# Practical Considerations For Full Duplex Deployments In N+x Environments

A Technical Paper prepared for SCTE•ISBE by

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# Introduction

Last year at EXPO the concept of expanding Full-Duplex DOCSIS (FDX) beyond N+0 architectures was introduced using bi-directional echo canceling amplifiers. The expansion of FDX beyond N+0 architectures greatly expands the deployment potential of FDX and the symmetric gigabit services that it enables. As operators gather more experience in the building of N+0 plant, it has become apparent that construction time and costs are greater than initial estimates. This has resulted in more limited N+0 builds in targeted areas and a desire to pursue other methods to expand plant capacity, particularly upstream capacity. In response to this desire, the MSO community and CableLabs started two exploratory working groups, one on Extended Spectrum DOCSIS (ESD) and one on FDX amplifiers. The continuing work of these groups has led to the creation of DOCSIS 4.0, which will bring both FDX and ESD together in a single specification. This paper focuses on FDX and how it might be deployed in existing plant.

# An FDX Primer

Full-Duplex DOCSIS was designed to work in N+0 plant, that is no active amplifiers beyond the node. The node is assumed to be a Remote PHY (RPD) or Remote MACPHY (RMD) device with a single coax span of five or six taps. The FDX band of operation spans from 108 MHz to 684 MHz, divided into six upstream subbands of 96 MHz each and three downstream subbands of 192 MHz each. The FDX node transmits downstream and receives upstream on the same frequencies in the FDX band using echo cancelation techniques to remove downstream interference from the upstream receiver. The FDX modem however operates in frequency division duplex (FDD) mode, transmitting upstream and receiving downstream on different frequencies within the FDX band.

Within a given node, based on the isolation between taps, some modems can receive downstream with minimal interference on the same frequencies that other modems are transmitting upstream. Using a procedure called sounding, the CMTS core sorts modems into interference groups (IG's) such that modems in different interference groups will not interfere with each other, while those in the same interference group would. One or more interference groups are then assigned to a transmission group (TG). Each TG is then assigned to which subbands it can transmit and which it can receive through a message called a Resource Block Assignment (RBA). This effectively divides the node into two or more virtual nodes. See Figure (1) for an illustration.

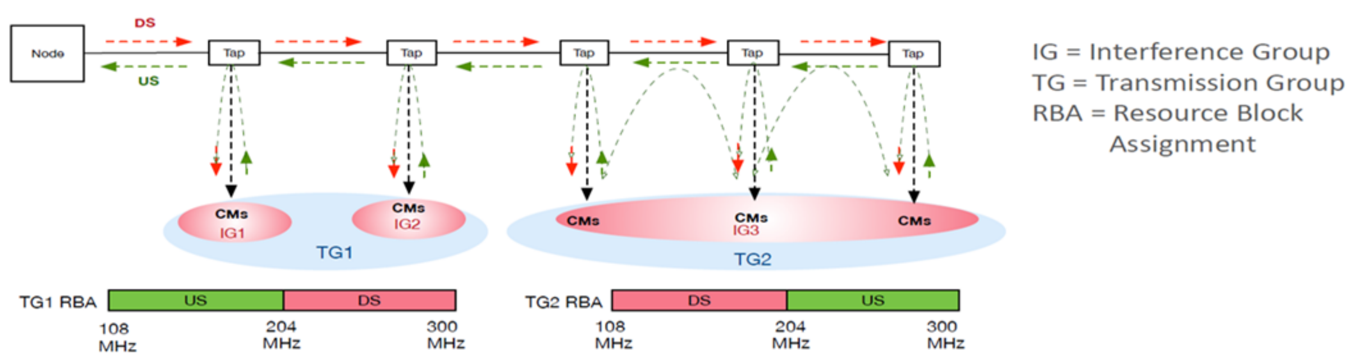


**Figure 1. N+0 Plant with FDX**

The primary benefit of FDX is not the re-use of frequencies, but the ability to dramatically increase upstream bandwidth as needed. Through an RBA change to a TG, it is possible to allow all of the FDX band to be used upstream; upstream capacity would be expanded to greater than 5 Gbps. RBA changes can be dynamic based on demand for capacity.

# Our Dilemma

The vast majority of our plant today is sub-split 1 GHz, typically N+5, averaging 400+ households passed (HHP). Node actions, either node splits or an N+0 conversion, are driven almost exclusively today based on upstream congestion. Modeling both upstream and downstream compounded annual growth rate (CAGR) on a node-by-node basis shows that a conversion to midsplit with a potential to offer 500 Mbps upstream virtually eliminates upstream congestion as a reason for a node action (See Figure (2)), and when coupled with a node split, pushes the next node action out 5+ years on average. Future node actions are then mostly driven by downstream congestion. This subsequent node action now could either be a node split, N+0 conversion, or ESD 1.8 GHz conversion. Midsplit however does not solve two issues, the first is the desire to widely offer symmetric gigabit services, , the second would be a desire to proportionately increase upstream capacity if downstream capacity was increased through an ESD conversion.

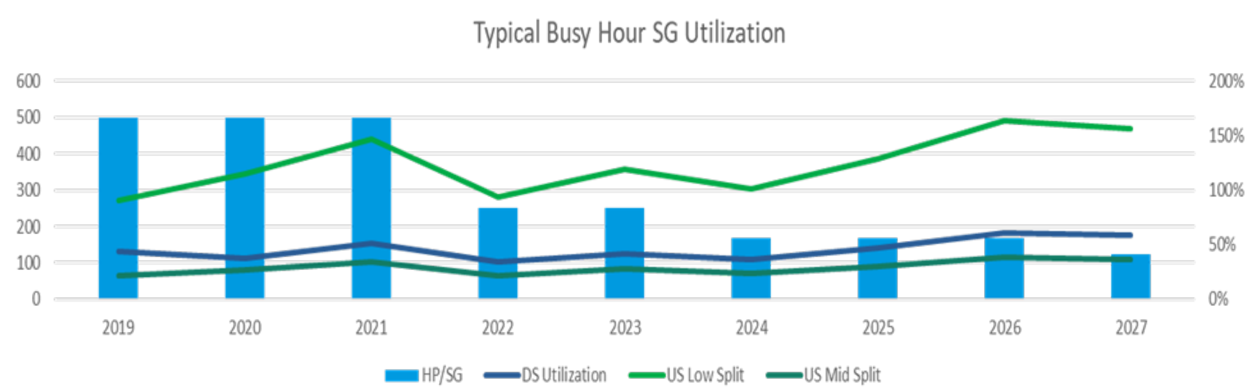


**Figure 2 Upstream and Downstream Utilization over Time Based on Current CAGR**

An ideal solution would allow FDX to operate in legacy N+x plants (N+5 or more) without changing plant topology by only replacing the node and all actives with FDX compatible products.

# Legacy Plant Modeling

We have performed network modeling associated with a “typical” legacy HFC cascade to approximate the RF performance that might be achieved with an expanded upstream (to 684 MHz) in conjunction with a 108-1000 MHz downstream. See Figure 3 for the configuration of the amplifier cascade.

 

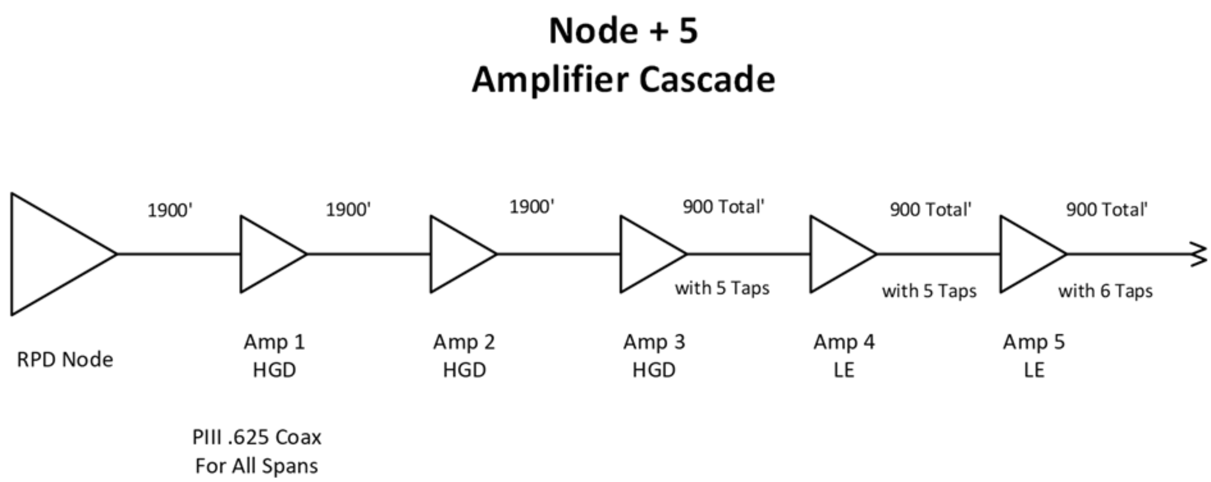


**Figure 3. Amplifier Cascade used in the Analysis**

On our typical Node + 5 amplifier cascade, with 36 amplifiers in total fed off the node, we calculated the following performance:

- Cumulative DS Composite Carrier to Noise (CCN) for the Node + 5 amp cascade = 41.6 dB (all ratios are relative to SC-QAM/OFDM channel power in a 6 MHz bandwidth)
- Cumulative US CCN for the 36 amplifiers plus the Node = 36.3 dB
- US Tx power for a Point of Entry Gateway device ranged from 27.9 to 35.5 dBmV/6 MHz at 20 MHz to 40.9 to 46.6 dBmV/6 MHz at 684 MHz. See Figure 4.

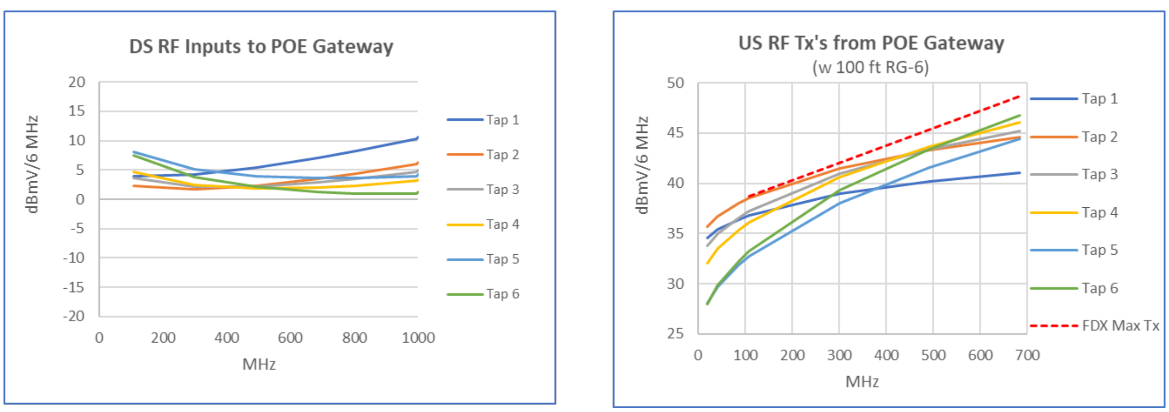


**Figure 4. Levels at POE Gateway**

For the modeled example the following assumptions were used:

- The node is an RPD node, with RPD module providing 55 dB composite intermodulation noise (CIN).
- Target RF output levels of the node and amplifiers are 32.8 dBmV/6 MHz at 108 MHz, and 46 dBmV/6 MHz at 999 MHz (for SC-QAM/OFDM).
- The first 3 amplifiers in cascade are "Express" multi-port amplifiers with their main output feeding directly to the next Express amplifier via non-tapped coax. The last 2 amplifiers are single port Line Extenders. Refer to the drawings of the amplifier cascade (Figure 3) and the tapped feeder line (Figure 5) for additional information.

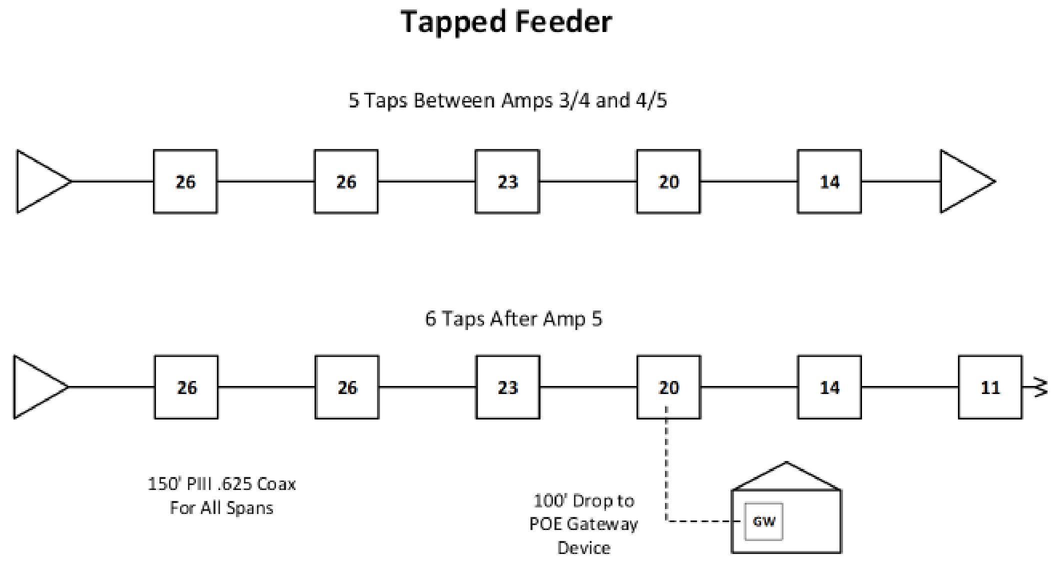


**Figure 5. Tapped Feeder Used in the Analysis**

- Downstream amplifier output levels, internal tilts, and gains are typical of the 1 GHz types of amplifiers used in our networks.
- Upstream amplifier input/output levels and required gains were calculated assuming the losses expected at 684 MHz, with a target RF receive level at the RPD node port of 6 dBmV/6 MHz.
- Amplifier station noise figures were increased relative to legacy amplifier noise figures under the assumption that if a non-diplexed (FDD/FDX) amplifier with echo cancellation is used, additional input/output losses for internal downstream/upstream splitters/combiners would increase the noise figures.
- Downstream CIN was estimated based upon amplifier data sheet specifications for RF loading to 1 GHz, using what are typically known as high output GaN amplifiers (assuming we could use that type of downstream amplifier for this application, with downstream total composite power (TCP) of only 62.7 dBmV. Note that these are not the "super-high output" amplifiers used in 1.2 GHz N+0 applications.
- Upstream CIN was a rough approximation based upon the assumption that the amplifier stations would make use of a dual-stage upstream amplification stage, with 10 dB of tilt (via inter-stage equalization) introduced between the stages to lessen the output TCP of the 2$^{nd}$ stage.
- 100 ft RG-6 was used for drop loss from Tap output to POE Gateway input.
- Upstream 684 MHz EQ losses were modeled.

All of the modeling here was based on a 1 GHz plant; however extending the plant to higher frequency, either 1.2 GHz or 1.8 GHz, will not invalidate this analysis since we must keep current levels to support legacy equipment below 1GHz.

 

Figure 6 shows one leg of a typical N+5 node. Note the extensive use of splitters and couplers in the node. This introduces a significant issue for FDX in the formation of interference groups; the upstream output of one amplifier can couple across a splitter at a sufficient level to interfere with the downstream input to an adjacent amplifier if they are on the same frequency (See Figure 7). This basically means that modems connected through the second amplifier will be in the same interference group (IG) as modems off the first amplifier. In fact, by tracing through the potential interference paths, we find that all modems on one leg of the node will be in the same interference group.

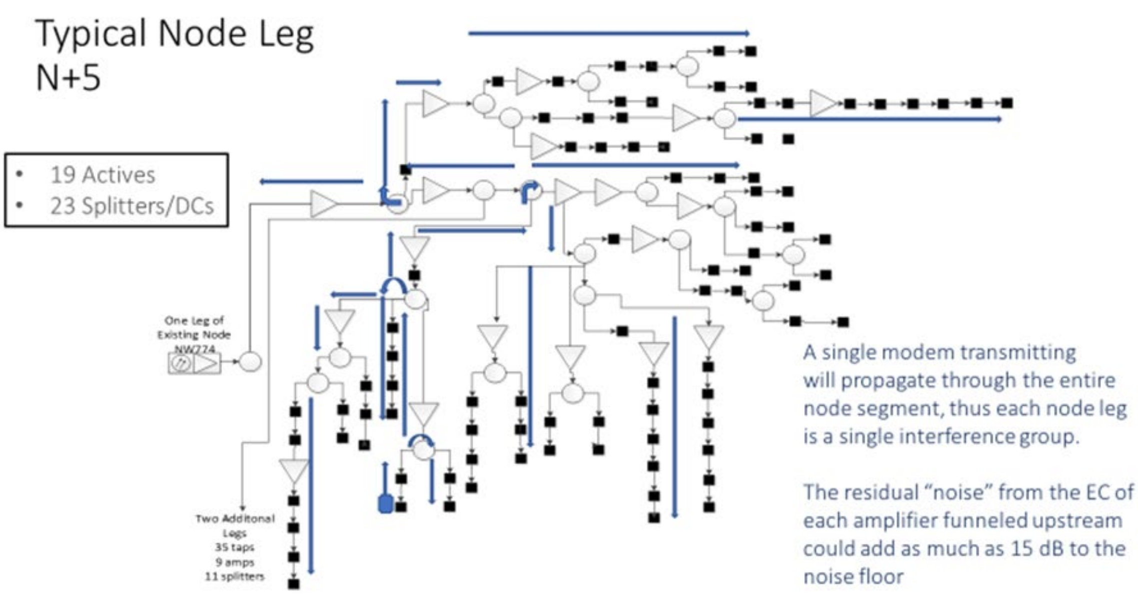


**Figure 6. Typical Node Leg**

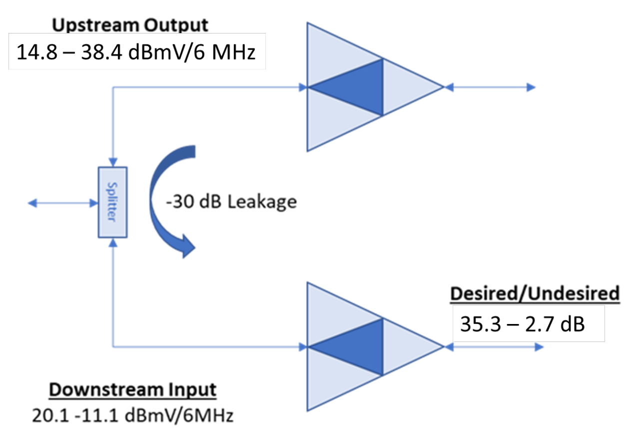


**Figure 7. Upstream Signal Leakage Into Adjacent Amplifier Downstream**

# FDX Amplifier Options

In order to implement FDX in an N+x environment, all actives must be replaced with FDX compatible devices. Three basic approaches for FDX amplifiers have been proposed:

## 1. A traditional high split or ultra high split (UHS) amplifier with diplex filter cutoff in the FDX band; 204, 300, 396, or 492 MHz.

This would allow FDX nodes and CPE to be used to provide extended upstream spectrum. Since all modems in a node leg in this example are in the same IG, simultaneous bi-directional use of the spectrum is not needed. We showed earlier that midsplit satisfies normal peak usage of a node, going to a higher split is needed to support higher billboard rates or to support ESD. Much of the time that additional upstream bandwidth will be unused. Further, the diplexer region grows proportionally with the upstream bandwidth, and all subtract from the downstream bandwidth. Figure 8 shows the approximate data rates available for each diplexer cutoff. The chart shows the potential upstream and downstream capacity assuming 2048 QAM D3.1 plus 32 D3.0 (256 QAM) carriers to fill the available spectrum downstream and 1024 QAM D3.1 upstream in the FDX band and four 6.4 MHz 64 QAM D3.0 carriers and one 1024 QAM D3.1 43 MHz BW block in the midsplit region. It also assumes that the plant was upgraded to the full 1.2 GHz FDX capability. Fractional D3.1 blocks indicate a block of less than 192 MHz. A 204 High Split can provide a limited 1 Gbps symmetrical service, but a 396 MHz UHS would be required to provide a 2 Gbps symmetrical service with a significant loss of DS capacity. It may be possible to have remotely switched diplexers that could switch between a lower split and a 396 UHS as demand requires.

**Table 1 Approximate Capacity with Traditional Diplexer**

| Upstream Freq (MHz) | FDX Blocks | US BW (Mbps) | Diplexer BW (MHz) | DS 3.1 Blocks | DS BW (Mbps) |
|---|---|---|---|---|---|
| | | | | | |
| Midsplit | 0 | 450 | 23 | 4.7 | 9000 |
| 204 | 1 | 1250 | 54 | 4 | 7800 |
| 300 | 2 | 2000 | 60 | 3.5 | 7000 |
| 396 | 3 | 2800 | 80 | 2.9 | 6000 |
| 492 | 4 | 3600 | 96 | 2.3 | 5000 |
| True FDX | 6 | 5100 | 0 | 4.7 | 9000 |

## 2. An amplifier using a triplexer design with a directionally switchable amplifier in all or part of the FDX band.

This design proposed by CableLabs overcomes some of the limitations of the previous approach in that the selected portion of the FDX band can be remotely switched from downstream to upstream, perhaps with proper signaling to form a time division mode of operation. This potentially introduces latency in that RBA changes are not instantaneous. Early discussions in the FDX WG considered time-division duplex (TDD) as a primary solution path, but the group formed a consensus against this path in part for this reason. However, the portion of the FDX band used is still fixed by the triplexer design and substantial bandwidth is still lost in the upper triplexer split. Figure 8 illustrates this design.

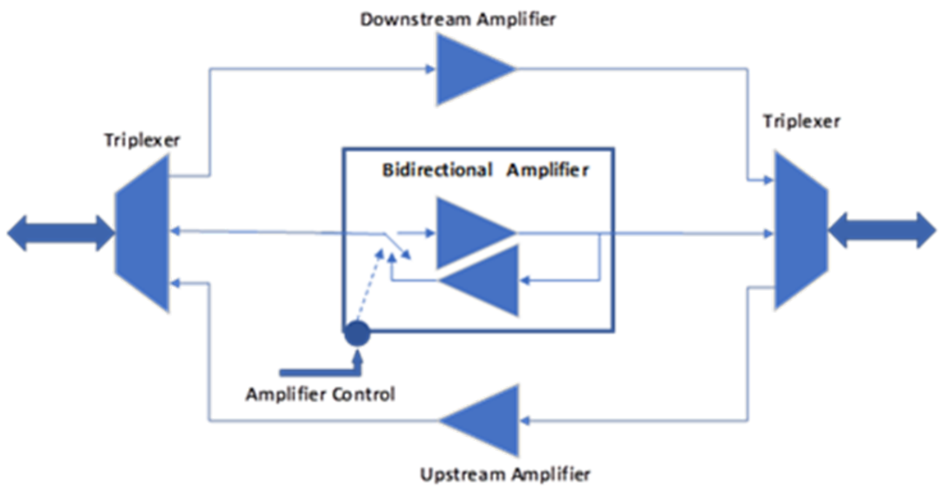


**Figure 8. FDX Amplifier Concept Using Direction Switchable Amplifier**

## 3. A true bi-directional FDX amplifier based on echo cancelation technology.

This type of amplifier uses the same echo cancelation (EC) technology that is used in the FDX RPD, except that there are two instances of EC used, one for the forward path and one for the reverse path as illustrated in Figure 9. This amplifier offers true bi-directional amplification throughout the FDX band. There is no loss of spectrum due to a diplexer region. There are however challenges in an EC FDX amplifier. EC is not perfect, there will be residual EC "noise" that will degrade the overall performance of the amplifier. This is a particular worry in the upstream direction where noise funneling from the cascade could significantly worsen upstream MER performance. A second major concern is amplifier stability. The loop gain around the amplifier, including any echoes from upstream and downstream components, must be less than one (0 dB) or the amplifier will oscillate. In order for that not to occur, the EC's must be trained prior to the amplifiers becoming operational.

The basic operation of EC is as follows. Consider the downstream port of the amplifier; the echo canceller samples the downstream amplifier in the FDX band to provide a reference signal and also samples the output of the upstream amplifier for training. Using a convolution process, the EC constructs a model of the leakage and echoes coming from the amplifier components and other components downstream. Using that model, it generates an out-of-phase replica of that echo that is combined with the input to the upstream amplifier, canceling the echo. The EC constantly monitors the output of the upstream amplifier and adjusts the model to minimize the resultant echo. The EC on the reverse port operates in a similar manner.

 

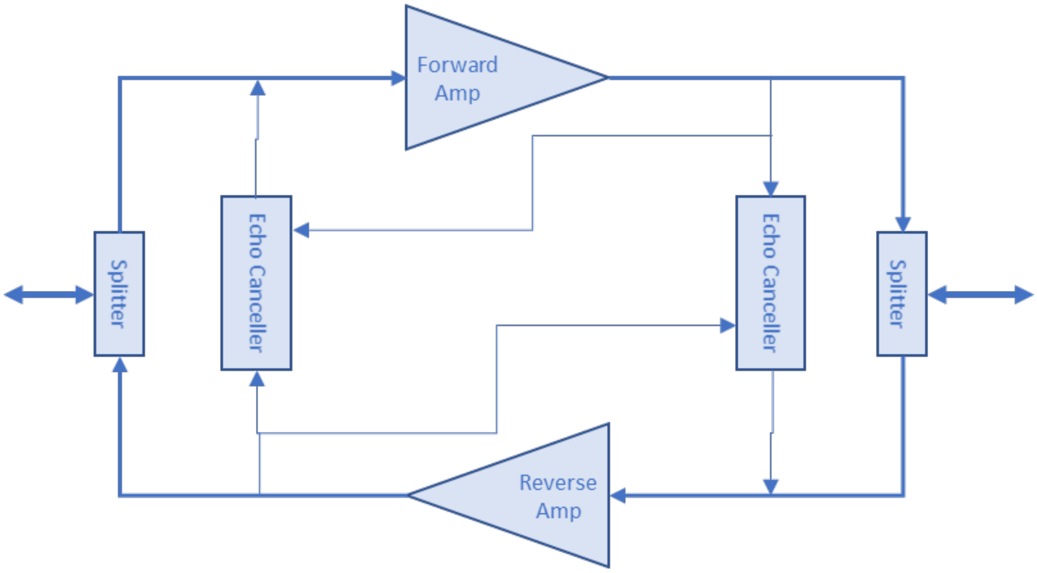


**Figure 9. Basic Echo Cancelling FDX Amplifier**

Current proponents for EC based amplifiers have proposed them to extend N+0 plant to N+1 or N+2. The focus of this paper is to understand the feasibility of using EC amplifiers in existing N+5 or higher plant.

# True EC FDX Amplifier Concepts

Two basic concepts for EC amplifiers have been explored as shown in Figure 10. The first is an analog implementation, in that the amplifier paths both forward and reverse are purely analog as in todays diplexed amplifiers. Additionally, the actual echo cancellation happens in the analog domain as well, in a directional coupler. Creation of the echo model and out-of-phase replica happens in a Digital Signal Processor (DSP) and it's associated D/A and A/D converters. Since echo cancellation is only needed in the FDX band, the digital converters and DSP only need to work below 700 MHz. However, since cancellation is done only in the analog domain there will be a limit to the amount of cancellation achieved.

The second concept is a more digital approach; the inputs of both the forward and reverse amplifiers are digitized and then converted back to analog before amplification. Like the analog approach, there is a first stage of analog cancellation to ensure that the A/D converters are not saturated by the echo and leakage levels. A second stage of digital cancellation in the DSP follows. Significantly higher levels of EC are obtained by this two-stage approach. Current designs for FDX nodes use this two-stage approach. Once both forward and reverse paths are digitized, there is significant flexibility in the processing that can take place such as gain control and equalization, or other functions such as upstream squelch to minimize noise funneling. A disadvantage of this approach over the analog is that the A/D and D/A converters have to digitize the full band downstream. For a full DOCSIS 4.0 compliant amplifier, this could mean digitizing the full band to 1.8 GHz with the inclusion of Extended Spectrum DOCSIS (ESD). To be compliant to the current DOCSIS 4.0 specification, which includes only the existing Full Duplex specifications at this time, this could be relaxed to 1.2 GHz.

Both approaches have issues that must be solved. As mentioned earlier, the loop gain around the forward and reverse paths must be less than one or the amplifier will oscillate. We will see in the next section that in order to achieve that requirement the EC's must be trained individually prior to the loop being closed.

 

While there are ways to do this in both designs, the greater flexibility of the digital design makes this more straightforward. Another problem with both designs is the zero-time echo. That is the echo associated with the leakage across the output splitter (or more likely, directional coupler (DC)) and from the connector on the amplifier occurs at almost zero time, so processing through the DSP and converter chain has to occur in near zero time in order to cancel that echo. A key issue is the level of EC needed to insure the SNR desired, both upstream and downstream which will be addressed in the next section.

Finally, for an EC amplifier to be viable, it's advantages over a diplexer-based amplifier must outweigh any cost or power disadvantage that it has introduced. In either approach, for both cost and power reasons, the DSP and converter functionality needs to be integrated into a single custom ASIC. FPGA implementations most likely would not meet cost or power requirements. Here the analog approach would seem to have the advantage in both cost and power. It has half the number of converters and operates at a significantly lower frequency, and since the main path is not digitized it's converters may not need to be as accurate. However, the added functionality of the digital approach including remote gain and equalization control, proactive network management (PNM) functions such as full band capture in both direction, and knowledge of return loss profiles in both directions, may outweigh the cost advantages of the analog approach.

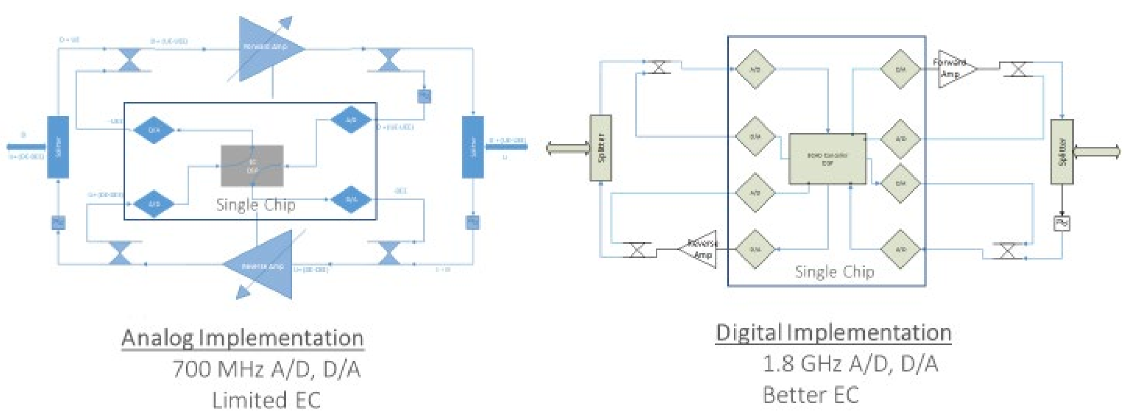


**Figure 10. FDX Amplifier Concepts**

# Echo Cancellation Requirements

For this exercise, High Gain Dual amplifiers have been analyzed since they contribute most heavily to both upstream and downstream noise and have higher gains. Similar requirements will apply to line extenders. The objective is to determine the level of echo cancellation required in order that the residual echo will not degrade the overall carrier to composite noise (CCN) of the node such that 2048 QAM OFDM will work downstream and 1024 QAM OFDMA will work upstream. Using the nominal input and output level of both forward and reverse paths, estimated CIN and carrier to thermal noise (CTN) performance of the amplifiers, plus a maximum reflected energy (echo) from the plant, the resultant SNR of combining thermal noise plus residual echo "noise" was calculated vs varying degrees of echo cancellation. For this calculation, the assumed value of maximum echo was -15 dB in both the forward and reverse directions from the amplifier.

Two scenarios were examined, the first was true FDX where the node is sending downstream on the same frequencies it is receiving upstream, and the second was an FDD mode where there is not simultaneous use of forward and reverse spectrum. In the first case, the full output power of the amplifier must be canceled such that the SNR of the input is not significantly degraded. In the second case the noise plus distortion products of the amplifier must be cancelled to that level. In this second case, active transmission only needs to be canceled to the point that it doesn't significantly affect the operating point of the amplifier. Figure 11 shows the worst-case calculated SNR for both upstream and downstream directions. Both the FDX and FDD scenarios are compared. Worst case performance in both scenarios occurred at the upper end of the FDX band.

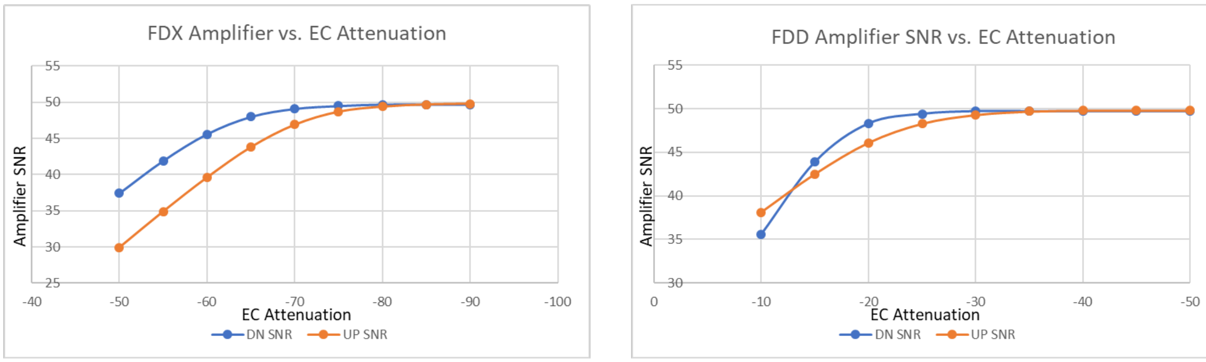


**Figure 11. Worst Case SNR vs. Echo Cancellation**

As can be seen, there is a dramatic difference in the degree of echo cancellation required in the two scenarios. The "knee" in the curve in the FDX scenario for both upstream and downstream EC's is about 75 dB. It is not known if this level of EC can be reliably achieved in an amplifier or if this level of isolation could be achieved in a single chip implementation. For the FDD case, both the upstream and downstream ports only require about 30 dB of echo cancellation. This value seems much more achievable.

A more detailed look at the full FDX case is shown in figure 12. Shown for a 75 dB EC, the upstream SNR and downstream SNR are plotted. The slight decrease in SNR versus frequency is due to the increasing power output with frequency and it's residual after EC. In the FDD scenario Figure 13 shows a similar result. Here the EC is 30 dB in each direction. An additional parameter is plotted here, the transmit leakage into the input side in of both the forward and reverse amplifiers. With significantly less EC than in the FDX scenario, the leakage of the active downstream and upstream paths into the opposite input path could contribute to the TCP of that amplifier. However, this result shows that at any given frequency that leakage is lower than the normal input signal and will not significantly contribute to the TCP of the amplifier.

In both cases the loop gain is well below 0 dB. The highest loop gain is in the FDD case where the worst-case loop gain is -28 dB. This will result in a low level ringing of the loop that will appear as low-level echo, easily handled by OFDM or the SC-QAM equalizer.

 

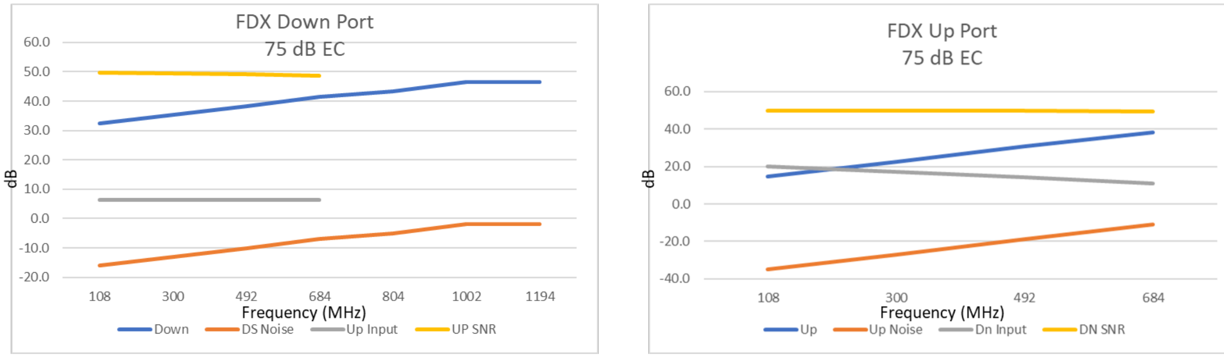


**Figure 12. FDX Scenario with 75 dB EC**

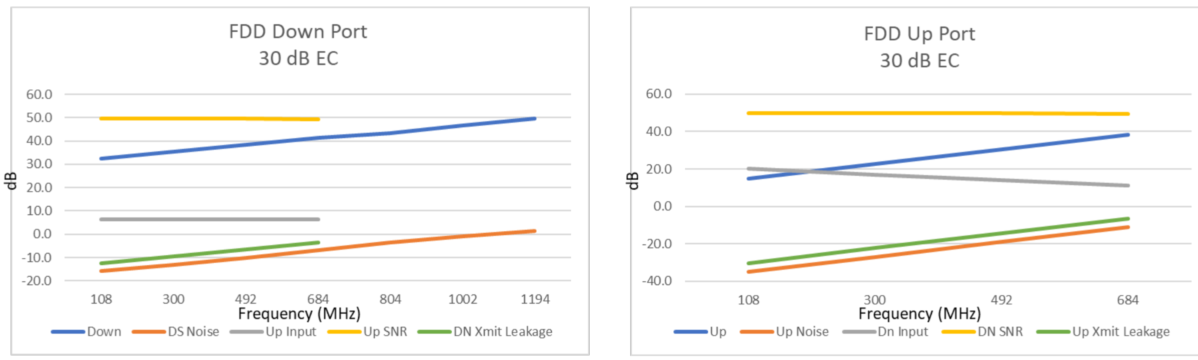


**Figure 13. FDD Scenario with 30 dB EC**

# The Case For FDD Operation

As shown earlier, each leg of a node in Figure 6 style N+x forms a single interference group, meaning all modems in that leg must be assigned the same FDX subbands for both upstream and downstream, operating in an FDD mode. If the RPD also operates in FDD mode, that is it will not transmit downstream on the FDX subbands assigned for upstream, then amplifiers with reduced EC capability can be used. There is no loss of capability in that leg since it is a single interference group. Such a mode, "static" FDX, is supported in DOCSIS 4.0.

It is possible to operate a node in full FDX, with each of up to four legs of a node being independent IG's and TG's. Modems on each leg now will be sharing the non-FDX spectrum so overall capacity of a leg will be reduced compared to each leg operating independently in FDD mode. Further, to operate in full FDX mode, each amplifier will have to support the much higher EC requirements. The cost of having separate RPD modules for each leg should be compared to the total cost of upgrading all actives, the potential of higher cost for the higher level of EC required to operate in full FDX mode, and the loss of capacity of having a single RPD in the node.

It is potentially possible to operate in a "dynamic" FDD mode where the upstream/downstream capacities are changed through an RBA message. Such changes could happen at millisecond time scales and react to demand requests from modems. This could allow for optimization of capacity utilization where both upstream and downstream capacities are scaled for normal busy hour with reserve bandwidth to support "Tmax" (maximum speed offered) billboard rates now shared between upstream and downstream, available on demand.

 

Dynamic FDD will likely require a specification enhancement. Current FDX specifications anticipate that the RPD, once provisioned, will transmit continuously downstream on the active FDX subbands. However, to operate in FDD mode, the RPD will need to mute downstream transmissions on subbands that are upstream. This will require an RBA-like message be sent to the RPD from the CCAP core and timed to be coincident with the RBA message to the modems.

There are a number of advantages of operating an FDX-based system in FDD mode with EC based amplifiers.

- First, it allows the operator to adjust his upstream/downstream splits as needed without touching the plant, only a configuration change at the CCAP core for static operation, or an RBA change for dynamic operation.
- There is no bandwidth lost in a diplexer region; this could amount to as much as a gigabit/sec of throughput for the higher splits.
- Legacy OOB operation will just pass through and is not affected.
- FDD operation reduces the EC requirements for both node and amplifiers. The EC requirements for full FDX operation in N+5 may not be achievable.
- The use of FDD rather full FDX simplifies operation in that sounding to establish IG's is not required.

# Conclusion

A potential path to the use of FDX in N+X plant has been described. Though both technical and cost challenges are present in the development of EC based amplifiers, they offer a number of advantages over fixed diplexer solutions. The use of dynamic or static FDD is shown to be a preferable solution over full FDX in an N+x plant, both from reduced EC requirements on the amplifiers as well as from higher overall capacity of the node. As the industry moves forward with DOCSIS 4.0 and extended spectrum, we urge the industry to push forward the development and the use of bi-directional EC based amplifier technology.

# Abbreviations

| | |
|---|---|
| A/D | Analog to digital |
| BW | Bandwidth |
| CAGR | Compounded annual growth rate |
| CCN | Carrier to composite noise ratio |
| CIN | Carrier to intermodulation noise ratio |
| CMTS | Cable modem termination system |
| CPE | Customer premis equipment |
| CTN | Carrier to thermal noise ratio |
| D/A | Digital to analog |
| dB | Decibel |
| dBmV | Decibel relative to one millivolt |
| DC | Directional Coupler |
| DOCSIS | Data over Cable system interface specification |
| DSP | Digital signal proccessor |
| EC | Echo cancellation |

 

| | |
|---|---|
| ESD | Extended spectrum DOCSIS |
| FDD | Frequency division duplex |
| FDX | Full duplex (DOCSIS) |
| GaN | Galium Nitride |
| GHz | Giga Hertz (10^9 Hz) |
| HFC | Hybrid fiber-coax |
| HHP | Households passed |
| Hz | Hertz |
| IG | Intrference group(s) |
| MAC | Media access control |
| MSO | Multi system operator |
| N+0 | Node plus zero actives |
| N+x | Node plus "x" actives |
| OFDM | Orthoganal frequency division modulation |
| PHY | Physical layer interface |
| RBA | Resource block assignment |
| RMD | Remote MAC PHY device |
| RPD | Remote PHY device |
| SC-QAM | Single carrier quadrature amplitude modulation |
| SCTE | Society of Cable Telecommunications Engineers |
| TCP | Total composite power |
| TG | Tansmission group |
| UHS | Ultra High Split |

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