FULL DUPLEX DOCSIS & EXTENDED SPECTRUM DOCSIS HOLD HANDS TO FORM THE 10G CABLE NETWORK OF THE FUTURE

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ABSTRACT

Hybrid Fibre-Coaxial (HFC) networks are in the best position to enable the future 10G networks, which are needed to support symmetrical services. Multiple technologies are available to augment the current capacities of HFC networks. Examples of these technologies are Full Duplex DOCSIS (FDX) and Extended Spectrum DOCSIS (XSD). This paper shows how these technologies are complementary in nature and explains how the XSD technology can use the same node technology and modem silicon chips that are currently being developed for FDX.

INTRODUCTION

Multiple System Operators (MSOs) are beginning to understand the bandwidth capacity requirements that they will need to compete within the 2020 decade. According to some, these bandwidth capacities may require 10 Gbps symmetrical services (or higher) by 2030. Supporting these higher bandwidth capacities will likely require several phased evolutionary changes over the next ten years. These evolutionary changes may ultimately require operators to consider a blended use of both FDX and XSD technologies. This paper will explore the details associated with some of these changes.

STATIC & DYNAMIC SOFT FDD

Frequency Division Duplex (FDD) can be viewed as a special case of an FDX operation. In particular, the Upstream (US) & Downstream (DS) spectra do not overlap in Frequency Division Duplexing (FDD) systems just like in today's HFC networks.

The introduction of FDX equipment will allow the US & DS spectra to overlap and therefore provide the ability to increase the US capacity without sacrificing the valuable DS spectrum. However, the FDX specifications [FDX_PHY] were created and optimised for Fibre Deep (FD) N+0 Distributed Access Architecture (DAA) systems. This provides a challenge to many MSOs because of the prohibitive cost that is associated with migrating the networks from N+x to N+0 architecture. (In this paper, N+x refers to a transmitting node followed by x chained amplifiers). Many MSOs will likely need a long time before arriving at N+0 network architecture. Therefore, CableLabs started a committee to focus on creating specifications for FDX amplifiers. FDX amplifiers will need to meet multiple requirements to be successful. These include low power, reasonable price, fit within the existing power/real estate amplifier housings, good Echo Cancellation (EC) performance, good isolation between the amplified US & DS paths, work in long cascades, etc.

One major challenge that is introduced by FDX amplifiers is the Interference Group (IG) elongation, which is a side effect of amplifying the US signals that can potentially interfere with other DS signals. Deploying FDX amplifiers will amplify weak US signals which will interfere with DS signals and therefore cause performance degradation to those DS signals. Figure 1 shows an example of the IG elongation problem for Model 1 when simulated for N+1 architecture. Adding more amplifiers will make the elongated IG in Fig. 1 even larger.

For example, in N+3 systems, all taps behind the second and third amplifiers will also be part of the large elongated IG. When most/all users are in one IG, then an FDX operation will not be feasible. Therefore, networks that deploy FDX amplifiers will likely need to be run in an FDD mode on that leg where the US and DS spectra do not overlap.

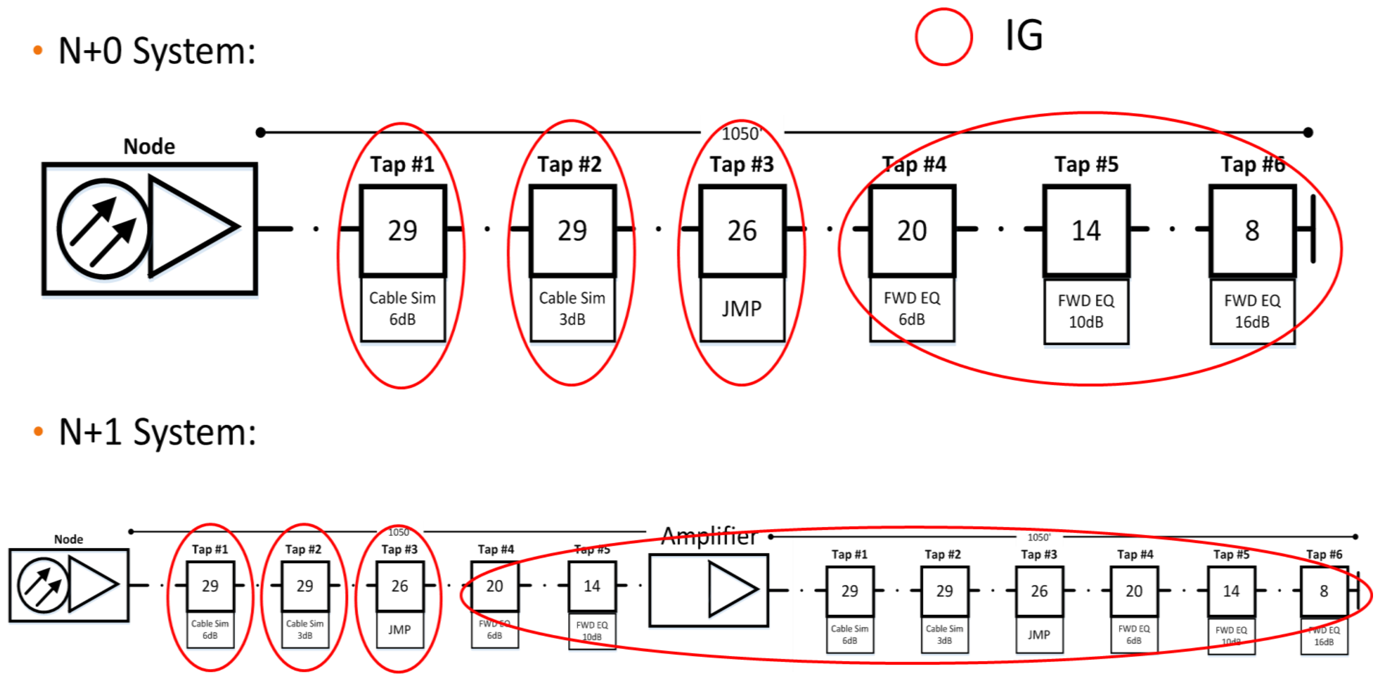

Figure 1 - IG Elongation due to FDX Amplifiers in N+1 system

If this is deemed undesirable by some operators, then they can consider using legacy FDD techniques instead of FDX techniques. The benefit that MSOs will get from this FDD-based deployment is the ability to change the US/DS split of the network via software in the node and FDX modems (aka Soft FDD mode), which will avoid rolling a truck to the node to change its configuration. This concept was originally proposed by ARRIS in the CableLabs Extended Spectrum DOCSIS (XSD) meeting in January of 2019 [XSD_Clabs] based on prior work to allow the utilisation of the FDX technology in N+x cascaded networks.

The follow-up questions are: What about the amplifiers? How can the split be changed in those amplifiers? Changing the split in the amplifier can potentially be done via multiple ways including the use of FDX amplifiers, switchable diplexer amplifiers, pluggable diplexer amplifiers, and embedded diplexer amplifiers.

The first two options above can allow changing the split via software configuration (Soft FDD). The last two options will need a visit to the amplifier location in order to change the diplexer or the module that contains the diplexer. Obviously, complexity and cost will be a factor in deciding which option the MSO may select.

If the MSO chooses to use one of the first two options, then Soft FDD operation on a system level can be supported. The US/DS split can be changed if/when needed. As a matter of fact, the split can be changed dynamically via software to yield a Dynamic Soft FDD operation. In this mode, the split can change dynamically to meet the demand in real time. For example, the split can be increased to 492 MHz to meet an US speed test and then switch back to, say, 204 MHz split to reclaim the DS spectrum after the US speed test is over.

The static and Dynamic Soft FDD modes can be supported using FDX-based equipment via utilising the Resource Block Assignment (RBA) messages, which are defined in the FDX specification [FDX_MULPI] and will allow the operator to configure a specific spectrum chunk to either US or DS direction dynamically over time. An example of how to do this is illustrated via Fig. 2, which shows the grid options that are supported in the FDX specifications [FDX_PHY].

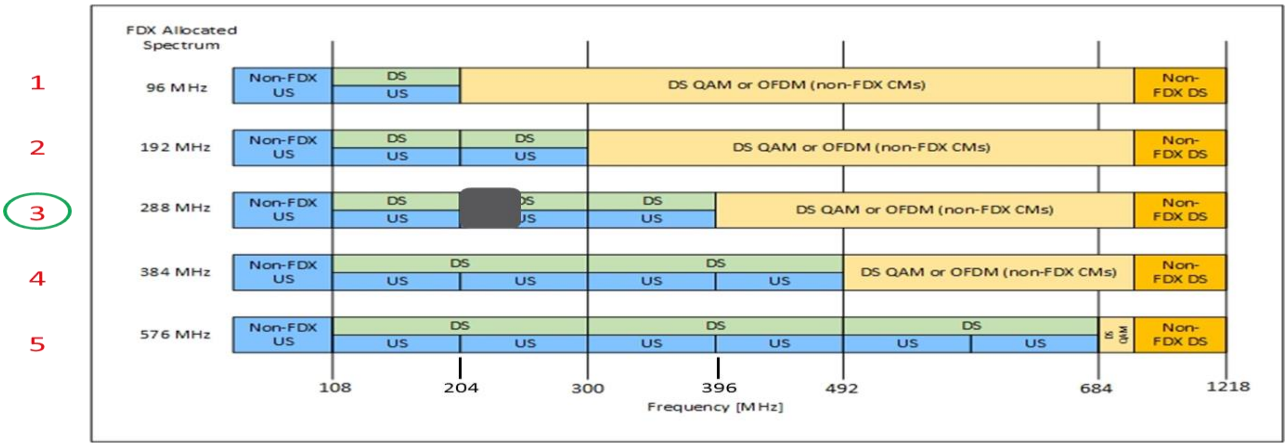

Figure 2 - FDX Grids used to change the split in Static/Dynamic Soft FDD operation

The example illustrated in Fig. 2 explains the configuration of a Static Soft FDD mode with 204 MHz US split using FDX-based DAA node. Assume that grid # 3 was selected and configured on the node. Note that depending on the type of the amplifiers in the network, those amplifiers could have a diplexer with a transition band from 204-258 MHz, which will not be usable. The configuration of the node at high-level follows these steps:
1) Configure an exclusion zone in 204-258 MHz. 2) All D3.1/FDX modems are assigned to the same IG/TG. 3) Node configures the RBAs such that 108-204 MHz always US and 300-396 MHz always DS (accessible by FDX CMs). 4) Decide on what to do with 258-300 MHz: Always DS - Accessible to FDX CMs and Exclude it & Use video and/or data SC-QAM. 5) Configure video and/or data SC-QAMs in 396-804 MHz.

If the node is to be run in a Dynamic Soft FDD mode where it will be switching between 204 MHz and 396 MHz splits, then the configuration of the node will follow these steps:
1) Configure exclusion zone to overlap with the transition region (if any) of the amplifier's diplexers. Assume this to be between 396 MHz and 465 MHz. 2) All D3.1/FDX modems

are assigned to the same IG/TG. 3) Node configures RBA such that 108-396 MHz always US. 4) Configure video and/or data SC-QAMs in 465-804 MHz.

Note that the exclusion zone effect can also be implemented via ‘unused’ subcarriers if the node does not support exclusion zone reconfiguration/movement without shutting down the channels. This is needed if the location of the split needs to be changed dynamically (i.e., Dynamic Soft FDD). Using the above configurations, the node can switch back and forth between 204 MHz and 396 MHz splits. Note that other splits are allowed using grid # 3 as well as using other grid options.

MODELLING EXTENDED SPECTRUM DOCSIS (XSD)

We now examine the potential capacity of existing cable infrastructure in Node+0 and Node+x architectures if the spectrum above 1218 MHz is used. We will mainly consider the impact on DS throughput, as the US capacity provided by mid-split, high-split and FDX up to 684 MHz are well known.

XSD in a Node+0 Architecture

A major consideration in evaluating the practicality of XSD is the RF power profile of the Downstream power amplifier, i.e. the Power Spectral Density (PSD) and consequent Total Composite Power (TCP) of the transmitter.

Traditionally, the aim of the HFC network architects has been to deliver a target RF power at the most remote (end of line or EoL) customer which is sufficient to provide an adequate SNR for 256-QAM (or at least 64-QAM) SC-QAM services across the entire frequency range. In fact, as the services carried on the SC-QAM channels are often loss-sensitive broadcast video streams, head-room may be required over the minimum received power per channel. As a result, the EoL PSD is ideally flat. As the attenuation of the coaxial cables and taps produces an (approximately) linear down-tilt which is only partly compensated by in-tap equalizers, the power amplifier (PA) is usually up-tilted at the transmitter, typically by 15-22 dB over the DOCSIS 3.1 DS frequency range.

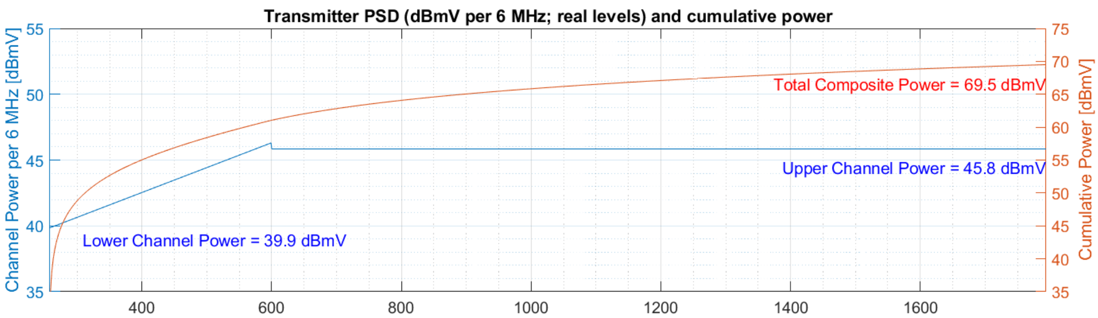

Figure 3 - Suggested PSD Profile and Total Power for XSD

However, when OFDM is employed, with the ability to vary the modulation per sub-carrier (“bit-loading”), the same constraints do not apply. Any supported modulation can be used at any frequency, and if the services are unicast IP rather than broadcast MPEG, the need for head-room is reduced. Therefore, it is not obvious that a flat EoL PSD is optimal. In fact, extending a typical “Fibre Deep” up-tilt out to 1.8 GHz or 3 GHz would result in a TCP of 85 dBmV or 107 dBmV respectively; these are clearly impractical. In previous publications [XSD_SpForum] the authors have shown that the optimum use of available RF power is in principle to provide a flat PSD *at the transmitter* and accept the resulting down-tilt at EoL. In practice, a slight modification of this profile is better, as the low attenuation at low frequencies (sub 500 MHz) would result in EoL SNR values in excess of those required for the maximum practical modulations (4K-QAM or possibly 8K-QAM, at which point other non-idealities become significant), so that the excess power is wasted.

For this reason, it may be wise to retain the traditional up-tilt at low frequencies; this has the additional advantage of permitting legacy SC-QAM and video services to be retained at these frequencies, if required. An example of the proposed PSD scheme is shown in Figure 3; the TCP in this case is 69.5 dBmV.

In a Node+0 architecture, the cable attenuation and tap frequency response are the principal limitations. Ideally, the taps would be upgraded to either 1.8 GHz or 3 GHz types, but this may be an expensive proposition. It is worth considering the performance that can be achieved in XSD while retaining legacy taps. We simulated a 1.8 GHz XSD system using 3 tap types, rated to 1.0 GHz, 1.2 GHz and 1.8 GHz. The EoL SNR and resulting bit-loading levels were calculated for several scenarios. All of these simulations were run with a transmitter TCP of 68 dBmV and 73.3 dBmV, and assume a high split with DS starting at 258 MHz; a 600-1200 foot (ft) hardline plus 100 ft drop cable with 5 taps is used in the model. While the 1.0 GHz taps produce a pronounced roll-off above 1 GHz, simulation shows that there is still useful throughput up to ~1.3 GHz. Similarly, the 1.2 GHz taps can be used out to ~1.6 GHz, although there is a “suck-out” at ~1.4 GHz. As expected, 1.8 GHz taps produce the best throughput, making a true 10 Gbps service achievable. The results of the simulations are illustrated in Figure 4.

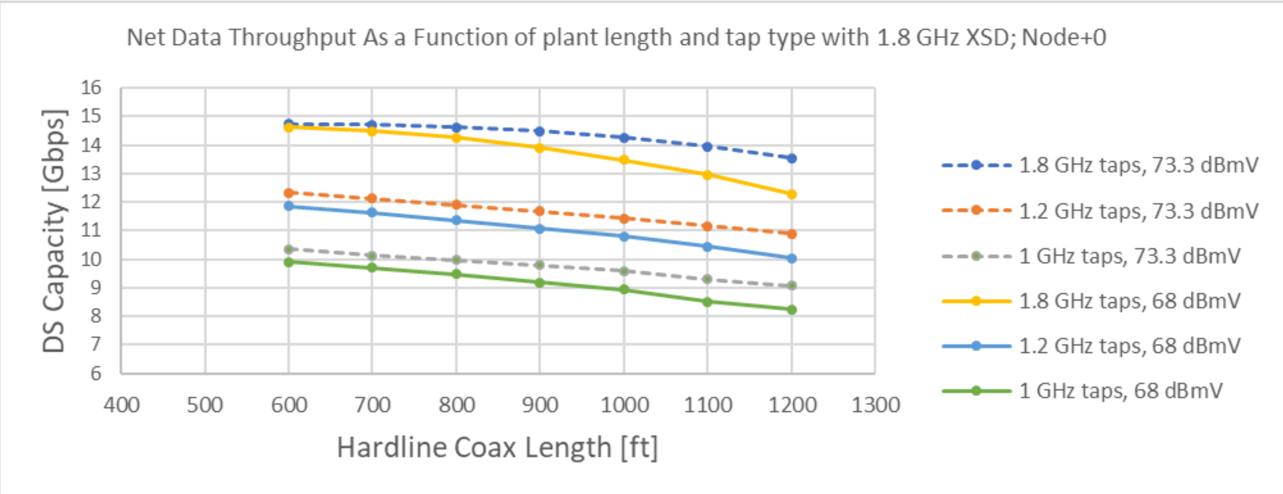

Figure 4 - XSD Simulation Results in N+0 Architecture

Similar approaches have been modelled and can be applied to 3.0 GHz systems of the future (and higher up to ~25 GHz), assuming that suitable tap designs become available or assuming that Fibre-To-The-Tap solutions are adopted. Throughputs of up to 25 Gbps are achievable with 3.0 GHz systems, and much higher throughputs are likely to be attainable with higher spectra.

XSD in a Node+x Architecture

The majority of MSOs still work with a Node+x architecture and are likely to continue with that for the foreseeable future. Here we will attempt to determine the performance of a Node+x plant using XSD. For Node+x, a critical decision is whether FDX is employed, and if so, what variety of FDX-compatible amplifiers will be used. Options include full echo-cancelling amplifiers, switched half-duplex, and Soft FDD (or “dynamic half duplex”) with or without guard bands. The first of these options requires digitization and re-generation of an analogue signal at every amplifier in a cascade; it is too early to determine what level of signal quality degradation would result from a cascade of such amplifiers, as potential implementations are still being evaluated. However, the half-duplex / Soft FDD amplifiers, particularly the versions employing guard bands, will have characteristics similar to those of current amplifiers. This analysis will assume the latter amplifier types are in use, so there is no difference from a straightforward FDD amplifier cascade.

Compared to a Node+0 architecture, we would expect two extra sources of performance degradation due to the amplifier cascade: 1) Accumulated noise from each amplifier stage, due to inter-amplifier attenuation bringing the signal towards the noise floor of the next amplifier. 2) Accumulated distortion from each amplifier due to its non-linear behaviour, especially when driving relatively high TCP signals.

While these two effects may appear similar, they can’t be lumped together, as distortion components are potentially coherent and aggregate differently compared to random noise. As a first-order approximation, we modelled the power amplifiers with a fixed SNR – implying a flat noise floor – and an average SDR (signal-to-distortion ratio) – implying a flat distortion level. Neither of these is strictly true, however, it allows us to examine the cascade effects qualitatively without needing precise RF models of every component used.

When the above-mentioned effects are added to the Node+x model, the effect is to degrade the EoL SNR. EoL received power per channel is largely unaffected, except for slight deviations from unity gain over each segment of the cascade. The resulting throughput is plotted in Figure 5 from Node+0 up to Node+10 for 3 values of SDR and 2 different distribution cable lengths, for the 1.8 GHz spectrum case. Similar behaviour was seen for a 3 GHz spectrum. In both cases, the TCP of the amplifiers are backed off slightly to 68 dBmV, for reasons discussed below.

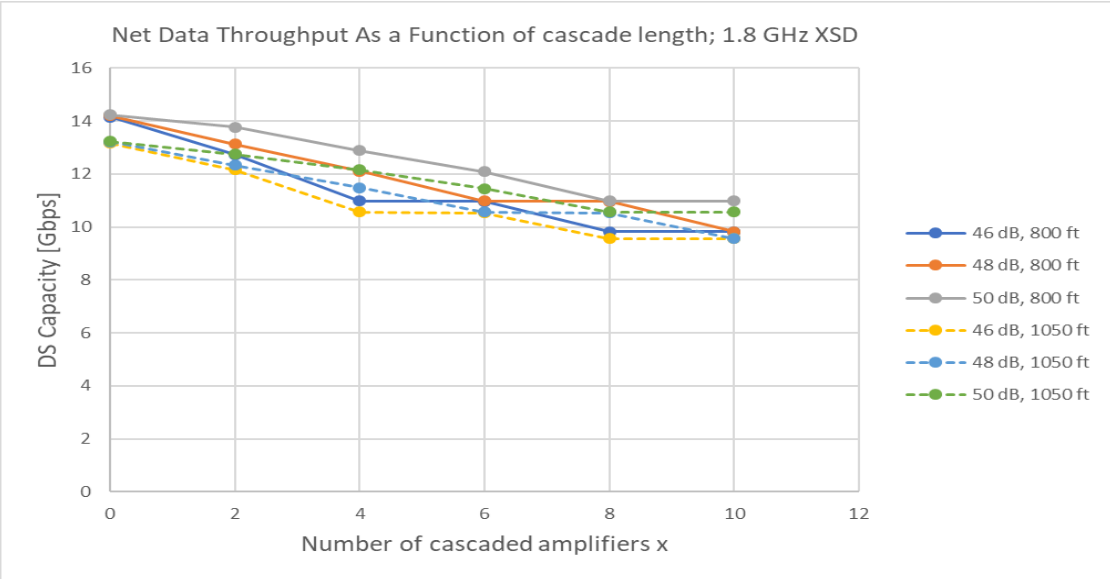

Figure 5 - XSD Simulation Results in N+x Architectures

Figure 5 shows that for short cascades (up to Node+2) and moderate distortion (SDR>48 dB) there is relatively little degradation and reduction in throughput (<5%). For longer cascades there can be significant degradation where the amplifiers are run at high TCP, producing high distortion and low SDR. For this reason, it is probably wise to run the amplifiers in the long cascade case at reduced power to achieve low distortion. Overall, though, a reasonable throughput can be achieved in long cascades, provided the SDR is sufficiently high. It's worth noting that, based on the traffic engineering calculations presented later in this paper, a 1.8 GHz XSD system has the potential to deliver 10 Gbps DS and 1 Gbps US services using a high split, while 3 GHz XSD could deliver symmetrical 10 Gbps services if a super-high split (e.g. 1.3/1.5 GHz) is used. Of course, if XSD is combined with FDX, even higher capacities could be achieved, provided that FDX amplifiers of sufficient quality become available.

BANDWIDTH EVOLUTION

We can use current bandwidth levels and growth rates to predict bandwidth requirements for the future HFC plant. If we ignore future traditional video bandwidth needs and focus on High-Speed Data Traffic in the Downstream (DS) and Upstream (US) directions, we can predict the results for a Soft-FDD & XSD solution in Table 1 and we can predict the results for an FDX & XSD solution in Table 2. These tables use a well-tested formula for Required Bandwidth Capacity given by [CL14] Bandwidth Capacity = Nsub*Tavg + 1.0*Tmax_max, where Nsub is the number of subscribers in a Service Group, Tavg is the average Bandwidth (in Mbps) used by the subscriber in the busy-hour, and Tmax_max is the largest Service Level Agreement Bandwidth level (in Mbps or Gbps). We also make the simplifying assumption that Symmetrical Service Offerings are desired beginning in 2020 (implying Downstream Tmax_max = Upstream Tmax_max).

Within these two tables, important points to observe include the following:

a) As the years progress from left to right, operators will likely extend the length of their fibre and reduce the number of amplifiers in the amplifier cascades. This leads to less homes passed per Service Group and less subscribers (Nsub) per Service Group.

b) The Average Upstream Bandwidth per subscriber (US Tavg) begins in 2020 at 300 kbps and increases at a rate of 25% per year.

c) The Maximum Upstream SLA Bandwidth per subscriber (US Tmax_max) begins in 2020 at 1000 Mbps and increases at a rate of 25% per year.

d) The Average Downstream Bandwidth per subscriber (DS Tavg) begins in 2020 at 2.8 Mbps and increases at a rate of 40% per year.

e) The Maximum Downstream SLA Bandwidth per subscriber (DS Tmax_max) begins in 2020 at 1000 Mbps and increases at a rate of 25% per year.

f) In a Soft-FDD environment, the required Upstream Spectrum ranges from 204 MHz to 1697 MHz over a 12-year period of time, whereas the Downstream Spectrum ranges from 440 MHz to 6013 MHz over a 12-year period of time. However, the MSO can continue to utilize a Node+1 architecture and can eliminate the expense of going to Node+0.

g) In an FDX environment, the required Upstream Spectrum ranges from 204 MHz to 1670 MHz over a 12-year period of time, whereas the Downstream Spectrum ranges from 317 MHz to 2936 MHz over a 12-year period of time. The MSO is required to utilize a Node+1 architecture operating in an FDX fashion. However, they can operate with equipment (such as nodes, amplifiers, and taps) using lower Downstream frequency ranges, which can also help eliminate some expenses.

Soft-FDD & XSD:	Year	2020	2022	2024	2026	2028	2030	2032
Plant Attributes:	Node Type (DSSG x USSG)	1x1	1x1	1x1	1x1	1x1	1x1	1x1
	Amplifier Cascade	Node+2	Node+2	Node+1	Node+1	Node+1	Node+1	Node+1
	# Homes Passed in Service Group	500	500	500	250	250	250	250
	Nsub in Service Group	240	240	240	120	120	120	120
Upstream BW:	US Tavg (Mbps) w/ 25% CAGR	0.3	0.4	0.6	1.0	1.5	2.3	3.6
	US Tmax_max (Mbps) w/ 25% CAGR	1000	1500	2300	3500	5400	8400	13100
	DS Req'd BW Capacity (Mbps)	1060	1594	2446	3614	5579	8679	13537
	Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5
	Top of US DOCSIS Spectrum (MHz) w/ 8 bps/Hz	204	300	396	492	684	1090	1697
Downstream BW:	DS Tavg (Mbps) w/ 40% CAGR	2.8	5.5	11	21	41	81	159
	DS Tmax_max (Mbps) w/ 25% CAGR	1000	1500	2300	3500	5400	8400	13100
	DS Req'd BW Capacity (Mbps)	1672	2817	4882	6030	10359	18119	32149
	Bottom of DS DOCSIS Spectrum (MHz)	240	353	465	578	804	1281	1994
	Top of DS DOCSIS Spectrum (MHz) w/ 8 bps/Hz	449	705	1075	1332	2099	3546	6013

Table 1 - Bandwidth Requirements with Soft-FDD & XSD

FDX & XSD:	Year	2020	2022	2024	2026	2028	2030	2032
Plant Attributes:	Node Type (DSSG x USSG)	1x1	1x1	1x1	1x1	1x1	1x1	1x1
	Amplifier Cascade	Node+2	Node+2	Node+1	Node+0	Node+0	Node+0	Node+0
	# Homes Passed in Service Group	500	500	250	125	125	125	125
	Nsub in Service Group	240	240	120	60	60	60	60
Upstream BW:	US Tavg (Mbps) w/ 25% CAGR	0.3	0.4	0.6	1.0	1.5	2.3	3.6
	US Tmax_max (Mbps) w/ 25% CAGR	1000	1500	2300	3500	5400	8400	13100
	DS Req'd BW Capacity (Mbps)	1060	1594	2373	3557	5489	8540	13318
	Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5
	Top of US DOCSIS Spectrum (MHz) w/ 8 bps/Hz	204	300	396	492	684	1072	1670
Downstream BW:	DS Tavg (Mbps) w/ 40% CAGR	2.8	5.5	11	21	41	81	159
	DS Tmax_max (Mbps) w/ 25% CAGR	1000	1500	2300	3500	5400	8400	13100
	DS Req'd BW Capacity (Mbps)	1672	2817	3591	4765	7879	13259	22625
	Bottom of DS DOCSIS Spectrum (MHz)	108	108	108	108	108	108	108
	Top of DS DOCSIS Spectrum (MHz) w/ 8 bps/Hz	317	460	557	704	1093	1765	2936

Table 2 - Bandwidth Requirements with FDX & XSD

EXAMPLE MSO MIGRATION SCENARIOS

The two tables above provide many insights into the various migration paths that MSOs may choose as they navigate the bandwidth capacity needs of the next decade.

In the Table 1 scenario, the MSO may opt to avoid any cost or power issues associated with recently-conceived FDX amplifiers and FDX nodes. Instead, the MSO may opt to use traditional FDD amplifiers which keep the Upstream and Downstream spectra separated by a 17.5% crossover diplex filter band. This approach can still utilize FDX chipsets within the modems and Nodes to offer 684 MHz Upstreams and 1.2 GHz Downstreams. Using Soft FDD functionality within nodes and amplifiers permits dynamic changes in the frequency of the FDD split, so this static FDX scenario can work quite well using currently-developing FDX chipsets until ~2025. In 2026, the Downstream spectrum is forced to move to frequency ranges above 1.2 GHz and begins forcing the use of XSD Downstreams with 1.8 GHz functionality in ~2026, 3.0 GHz functionality in ~2028, and 6.0 GHz functionality in ~2029.

In the Table 2 scenario, the MSO may opt to move quickly towards the bandwidth-sharing benefits of FDX chipsets operating in dynamic FDX mode. While this may lead to higher-cost and higher-power amplifiers and nodes, it helps MSOs deal with the rapid bandwidth growth by delaying the year when XSD functionality is required. With the Upstream and Downstream spectra overlapped in the FDX band's 108-684 MHz range, this Table 2 scenario can live with the Downstream staying within the 1.2 GHz spectrum until ~2028, which is three years longer than the Table 1 scenario. After 2028, this scenario would still require the use of XSD Downstreams providing 1.8 GHz functionality in 2029 and 3.0 GHz functionality in 2031.

Studying the pros and cons of the previous two scenarios may suggest benefits in a blended approach that utilises lower-cost and lower-power FDD amplifiers in the early years and then uses dynamic FDX in the later years. This blended scenario would start out in a fashion that is identical to the Table 1 scenario until 2025. In 2026, the MSO could node-split down to a Node+0 architecture and begin to use the dynamic FDX operation of the Table 2 scenario, which permits operation within 1.2 GHz until ~2028. In the end, XSD operation would still be required with 1.8 GHz functionality in 2029 and 3.0 GHz functionality in 2031. It should be noted that this approach uses lower-cost and lower-power FDD amplifiers until 2025, and then it eliminates all amplifiers and converts to Node+0 Dynamic FDX for the remaining years.

CONCLUSIONS

This paper illustrates that FDX and XSD can be used together in various fashions to provide MSOs with the 10 Gbps+ bandwidth capacity requirements that will be needed in the 2020 decade and beyond. Our simulations indicate that, with careful system design, XSD can produce useful capacity increases in Node+x systems. The critical factors which will enable this are the use of low-distortion, wideband, power amplifiers and the production of high quality 1.8 GHz and 3 GHz taps.

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