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VALUE OF TRANSPARENCY IN THE EVOLUTION OF HFC NETWORKS:

HOW OPTICAL TRANSPARENCY ENHANCES CAPACITY, PROMOTES INNOVATION AND PRESERVES INFRASTRUCTURE IN HFC NETWORKS

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Value of Transparency

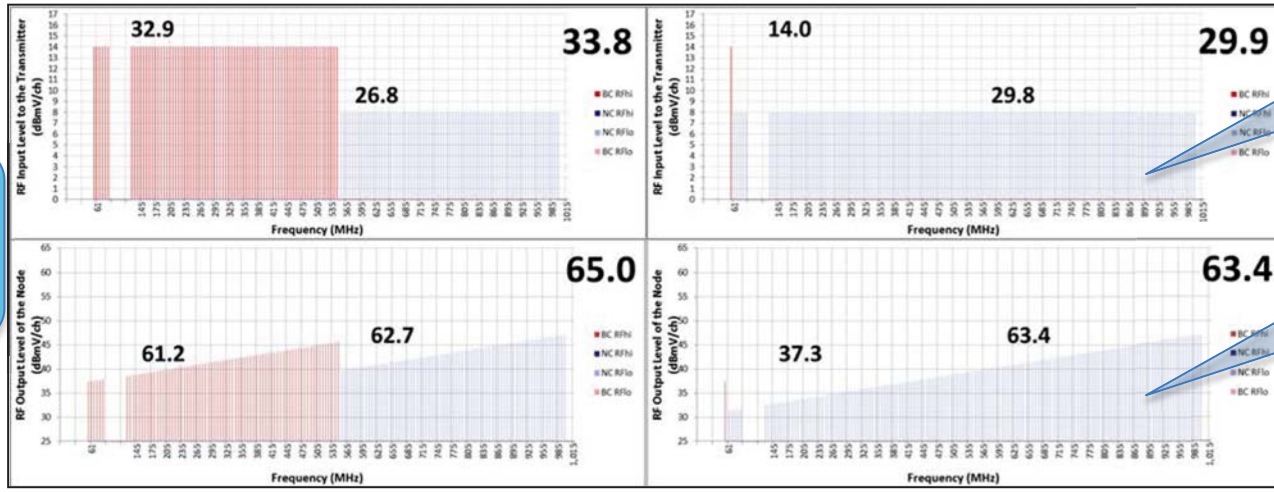
- Recent Advances in Analog Optics
- Optical Nonlinearities and the RF spectrum
- RF Levels in Transition
- Figures of Merit for the New Network
- Analog Harvesting and the Digital Dividend
- Baseband Digital Forward
- Recent Advances in 25G Optics
- DSP and Compression in BDF
- Architecture Options with Compressed Digital Forward
- Beyond D3.1: Bandwidth Upgrades and Power Consumption
- QAM Constellations in Multiple Operating Conditions
- Conclusions

Recent Advances in Analog Optics

- Effective and Efficient MWL Wavelength Plan
  - Up to 16 DS and 16 US on one fiber
  - Full Use of remaining 12 wavelengths for 10 Gbps
- “Set and Forget” Optical Links
  - Low Noise Optical AGC Receivers
  - Variable Power Transmitters
  - Redundant Optical Links without Intervention
- Cost Effective EML transmitters
  - High Performance Electro Absorption Modulator Lasers
  - C-Band Operation without External DCMs
- Enhanced Critical Infrastructure
  - Innovative Elimination of RF Splitting and Combining Networks
  - Higher Density, Lower Power Consumption

RF Levels in Transition

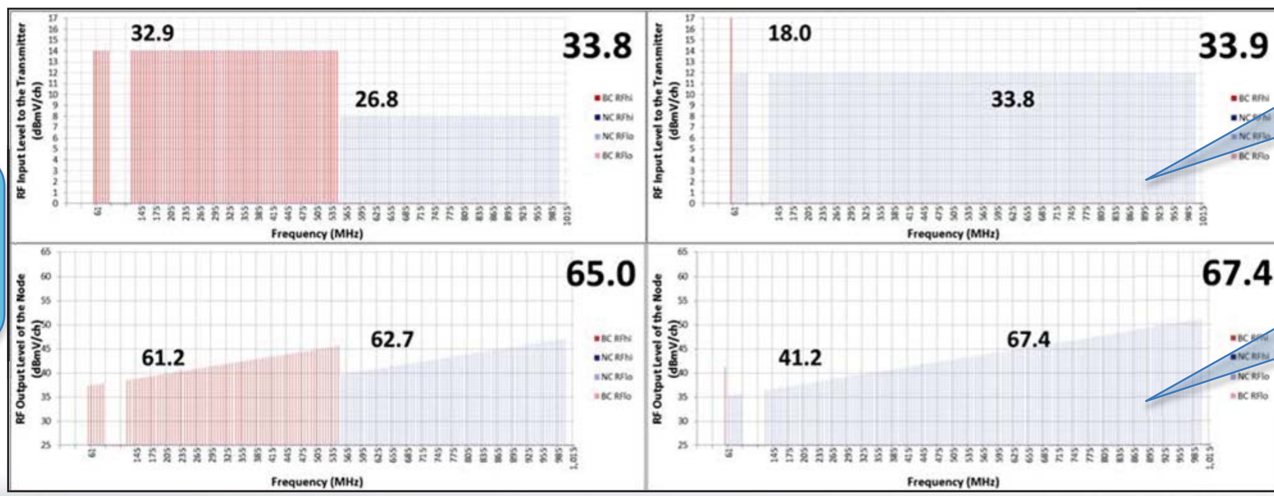
Tx MGC Mode



Total Tx RF Level is Reduced

Total Node RF Level is Reduced

Tx AGC Mode

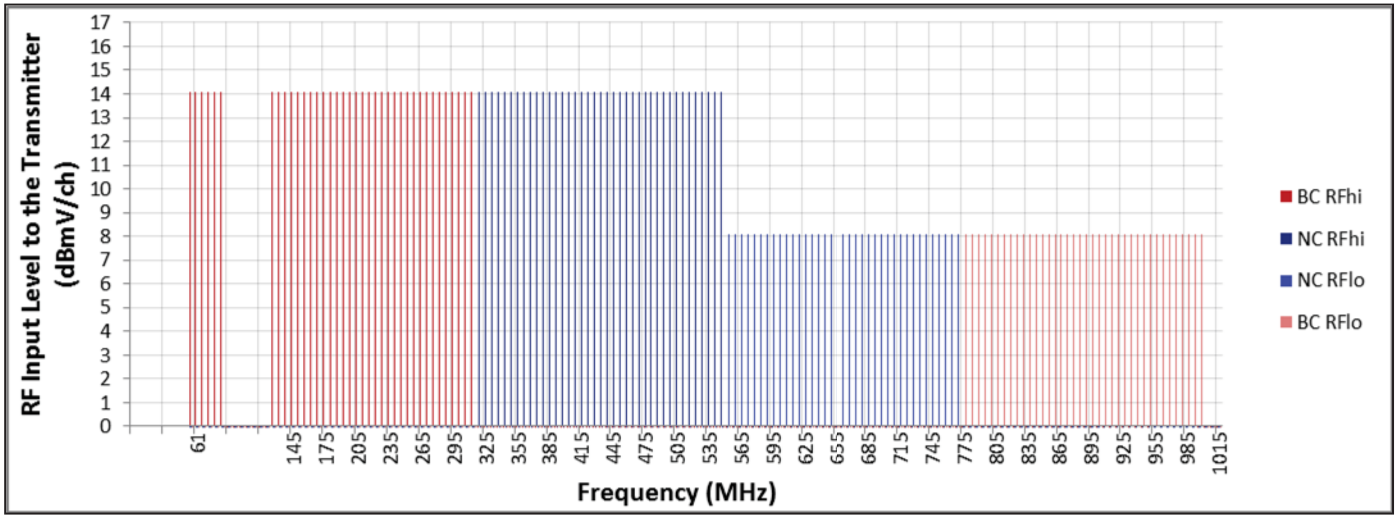


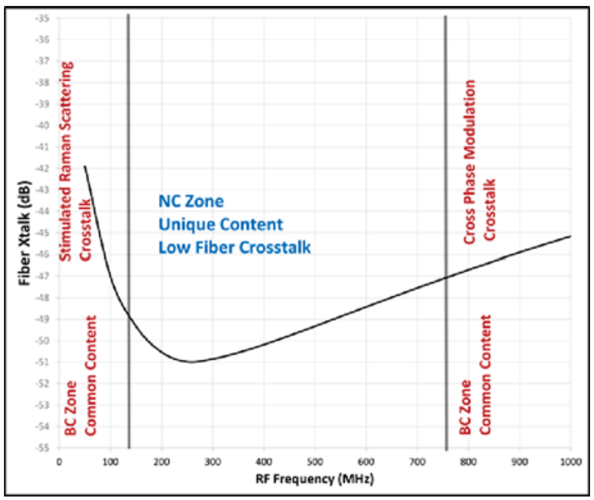
Total Tx RF Level is the Same

Total Node RF Level is Increased

Possible Compression

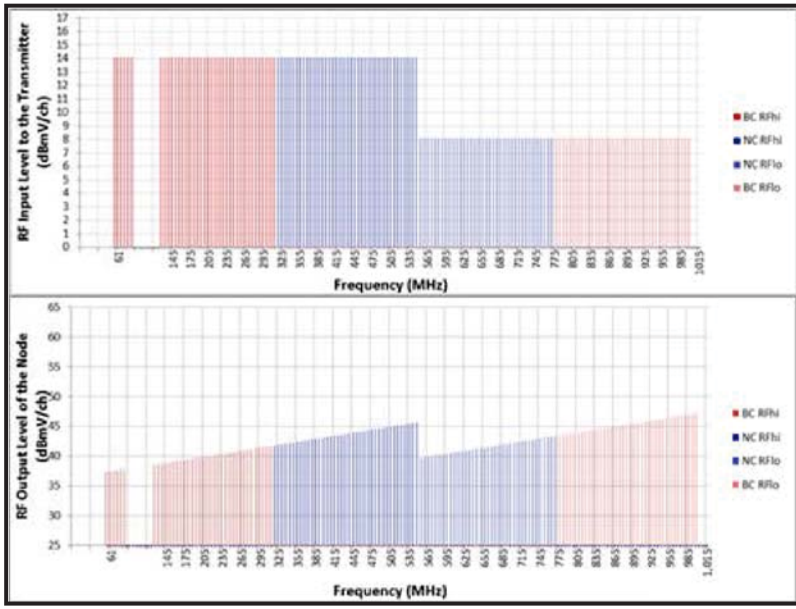
Optical Nonlinearities and The RF Spectrum





- SRS and XPM more severe at spectrum extremities
- Placing BC at extremities is helpful
- Placing NC in the Middle enhances Capacity

New Figures of Merit

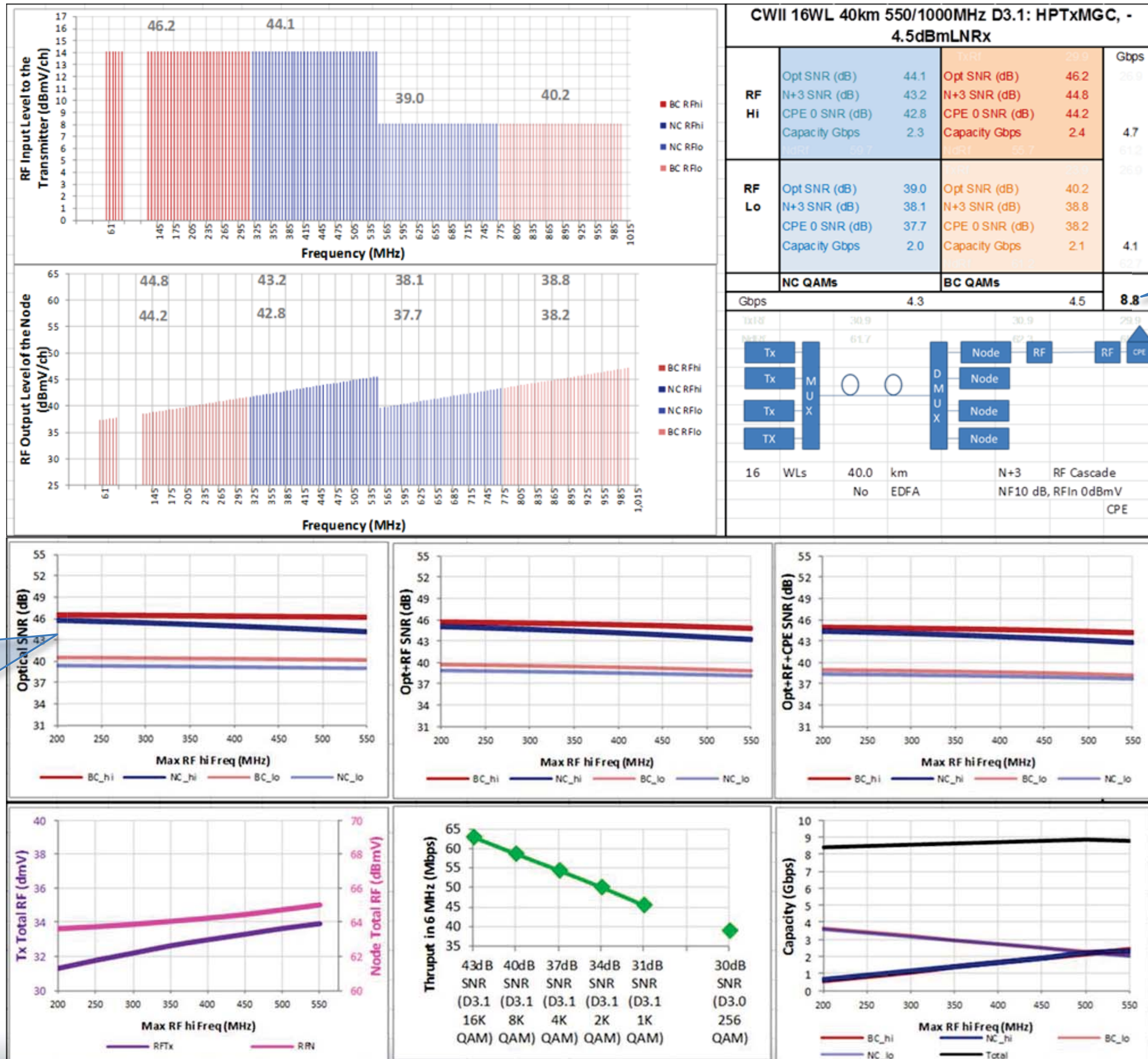


	NC QAMs	BC QAMs
RF Hi	HIGH SNR OPTICAL XTALK Present MID PERFORMANCE	HIGH SNR No OPTICAL XTALK HIGH PERFORMANCE
RF Lo	LOW SNR OPTICAL XTALK Present LOW PERFORMANCE	LOW SNR No OPTICAL XTALK MID PERFORMANCE

- **The BC RF hi zone** High SNR and no effects of Optical Crosstalk. Best Performance 8K-16KQAM
- **The NC RF hi zone** High SNR but moderate Optical crosstalk. Medium Performance 4K-8KQAM
- The BC RF lo zone Low SNR but no effects of optical crosstalk. Medium Performance 4K-8KQAM
- The NC RF lo zone Low SNR and moderately high Optical Crosstalk. Low Performance 1K-4KQAM

- **Mostly Only** NC RF Lo **is reported, causing very pessimistic Capacity estimates**

C-Band 16WL 40km D3.1

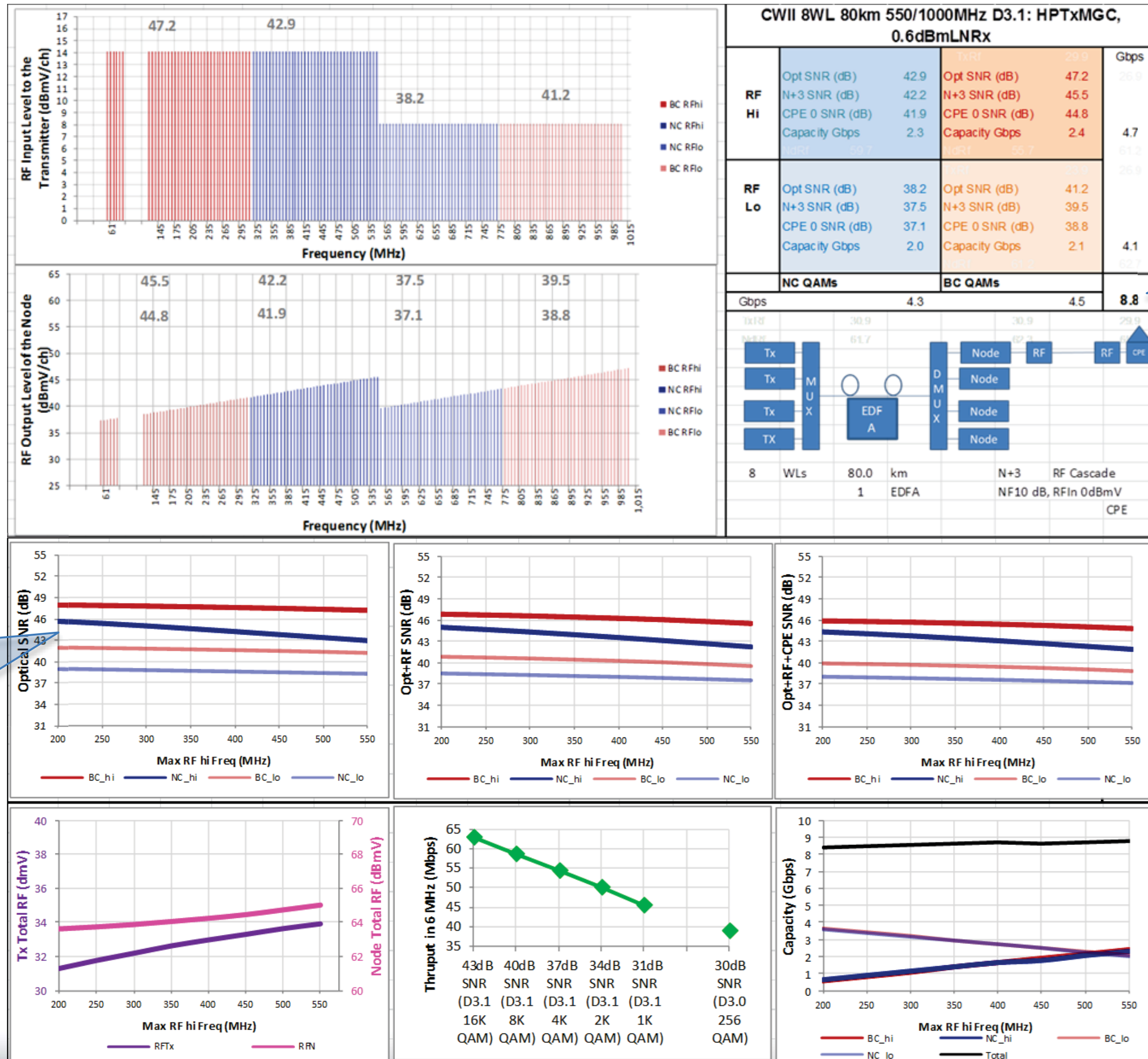


Total Capacity
8.8 Gbps/WL

140.8Gbps over one fiber

Robust Performance across the spectrum

C-Band 8 WL 80 km D3.1

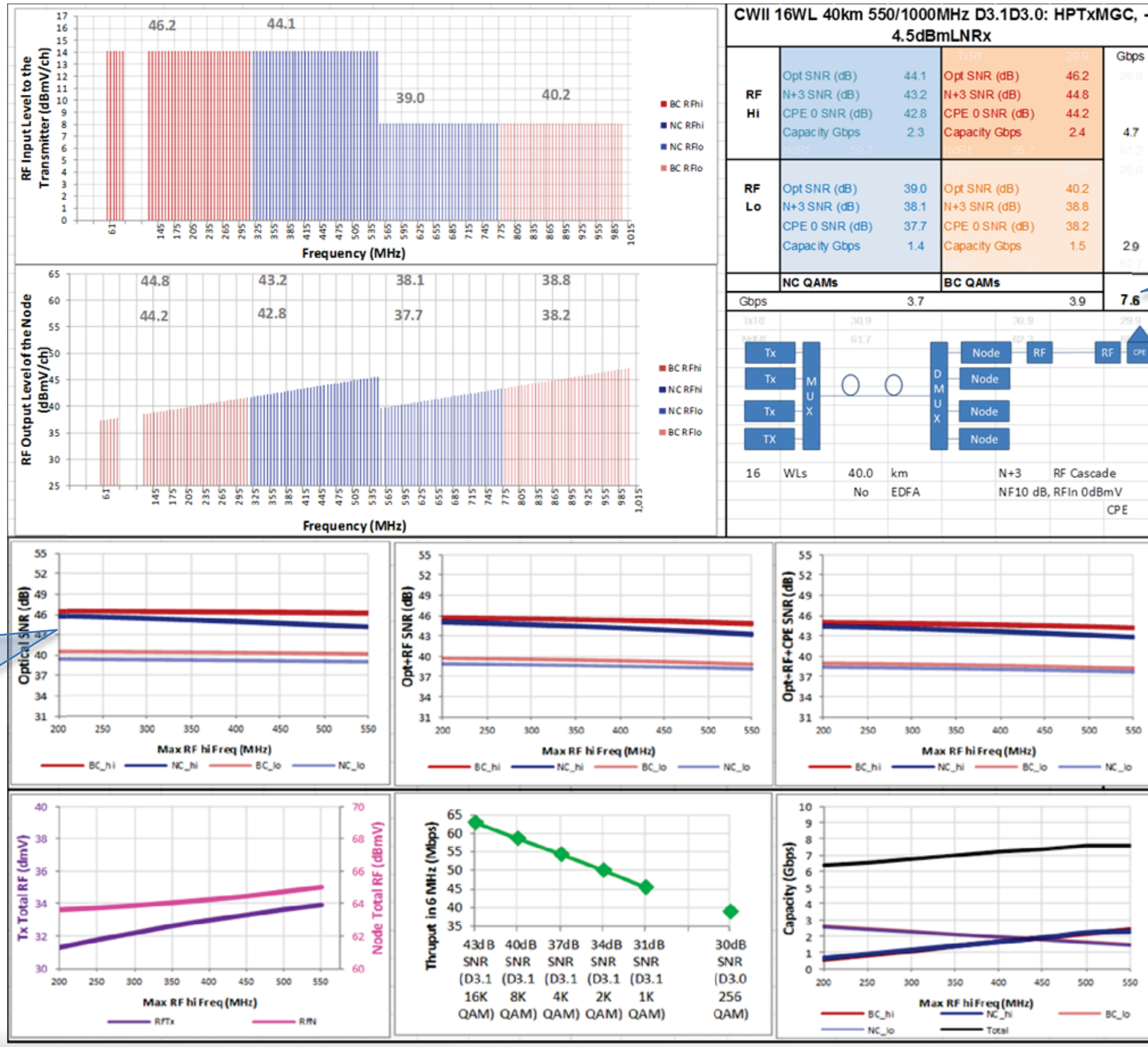


Total Capacity 8.8 Gbps/WL

70.4Gbps over one fiber

Robust Performance across the spectrum

C-Band 16 WL 40 km D3.1/D3.0

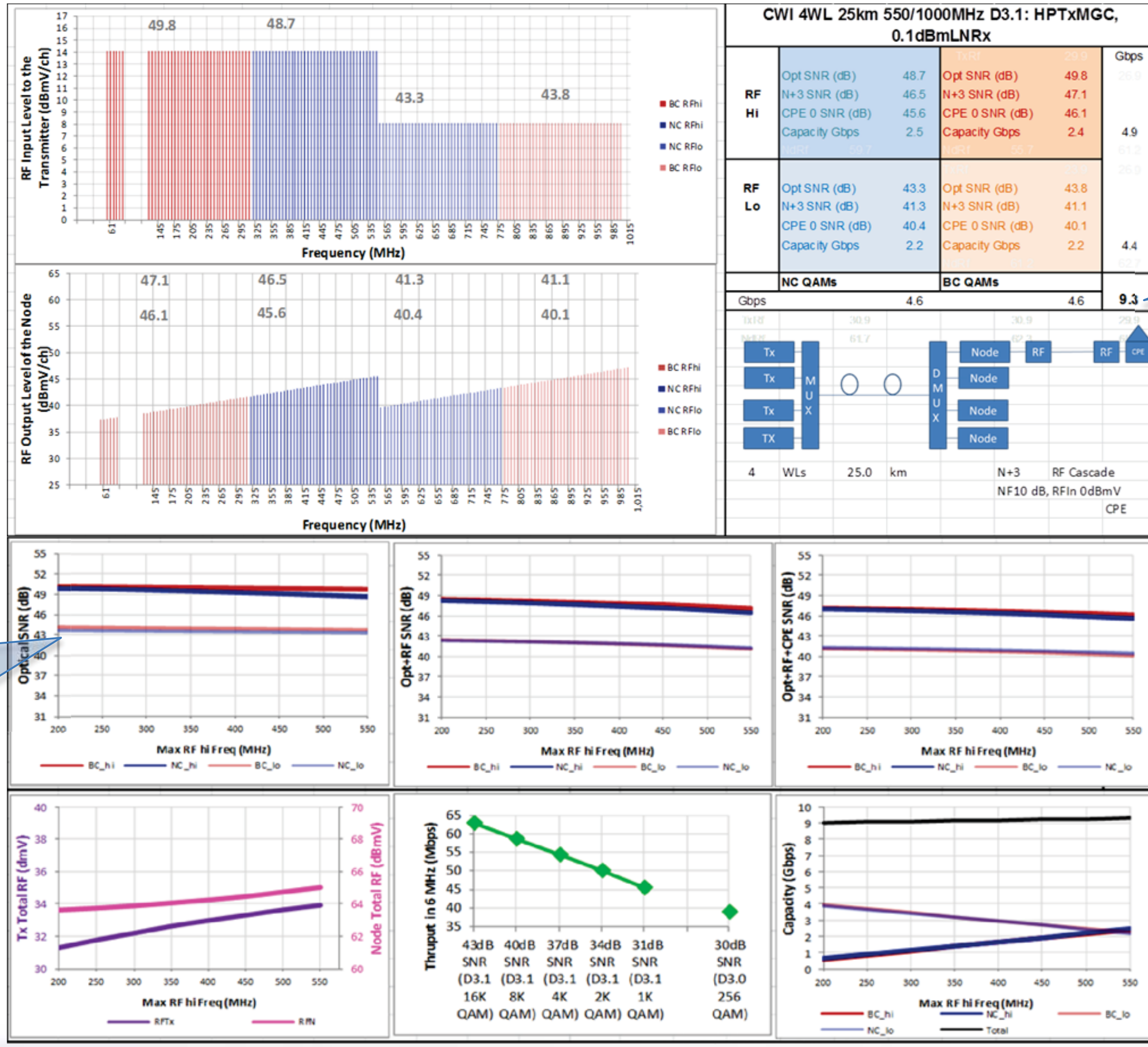


Total Capacity 7.6 Gbps/WL

121.6Gbps over one fiber

Robust Performance across the spectrum

O-Band 4 WL 25 km D3.1



Robust Performance across the spectrum

Total Capacity 9.3 Gbps/WL

37.2Gbps over one fiber

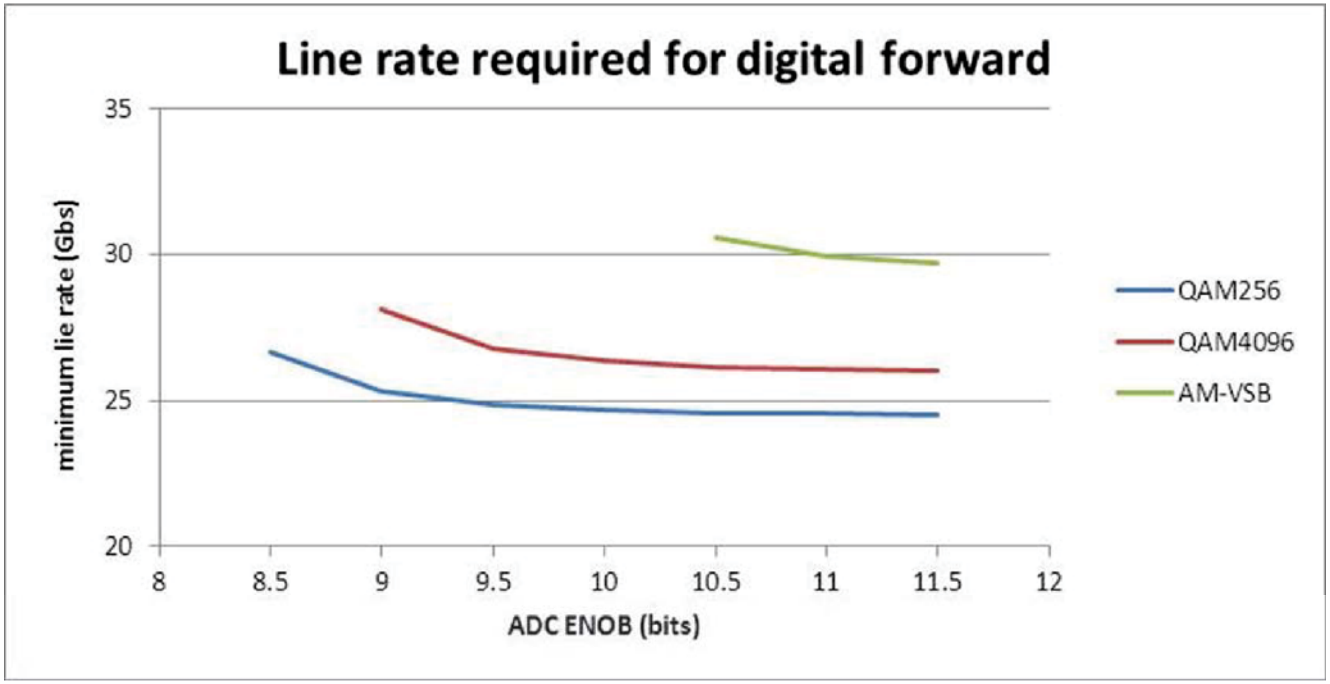
MOST DEPLOYED LINKS

MOST COST EFFECTIVE SOLUTION

Transparency Capacity and Reach

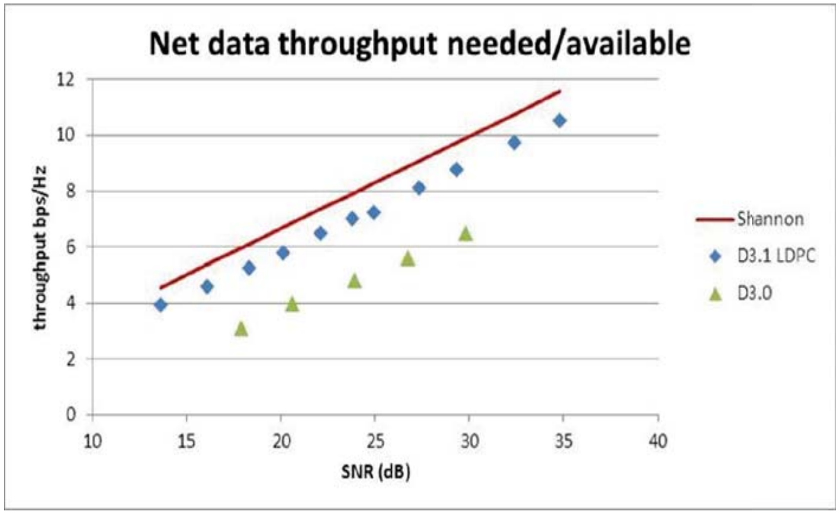
- Analog Transmission is transparent, has good performance for 25-80 km lengths and for 8 to 16 WLs
- Baseband Digital Forward affords similar transparency as Analog but with reach up to 150km and up to 44 wavelengths
- Similar in concept to deployed BDR. Newer Optical components, better compression algorithms make BDF cost effective and enable innovative architectures
- Major areas of use for transparent distributed digital architectures, long reach regional hub consolidations, and fiber deep architectures

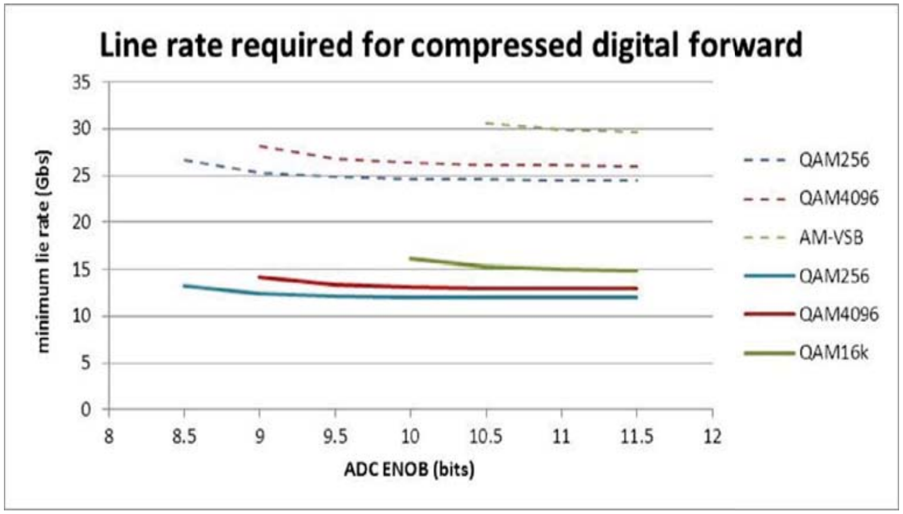
Baseband Digital Forward



- Baseband digital forward can support 256QAM, 4KQAM or AM-VSB with currently available ADC performance
- Required bitrate to encode spectrum up to 1.2 GHz is around 25 Gbs or higher
- Baseband digital forward is a drop-in replacement for analog transmission

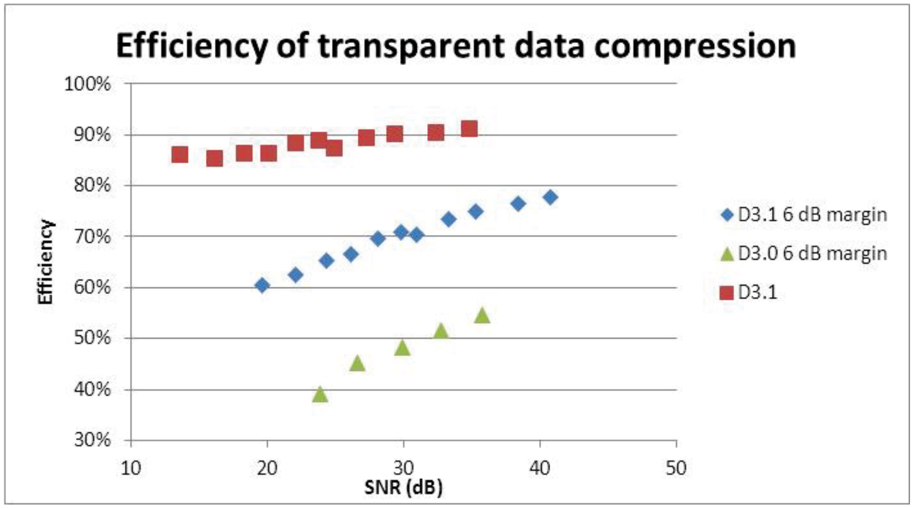
Shannon and Compression





- Shannon limit (red) is compared to OFDM with LDPC (blue markers) and D3.1 (green triangles) in left plot
- Shannon limit is equal to information content in signal and therefore a measure of minimum required line rate for a compressed signal
- Per channel filtering without guard bands is possible for instance with QMF filter banks and highly efficient compression algorithms are available
- Resulting minimum line rates are shown to the right (solid) and compared to uncompressed case, required line rates are reduced by a factor two and RF channel information is individually available

Compressed Digital Forward

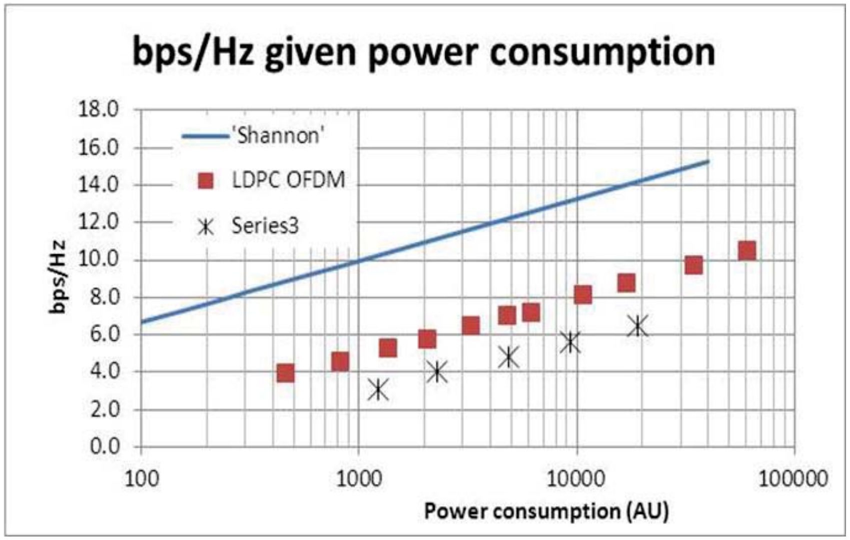


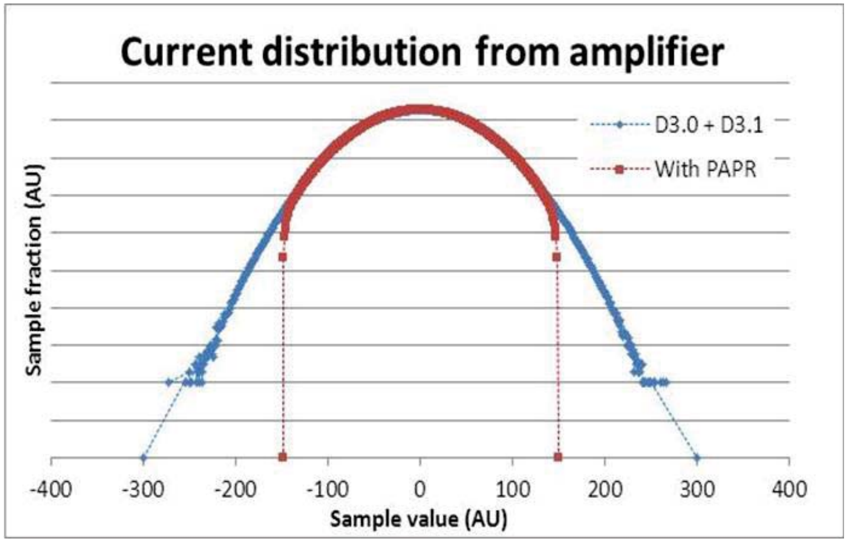
System f_max (MHz)	750	870	1000	1200	1200	1700	200
System f_min (MHz)	54	54	54	85	250	250	5
system BW (MHz)	696	816	946	1115	950	1450	195
Line rate legacy (Gbs)	8.9	10.4	12.1	14.2	12.1	18.5	2.5
Line rate D3.1 (Gbs)	9.7	11.3	13.1	15.5	13.2	20.1	2.7
Line rate QAM 16k (Gbs)	11.0	12.9	15.0	17.7	15.1	23.0	

- Compressed line rate is close to data payload for OFDM with LDPC (red markers), up to 90% efficiency
- With 6 dB margin attainable efficiency still high, growing to > 80% for complex modulation formats - QAM16k
- Results shown for transparent compression, independent of modulation format specifics, most efficient for new complex modulation formats, will efficiently handle any next generation high bps/Hz modulation format
- D3.0 efficiency lower ~ 50%, enough for current system loads in 10 Gbs optics, segmented return in 10 Gbs optics.

Beyond D3.1

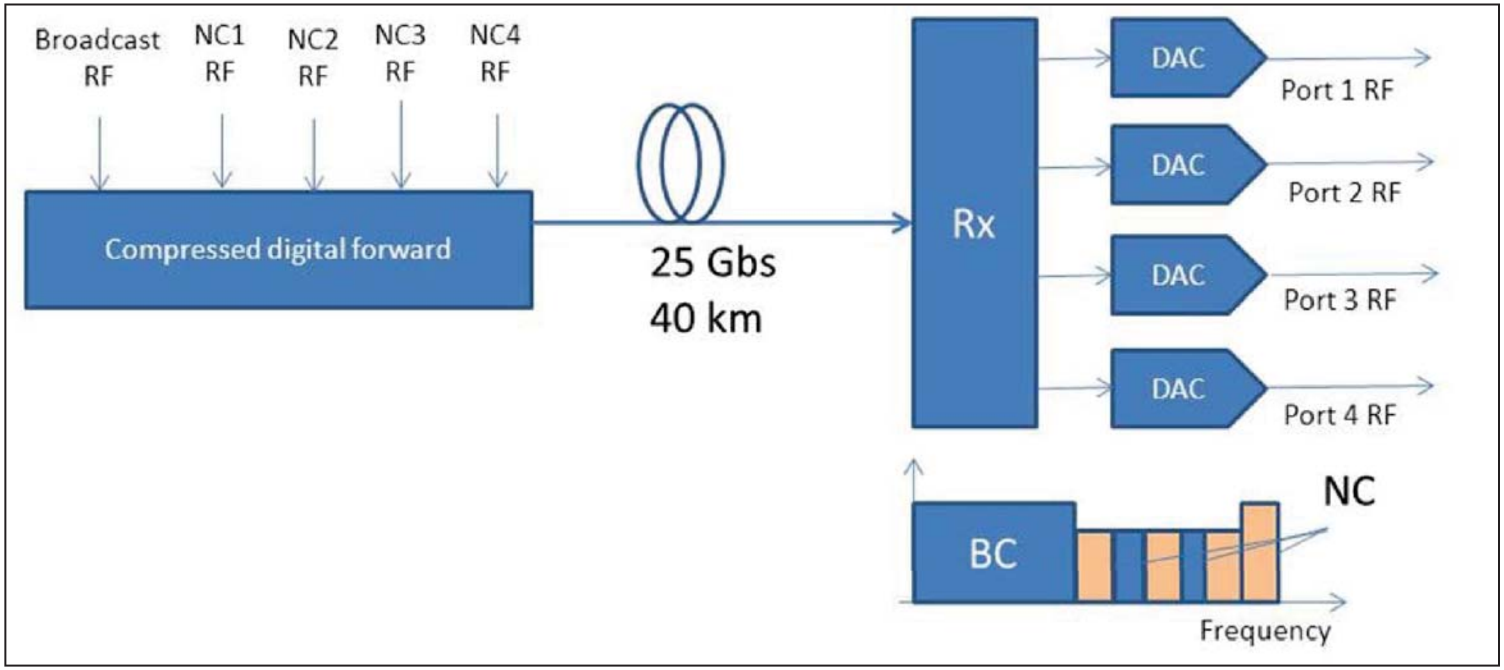
Power Considerations - Potential for Innovations





- Peak-average power ratio (PAPR) of current and planned modulation formats is poor, on the order of 5 to 7 peak to rms amplitude ratio
- Class A amplifiers are biased to support peaks, average output power is often a factor 10 lower. Re-plotting the Shannon SNR limit as a 'Shannon' limit for energy consumption needed per bps/Hz throughput results in the plot to the left; current and planned modulation formats operate more than a factor 10 off this limit
- Plant SNR interchangeable with plant power dissipation (more power gives better cascade SNR); energy consumption per bps/Hz is a better indicator than just SNR of modulation format performance
- Modulation formats can be redesigned to have good PAPR as shown to the right comparing amplifier output amplitude probability distribution (log scale) for OFDM with (red) and without (blue) PAPR reduction algorithms. Significant improvements are possible, transparency to support these remains valuable

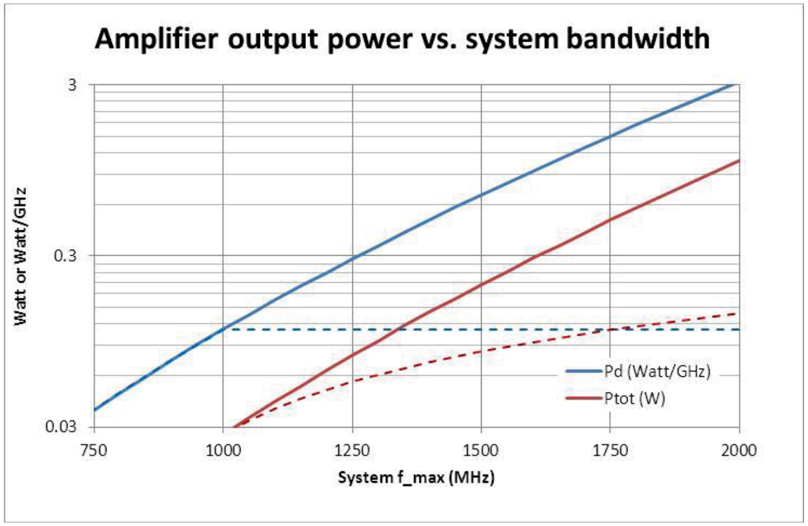
Transparent Segmented Node

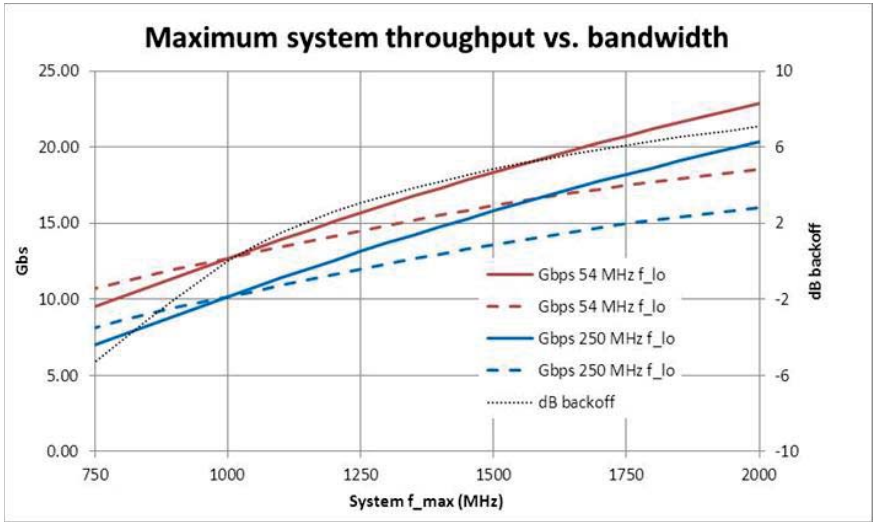


- Per channel filtering and subsequent compression of data permits targeting of individual channels to different DAC ports of one or multiple receivers for a transparent digital link
- Each DAC port can receive a broadcast signal (blue) and a selection of narrowcast signals (pink) that differs per port and can be selected through software
- More than 40 narrowcast channels per port plus broadcast to 1 GHz can be supported on a single 25 Gbs link or multiple 10 Gbs links
- Passive optical splitting is sufficient for distribution to multiple nodes that each can process their own payload

Beyond 1GHz

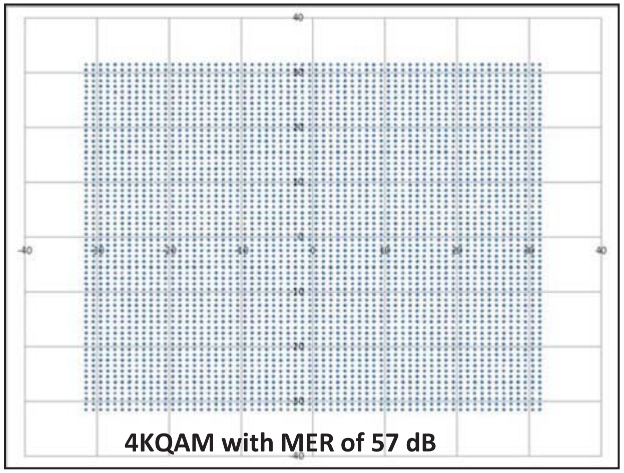
RF Plant Maximum Capacity

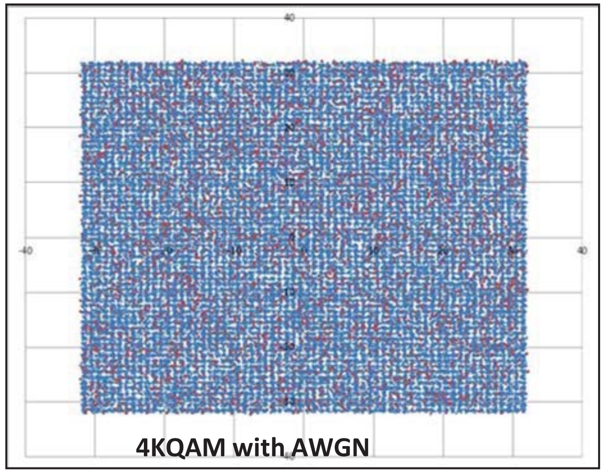


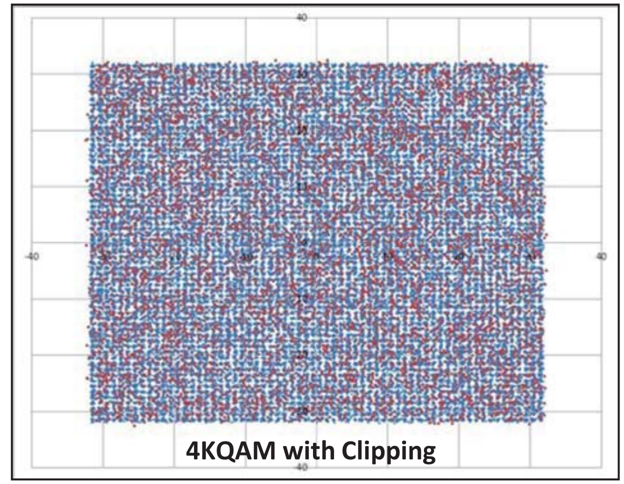


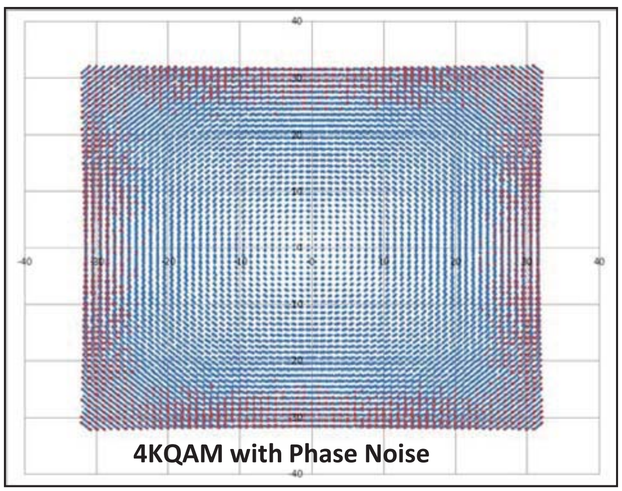
- Exponential growth of power results in unrealistic RF power requirements (left solid lines), capping the power spectral density (dashed) or capping the total RF power to the current state leads to aggressive and conservative estimates of SNR available from upgraded plant (nodes and or amplifiers)
- Network forward data capacity estimates based on OFDM with LDPC performance curves with 3 dB additional margin are shown to the right for aggressive (solid lines) and conservative (dashed lines) cases. dB back-off represents the power back-off between aggressive and conservative case such that total RF power does not exceed current 1 GHz plant performance. Results shown for low split (54 MHz, red) and high split (200 MHz, blue)
- Network capacity is between 15 and 20 Gbs for realistic expansion of plant bandwidth, split change and output power required from the actives. This can be supported with 25 Gbs optics or multiple 10 Gbs optics

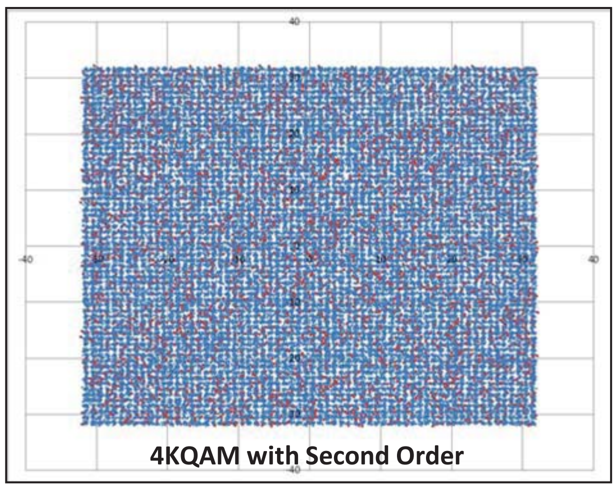
4096QAM Constellations Under Various Operating Conditions


4KQAM with MER of 57 dB


4KQAM with AWGN

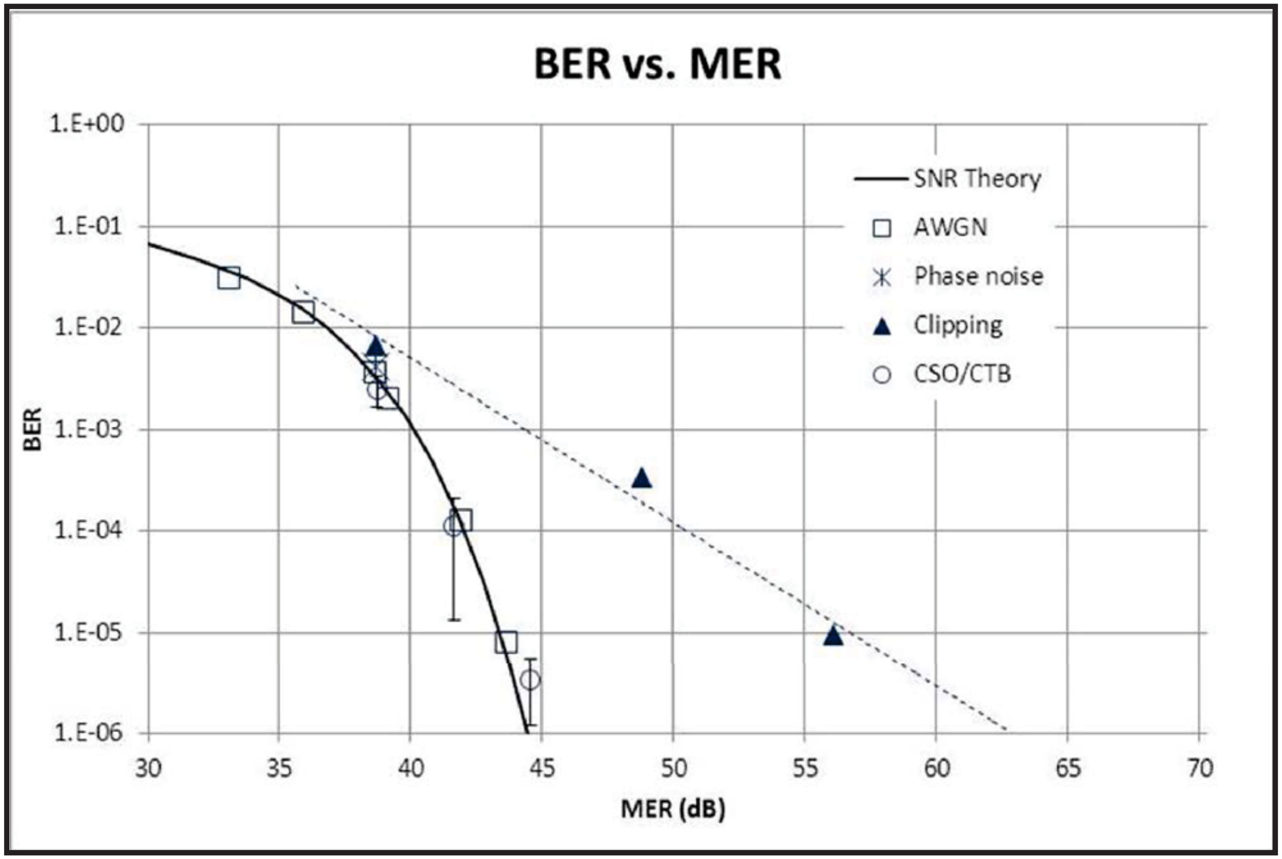

4KQAM with Clipping


4KQAM with Phase Noise


4KQAM with Second Order

- 156 6MHz wide 4KQAMs on the NTSC Plan simulated
- Various Impairments presented
- 20 QAMs demodulated and constellations overlaid
- MER and BER calculated for a cumulative of 100 k Symbols

4096 QAM MER and BER



- MER and BER performance with AWGN, Phase Noise and CSO/CTB is well behaved and easily met with Analog or BDF systems
- Clipping penalty on the BER is very severe. Avoid Clipping at all costs!

Conclusions

- Analog Systems deployed today are transparent and continue to provide high value, preserve infrastructure and support higher order modulation formats of tomorrow
- For long reach or high wavelength counts, where the design of analog transmission systems is challenging, current technology permits transparent cost effective BDF transmitters using 25 Gbps optics
- Transparent compressed digital forward transmitters can support current system channel loading and bandwidth requirements with 10 Gbps optics and can support software configurable system segmentation with 25 Gbps optics without the need to install additional fiber or wavelengths
- 4KQAM constellation diagrams and BER and MER performance analysis with realistic system impairments indicate that requirements are easily met with Analog or BDF systems
- Bandwidth increases and further development in modulation formats may occur beyond D3.1 especially in areas of power efficiency for which transparency of optical link is a valued asset

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