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10G Full Duplex DOCSIS Implementation Exceeds Expectations

A Technical Paper prepared for SCTE by

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1. Introduction

The advent of DOCSIS 4.0 Full Duplex (FDX) technology has arrived after several years of industry collaboration and the publication the DOCSIS 4.0 FDX specifications. Implementation of an FDX node reference design incorporating the remote PHY ASIC SoC has been initially evaluated in the Comcast labs. The key technology to enable simultaneous transmission and reception in the same spectrum requires real-time removal of the high-power cable plant reflections of the transmitted downstream signal from the low-power upstream signal received using “echo cancellation”.

The successful performance of this enabling technology demonstrates the potential for greatly increasing upstream throughput in an additional nearly 600 MHz of spectrum shared concurrently with the transmission of the downstream signal. Evaluations indicate increased spectral efficiency beyond the minimum performance requirements in the FDX specification. This paper will analyze the implied capacity limitations in the specs. A comparison to the measured performance is made which demonstrates exceeding these limits. This comparison will conclude that the performance limits in the FDX specification should be reexamined to update the expected efficiency gains enabled by full duplex echo cancellation technology as currently realized.

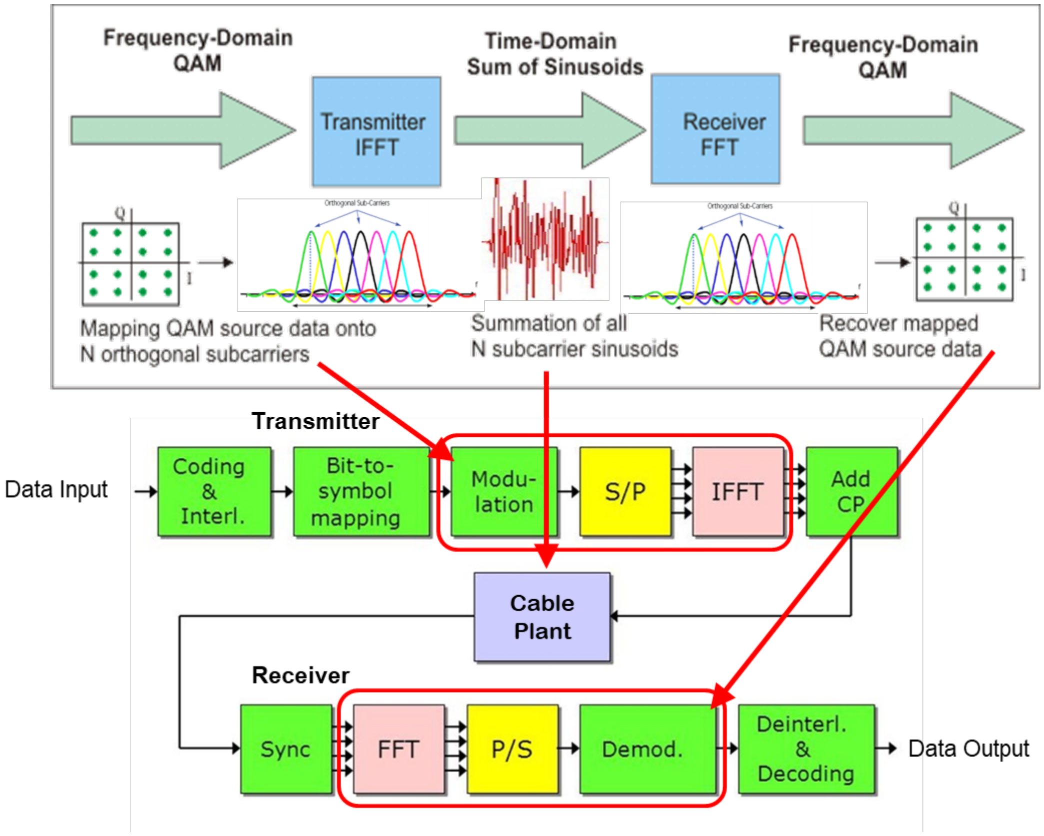
2. DOCSIS 3.1 – The Basis of DOCSIS 4.0 Full Duplex Modulation

DOCSIS 3.1 provides higher throughput and greater flexibility for cable data systems. The PHY layer based on Orthogonal Frequency Division Multiplexing (OFDM) differs significantly from that in previous generations based on Single Carrier Quadrature Amplitude Modulation (SC-QAM).

OFDM is a modulation scheme where many closely spaced, complex valued, harmonically related (orthogonal) QAM data subcarriers of various modulation orders are transformed into a time domain waveform or OFDM symbol. The resulting OFDM symbol in the time domain can be reversibly transformed back into the original QAM data subcarriers in the frequency domain. This reversible process uses the mathematically efficient implementation of the Discrete Fourier Transform (DFT) called the Fast Fourier Transform (FFT) to accomplish this reversible transformation. The N-point FFT transforms a group of N time samples into an equal number of N frequency domain complex valued subcarriers. The inverse FFT reverses this transformation from the frequency domain into the time domain.

As shown in Figure 1, forward error correction (FEC) coding and interleaving is applied to the input data bits. The error protected data bits are mapped into N frequency domain QAM symbols modulated onto N orthogonal subcarriers. These QAM subcarriers are serial-to-parallel converted and input into an inverse Fast Fourier Transform (iFFT). This transformation produces a single time domain OFDM symbol comprised of the summation of all N subcarriers. A portion of the end of each OFDM symbol known as a cyclic prefix (CP) is prepended to the beginning of the same symbol to prevent inter-symbol interference (ISI) due to signal micro-reflections or “echoes”.

Any contiguous group of samples within each OFDM symbol can be used to recover the subcarriers using the periodicity property of the DFT. If the latter part of the symbol past the prepended cyclic prefix is used, and the micro-reflections are confined in time to the duration of the cyclic prefix, then the remaining samples in the OFDM symbol are free of inter-symbol interference. Consecutive groups of QAM subcarriers are thus transformed into OFDM symbols and transmitted successively over the cable plant.

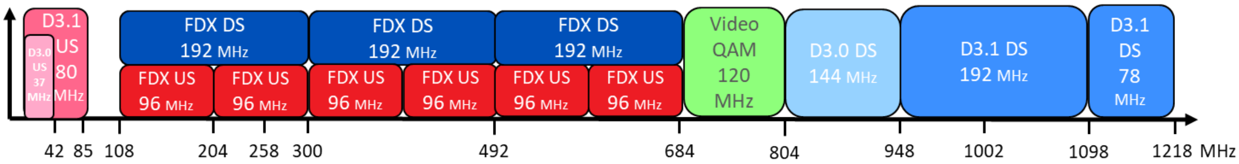


The reverse process at the cable modem receiver synchronizes the ISI free portion of each OFDM symbol, performs an FFT and parallel-to-serial conversion to recover the QAM modulated data subcarriers which are then demodulated, deinterleaved, and FEC decoded to recover the error-corrected data bits. Details of the DOCSIS 3.1 OFDM/OFDMA transmission and reception are described in a prior paper [1].

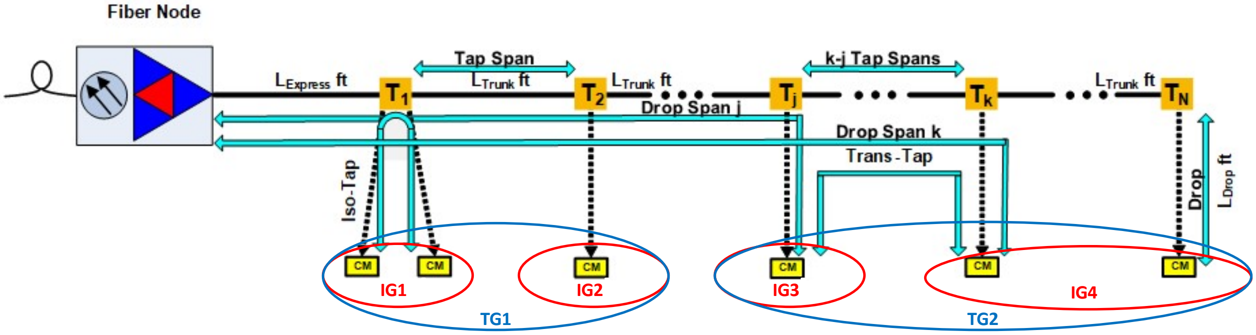
3. DOCSIS 4.0 - Full Duplex Spectrum Sharing

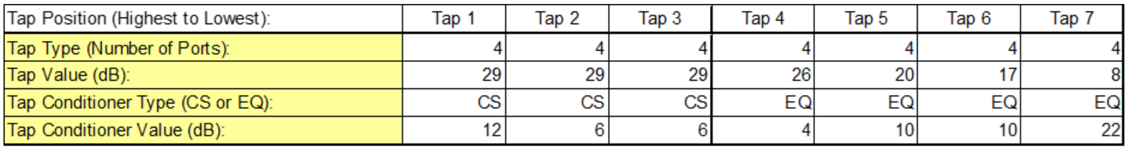
Full Duplex DOCSIS 4.0 uses the same OFDM/OFDMA modulation as DOCSIS 3.1 but overlaps downstream transmissions from node to modem and upstream transmissions from modem to node within the same frequency spectrum in the 108 MHz to 684 MHz FDX band. This greatly increases the upstream bandwidth yielding a total channel data rate up to 5.7 Gbps with 1024 QAM subcarriers and over 4 Gbps total data payload rate without overhead.

Legacy upstream DOCSIS 3.0 and 3.1 signals remain in the 5 to 85 MHz (mid-split) band. Legacy downstream DOCSIS 3.0 and 3.1 signals occupy the 804 MHz to 1002 MHz band, and only DOCSIS 3.1 OFDM signals occupy 1002 MHz to 1218 MHz. An example of such spectrum allocation is shown in Figure 2 with downstream (DS) and upstream (US) frequency bands.



The FDX band is divided into three 192 MHz sub-bands in the FDX band containing three downstream OFDM channels overlapped with six upstream OFDMA channels. The FDX node simultaneously transmits and receives these channels within the FDX band. Cable modems operate in a dynamic FDD mode with the direction of each sub-band upstream transmission or downstream reception dynamically assigned with a Resource Block Allocation (RBA) message allocating the upstream or downstream capacity within the FDX band in a flexible manner as capacity demands require.





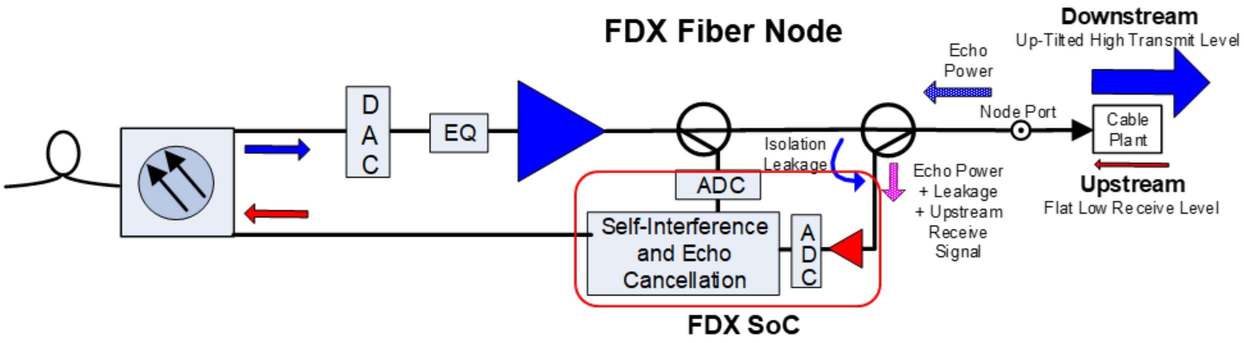
Tap Position (Highest to Lowest):	Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6	Tap 7
Tap Type (Number of Ports):	4	4	4	4	4	4	4
Tap Value (dB):	29	29	29	26	20	17	8
Tap Conditioner Type (CS or EQ):	CS	CS	CS	EQ	EQ	EQ	EQ
Tap Conditioner Value (dB):	12	6	6	4	10	10	22

Full Duplex DOCSIS 4.0 was originally specified for a Node + 0 plant without amplifiers beyond the node. The Node + 0 cable plant architecture is shown in Figure 3. When a modem transmits in an FDX sub-band, modems on the same tap (Iso-Tap) cannot receive on the downstream in the same sub-band due to the high upstream interference introduced across tap ports into the low downstream receive level of the other modems on the same tap. These modems are said to belong to the same interference group (IG). However, modems separated sufficiently apart across different taps can have sufficient isolation to interference. Such separated modems can belong to different IGs where the transmission of a modem in a sub-band does not significantly interfere with the reception of other modems in other IGs within the same sub-band. Identification of each modem IG is performed in the "sounding" process in which each modem in turn transmits a test upstream transmission while all other modems measure the received level relative to the downstream received level in a modulation error ratio (MER) triggered measurement window. Low received MER modems are placed in a common IG while higher MER modems remain in other IGs that are isolated from the test modem interference.

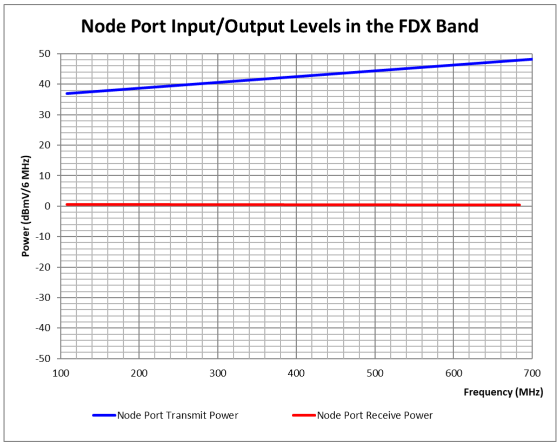
Modems in different IGs can be grouped into a single Transmission Group (TG) with common sub-band RBA transmit/receive assignments. Other TGs can operate with complementary RBA assignments providing full duplex simultaneous transmission and reception across all TG sub-bands at the node. A detailed treatment of FDX PHY layer operation of interference management is described in [2].

4. FDX Node Evaluation in the Comcast Lab Cable Plant

The operation of the simultaneous transmission and reception in the FDX node reference design that was evaluated in our lab. The 7 tap Node + 0 cable plant design used in this evaluation is shown in Figure 3. The FDX node reference design is depicted in Figure 4. The Remote PHY device (RPD) containing the FDX system-on-chip (SoC) in the FDX node receives legacy upstream below 85 MHz and legacy downstream from 804 MHz to 1218 MHz (not shown). These legacy bands are needed to initialize the node as well as cable modems in DOCSIS 3.1 mode prior to adding DOCSIS 4.0 FDX functionality in the FDX band.

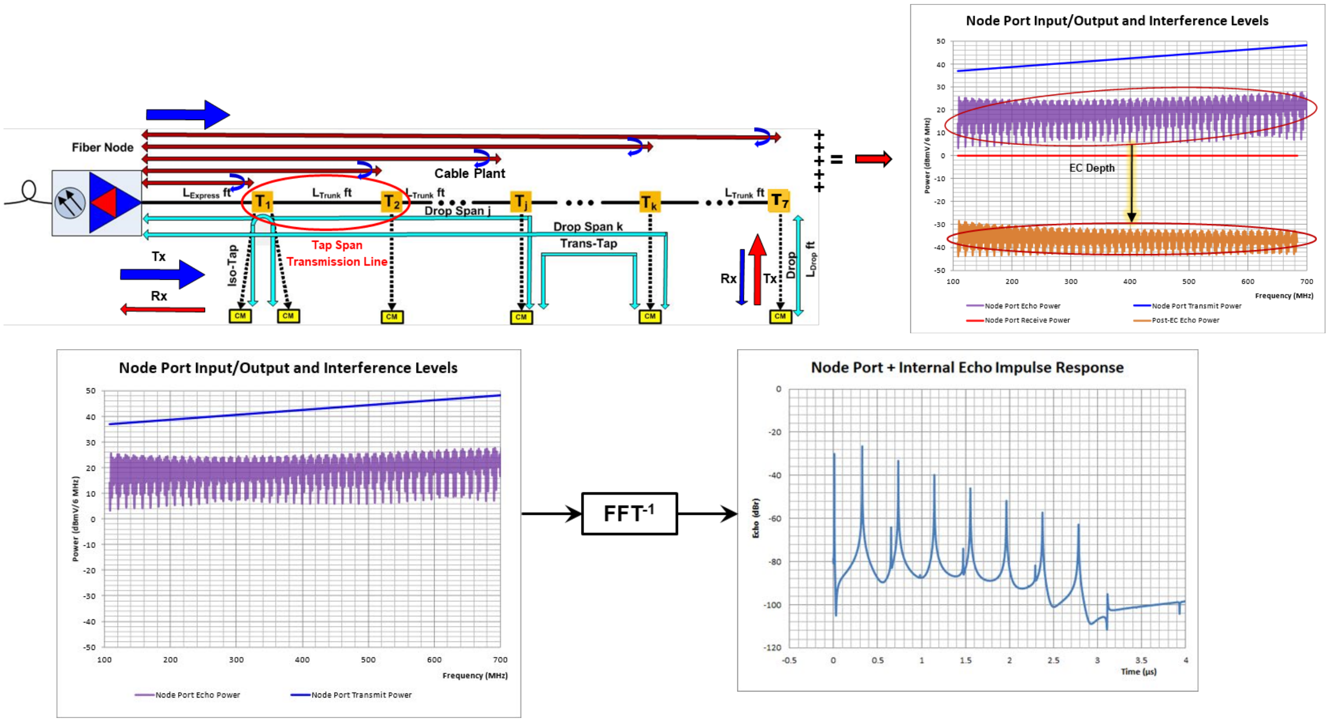


The downstream continuous OFDM signal is launched from the node port at a level from 37 to 48 dBmV/6 MHz with a 10 dB uptilt in the FDX band (see Figure 5). The downstream level determines the maximum reach (number of equalized taps and feeder plus drop cable lengths) for a modem receive level of 0 dBmV/6 MHz across the entire FDX and legacy bands.



The combined upstream burst OFDMA signals of all granted modem minislots arrives at the node port without significant tilt at a low level near 0 dBmV/6.4 MHz. The upstream receive level is limited by the 65 dBmV total composite power (TCP) of the cable modems in the highest loss path from the modem to the node. Thus, the upstream path being essentially equal path loss will transmit with the same power spectral density resulting in the same 0 dBmV/6.4 MHz across the FDX band at the node port.

The high-level downstream signal launched into the cable plant will result in reflected signal energy back toward the node due to tap return losses causing impedance mismatches with the cable characteristic impedance in the cascade of connected tap-to-tap transmission lines. The node echo paths and the resulting reflected signals or echoes are shown in Figure 6.



Note that the downstream echo power is below the downstream launch power at the node port but the echo is higher than the received upstream signal at the node port. Taking the inverse FFT of the reflected signal power shows the distribution of the relative echo level and delay of the echo path components from the node port and each tap relative to the 0 dB node launch signal reference. This echo level being higher than the received upstream signal at the node port results in a negative signal-to-noise ratio (SNR). The upstream signal would not be recoverable with a negative SNR. Hence echo cancelation technology of sufficient cancelation depth to suppress this interference and increase upstream received SNR is required.

5. Echo Cancellation Performance Exceeded

The RPD SoC in the FDX node reference design of Figure 4 reduces the echo level below the upstream receive level using self-interference and echo cancelation of the downstream echo. The node downstream signal is sampled and digitized as a reference for echo cancelation. The upstream signal with the downstream echo through and the leakage across the FDX node port directional coupler of Figure 4 (replacing the frequency division duplex diplexer) is also digitized. Using the downstream reference signal, the echo cancelation operation within the FDX SoC subtracts the echo plus leakage signals from the upstream input plus interference.

The evaluated performance of the echo cancelation is shown in Figure 7. The resultant bit-loading achieved was 1024-QAM subcarriers in the received OFDMA symbols with zero codeword errors after LDPC decoding. The echo is substantially cancelled. The residual post EC signal to echo ratio is increased to 35 dB to support 1024-QAM an shown in Table 2, Upstream CNR Performance for D3.1 – a significantly positive upstream receiver SNR!

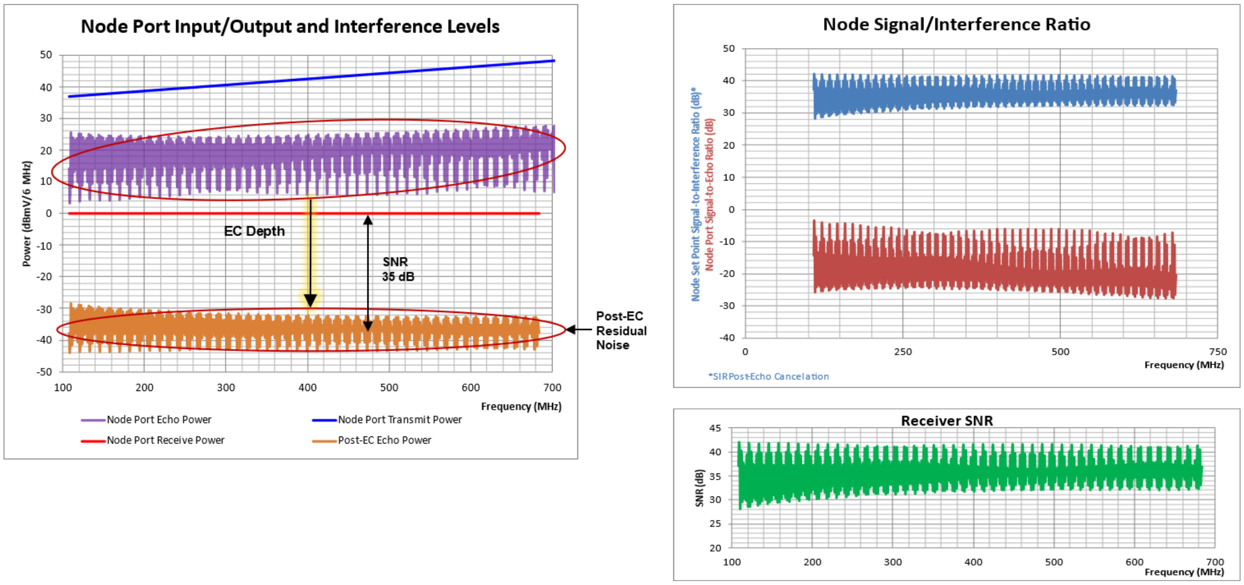


Figure 7 – Node Signal to Echo Interference (Pre and Post Echo Cancelation)

The upstream and downstream data rates per channel type and the total aggregate data rates for the channel plan of Figure 2 are calculated in Table 1.

Table 1 – FDX Cable System Data Rates

FDX OFDMA Upstream per 96 MHz Channel

Modulation	SNR (dB) @ BER=1E-8	Bits/Symbol	Spectral Efficiency (b/s/Hz)	Spectral Efficiency w/ Total Overhead (b/s/Hz)	Loss w/ Total Overhead (b/s/Hz)	Modulated Bandwidth (MHz)	Non-Excluded Subcarriers	Minislot Subcarriers	Minislot Symbols	Pilots (#4 :2⁴=16)	Low Density Pilots	Cyclic Prefix (us)	FEC Rate	FEC Rate w/ Minislot Overhead	FEC Rate w/ Total Overhead	Bit Rate (Mbps)
1024-QAM	35.5	10	8.888888889	6.772486772	2.116402116	94.8	1896	8	14	16	2	2.5	0.888888889	0.761904762	0.677248677	642

Non-FDX SC-QAM Upstream per 6.4 MHz Channel

Modulation	SNR (dB) Low Pkt Loss	Bits/Symbol	Bandwidth (MHz)	Symbol Rate (Msymbol/s)	Efficiency	Bit Rate (Mbps)
64-QAM	22.8	6	6.4	5.12	0.834	25.6

FDX OFDM Downstream per 192 MHz Channel

Modulation	SNR (dB) @ BER=1E-8	Bits/Symbol	Spectral Efficiency (b/s/Hz)	Spectral Efficiency w/ Total Overhead (b/s/Hz)	Loss w/ Total Overhead (b/s/Hz)	Modulated Bandwidth (MHz)	Non-Excluded Subcarriers	PLC	Continuous Pilots	Scattered Pilots	NCP	Cyclic Prefix (us)	FEC Rate	FEC Rate w/ CW Hdr (2 B PDU Ptr)	FEC Rate w/ Total Overhead	Bit Rate (Mbps)
1024-QAM	27.2	10	8.785185185	7.527264746	1.257920439	190	3800	8	48	29	48	2.5	0.8785185	0.8775309	0.7527265	1430

Non-FDX OFDM Downstream per 192 MHz Channel

Modulation	SNR (dB) @ BER=1E-8	Bits/Symbol	Spectral Efficiency (b/s/Hz)	Spectral Efficiency w/ Total Overhead (b/s/Hz)	Loss w/ Total Overhead (b/s/Hz)	Modulated Bandwidth (MHz)	Non-Excluded Subcarriers	PLC	Continuous Pilots	Scattered Pilots	NCP	Cyclic Prefix (us)	FEC Rate	FEC Rate w/ CW Hdr (2 B PDU Ptr)	FEC Rate w/ Total Overhead	Bit Rate (Mbps)
4096-QAM	27.2	12	10.54222222	9.032717695	1.509504527	190	3800	8	48	29	48	2.5	0.8785185	0.8775309	0.7527265	1716

Non-FDX SC-QAM Downstream per 6.4 MHz Channel

Modulation	SNR (dB) @ BER=1E-8	Bits/Symbol	Spectral Efficiency (b/s/Hz)	Spectral Efficiency w/ Total Overhead (b/s/Hz)	Loss w/ Total Overhead (b/s/Hz)	Bandwidth (MHz)	Symbol Rate (Msymbol/s)	FEC Rate RS Code	FEC Rate Trellis Code + Framing	FEC Rate w/ Total Overhead	Bit Rate (Mbps)
256-QAM	30	8	7.625	7.2400768	0.3849232	6	5.360537	0.953125	0.953125	0.9050096	38.8

Frequency Band	DOCSIS Bit Rate (Mbps)
FDX US	3852
Non-FDX US	394
Total US	4246
FDX DS	4291
Non-FDX DS	3343
Total DS	7634

Table 2 – DOCSIS Bit-Loading Specifications

Upstream CNR Performance for D4.0 FDX

QAM Order	Modulation Efficiency (bits/subcarrier)	CNR Threshold (dB)*	Minimum Power (dBmV/6 MHz)
QPSK	2.0	12.5	0.0
8-QAM	3.0	15.5	0.0
16-QAM	4.0	18.5	0.0
32-QAM	5.0	22.0	0.0
64-QAM	6.0	25.5	0.0
128-QAM	7.0	29.0	1.0
256-QAM	8.0	32.0	3.0
512-QAM	9.0	36.0	5.0
1024-QAM	10.0	44.0	7.0

Upstream CNR Performance for D3.1

QAM Order	Modulation Efficiency (bits/subcarrier)	CNR Threshold (dB)*	Minimum Power (dBmV/6 MHz)
QPSK	2.0	11.0	-4.0
8-QAM	3.0	14.0	-4.0
16-QAM	4.0	17.0	-4.0
32-QAM	5.0	20.0	-4.0
64-QAM	6.0	23.0	-4.0
128-QAM	7.0	26.0	0.0
256-QAM	8.0	29.0	0.0
512-QAM	9.0	32.5	0.0
1024-QAM	10.0	35.5	0.0
2048-QAM	11.0	39.0	7.0
4096-QAM	12.0	43.0	10.0

The upstream bit-loading is a function of the echo level present relative to the minimum upstream receive level. This relationship is illustrated in Figure 8 where lower echo levels yield higher bit-loading post echo cancelation and vice versa. The assessment of this trade-off for a given minimum upstream receive level is ongoing for a more complete characterization of the echo cancelation performance as implemented.

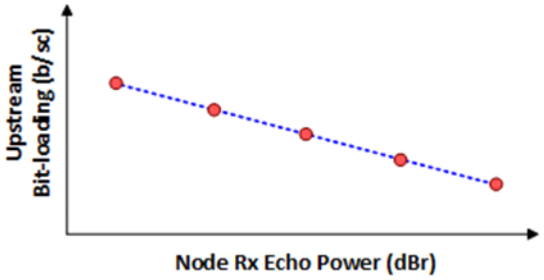


Figure 8 – Upstream bit-loading vs. relative echo power

6. The Future Evolution of FDX Technology

The demonstrated results of this technology in our labs indicates a path forward to extend the reach of echo cancelation beyond all-passive Node + 0 cable systems. The depth of echo cancelation with the system designed transmit and receive signal levels and resulting echo levels shows 1024-QAM OFDMA modulation is achievable in a Node + 0 cable system. The use of this technology in FDX amplifiers can extend the reach into Node + N system designs.

Managing downstream output and upstream input levels in amplifier cascades such that the upstream signal to echo ratio is reduced below that of the node can increase the achievable SNR at the upstream amplifier output for the same echo cancelation depth in the node. Longer amplifier cascades will accumulate the reduced echo cancelation residual interference lowering the received SNR and achievable bit-loading at the node. But as shown in the Table 2 SNR vs. bit-loading, a 6 dB decrease in SNR to 29 dB lowers the modulation efficiency from 10 to 8 bits per subcarrier. This compromise could enable the use of FDX amplifiers with echo cancelation in limited cascade depths for a 20 percent decrease in overall upstream capacity over the 576 MHz wide FDX band. Such a compromise may be entirely acceptable in exchange for the still very significant increase in wideband upstream capacity with amplifier cascades extending the reach of FDX technology to Node + N cable systems.

7. Conclusion

The initial evaluation of echo cancelation technology of an ASIC SoC enabled RPD in a DOCSIS 4.0 FDX node reference design was described. The performance in a representative Node + 0 cable system design in our labs demonstrated the successful implementation of FDX echo cancelation in a representative but challenging Comcast Node + 0 cable system design. The measured 1024-QAM OFDMA error-free performance exceeded the upstream capacity of 64-QAM OFDMA in the DOCSIS 4.0 FDX PHY specification – a 67 percent capacity increase.

The echo cancelation performance utilized in a future FDX amplifier can extend the reach of FDX beyond all-passive Node + 0 cable systems. A trade-off of amplifier cascade depth vs reduced upstream spectral efficiency could provide significant increases in total upstream capacity in existing 1.2 GHz Node + N cable systems.

Abbreviations

CP	cyclic prefix
DFT	Discrete Fourier Transform
DS	downstream
FDX	Full Duplex
FEC	forward error correction
FFT	Fast Fourier Transform
iFFT	inverse Fast Fourier Transform
IG	interference group
ISI	inter-symbol interference
MER	modulation error ratio
OFDM	Orthogonal Frequency Division Multiplexing
RBA	Resource Block Allocation
RPD	Remote PHY device
SC-QAM	Single Carrier Quadrature Amplitude Modulation
SNR	signal-to-noise ratio
SoC	system-on-chip
TCP	total composite power
TG	transmission group
US	upstream

Bibliography & References

[1] *Demystifying the DOCSIS 3.1 PHY*, R. Prodan, L. Montreuil, A. Kliger, BZ Shen, SCTE Cable-Tec Expo 2014

[2] *Full Duplex DOCSIS PHY Layer Design and Analysis for the Fiber Deep Architecture*, R. Prodan, SCTE Cable-Tec Expo 2017