WHITE PAPER

How a Flexible Upstream Architecture in Amplifiers & Nodes Can Meet Higher Split Requirements

Introduction

The broadband hybrid fiber coax (HFC) network has had unprecedented increase in demand since March of 2021. Internet traffic has increased 25% to 45% around the world over this time. Multiple system operators (MSOs) around the globe are evaluating the latest DOCSIS® specifications to upgrade their current networks to meet this increased demand.

Currently, the weakest link in most HFC networks is the upstream capability. DOCSIS 3.1 and DOCSIS 4.0 will help MSOs improve the upstream capacity and speed. One of the benefits of DOCSIS 3.1 and DOCSIS 4.0 is the provision for higher upstream frequency splits, providing greater bandwidth and higher capacity in the HFC network.

This paper focuses on the upstream architecture inside the amplifiers and nodes for these higher frequency splits, and how Qorvo® products can help network equipment manufacturers provide a flexible network architecture to meet all the MSO's needs.

Current Upstream Capacity and Expansion

Demand for streaming content, video conferencing, etc., has accelerated the push to look beyond the capacity of legacy 5-42 MHz and 5-85 MHz upstream splits. DOCSIS 3.1 currently provides for a "high split" of 204 MHz and adds the capability to use up to 96 MHz wide orthogonal frequency division multiple access (OFDMA). OFDM is employed for downstream as a single-user broadcast channel from the cable plant while OFDMA is a "multiple access" format for upstream that allows multiple customers to share a channel using a time-division multiple access format (TDMA).

OFDM forms a channel out of multiple orthogonally spaced QAM (quadrature amplitude modulation) sub-carriers with narrow bandwidths and orders as high as 4096 QAM for OFDM and 1024 QAM for OFDMA (higher orders of QAM are optional). OFDM has a higher payload capacity versus 256 QAM over a comparable bandwidth. It is also able to dynamically adapt to current channel conditions by increasing or reducing the modulation order of each subcarrier to maintain signal integrity with best possible capacity.

Extended spectrum DOCSIS (ESD, DOCSIS 4.0) and full duplex (FDX) are new standards working to accomplish the goal of extending carrying capacities for both downstream and upstream. Both standards have the option to extend the maximum usable bandwidth of the upstream amplifiers as high as 684 MHz.

Figure 1 shows the primary proposed upstream frequency plans for ESD, while Figure 2 shows the proposed frequency plans for FDX.

Figure 1. DOCSIS 4.0 ESD spectrum and splits between upstream (US) and downstream (DS).

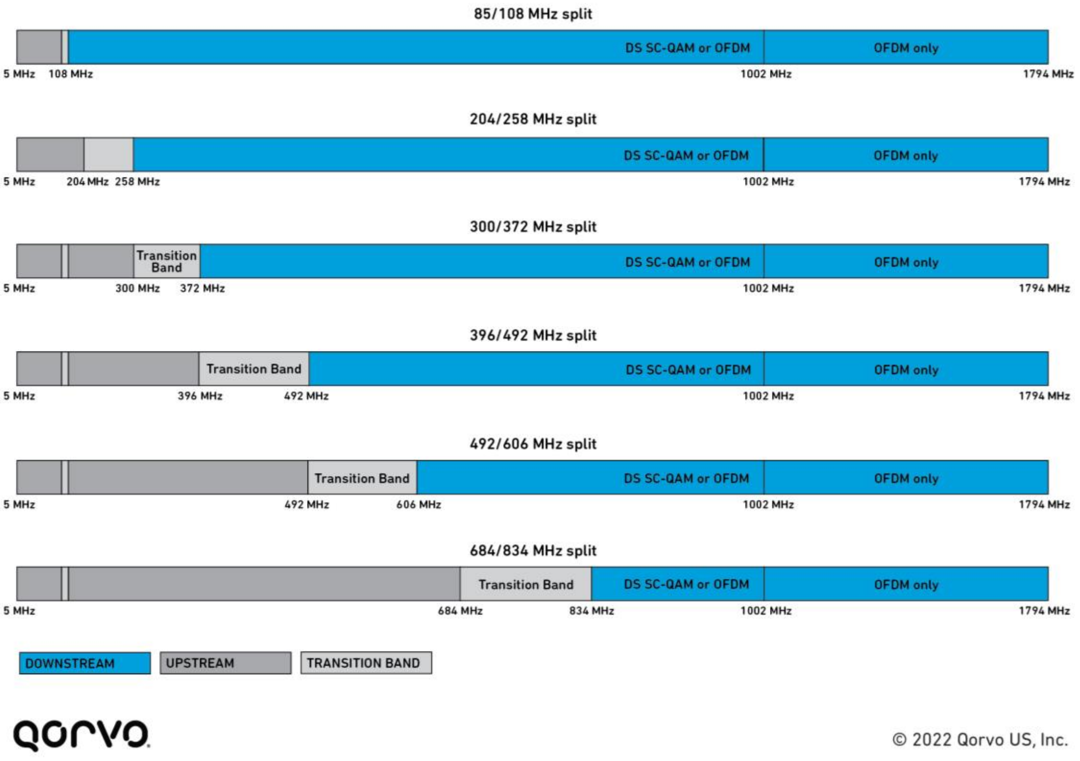
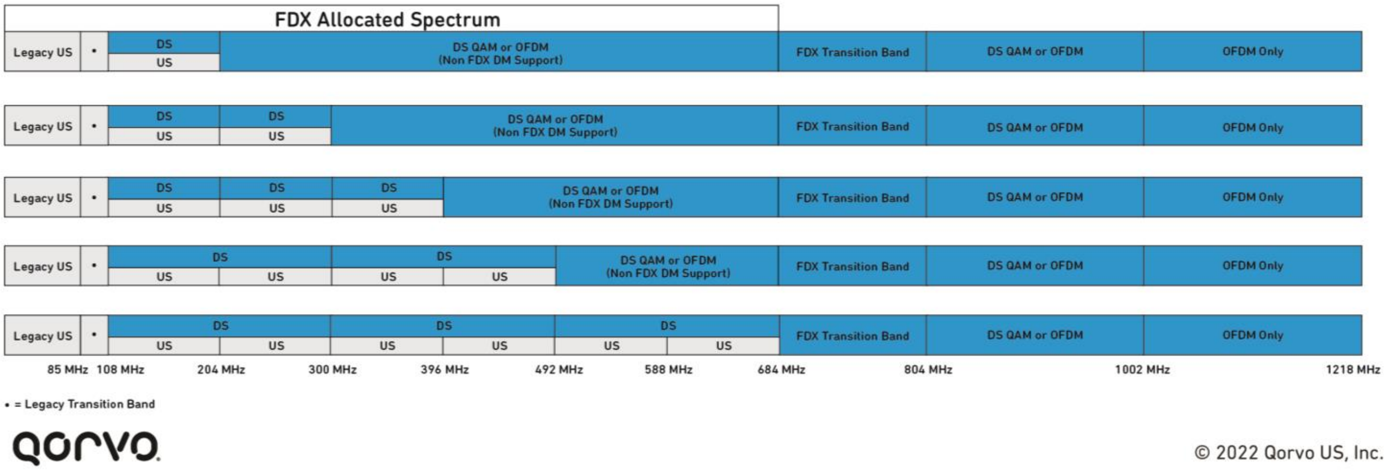


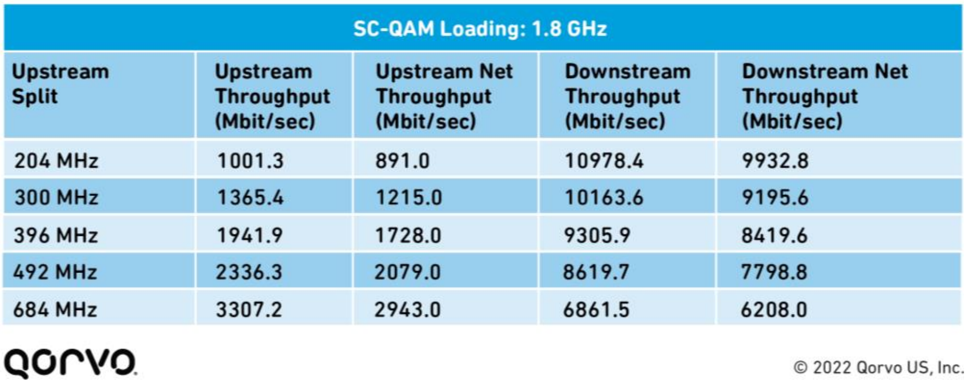
Figure 2. DOCSIS 4.0 FDX spectrum for upstream (US) and downstream (DS).



As the bandwidths of the upstream plans increase, the performance of the upstream amplifier MMICs correspondingly increases. We need to consider the total composite signal level requirements, losses and tilt levels, which becomes more of an issue as the bandwidth increases and tilt increases.

Full duplex can more readily rely on bandwidths up to 684 MHz in the upstream since the architecture utilizes simultaneous operation in both the upstream and downstream within the same bandwidth, while extended spectrum DOCSIS, being a frequency division duplexing scheme (FDD) is compelled to balance bandwidth requirements between upstream and downstream. It may be intuitive from Figure 1 that increasing upstream bandwidth reduces bandwidth available for the downstream path, but in Figure 3 we can see a more direct impact on actual throughputs using existing SC-QAM data rates versus the new 1.8 GHz ESD splits.

Figure 3. Impact of SC-QAM data throughput versus increasing upstream bandwidth.



SC-QAM Loading: 1.8 GHz

Upstream Split	Upstream Throughput (Mbit/sec)	Upstream Net Throughput (Mbit/sec)	Downstream Throughput (Mbit/sec)	Downstream Net Throughput (Mbit/sec)
204 MHz	1001.3	891.0	10978.4	9932.8
300 MHz	1365.4	1215.0	10163.6	9195.6
396 MHz	1941.9	1728.0	9305.9	8419.6
492 MHz	2336.3	2079.0	8619.7	7798.8
684 MHz	3307.2	2943.0	6861.5	6208.0

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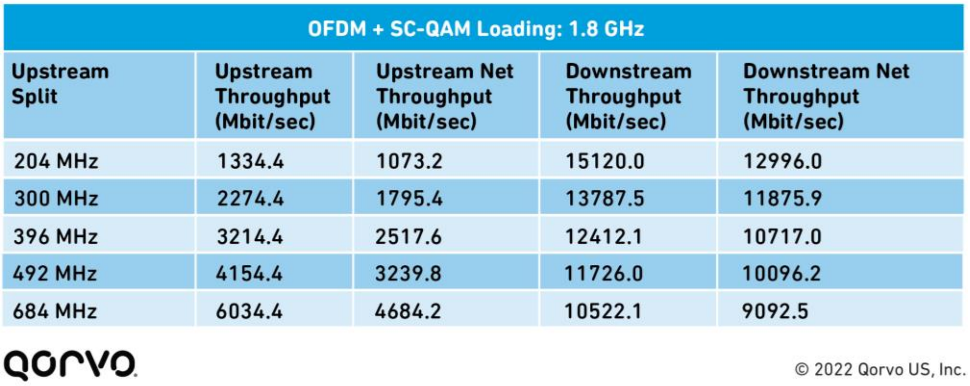
If we explore the possibility of adding as many OFDM and OFDMA channels as the upstream and downstream band plans will allow (Figure 4), we can see that adding OFDM does add data capacity, but the bandwidth tradeoff still works to push operators away from maximum upstream bandwidths and more toward splits such as 204 and 396 MHz, where they can advertise 1 and 2 Gbit upstream service and still achieve 10 Gbit downstream rates.

Figure 4. Improving data throughput versus upstream bandwidths by employing OFDM.



OFDM + SC-QAM Loading: 1.8 GHz

Upstream Split	Upstream Throughput (Mbit/sec)	Upstream Net Throughput (Mbit/sec)	Downstream Throughput (Mbit/sec)	Downstream Net Throughput (Mbit/sec)
204 MHz	1334.4	1073.2	15120.0	12996.0
300 MHz	2274.4	1795.4	13787.5	11875.9
396 MHz	3214.4	2517.6	12412.1	10717.0
492 MHz	4154.4	3239.8	11726.0	10096.2
684 MHz	6034.4	4684.2	10522.1	9092.5

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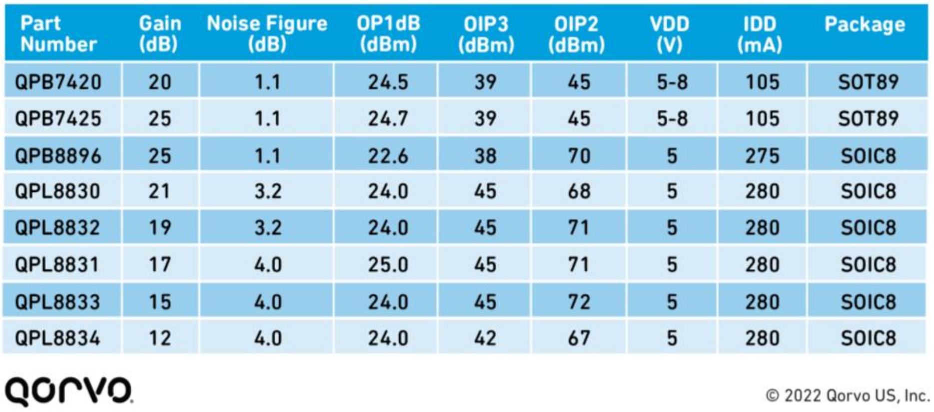
Qorvo Upstream Solutions

Legacy D3.0 upstream applications could make use of narrower bandwidth MMICs or transistors for their applications where the target bandwidths were 42 MHz or 85 MHz. MMICs for the evolving DOCSIS 4.0 markets need to be able to provide the full bandwidth up to 684 MHz to meet FDX requirements and to allow options for extended spectrum applications.

Qorvo's solution is a building block approach – consisting of small form factor, low power consumption amplifiers plus attenuators, equalizers and switches – that allows customers to put the devices where needed in their end application. Qorvo's amplifier lineup for this challenging new market is shown in Figure 5.

Figure 5. Qorvo's solutions for a building block approach.



Part Number	Gain (dB)	Noise Figure (dB)	OP1dB (dBm)	OIP3 (dBm)	OIP2 (dBm)	VDD (V)	IDD (mA)	Package
QPB7420	20	1.1	24.5	39	45	5-8	105	SOT89
QPB7425	25	1.1	24.7	39	45	5-8	105	SOT89
QPB8896	25	1.1	22.6	38	70	5	275	SOIC8
QPL8830	21	3.2	24.0	45	68	5	280	SOIC8
QPL8832	19	3.2	24.0	45	71	5	280	SOIC8
QPL8831	17	4.0	25.0	45	71	5	280	SOIC8
QPL8833	15	4.0	24.0	45	72	5	280	SOIC8
QPL8834	12	4.0	24.0	42	67	5	280	SOIC8

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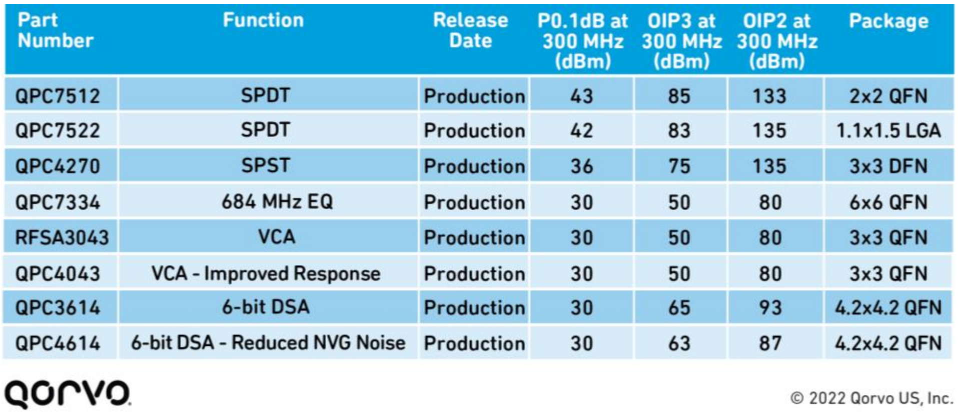
Qorvo has a family of devices, some with very low noise figure, that make excellent driver ICs that can cover this full bandwidth. All of the SOIC8 ICs are pin for pin compatible with gain ranging 12 dB to 25 dB capable of working with all of the available splits out to 684 MHz. With the same pinouts, you can mix and match desired gain, output power, linearity and NPR to match the requirements for all upstream application from 5 MHz to 684 MHz.

In addition to amplifier MMICs, Qorvo offers control products for the upstream designer as shown in Figure 6.

Figure 6. Qorvo control products for upstream designs.



Part Number	Function	Release Date	P0.1dB at 300 MHz (dBm)	OIP3 at 300 MHz (dBm)	OIP2 at 300 MHz (dBm)	Package
QPC7512	SPDT	Production	43	85	133	2x2 QFN
QPC7522	SPDT	Production	42	83	135	1.1x1.5 LGA
QPC4270	SPST	Production	36	75	135	3x3 DFN
QPC7334	684 MHz EQ	Production	30	50	80	6x6 QFN
RFSA3043	VCA	Production	30	50	80	3x3 QFN
QPC4043	VCA - Improved Response	Production	30	50	80	3x3 QFN
QPC3614	6-bit DSA	Production	30	65	93	4.2x4.2 QFN
QPC4614	6-bit DSA - Reduced NVG Noise	Production	30	63	87	4.2x4.2 QFN

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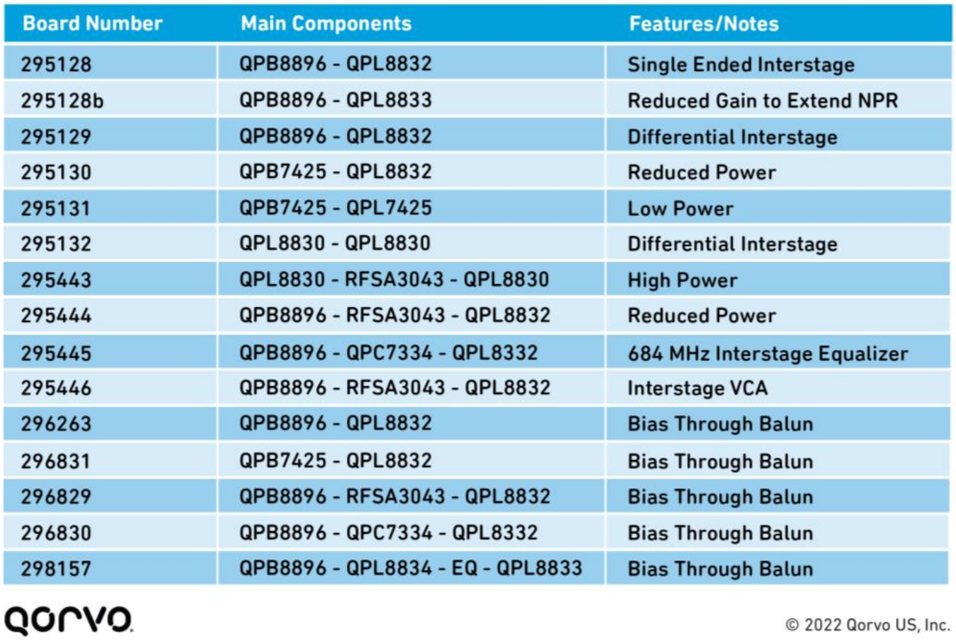
Qorvo offers a family of SPDT and SPST switches in the upstream band that offer excellent performance in the upstream band. Qorvo also has a family of voltage-controlled attenuators and digital-step attenuators. All are 75 ohms with up to 31 dB range of attenuation. QPC4043 employs a new, closed-loop architecture that more tightly controls the attenuation response versus voltage, temperature and lot, reducing calibration complexity. Return loss is also more tightly controlled as a result, making predictable behavior between amplifiers or within an equalizer circuit more advantageous to designers. QPC4614 has an enhanced, internal, negative voltage generator to reduce internally generated spurs in the low frequency regions. QPC7334 is a voltage variable equalizer providing a linear tilt from 5 MHz to 684 MHz.

Qorvo Upstream Reference Designs

Using the above building blocks, Qorvo has developed several reference boards to be able to test various lineups against the new splits and signal requirements. The following table is a list of upstream reference boards in development. These boards are intended to demonstrate the various capabilities and options available.

Figure 7. Qorvo reference boards with various capabilities for flexible design options.



Board Number	Main Components	Features/Notes
295128	QPB8896 - QPL8832	Single Ended Interstage
295128b	QPB8896 - QPL8833	Reduced Gain to Extend NPR
295129	QPB8896 - QPL8832	Differential Interstage
295130	QPB7425 - QPL8832	Reduced Power
295131	QPB7425 - QPL7425	Low Power
295132	QPL8830 - QPL8830	Differential Interstage
295443	QPL8830 - RFSA3043 - QPL8830	High Power
295444	QPB8896 - RFSA3043 - QPL8832	Reduced Power
295445	QPB8896 - QPC7334 - QPL8332	684 MHz Interstage Equalizer
295446	QPB8896 - RFSA3043 - QPL8832	Interstage VCA
296263	QPB8896 - QPL8832	Bias Through Balun
296831	QPB7425 - QPL8832	Bias Through Balun
296829	QPB8896 - RFSA3043 - QPL8832	Bias Through Balun
296830	QPB8896 - QPC7334 - QPL8332	Bias Through Balun
298157	QPB8896 - QPL8834 - EQ - QPL8833	Bias Through Balun

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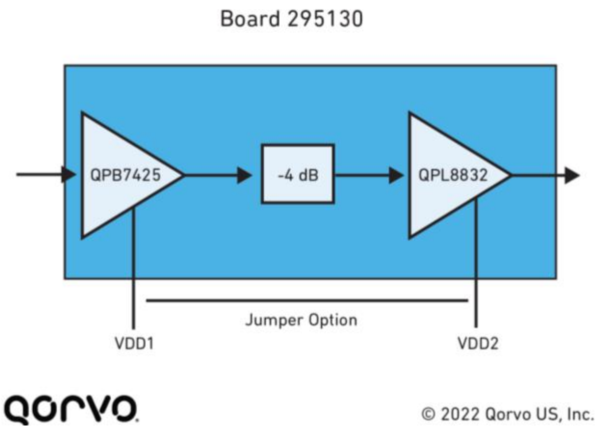
295128 with Single-Ended Interstage

The QPB8896-QPL8832 on Reference Board 295128, in the block diagram below, is one example of a flexible design meant to address the extended spectrum upstream environment.



This first stage QPB8896 driver features 25 dB of gain while the output stage, QPL8832 has 19 dB. A 4 dB pad is implemented between the stages to approximate the losses that might be seen in an application, such as automatic level and slope control (ALSC), thermal tracking or equalization. This provides a total gain of 44 dB with a usable gain of 40 dB. Gain can be fine-tuned on the board or changed in larger steps by changing the output device.

The flexibility of the power supplies allows the user to tie them together, or they can be separated to allow the output stage to be run from a higher bias voltage to increase output capability.

Bias Flexibility

By utilizing the bias flexibility of the QPL883x family of parts, the QPL8832 can be re-biased if more output capacity is needed for the higher splits. As device current (IDD) is increased, a modest increase is realized in linearity and output capacity, but as the device voltage (VDD) is increased, a more substantial improvement is realized due to the larger impact to IP2 and IP3. The linearizer current of QPL883x is also optimized for a given operating condition to provide a small amount of fixed predistortion at the RF inputs and further optimize the MER. The optimal linearizer current is dependent on VDD, IDD and the load conditions (refer to the relevant datasheet for further details). This allows devices in the QPL883x family to be optimized for a wide variety of load and supply conditions.

Noise Power Radio

Noise power ratio (NPR) as defined in ANSI/SCTE 119 2018, is tested by injecting broadband noise into an amplifier and notching out a measurement channel, typically in the center of the test bandwidth. The injected broadband noise is the “signal power,” while the energy in the notched channel is the “noise power” and is the combination of noise and intermodulation products produced by the amplifier being tested. NPR is expressed as the ratio of the signal power density of the total signal bandwidth to the noise power density within the notch. If NPR is taken at various power levels, a curve can be plotted that shows the dynamic range of the device being tested. This curve allows a designer to determine the signal capacity for a device or system over a given bandwidth.

NPR is tested at Qorvo using an Applied Instruments NPRT 2200 test system, which is an automated test set with bandwidths of 42, 85, 204 and 300 MHz. Manual systems can be constructed using wideband noise generators and external passband and notch filters as described in ANSI/SCTE 119 2018. There are also existing older downstream systems from Noise Com that may be adaptable to upstream use given some filter work by resourceful engineers. Arbitrary waveform-based systems evaluated previously can only reach a peak NPR in the mid 40s unless external filtering is added.

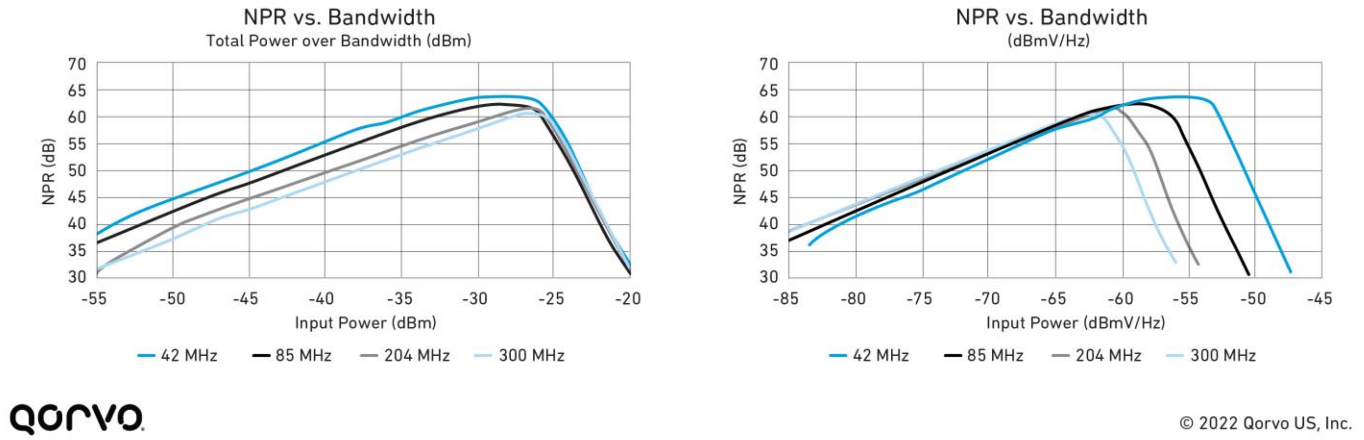
Figure 8 shows the effect of testing NPR versus input power with various bandwidths, while using differing power terms. Both plots were taken by testing the 8896-8832 reference board (295128) versus the available bandwidths in the NPRT 2200 system. The plot on the left is shown with input power expressed as total power over bandwidth (dBm), while the plot on the right dereferences the bandwidth by expressing power in dBmV/Hz.

For the curves expressed in dBm, since the power is expressed as total power over bandwidth, the compression side of the curve remains unchanged as the bandwidth is increased from 42 MHz to 300 MHz. The noise side of the curve is impacted by the increasing noise bandwidth.

The plot on the right has the power axis expressed in dBmV/Hz, which changes the x axis reference from total bandwidth to a “per Hz” power density. Now, the noise curves have shifted to overlay each other and the compression curves “fan out.” Plots in dBmV/Hz are more convenient for designers in estimating channel capacity (and in keeping with the SCTE “power density” definition), while plots in dBm can be convenient for showing MMIC compression characteristics independent of bandwidth.

NPR dynamic range for a cascade design can be manipulated by adjusting loss in front of the driver IC, adjusting losses before the output stage, and setting the overall gain by selecting the QPL883x output stage that best fits the overall gain budget.

Figure 8. Plotting NPR versus power density or absolute power using multiple bandwidths.



NPR vs. Bandwidth
Total Power over Bandwidth (dBm)

NPR vs. Bandwidth
(dBmV/Hz)

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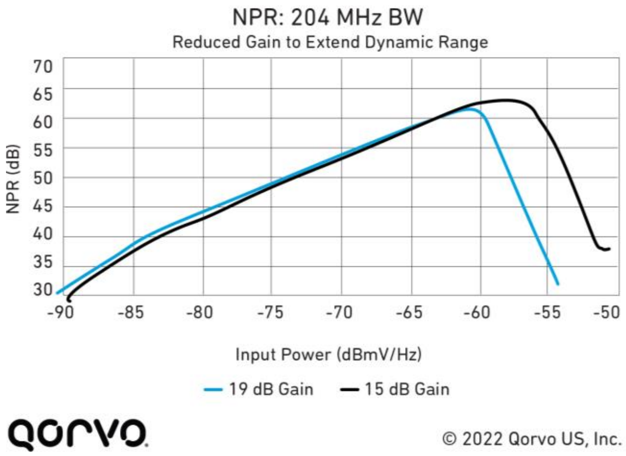
Figure 9 shows the result of changing the output stage to reduce the gain of the output stage from 19 dB to 15 dB. In this test, the bandwidth was 204 MHz for both sweeps, so the left side of both NPR curves remain unchanged, being set by the noise bandwidth of the system. Reducing the gain has the effect of extending the compression side of the NPR curve, which extends the overall dynamic range. The compression side of the curve can also be extended by raising the output voltage and current of the output stage, or by adjusting the loss between the stages to reduce the signal level reaching the final stage, assuming the signal is not noise limited by the added losses.

Figure 9. Effect on NPR dynamic range of changing the output gain stage.

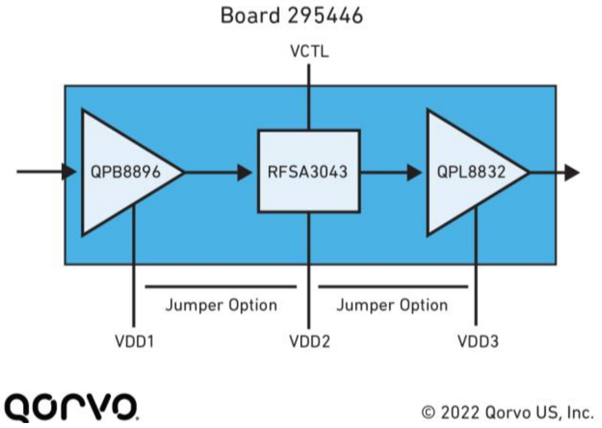


Device Flexibility

The QPL883x family offers the flexibility to swap devices due to pin for pin compatibility. This allows the user to change the overall system gain by changing the output device by utilizing any QPL883x device with gains of 12, 15, 17, 19 and 21 dB.

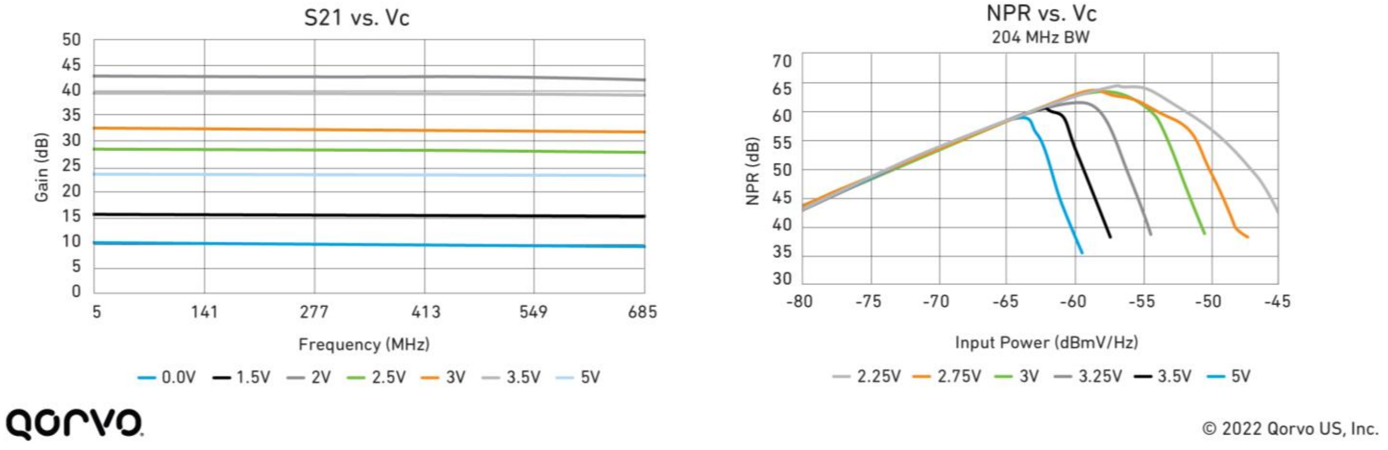
Board 295446: Utilizing an Interstage Voltage Controlled Attenuator

The effect of changing the amount of attenuation between the stages can be seen in the following reference design using the QPB8896, RFSA3043 and QPL8832.



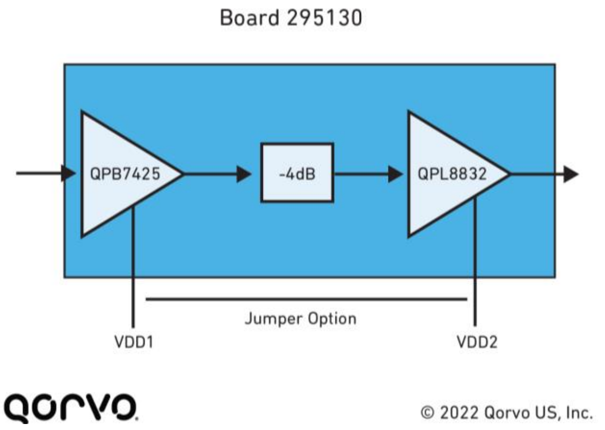
The S21 versus VC plot in Figure 10 shows the gain increasing as the control voltage to RSA3043 increases from 0V to 5V and its attenuations approaches 0dB. The NPR versus VC plot shows that, as the RFSA3043 attenuation decreases, the compression side of the NPR curve shifts to the left as higher signal levels are applied to the output stage.

Figure 10. Effect on NPR dynamic range of varying interstage attenuation.



Reduced Power Consumption Option

Board 295130, shown in the block diagram below, utilizes the QPB7425 as a driver, followed by the QPL8832. QPB7425 is a single-ended device with the same noise figure performance as QPB8896, but at a reduced power consumption and a lower linearity than the differential QPB8896 (particularly OIP2). The advantage this reference design offers is reduced power consumption for designers who may not need as much output capability as the QPB8896-QPL8832 reference design (295128).

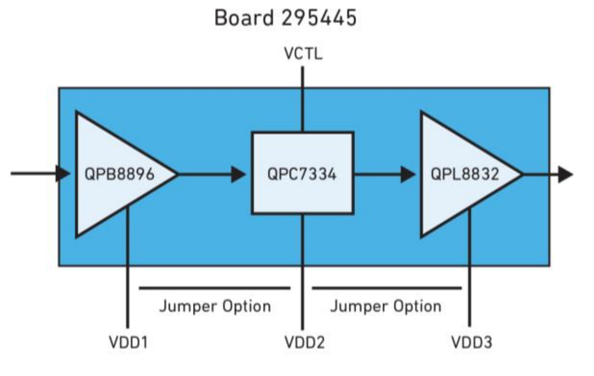


To better handle signal requirements for DOCSIS 4.0, the QPB7425 bias current is increased by adding a 150K pullup resistor from the input to VDD.

The output TCP capability is close to the QPB8896-QPL8832 version for a flat load, with some limitation from the single-ended first stage showing at the upper end. As tilt increases, these limitations become more noticeable at the lower end. This approach offers a means of delivering the same levels of gain and noise figure at a lower dissipation for designers not needing the higher linearity performance levels of the QPB8896 + QPL883x combination. QPB7425 can also be run from flexible voltage and current for designs needing to be tailored to other operating environments from 5V to 8V (refer to QPB7425 datasheet for biasing details).

Upstream Tilt

As bandwidth increases in the upstream, compensating for loss between amplifiers needs to be considered. Qorvo has an integrated linear equalizer from 5 to 684 MHz, the QPC7334, that is used in the reference board 295445. Similar to the first example, we use the QPB8896 to drive the QPC7334 equalizer and the QPL8832 output stage.



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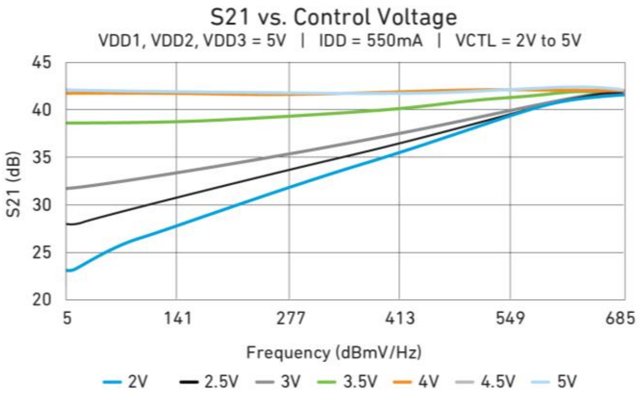
Since the QPC7334 is a 684 MHz device, the QPB8896 in this case uses a 700 MHz 1.33:1 balun with slightly higher insertion loss to improve output return loss throughout 684 MHz. This increases noise figure, which will slightly shift the NPR curve, but it provides improved output return loss when operating in 684 MHz bandwidths (see QPB8896 datasheet for details).

Figure 11. Reference board gain response versus control voltage.



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Since the tilt is applied after the QPB8896, the effect of increasing tilt is only applied to the QPL8832 output stage.

The gain of the system is not changing to accommodate the composite power loss as tilt level increases and the CNR of the lower channels is dropping toward the noise and intermod floor of the output device.

As shown earlier, the QPL883x family has the ability to operate over a wide range of currents and voltages, which will help overcome lost performance at high tilts. Increasing IDD will show some modest improvements in linearity, but the largest gain in linearity can be found by increasing VDD.

Discrete active circuits based on QPC3043, QPC4043, or fixed passive equalizers may also be employed for other splits targeting linear loss or cable loss curves.

Stability

Stability for the complete path can be checked out to 3 GHz in a 75 ohm environment, or if higher bandwidth systems are available in 50 ohms, 6 to 8 GHz should be sufficient to ensure stability for these devices.

Bandwidth Limiting

A final consideration for DOCSIS 4.0 upstream designs is providing sufficient bandwidth limiting for the upstream path to ensure the downstream and upstream paths don't interact to prevent systemic instability. Since the upstream MMICs are designed to deliver power out to 684 MHz, their gain bandwidth product will extend beyond 684 MHz, which implies good design practice will likely require low pass filtering in the upstream path in addition to the system diplexers tailored to the desired upstream split. Other tools in the designer's toolbox that can aid in increasing out of band rejection would be use of narrower bandwidth baluns on the upstream MMICs (such as a 5-200 MHz balun for a 204 MHz split) and increasing output shunt capacitance on the QPL8896 and QPL883x to roll off the out of band gain, which may require additional tuning to the output match, depending on amount of capacitance applied.

Conclusion

As the bandwidths of the upstream systems increase, the performance of the amplifier and complexity increase. Today, most upstream plants operate to 108 MHz, with some reaching 204 MHz. Future networks need to plan for capability up to 684 MHz, requiring more gain, power and tilt capability. By utilizing Qorvo's building block approach – consisting of small form factor, low power consumption amplifiers plus attenuators, equalizers and switches – customers can place devices where needed in their end application. As an added service, Qorvo can supply customized evaluation boards to allow a customer to test a solution prior to final design and implementation.

About the Author

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After earning a Bachelor of Science in Electrical Engineering from Texas A&M University in 1990, Glen worked as a designer in the microwave telecom industry at Microwave Networks in Houston, Texas. Several years later he designed satellite set top boxes and HDTV receivers for Thomson, Inc. More than a decade later, brought his expertise to Qorvo as a senior applications engineer in the Multi-Products Group. For several years now, he has applied his experience in the Broadband business primarily serving the CATV industry.

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