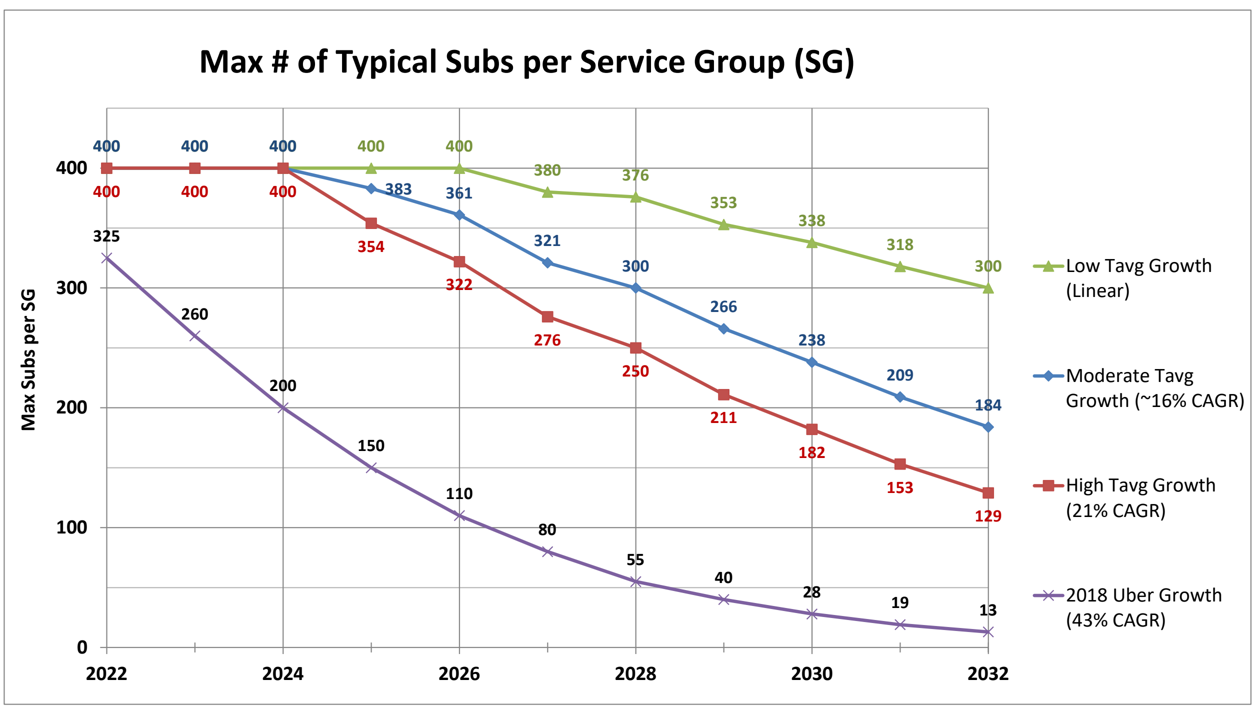


Figure 54 – Max Subs per SG for Low, Moderate & High DS Tavg growth, 1794/396 MHz

Abbreviations

AC	alternating current
BW	Bandwidth
CAGR	compounded annual growth rate
CCAP	Converged Cable Access Platform
CDF	cumulative distribution function
CM	cable modem
CMTS	Cable Modem Termination System
CP	cyclic prefix
CPE	consumer premises equipment
D3.1	Data Over Cable Service Interface Specification 3.1
D4.0	Data Over Cable Service Interface Specification 4.0
DAA	distributed access architecture
DC	direct current
DOCSIS	Data Over Cable Service Interface Specification
DS	downstream
EIA	electronic industries association
EOL	end of line
EPON	Ethernet Passive Optical Network (aka GE-PON)
ESD	extended spectrum DOCSIS
FDX	full duplex (i.e. DOCSIS)
FFT	fast fourier transformation
FTTH	fiber to the home
FTTP	fiber to the premise
Gbps	gigabit per second
GHz	gigahertz
HFC	hybrid fiber-coax
HSD	high speed data
HP	homes passed
HW	hardware
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunication Union
K	QoE constant
MAC	media access control
MB	multi-port bridger
Mbps	megabit per second
MHz	megahertz
MSO	multiple system operator
N+0	node+0 actives
NCTA	The Internet & Television Association
Nsub	number of subscribers
OFDM	orthogonal frequency-division multiplexing
OFDMA	orthogonal frequency-division multiple access
PDF	probability distribution functions
PHY	physical interface
PON	passive optical network

QAM	quadrature amplitude modulation
QoE	quality of experience
SC-QAM	single carrier QAM
SG	service group
SCTE	Society of Cable Telecommunications Engineers
SLA	service level agreement
Tavg	average bandwidth per subscriber
Tmax	maximum sustained traffic rate – DOCSIS Service Flow parameter
TX	transmit
UHD	ultra high definition
US	upstream
VOD	video on demand
VR/AR	virtual reality / augmented reality
YoY	year over year

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