FDX DOCSIS Line Extender

Deploying FDX DOCSIS Beyond N+0

A Technical Paper prepared for SCTE•ISBE by

John T Chapman
CTO Cable Access and Cisco Fellow
Cisco Systems
170 W Tasman Dr, San Jose, CA 92677
408-526-7651
jchapman@cisco.com

Hang Jin
Cisco Distinguished Engineer, Office of Cable CTO
Cisco Systems
170 W Tasman Dr, San Jose, CA 92677
469-255-2666
hangjin@cisco.com

Table of Contents

Title **Page Number**

List of Figures

Title **Page Number**

List of Tables

Title **Page Number**

Introduction

The 42 MHz (65 MHz for Europe) upstream return path is running out of bandwidth. The 90 to 100 Mbps it has today is enough to support the 1 Gbps DOCSIS downstream of today, but it is not enough to support the oncoming 10 Gbps DOCSIS downstream of tomorrow.

That means that the entire HFC plan will need to be upgraded to a new return path. There are multiple options available: 85 MHz and 204 MHz using classic FDD and up to 684 MHz using FDX DOCSIS. 85 MHz only offers 400 Mbps of bandwidth which could support a 4 Gbps downstream, assuming a 10:1 ratio in bandwidth, but is still not enough for a full 10 Gbps downstream.

FDX DOCSIS offers the most bandwidth possible in the return path with the least impact on forward path bandwidth. However, the cost of deploying FDX DOCSIS today is high as FDX DOCSIS currently is specified to work on an N+0 HFC plant whereas the 204 MHz does not required N+0. However, 204 MHz does require upgrading every single amp as well as the node. What if FDX DOCSIS could be deployed by also just upgrading the amps and nodes, rather than trenching new fiber for new node locations? This would make FDX DOCSIS be much closer to cost parity with 204 MHz. In fact, it could save operators billions of dollars. [1]

This white paper will show how FDX DOCSIS can be taken beyond N+0. It will do so by describing a deployment model that scalable and allows the cable operator to trade-off cost versus performance.

Deployment Model

1. FDX DOCSIS Background

Full Duplex (FDX) is a new option in DOCSIS 3.1 that was introduced via an ECN in DOCSIS 3.1 [2] [3] in October 2017. FDX DOCSIS is the result of highly innovative work in the cable industry [4][5][6][7][8][9][10] .

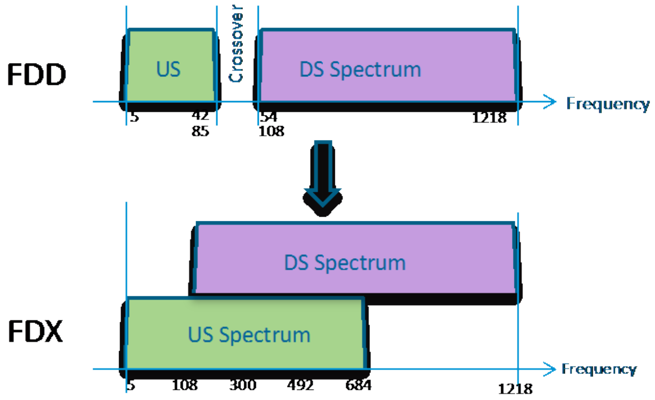


Figure 1 – FDX Spectrum

The fundamental premise of FDX DOCSIS is to share a common frequency spectrum between the Hybrid Fiber Coax (HFC) forward path and the reverse path. Note that when referring to the HFC fiber or coax paths, the terms “forward path” and “reverse path” are used. In DOCSIS, there is a “downstream” and an “upstream” path. With DOCSIS and HFC technologies being blended with technologies like Remote PHY, these terms tend to get used interchangeably.

The frequency spectrum sharing is shown in Figure 1. The spectrum plan for FDX DOCSIS is:

- 5 to 42 MHz: legacy upstream spectrum for DOCSIS 3.0/2.0/1.1 ATDMA
- 42 to 85 MHz: new upstream spectrum for ATMDA and/or OFDMA
- 85 to 108 MHz: cross-over band. Also used for OOB.
- 108 MHz to 684 MHz: shared downstream and upstream spectrum
- 684 MHz to 1218 MHz: downstream spectrum for DOCSIS and legacy MPEG Video

It is this shared spectrum that is unique for FDX DOCSIS. The current HFC plant is built on the principle of what is called Frequency Division Duplex (FDD), where the direction of the HFC plant is defined at a particular frequency. All optical nodes, coax amplifiers and line extenders (LE) today are built on those principles and contain diplexers that enforce this frequency division. FDX DOCSIS basically uses an echo cancellation mechanism instead of a diplexer.

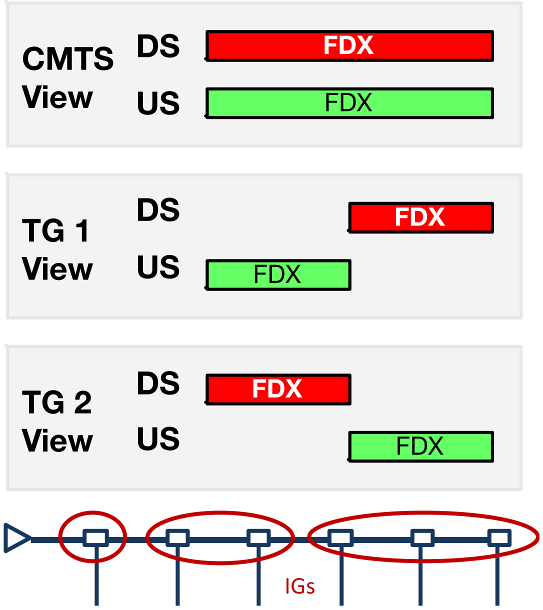


Figure 2 – FDX Operation

Here is a brief recap of how FDX DOCSIS works.

1. We echo cancel at the CMTS PHY.
    - This is a PHY operation that works beneath the DOCSIS 3.1 protocol.
    - The CMTS PHY is located in the Remote PHY Device (RPD) in the node
    - The RPD receives the upstream signal that also has the downstream signal combined with it. The downstream signal is effectively now noise in the upstream path. The downstream signal is higher in power than the upstream signal, so there is a negative signal-to-noise (SNR) ratio.
    - The RPD contains an echo canceller (EC) that subtracts the downstream signal from the upstream signal. The EC effectively attenuates the noise generated by the downstream

signal and creates enough positive SNR that 2K modulation will work.

2. We measure and sort CMs into interference groups (IG) and IGs into transmission groups (TG).
    - This is a MAC operation.
    - CMs use an EC to eliminate self-interference but cannot use an EC to eliminate interference from neighbors.
    - We measure the attenuation between all CMs and sort them into IGs. CMs within an IG can hear each other; CMs in different IGs cannot hear each other.
    - There are usually too many IGs to separately schedule, so we combine them into two or three TGs for scheduling purposes.

3. We use FDD within a TG so that those CMs do not interfere with each other.
    - Each TG is like a small DOCSIS 3.1 MAC domain with its own FDD frequency plan.

4. We overlap TGs in frequency and time so that 100% of the spectrum and 100% of the timeline are used for both DS and US.
    - Each TG is like a DOCSIS 3.1 island with its own unique FDD frequency plan
    - The sum of all the separate FDD frequency plan is an FDX frequency plan.
    - In the example in Figure 2, there are two TGs, each with the DS and US frequency spectrums swapped. When added together at the CMTS, it appears as if the entire DS and US spectrum is simultaneously used.

FDX DOCSIS was originally specified to work on a node plus zero amplifier (N+0) system where the node was redesigned to accommodate FDX DOCSIS. If FDX DOCSIS could work in say an N+2 system, then there is the potential to dramatically lower installation costs as there will be less additional nodes and less fiber pulled to those nodes.

In this white paper, we will look at redefining the HFC amplifier and HFC line extender (LE). In the HFC world, an HFC LE is a single output amplifier, where as an HFC amplifier has two or three outputs. Although this white paper will focus on the HFC LE use case, all these principles are extensible to an HFC amplifier.

2. Introducing N+M(T) Nomenclature

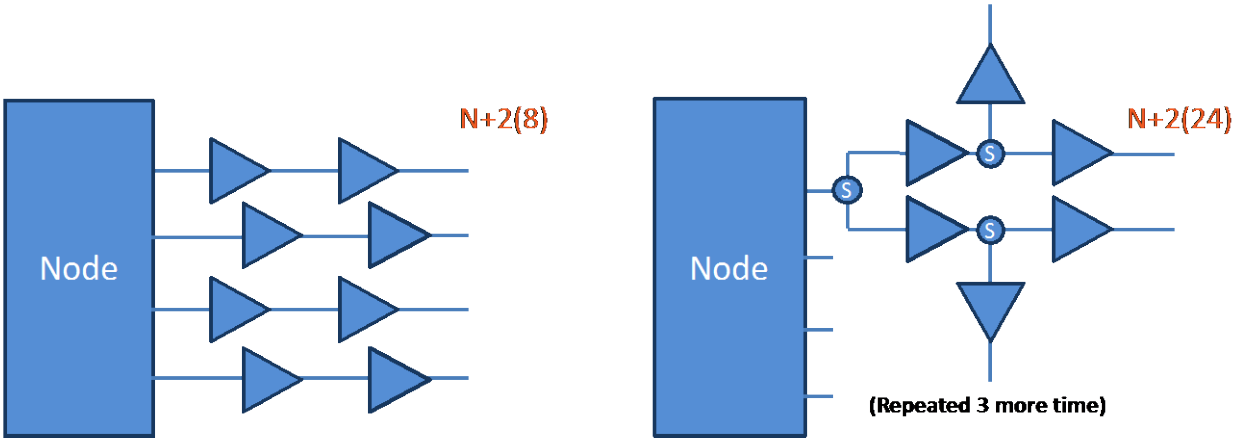


Figure 3 – N + M(T)

Before proceeding into the details of an FDX LE, we need to look at the HFC plant that the LE will be located in. Classically, an HFC plant is described by how many amplifiers exist in a chain from the node to a home. Thus, an N+2 HFC plant had a depth of two amplifiers from the node to the home.

For FDX DOCSIS, we will soon see that it is important to know not only the depth of the amplifier chain, but the total number of amplifiers as well. An example is show in Figure 3. Both systems are N+2 in that there are two amplifiers in any one downstream path. However, in the second example, the downstream path has been split and there is actually a total of six amplifiers, although only two in any one downstream path. The system on the right uses more amplifiers to be able to pass more homes but maintains the downstream signal quality by keeping the path length to two amplifiers.

While the downstream path is similar, from an upstream path viewpoint, it is quite different. There is a classic phenomenon in HFC called noise funneling where every extra upstream path adds more noise, and the total noise that is at the upstream path in the node is related to the sum of all the noise on all the paths.

One of the design criteria for FDX LE deployment will be to limit the total number of amplifiers and thus the total number of paths associated with those amplifiers. A proposed nomenclature to represent both the amplifier depth and the total number of amplifiers is:

$$N + M(T)$$

Where:

N = Node
M = amplifier depth from node to home
T = total number of amplifier outputs from a node to all homes serviced by that node.

So in the example in Figure 3, the system on the left is N+2(8) since there is two amps in any chain, but eight amp outputs in total, while the system on the right is N+2(24) since it is also two amps in any chain, but has twenty-four amps per node.

3. FDX Node Functional Model

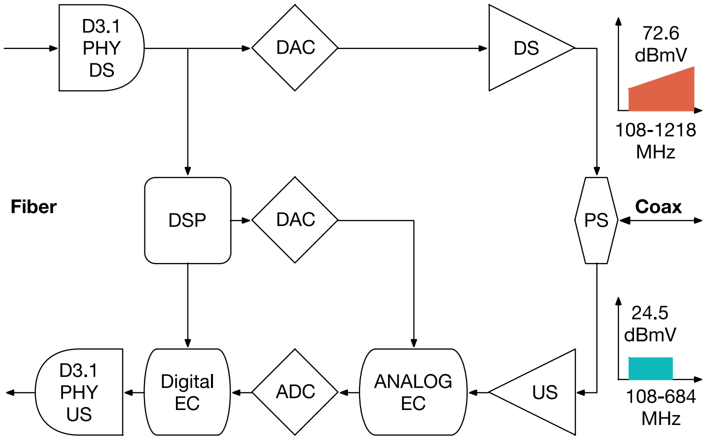


Figure 4 – Simplified FDX Node

A simplified diagram of an FDX node is shown in Figure 4. This diagram is meant to include the signal path that is comprised of the Ethernet over Optics, the RPD and the HFC node analog electronics.

The downstream path consists of the DOCSIS 3.1 modulation followed by a digital to analog converter and an amplifier path to a power splitter. Note the use of a power splitter instead of a diplexer. A diplexer would enforce an FDD frequency plan whereas a power splitter permits both the downstream and upstream spectrum to coexist.

The upstream path is received and buffered. At this point, the upstream path contains both the upstream and downstream signals. The downstream signal power is higher than the upstream signal power. This has an impact on the dynamic range of the ADC. To address this practical constraint, an analog EC is used to lower the interfering downstream signal level to be equal to or lower than the upstream signal level. The signal is then digitized and a digital echo canceller removes most of the rest of the interfering downstream signal such that the upstream signal can be recovered by the DOCSIS 3.1 upstream receiver.

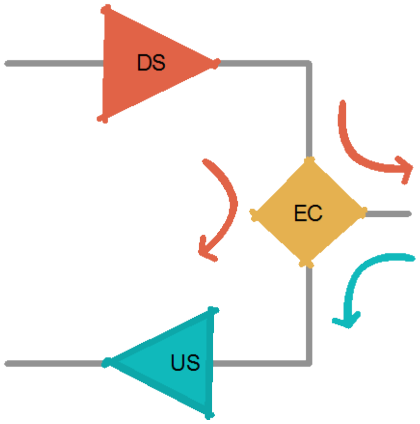


Figure 5 – Functional FDX Node

Even the simple model of Figure 4 can get overwhelming and contains more information that is needed for basic understanding and deployment analysis. Figure 5 represents a truly barebones functional model of an FDX Node. There is a downstream path, an upstream path, and an echo canceller separates the upstream spectrum from the downstream spectrum.

Now with this functional model of an FDX node, let’s move on to an FDX LE.

4. FDX LE Functional Model

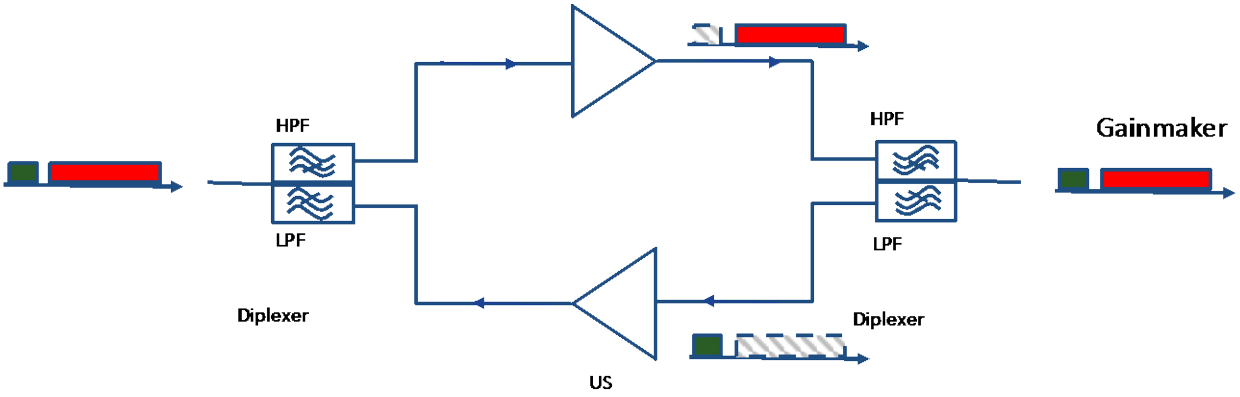


Figure 6 – Simplified Analog Line Extender

A simplified diagram of a classic HFC amplifier is shown in Figure 6. There is an amplified forward path and an amplified reverse path. A diplexer separates both paths on both ports. The amplifier is FDD based so that the forward and reverse paths do not interfere with each other and can be separated with passive filters.

What we have learned in an FDX node is that an echo canceller along with a power splitter can convert a bi-directional coax path into two separate forward and reverse amplified paths. If that is true, could two echo canceller circuits be placed back-to-back to create an FDX amplifier? To keep the diagram simple and to focus on the outcome, Figure 7 shows a functional model of an FDX LE.

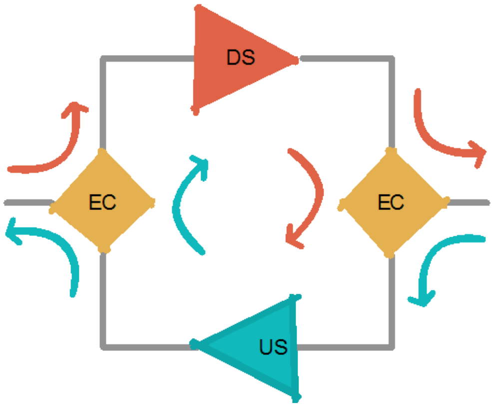


Figure 7 – Functional FDX Node

Does this work? In theory, if the echo cancellation was perfect, it should work just fine. In practice, what is required?

We can see in Figure 7 that the downstream signal leaks into the upstream path and results in noise that is attenuated by the reverse path echo canceller. By placing a forward path echo canceller on the northbound port of the amp, some of the upstream signal is reflected into the downstream path and results in noise that is attenuated by the downstream echo canceller. Note that some of noise in the downstream path could actually originate from the downstream path; that is downstream signal power that has been circulated and attenuated by both the forward and reverse path echo cancellers.

But what if the echo cancellers are not perfect? What if that energy kept circulating around the forward and reverse paths? If that happened, the whole system would become unstable. So, the echo cancellation performance must be good enough to ensure that this does not happen. As we will see in the section on Technical Considerations, that means that the echo cancellation level in each direction has to be on the order of 50 dB or more.

Assuming this can be built and that it works, what is the impact on performance? The answer is that the EC just becomes another noise source that needs to be managed and accounted for.

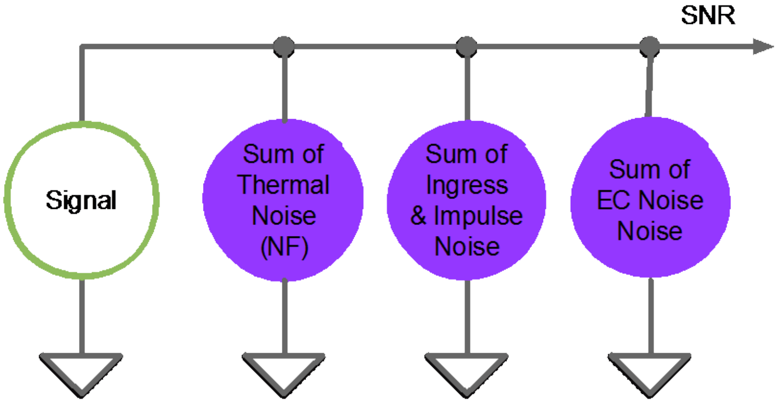


Figure 8 – FDX Noise Model

A simple noise source model is shown in Figure 8. This works for both the forward and reverse paths.

Each amplifier in the signal path contributes a noise floor which is determined by the thermal noise of the amplifier and is measured by the noise factor (NF). NF is one of the reasons that amplifier chains are limited to no more than 5 amplifiers in order to keep the noise accumulated noise floor low. Note that the thermal noise in each amplifier is not correlated, so the noise does not directly add in terms of dB.

Next is ingress noise. In the upstream, this tends to be lower frequency noise that can be across frequency or impulse noise and tend to come from homes. In the downstream, the ingress noise tends to be LTE energy (~700 to 800 MHz). This energy is very dependent on noise source location and bad connector locations, so the noise again is not always additive.

The EC noise in the upstream is always from the downstream path. It is the same signal, just delayed by different amounts at each EC. So, the energy is more additive, although the delay of each echo will impact that additivity.

For the forward path, the signal originates in the node. In the reverse path, the signal originates in the cable modem (CM). There is a fundamental difference in these paths when it comes to noise accumulation. The HFC forward path is a series of splitters. Thus the noise in any one path from the node to the home is contributed by that singular path. The HFC reverse path is a series of combiners. Thus the noise in the combined upstream path that arrives at the node is the combination of all noise sources in the upstream from all upstream paths. This is referred to as noise funneling.

That means that an N+2(8) system as shown in Figure 3 would have two amplifier noise sources in any one downstream path but eight amplifier noise sources in the singular upstream path. The N+2(24) system shown in Figure 3 would also have two amplifier noise sources in any one downstream path but 24 amplifier noise sources in the singular upstream path.

The exact noise models, their frequency dependencies, delay dependencies and additive properties will be left for future papers. For now, let’s assume that the thermal and ingress noise problems are already accommodated by the current network designs and that EC noise is additive. For the sake of example, let’s assign a value of 1.5 dB of noise contribution per EC.

Here’s the thing. What if we allow the system to get noisier in order to lower the cost of a system deployment? More noise can be managed by lower the modulation order which will lower throughput. Lower modulation orders mean lower throughput. Lower throughput results in lower cost. What is the right throughput versus cost ratio? That might be different for every operator and may differ from year to year.

We now have a scenario where cost can be traded off against performance.

5. FDX LE Basic Deployment Model

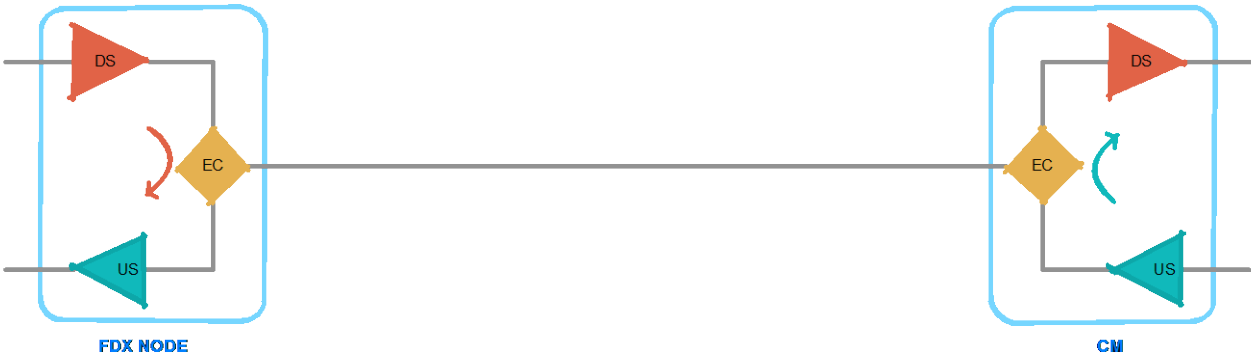


Figure 9 – FDX DOCSIS N+0

In the functional diagram Figure 9 we have an N+0 system where a node has an RPD with an FDX EC in the upstream direction. The shared spectrum is passed between the node and the CM over a passive networks of splitters and combiners known as taps (not shown). The CM has a single EC that separates the spectrums back into downstream and upstream paths. The total number of ECs in the path are two and there are two open loop EC paths.

This system has been carefully specified and designed to work in the DOCSIS 3.1 specifications. The performance targets are 4K modulation in the downstream and 2K modulation in the upstream.

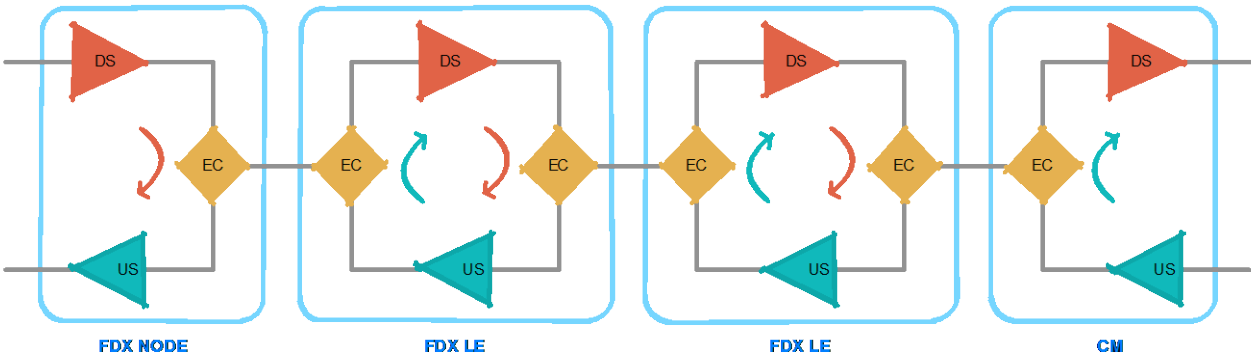


Figure 10 – FDX DOCSIS N+2(2)

In the functional diagram of Figure 10, two FDX line extenders have been inserted between the node and the CM. We are using the N+M(T) nomenclature introduced earlier to state that the amplifier depth is two and the total number of amplifiers is also 2. The total number of ECs in the path has been increased to six and there are now two closed loop EC paths and two open loop EC paths.

In this simple example, if we assume the ECs are doing their job, the forward and reverse paths will be intact and working. However, the noise floor will be elevated. In this basic example, we can see three EC noise contributions in the downstream path and three EC noise contributions in the upstream path. If each noise contribution is 1.5 dB, then the total noise contribution is 4.5 dB. If we subtract out the noise contributions at each end that are already included in the FDX N+0 design, the increased noise floor is 3 dB in each direction.

A 3 dB increase in noise floor can be managed by reducing the modulation order by one. *Thus, when compared to an FX N+0 system that is expected to work at 4K modulation in the downstream and 2K modulation in the upstream, this FDX N+2(2) system should be expected to work at 2K modulation in the downstream and 1K modulation in the upstream.*

That is a nice cost versus performance trade-off. How does this scale? What more trade-offs can be made?

6. FDX LE N+2(8) Deployment Model

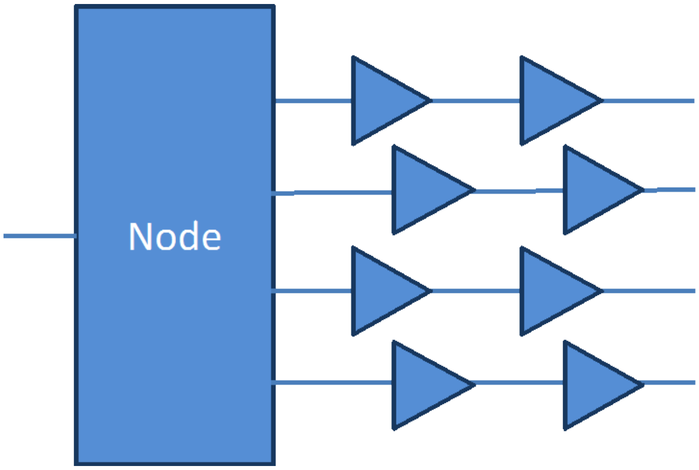


Figure 11 – FDX DOCSIS N+2(8)

Let’s now scale this example to a full four port node with two line extenders on each port for a total of eight amplifiers. The N+2(8) system is shown in Figure 11. The node itself is a splitting/combining system. The downstream spectrum is derived from a fiber input and split out to four outputs and the four return paths are combined into a single optical return path.

There may be some new examples to a node split/combine model when an RPD is present. If the RPD is a 1x1 configuration, containing one downstream port and one upstream port, then the split/combine model is the same as the analog optical node. If the RPD is a 2x2 or a 4x4 where node ports are truly independent of each other, then the node will perform as a segmented node and the four ports will not be combined. This analysis will assume a non-segmented node with a 1x1 RPD.

Doing the math for the upstream, there are eight amps and hence eight ECs dumping FDX related noise into the upstream path in addition to the one EC in the RPD in the node that is already accounted for. Eight noise sources at 1.5 dB each, assuming direct addition, would be 12 dB of increased noise floor. Dividing that by 3 dB per modulation level says that the modulation level must be taken down by four orders. The starting modulation for N+0 systems is 2K QAM which has an order of 11. Subtracting four results in a modulation order of 7 which is 128K QAM. This is shown in formula 1.

US Modulation Order = 11 – Ceiling[Total Amps * Amp Noise / 3 dB] **formula #1**

US Modulation Order = 11 – Ceiling[8 * 1.5 / 3] = 7 (128 QAM)

Doing the math for the downstream, we only care about amplifier depth and the starting point is 4K QAM which has a modulation order of 12.

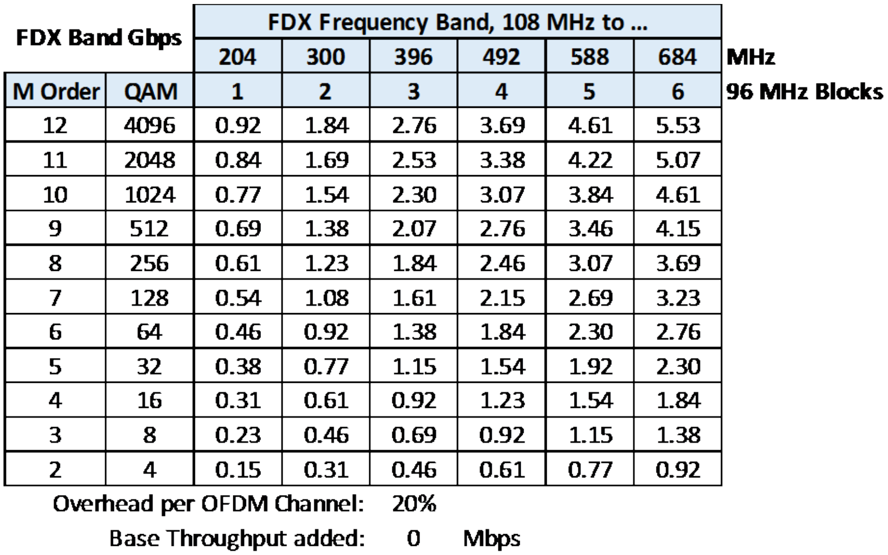
DS Modulation Order = 12 – Ceiling[Amp depth * Amp Noise / 3 dB] **formula #2**

DS Modulation Order = 12 – Ceiling[2 * 1.5 / 3] = 11 (2K QAM)

To translate these modulation order to throughputs, we have created a series of tables. Table 1 shows the throughput in the FDX DOCSIS band from 108 MHz to 684 MHz. The calculations in the table assume 20% total overhead between raw bits and packets and can be used for both the upstream and downstream direction. Keep in mind that for N+0 FDX operation today, the starting point is a modulation order of 11 for the upstream (2K QAM) and 12 for the downstream (4K QAM).

Table 2 is for a full upstream band and adds in 400 Mbps, 100 Mbps for 5 to 42 MHz and 300 Mbps for 42 to 85 MHz. Table 3 is for a full downstream band and adds in 4.91 Gbps, 3.68 Gbps for two more 192 MHz OFDM channels running at 4K QAM and 1.23 Gbps for 32 channels of 256-QAM, both with 20% overhead.

Table 1 – FDX DOCSIS 576 MHz Band Throughput



FDX Band Gbps		FDX Frequency Band, 108 MHz to ...						
		204	300	396	492	588	684	MHz
M Order	QAM	1	2	3	4	5	6	96 MHz Blocks
12	4096	0.92	1.84	2.76	3.69	4.61	5.53	
11	2048	0.84	1.69	2.53	3.38	4.22	5.07	
10	1024	0.77	1.54	2.30	3.07	3.84	4.61	
9	512	0.69	1.38	2.07	2.76	3.46	4.15	
8	256	0.61	1.23	1.84	2.46	3.07	3.69	
7	128	0.54	1.08	1.61	2.15	2.69	3.23	
6	64	0.46	0.92	1.38	1.84	2.30	2.76	
5	32	0.38	0.77	1.15	1.54	1.92	2.30	
4	16	0.31	0.61	0.92	1.23	1.54	1.84	
3	8	0.23	0.46	0.69	0.92	1.15	1.38	
2	4	0.15	0.31	0.46	0.61	0.77	0.92	

Overhead per OFDM Channel: 20%

Base Throughput added: 0 Mbps

Table 2 – FDX DOCSIS US Full Band Throughput

Total US Gbps		FDX Frequency Band, 108 MHz to ...						
		204	300	396	492	588	684	MHz
M Order	QAM	1	2	3	4	5	6	96 MHz Blocks
11	2048	1.24	2.09	2.93	3.78	4.62	5.47	
10	1024	1.17	1.94	2.70	3.47	4.24	5.01	
9	512	1.09	1.78	2.47	3.16	3.86	4.55	
8	256	1.01	1.63	2.24	2.86	3.47	4.09	
7	128	0.94	1.48	2.01	2.55	3.09	3.63	
6	64	0.86	1.32	1.78	2.24	2.70	3.16	
5	32	0.78	1.17	1.55	1.94	2.32	2.70	
4	16	0.71	1.01	1.32	1.63	1.94	2.24	
3	8	0.63	0.86	1.09	1.32	1.55	1.78	
2	4	0.55	0.71	0.86	1.01	1.17	1.32	

Overhead per OFDM Channel: 20%
Base Throughput added: 400 Mbps 20-85 MHz

Table 3 – FDX DOCSIS DS Full Band Throughput

Total DS Gbps		FDX Frequency Band, 108 MHz to ...						
		204	300	396	492	588	684	MHz
M Order	QAM	1	2	3	4	5	6	96 MHz Blocks
12	4096	5.84	6.76	7.68	8.60	9.52	10.44	
11	2048	5.76	6.60	7.45	8.29	9.14	9.98	
10	1024	5.68	6.45	7.22	7.99	8.75	9.52	
9	512	5.61	6.30	6.99	7.68	8.37	9.06	
8	256	5.53	6.14	6.76	7.37	7.99	8.60	
7	128	5.45	5.99	6.53	7.06	7.60	8.14	
6	64	5.37	5.84	6.30	6.76	7.22	7.68	
5	32	5.30	5.68	6.07	6.45	6.83	7.22	
4	16	5.22	5.53	5.84	6.14	6.45	6.76	
3	8	5.14	5.37	5.61	5.84	6.07	6.30	
2	4	5.07	5.22	5.37	5.53	5.68	5.84	

Overhead per OFDM Channel: 20%
Base Throughput added: 4914 Mbps (2 OFDM ch, 32 QAM ch)

In the N+2(8) example, the upstream could:

- reduce modulation order from 11 to 7 in the FDX band, so from 2K QAM to 128K QAM
- in the FDX band, it would reduce from 5.07 Gbps to 3.23 Gbps, a 36% reduction
- in full band, it would reduce from 5.47 Gbps to 3.63 Gbps, a 34% reduction

and the downstream could:

- reduce the modulation order from 12 to 11 in the FDX band, so 4K QAM to 2K QAM
- in the FDX Band, it would reduce from 5.53 Gbps to 5.07 Gbps, a 9.2% reduction
- in the DS full band, it would reduce from 10.44 Gbps to 9.98 Gbps, a 4.4% reduction

Here is where the cable operator can make trade-offs between cost and performance. If the service offering for the DOCSIS Service Group only needed say 5 Gbps down and 3 Gbps up, then this extra bandwidth was not needed and money can be saved by deploying a N+2(8) configuration rather than a N+0 configuration. Conversely, if the top performance is needed, then an N+0 network would have to be deployed.

Bear in mind that that these are theoretical numbers. The amplifier noise figure for FDX is purely a budget number and has not been measured. It could be better or worse. It has also not been proven or disproven if the noise is strictly additive. There is also unknown margin in the N+0 design that has not been accounted for. And one of the most interesting parts is that since DOCSIS 3.1 manages modulation profiles based upon measured SNR, DOCSIS 3.1 will automatically manage and optimize this for us.

7. FDX LE Maximum Model

This is always the next question – what is the maximum number of line extenders that could be deployed?

The design limit is obviously the upstream as it degrades faster since it is a function of the total number of amps instead of the number of amps in cascade. The answer in theory would be to run the FDX upstream spectrum at its lowest modulation level which is QPSK and reverse calculate the number of amps.

Also, it might be prudent to add an extra 3 dB of margin just to allow for SNR room when the network changes. The FDX network is constantly cancelling echoes. Those echoes can change due to physical conditions such as temperature, wind and vibration. So, when the plant changes and there are a large number of amps each changing at once, or at slightly different times, does this cause brief periods of increased noise floor?

Table 4 – Modulation Order vs Amp Count

Mod Order	Modulation	Throughput	#LE	#LE + 3dB
11	2K	5.47 Gbps	0	0
10	1K	5.01 Gbps	2	0
9	512	4.55 Gbps	4	2
8	256	4.09 Gbps	6	4
7	128	3.63 Gbps	8	6
6	64	3.16 Gbps	10	8
5	32	2.70 Gbps	12	10
4	16	2.24 Gbps	14	12
3	8	1.78 Gbps	16	14
2	QPSK	1.32 Gbps	18	16

The results are shown in Table 4. The approach uses the basic theory of the paper. It assumes a reference FDX N+0 system at 2K QAM as a baseline and then drops one order of modulation for every two LEs added to the system. The far right-hand column allows an additional 3 dB of system noise margin.

So, in theory, if 1.32 Gbps was sufficient performance for the deployment time period under review, then 16 to 18 amplifiers could be deployed. That could then support an N+2(16) system but would not support the N+2(24) system that was shown in Figure 3. Now if the system in Figure 3 was a three-port node with six amps per port, that would fit without the extra 3 dB of noise margin. Or, if N+2(16) was a four-port node with four LE (or amp equivalents) per port total, that could very well work.

When extending this concept to a two or three port line amp instead of a port extender, the question to ask is how many ECs are in a two or three port amplifier. Typically, the EC will be associated with the single north bound port and the two or three southbound ports are just separate amplified paths. In that case, the two or three port amp is equivalent to a LE load. If, however, the amp was designed with the EC on each southbound port, then there would be two to three ECs per amp which would then be equivalent to two or three LE loads. The net result is to count the EC noise sources, not the amplifier outputs.

Technical Considerations

8. Echo Cancellation Concepts

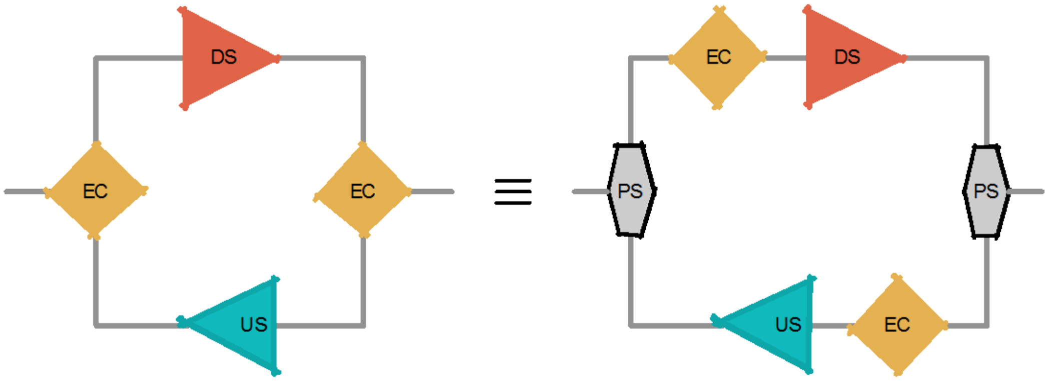


Figure 12 – FDX LE Partial Decomposition

Full Duplex transmission and echo canceller technology has been around in other technical venues such as telephony for a long time [11]. If we choose to re-use those concepts and definitions, there are a few worth noting.

Echo Return Loss (ERL)

ERL (dB) = Original Signal Level (dBm) – Echo Signal Level (dBm)

This is a measure in dB of the signal that is reflected back when compared to the signal being sent out. The correct use would be from a reference point in the downstream path to a reference point in the upstream prior to the EC.

Echo Return Loss Enhancement (ERLE)

ERLE is the additional echo attenuation provided by the echo canceller.

These values are shown in Figure 12. The point of having two separate values is the ERL embodies the reflections from the power splitter, the shell housing and the outside plant. ERLE is focused on the EC itself. The downstream signal will get attenuated by the combination of ERL and ERLE to create an upstream noise floor. As explained above, back-to-back echo cancellations need be implemented in FDX LE to cancel or suppress the echoes on both input and output ports. There are two types of EC techniques.

8.1. Analog EC

An analog EC is used to cancel out the echoes in the analog domain before the ADC. Conventionally, the analog EC will take a copy of the transmitted signal and manipulate its phase and magnitude to generate a canceling signal that has the same magnitude but 180 degrees out-of-phase from the echo. This canceling signal is then added to the receiver path to cancel out the echo. As there will be multiple echoes coming from multiple sources (FDX LE output connectors, taps, etc.), multiple cancelling signals need be generated, one for each echo. All these need to be done in the analog domain.

The analog EC used in FDX LE is actually a hybrid solution. The cancelling is still in the analog domain before the ADC to enable the benefits of analog EC, but the cancelling signal is generated in digital domain first and then converted into analog domain through a digital-to-analog converter (DAC). All the delays and magnitudes are computed and set in the digital domain through EC digital signal precessing (DSP).

8.2. Digital EC

Digital EC cancels out the echoes in the digital domain after ADC. After the echoes pass through the ADC and are converted into bits in digital domain, their magnitude and phase can be computed, and the cancelling signal can be generated from the transmitted reference signal with the proper magnitude and phase and subtracted from the received signal. Unlike analog EC which must be implemented in time domain, digital EC can be implemented in either time domain or frequency domain or combination of both.

8.3. Reference Signal for EC

The cancelling signal is generated from the transmitted signal with the proper magnitude and phase computed from the echoes embedded in the received signal. The transmitted signal used to generate the cancelling signal is called the EC reference signal. The theoretic base of the EC (both analog and digital EC) is that all the reflections are true copies of the same transmitted signal, just with various magnitudes and phases, depending on how the echoes are generated.

The same EC algorithm could be implemented for both input and output ports (back-to-back EC). One just needs to keep in mind that the reference signal used is different. For the input port, the transmitted signal is the US, and the received signal is the DS. Thus the reference signal for the input port EC will the US signal. On the contrary, for the output port, the transmitted signal is the DS, the received signal is US, thus the reference for the output port EC is the DS signal.

9. FDX LE Design Guidelines

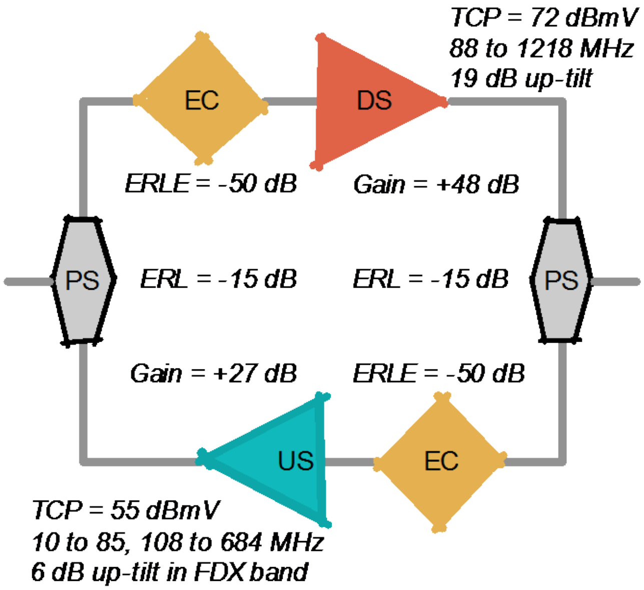


Figure 13 – FDX LE with Specs

There is no design specification for an FDX LE yet as this is a new device, so this white paper will propose some rough guidelines to help drive feasibility. The final values may vary.

9.1. FDX LE Specifications

Forward Path

- The downstream path frequency response is 88 MHz to 1218 MHz with 19 dB tilt
- The input power level is 0 dB and flat.
- If the LE had the same output power level as a FDX node, it would be 72.6 dBmV.
- Power could be dropped by 3.5 dB from 1002 to 1218 MHz if the output total composite power (TCP) is reduced to 71 dBmV
- Gain is 48 dB

Reverse Path

- US Frequency response
    - 10 MHz to 85 MHz, flat
    - 108 MHz to 684 MHz, with 6 dB up-tilt
    - 85 to 108 is notched out of the upstream path with DSP
- TCP output is 55 dBmV
    - Assuming to be the similar but less than a CM upstream output
- Gain is 27 dB

9.2. Echo Cancellation Performance Target

One of the design criteria for FDX LE is that the total close loop echo suppression must be greater the total close loop gain, as expressed as follows:

$$ERL1 + ERL2 + ERLE1 + ERLE2 > G1 + G2 + A \qquad \textbf{formula \#3}$$

Where ERL1 and ERL2 are, respectively, the Echo Return Losses of input and output ports, ERLE1 and ERLE2 are, respectively, the EC gains of input and output ports. G1 and G2 are, respectively, the forward and reverse path gains. A is the design margin. A needs to be >10dB.

If we design the gains of FDX LE as the same as a legacy LE, where the forward gain is <= 50dB and the reverse gain is <=30dB; And set A=10, we have:

$$ERL1 + ERL2 + ERLE1 + ERLE2 > 90\text{ dB} \qquad \textbf{formula \#4}$$

Then assume ERL1 and ERL2 are around 15dB (reflection from input/output connectors, taps), we have:

$$ERLE1 + ERLE2 > 60\text{ dB} \qquad \textbf{formula \#5}$$

With the state-of-art ADC/DAC, it is expected that each echo cancellation can achieve 50dB echo suppression (ERLE1/ERLE2 >= 50dB). Thus, 60 dB closed-loop echo suppression can be readily achieved.

Using the numbers in the above example and inserting into formula #3 and solving for A,

$$A = -15\text{ dB} - 15\text{ dB} - 50\text{ dB} - 50\text{ dB} + 48\text{ dB} + 27\text{ dB} = 55\text{ dB} \qquad \textbf{formula \#6}$$

This is much higher than the 10 dB we were looking for, so there appears to be plenty of design margin.

In practice, for this to work in a field deployment, the performance of each echo canceller must be:

- across the entire spectrum of FDX operation and for every subcarrier within that spectrum,
- across operating temperature, so -20 C to + 85 C (internal node temperatures),
- across device variations,
- across all deployment time,
- when switching EC coefficients.

Conclusion

In this white paper, we have introduced a technology and a deployment methodology to deploy FDX DOCSIS in networks with amplifier depths greater than N+0. We showed that a reverse path echo canceller that is in an FDX node today could be combined with a forward path echo canceller to create an FDX line extender (single port) or FDX amplifier (multi-port).

As each EC restores a forward or reverse path, it also introduces noise into that path. The existence of multiple ECs can mean degraded performance, since the noise in the downstream is the sum of all noise in a particular path and the noise in the upstream is the sum of all ECs in the upstream. That noise could be accommodated by adjusting the performance of DOCSIS 3.1 channels within the FDX band. Thus, the FDX LE and the FDX amp allows an operator to tradeoff deployment costs by having more amplifier stages past a node against throughput performance of that node.

We introduced a new terminology for measuring the depth and size of an HFC plant, N+M(T), where N referred to a node, D to the depth of the amplifiers, and T for the total number of amplifiers attached to the node.

A conservative example was given where an N+2(8) system. Assuming each LE inserted 1.5 dB of additional noise, and an extra 3 dB of operating margin, then the upstream throughput for FDX might be reduced from about 5 Gbps to about 2.5 Gbps which is still much higher than the 100 Mbps of today.

This example may be a worst case scenario since:

- The FDX LE may contribute much less than 1.5 dB of noise (these have not been built yet)
- The noise may not be strictly additive.
- There is design margin in the current FDX designs that has not been used in these calculations
- DOCSIS 3.1 Profile Management Application (PMA) will optimize the downstream and upstream performance.

The example could be a best case scenario as well as the HFC plant is not always a stable environment. When the HFC plant moves due to wind and temperature changes, the echoes may change as well which may then require a change in the EC coefficients. With more ECs, there are more coefficient changes in more places. Thus, there is a living, breathing HFC plant to be managed.

What is now obvious is that it is possible to extend beyond N+0 to at least N+1 and some N+2 HFC systems, and maybe even beyond that. This will lower the cost of an FDX deployment and allow a cost/performance trade-off to be made by cable operators on their network design.

Abbreviations

ADC	analog to digital converter
CM	cable modem
CMTS	cable modem termination system
DAC	digital to analog converter
dB	decibel
DOCSIS	Data Over Cable System Interface Specification
DS	downstream
EC	echo canceller
ERL	echo return loss
ERLE	Echo return loss enhancement
FDD	frequency division duplex
FDX	full duplex
Gbps	gigabits per second
HFC	hybrid fiber-coax
HPF	high pass filter
Hz	Hertz
IG	interference groups (used in FDX DOCSIS)
ISBE	International Society of Broadband Experts
LE	line extender (one port HFC amplifier)
LPF	low pass filter
Mbps	Megabits per second

N+0	node plus zero amplifiers
N+M(T)	node plus amplifiers with a depth of M and a total of T
NF	noise factor
OFDM	orthogonal frequency division multiplexing
PMA	Profile management application (used in DOCSIS 3.1)
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying
RPD	Remote PHY Device
SCTE	Society of Cable Telecommunications Engineers
SNR	signal to noise ratio
TCP	total composite power
TG	transmission groups (used in FDX DOCSIS)
US	upstream

Bibliography & References

[1] *HFC Evolution – The Best Path Forward*, by Nader Foroughi, Shaw Communications, SCTE Expo 2018 Fall Technical Forum, October 22, 2018

[2] *DOCSIS 3.1 Physical Layer Specification*, CM-SP-PHYv3.1-I15-180926, CableLabs, September 26, 2018, https://apps.cablelabs.com/specification/

[3] *DOCSIS 3.1 MAC and Upper Layer Protocols Interface Specification*, CM-SP-MULPIv3.1-116-180926, CableLabs, September 9, 2018, https://apps.cablelabs.com/specification/

[4] *Full Duplex DOCSIS*, by John T. Chapman & Hang Jin, Cisco Systems, INTX 2016 Spring Technical Forum, May 16, 2016, https://www.nctatechnicalpapers.com/Paper/2016/11-Jin

[5] *Interference-Aware Spectrum Resource Scheduling for FDX DOCSIS,* by Tong Liu, John T Chapman and Hang Jin, Cisco Systems, SCTE Journal, August 11, 2016

[6] *Interference Group Discovery for FDX DOCSIS*, by Tong Liu, Cisco Systems, SCTE Expo 2017 Fall Technical Forum, October 17, 2017, https://www.nctatechnicalpapers.com/Paper/2017/2017-interference-group-discovery-for-fdx-docsis

[7] *Echo Cancellation Techniques for Supporting Full Duplex DOCSIS*, by Hang Jin & John Chapman, Cisco Systems, SCTE Expo 2017 Fall Technical Forum, October 17, 2017, https://www.nctatechnicalpapers.com/Paper/2017/2017-echo-cancellation-techniques-for-supporting-full-duplex-docsis

[8] *Characterization of Spectrum Resource Scheduling in FDX DOCSIS, by* Tong Liu, Cisco Systems, SCTE Expo 2018 Fall Technical Forum, October 22, 2018

[9] *Full Duplex DOCSIS Technology over HFC Networks*, by Belal Hamzeh, CableLabs, INTX 2016 Spring Technical Forum, May 16, 2016, https://www.nctatechnicalpapers.com/Paper/2016/2016-full-duplex-docsis-technology-over-hfc-networks

[10] *Full Duplex DOCSIS PHY Layer Design and Analysis for the Fiber Deep Architecture*, Richard S Prodan, Broadcom, SCTE Expo 2017 Fall Technical Forum, October 17, 2017, https://www.nctatechnicalpapers.com/Paper/2017/2017-full-duplex-docsis-phy-layer-design-and-analysis-for-the-fiber-deep-architecture

[11] *Recommendation ITU-T G.168 Digital network echo cancellers,* ITU-T, April 2015, https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.168-201504-I!!PDF-E&type=items