FDX & D3.1 Capacity Scenarios

Understanding overheads and RBA configurations

A Technical Paper prepared for SCTE•ISBE by

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Table of Contents

Title **Page Number**

List of Figures

Title **Page Number**

List of Tables

Title **Page Number**

Introduction

Full Duplex DOCSIS 3.1 (FDX) represents the next evolution of DOCSIS 3.1 (D3.1) technology, significantly increasing upstream capacity and enabling multi-Gbps symmetric service tiers over HFC networks.

Over the last many years, service offerings and IP capacity needs have continued to grow at a rapid pace. As a result, operators will require cost effective means of adding capacity to their HFC networks in order to provide the services that their customers will expect, eventually reaching gigabit and multi-gigabit speeds. D3.1 was designed to be a cost-effective way of meeting these performance targets, especially for typical consumption patterns where downstream consumption is much higher than upstream consumption. FDX is an evolution of D3.1 that increases the upstream capacity to similar levels as the downstream.

FDX fundamentally changes the nature of information delivery across the cable plant, and how it will be maintained and managed. FDX significantly increases the upstream capacity by enabling upstream and downstream channels to concurrently exist over the same spectrum without the need to time share the use of the spectrum. The upstream and downstream channels each fully access the same spectrum at the same time, practically doubling the use of the spectrum. Using D3.1 as a foundation, FDX accomplishes this by using a combination of interference cancellation and intelligent scheduling at the CMTS through enhancements to the existing D3.1 technology. This allows a migration path that allows operators to cost effectively migrate to FDX, while still maintaining and leveraging their existing installed base.

New FDX procedures such as sounding and echo cancellation happen at FDX initialization as well as periodically. The FDX channel may not be available for data transmission during this for some amount of time. These processes place some overhead on the raw bandwidth available. D3.1 allows for multiple OFDM/OFDMA profiles each tuned to account for plant conditions experienced by a set of CMs, using different modulation orders on the same channel. Aggregate channel capacity varies with the CMs and the profiles in use at a time. In FDX operation interference from other CMs, and Echo Cancellation training at the CM and at the FDX Node, the MER signature at the Node & CM will be different, the question is how the full duplex operation will affect the capacity of the channel and the network.

The FDX band is divided into sub-bands and the CMTS assigns sub-band(s) for upstream or downstream operation. Now this Resource Block Assignment (RBA), where a sub-band can change direction at a given time, directly impacts the available DS and US bandwidth seen by the CM in the FDX Band. Different CMs will have different bandwidth demand for both the upstream and downstream directions which can change over time, and FDX allows for the RBA to be changed dynamically to match. FDX CMs are grouped into Interference groups and Transmission groups each with a unique RBA.

This paper helps understanding how an operator can estimate US and DS capacity for FDX channels in different scenarios. The channel capacity affects how many subscribers can be assigned to use the same set of channels and affects traffic engineering and operational decisions (such as when an operator would need to split the node to increase available capacity). This paper presents a framework to understand the FDX/D3.1 downstream and upstream channel capacities across a range of MSO operational scenarios.

FDX Overview

1. FDX Overview

Full Duplex DOCSIS 3.1 (FDX) technologies significantly increases the upstream capacity by enabling upstream and downstream channels to concurrently exist over the same spectrum without the need to time share the use of the spectrum. The upstream and downstream channels each fully access the same spectrum at the same time, practically doubling the traffic-carrying capacity of the spectrum. Using D3.1 as a foundation, FDX accomplishes this by using a combination of interference avoidance, echo cancellation and intelligent scheduling at the CMTS. The evolution to an FDX network is an incremental evolution of D3.1 technology and will support both backward compatibility and coexistence with previous generations of DOCSIS technology deployments.

The FDX band will occupy a subset of the RF spectrum, 108-684 MHz. The FDX spectrum is divided into one, two, or three sub-bands. Each sub-band contains 1 OFDM downstream channel and 1 or 2 upstream OFDMA channels. From the CMTS perspective, traffic will be simultaneously flowing upstream and downstream in each sub-band. From the CM perspective, the spectrum will still be frequency division multiplexed, i.e. each CM will use a sub-band only for upstream or downstream operation for a given time. But one set of CMs can use the sub-band for upstream at the same time that a different set of CMs has been assigned to use that sub-band for downstream.

In order to transmit and receive at the same time in each sub-band, the CMTS/FDX Node will use echo cancellation techniques to separate the upstream and downstream transmissions. An FDX Node supports simultaneous upstream and downstream communications over each FDX channel enabled by echo cancelation techniques for self-interference and echo-cancellation. FDX cable modems will operate in frequency division duplexing (FDD) mode, where on any FDX sub-band, the CM is either transmitting in the upstream or receiving in the downstream. An FDX CMTS allocates FDX channels to cable modems by providing modems access to upstream and downstream channels through FDD; a CM's operation on an FDX band in either US or DS can be changed by the CMTS. FDX channels can be bonded with non-FDX channels and with other FDX channels.

Due to the lack of complete isolation between a pair of CMs, if one CM is transmitting in the upstream in one sub-band while another CM is trying to receive in that same sub-band, energy from the first CM upstream transmission can leak into the location of the second CM and prevent it from successfully receiving downstream transmissions. Simultaneous transmission and reception within the same frequencies in different interference groups introduces co-channel interference (CCI) lowering spectral efficiency.

Adjacent Leakage Interference (ALI) refers to the power that leaks from an upstream transmission of the CM into a downstream channel of the same CM in another part of the FDX spectrum. The CM has to transmit at a relatively high-power level to be received by the FDX Node, and as a result the power of the out-of-band components of this upstream transmission are comparable to the power of a downstream signal in an adjacent channel at CM input. Some of this upstream out-of-band power gets coupled into the receiver path through the coupler within the CM. Further out-of-band power gets added to the received signal through reflections in the drop cable and at the connection with the main cable. The sum of all these out-of-band components of the upstream transmission that gets added to the downstream signal is referred to as ALI.

Adjacent Channel Interference (ACI) refers to the power that remains in the same band as the transmitted signal but gets added into the receiver path through the coupler within the CM as well as through reflections in the cable and its taps. This is significantly stronger than ALI, but it is not an in-band interference like ALI. Its main effect is in overloading the receiver circuitry. Hence precise cancellation is not needed as in the case of ALI, though some cancellation is beneficial to reduce the load on the receiver and analog-to-digital conversion circuitry. In the context of FDX, this ALI and ACI are interferences resulting from upstream transmissions of the specific receiving CM, and hence these can be categorized as self-ALI and self-ACI, respectively. The reception at a CM can also be impacted by ALI and ACI from upstream transmissions of other CMs in the cable plant, in particular, other CMs in the same IG.

To avoid the risk of co-channel interference (CCI) and adjacent channel interference (ACI) between CMs, the CMTS schedules transmissions and grants such that a CM does not transmit at the same time as other CMs that are susceptible to interference and are receiving. CM to CM interference susceptibility is measured through a sounding process. A sounding method is used to identify groups of CMs, called Interference Groups (IGs), that would interfere with each other if they were allowed to transmit and receive at the same time in a sub-band. After measuring CM to CM interference susceptibility, the CMTS creates IGs, and schedules transmissions and grants to CMs to avoid having a CM transmit when other CMs in its IG are receiving.

IGs will be grouped together into a small number of Transmission Groups (TGs). These TGs will be used to load balance the upstream and downstream traffic within each sub-band. Each TG will be given a Resource Block Assignment (RBA), which assigns the direction of traffic in each sub-band for that TG. A TG can use some sub-bands in the upstream direction while using other sub-bands in the downstream direction. While a TG can only use a sub-band in one direction at a given time, the RBA for a TG can be changed, allowing the direction of traffic for that TG in the sub-band to be changed. The CMTS coordinates the change of the RBA to ensure that the traffic in one direction is stopped before starting traffic in the opposite direction in order to prevent interference.

There is a significant difference in power levels between data transmission and reception at a given CM. Normally, diplex filters keep the upstream channel transmissions from interfering with neighboring downstream channel reception in the CM. However, FDX CMs will not have diplexers between FDX sub-bands, in order to allow the CM to efficiently change the direction of the spectrum in a sub-band. In order to prevent upstream channel transmissions from interfering with adjacent downstream channels in the CM, the CM will use echo cancellation techniques to reduce the upstream interference ACI & ALI. Because the CM does not have control over downstream transmissions, the CMTS will assist in coordinating upstream and downstream transmissions to allow the CM to train its echo canceller.

1.1. FDX Frequency Plan

The FDX Band refers to the spectrum where FDX operation can occur. Occupied FDX Band refers to the part of the FDX Band where FDX operation is occurring, this can be a subset of the FDX Band. FDX Downstream Channels are downstream channels in the Occupied FDX Band. FDX Upstream Channels are upstream channels in the Occupied FDX Band. FDX Sub-band refers to a single FDX Downstream Channel and the associated FDX Upstream Channel(s)(1 or 2) sharing the same spectrum.

The frequency range defined for FDX is 108 MHz to 684 MHz. The upper limit of 684 MHz is derived from starting with the lower band edge of mid-split (108 MHz) and allowing for three OFDM channels at 192 MHz

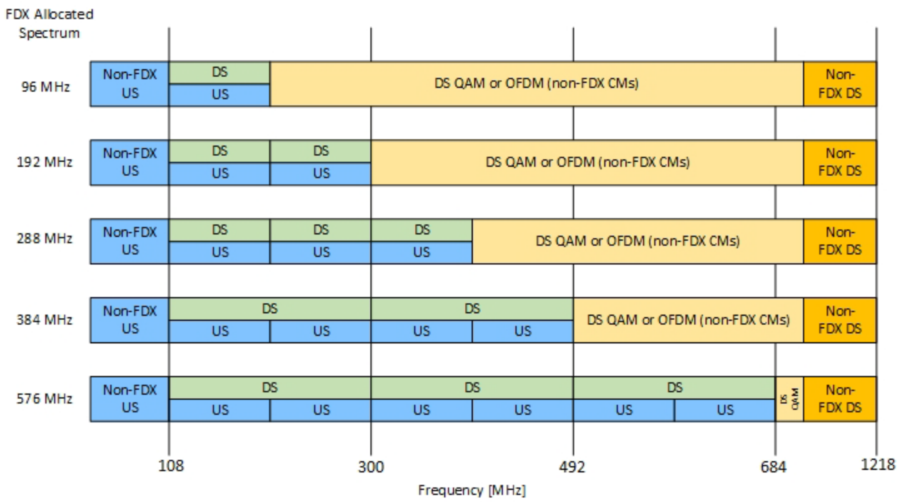


Figure 1 – FDX spectrum

The FDX CM can receive 4 total OFDM channels both FDX and non-FDX combined and optionally may support 5 OFDM channels. The FDX Node/CMTS support a minimum of 6 independently configurable OFDM channels.

The FDX CM supports a minimum of 7 independently configurable OFDMA upstream channels. The FDX Node /CMTS supports 8 configurable OFDMA upstream channels, each occupying a spectrum of up to 95 MHz.

FDX CMs are new purpose built CMs, and are designed with hardware and software capable of supporting FDX functionality. A D3.1 CM can be software upgraded to support a number of features in order to be capable of handling limited FDX functionality, these CMs are known as FDX-L CMs. FDX-L CMs are D3.1 CMs software upgraded with limited capabilities for operating within the FDX Band. Since there are two types of D3.1 CMs: mid-split and high-split, those are the flavors of the FDX-L CMs.

There are three FDX Operational Modes in the Occupied FDX Band.

- FDX-only: only FDX CMs in operation.
- FDX/High-split Coexistence : FDX CMs and high-split FDX-L CMs operate simultaneously.
- FDX/Mid-split Coexistence : FDX CMs and mid-split FDX-L CMs operate simultaneously

FDX CMs can transmit or receive in any FDX Sub-band and any FDX Operational Mode. In FDX/High-split Coexistence mode, high-split capable FDX-L CMs can transmit in FDX Sub-bands located up to 204 MHz and can receive in FDX Sub-bands that are positioned at or above 258 MHz. In FDX/Mid-split Coexistence mode, mid-split capable FDX-L CMs can receive in any FDX Sub-band.

1.2. FDX Initialization Overview

An FDX-capable CM first becomes operational as a D3.1 CM. The FDX-specific CM initialization is commenced under direction of the CMTS. The FDX initialization needs to be complete before the CM can transmit or receive data within the Occupied FDX Band.

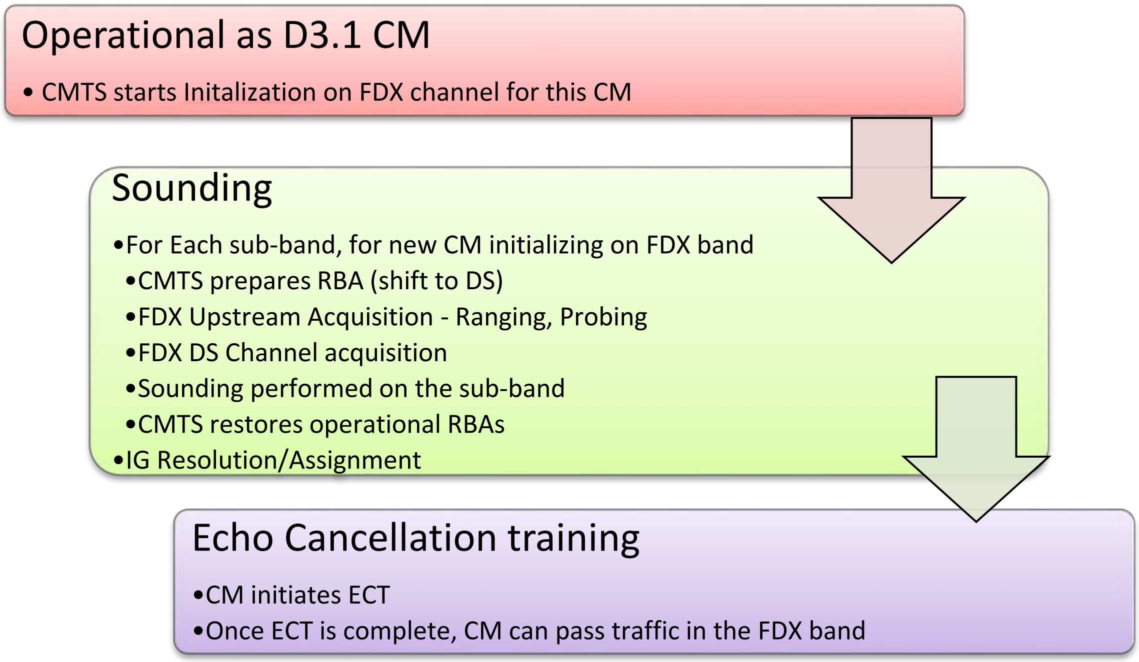


Figure 2 – FDX CM Initialization

The framework for FDX-specific CM initialization is shown in Figure above. The CMTS directs an initializing FDX-capable CM through specific procedures for each FDX Sub-band. The procedures depend upon the FDX Operational Mode, the current FDX Sub-band under consideration and the type of CM that is being initialized.

For each FDX Sub-band where an initializing FDX-capable CM will transmit and/or receive, the CMTS first coordinates RBA reconfigurations as needed so that Sounding may be performed on the sub-band. FDX Upstream Channel acquisition is then done for CMs that will transmit in the FDX Sub-band. FDX Downstream Channel acquisition is done for FDX-capable CMs that will receive in the FDX Sub-band. The Sounding is performed on the sub-band.

Once all relevant FDX Sub-bands have been addressed for the initializing FDX-capable CM, the CMTS coordinates RBA reconfigurations as needed to restore normal traffic-bearing conditions. The CMTS then assigns an IG, TG (and RBA) to the CM and directs any necessary channel acquisition steps to align the CM's active FDX channels with the assigned RBA. If per the RBA the initializing FDX-capable CM will be transmitting on either one or two active FDX Upstream Channels, the CMTS will coordinate Echo Canceller Training procedures with the CM prior to providing data transmission opportunities on those channel(s).

The FDX-capable CMs use the timing offset from a ranged legacy upstream channel as the initial timing offset for an FDX upstream channel. When adding an FDX upstream channel to an FDX-capable CM, the CMTS ensures that for the new FDX channel it allocates a fine ranging opportunity, receives a fine ranging burst, and responds with a timing adjustment in a ranging response before allocating any other type of transmission to that CM for that upstream FDX channel. After performing fine ranging on an FDX upstream channel being added to an FDX CM, the CMTS probes the CM on that upstream channel at least once to ensure the power level for that channel is properly set before requesting an FDX CM to transmit any burst that is not ranging or probing.

Any sounding measurement performed by an FDX CM prior to ECT convergence on an RBA is for reference purposes and for sorting out the initial IG. RxMER measurements prior to ECT convergence are not too useful for downstream profile determination. Prior to assigning an FDX CM a TG-ID, the CMTS adds all FDX upstream channels and all FDX downstream channels that the CM is expected to use.

2. FDX Sounding

In FDX, interferences between the bi-directional transmissions need to be mitigated for the signals to be properly received. When one CM transmits upstream to the CMTS, the US signal may leak through the cable plant and becomes interference in the DS direction at the receiving CMs. FDX addresses this by grouping CMs that interfere with each other, CMs in the same group transmit or receive along the same direction at any given frequency and time. CMs from different groups have enough RF isolation to allow simultaneous US and DS transmissions at the same frequency.

2.1. Sounding

An Interference Group (IG) is a group of CMs that can interfere with each other when the downstream and upstream channels they share are used simultaneously. This occurs when the levels of the CM-to-CM co-channel interference (CCI) are above a design threshold when one CM transmits and other CMs receive simultaneously over the same FDX spectrum. IG Discovery includes a test process, known as Sounding, to allow the CMTS to assess the CCI level between any CM pair that may share the same spectrum for FDX operation. During Sounding, the CMTS selects one or more FDX capable CMs as ‘test’ CMs to transmit test signals on designated subcarriers, while directing other CMs as ‘measurer’ CMs to compute and report the received MER (RxMER) on the same set of subcarriers. The CMTS repeats this procedure until the interference levels are tested on all relevant subcarriers and between all CM combinations. A Test CM refers to an FDX-Capable CM that transmits the sounding test signal in an FDX sub-band to allow the CMTS to detect potential co-channel interferences that other FDX-Capable CMs may experience when operate in the DS direction in the same FDX sub-band. A Measurer CM refers to an FDX-Capable CM that measures and reports the RxMER in an FDX sub-band to allow the CMTS to detect the co-channel interference caused by one or multiple Test CMs’ transmitting the sounding test signals in the same FDX sub-band.

For a given FDX sub-band, the CMTS selects one or more FDX-capable CMs as the Test CMs to transmit test signals, while directing other FDX-Capable CMs to measure and report the DS RxMER as the Measurer CMs. The CMTS repeats this procedure until the interference relationships are tested on all relevant frequencies in the FDX sub-band and between all intended Test and Measurer CM pairs.

2.1. Sounding methods

To assess the CM to CM CCI, the CMTS allocates one or multiple sounding opportunities in the FDX spectrum. A Sounding Opportunity can be either a CWT Sounding Opportunity or an OUDP Sounding Opportunity, see figure below.

A CWT (Continuous Wave Tone) Sounding Opportunity is narrow in frequency but lasts longer in time; an OUDP (OFDM Upstream Data Profile) Sounding Opportunity covers the entire FDX sub-band but lasts shorter in time. Regardless of the type of the test signal used for sounding, a Sounding Opportunity consists of a Test Signal Transmission Opportunity and a Test Signal Interference Region. A Test Signal Transmission Opportunity specifies a minislot region that contains the subcarrier locations for transmitting the test signals and necessary guard subcarriers adjacent to the neighboring regular US transmission region. A Test Signal Interference Region contains a consecutive set of DS subcarriers that encompasses the test signal transmissions in both time and frequency. The CMTS protects the DS transmissions in the Test Signal Interference Region with zero-bit-loaded subcarriers in case of CWT sounding or zero-bit-loaded symbols in case of OUDP sounding.

An FDX CM has the capability to generate multiple CWTs at specific frequency locations. Similar to the sounding routine using the CWT Test Signal as an interference source, there is an alternative approach that allows using the OUDP Test Bursts as an interference source. These OUDP Test Bursts can be used as the test signal for sounding when the measurer CMs involve only FDX CMs. However, both FDX CMs and FDX-L CMs may operate as test CMs.

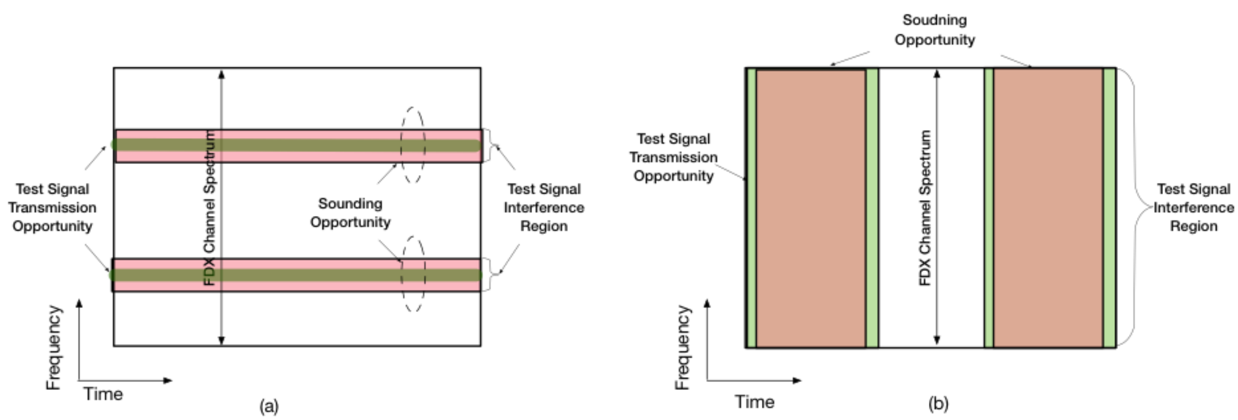


Figure 3 – Sounding Opportunities (a) CWT Sounding (b) OUDP Sounding

2.2. IGs & TGs

The measured interference allows the CMTS to sort CMs into IGs per FDX sub-band, such that for a given IG, the CCI experienced by any CM inside the IG due to the US transmission from at least one other CM in the IG is greater than the desired design limit and the CCI experienced by any CM outside the IG due to the US transmission from any CM inside the IG is less than the desired design limit.

Since the path loss, which determines the interference between a Test CM and a Measurer pair, could vary significantly over frequency, a Test CM may be required to send test signals at multiple subcarrier locations for IG discovery within the FDX sub-band. Consequently, the CCI limit of an IG can be represented as a function of frequency, for example, as a list of threshold values corresponding to different frequency locations in the FDX sub-band under test. The algorithm that determines the IG CCI limit and the test signal frequency locations are CMTS vendor-specific.

Interference Groups (IGs): Identify groups of CMs, that would interfere with each other if they were allowed to transmit and receive at the same time in a sub-band

Transmission Groups (TGs): IGs are grouped together into smaller number of TGs, which is used by the CMTS scheduler. CMs in same TG either transmit or receive on any given sub-band & time. CMs from different TGs have enough isolation to transmit and receive at same time in the same sub-band

2.3. Initial and Periodic Sounding

Initial sounding is the sounding operation the CMTS conducts before an IG has been identified for an FDX-Capable CM in an FDX sub-band. It's the first stage in IG Discovery for the CMTS to establish the initial interference relationship between the sounding CM and other FDX-Capable CMs operating in the sub-band.

Periodic sounding refers to the subsequent sounding operations after the initial sounding. It's the second stage in IG Discovery for the CMTS to monitor the CCI variations over time among the FDX cable CMs operating in a given FDX sub-band. Periodic sounding is also used by the CMTS to incrementally refine CCI estimations with more test samples at different frequencies and time.

2.4. CWT Sounding Overhead

For the CWT sounding, a sounding test opportunity includes a set (one or more) of CWT subcarriers and a few guard subcarriers on both sides, to prevent inter-symbol interference at adjacent data subcarriers. Comparing to the OUDP sounding, a CWT test opportunity occupies much narrower spectrum however lasts longer in time. A CWT tone typically lasts around 800 ms and the corresponding time in the DS is an additional amount of time on each side to make sure the measurement is aligned and complete. It typically takes around 200~300 milliseconds for the RxMER measurement scheme to converge.

In case of the CWT sounding, given a Sounding Opportunity only occupies a fraction of an FDX US/DS channel spectrum, simultaneous US data transmissions (data or CWTs from other CMs) may coexist with the CWTs at frequency locations outside the CWT Transmission Opportunity in the same FDX US channel. A CWT Transmission Opportunity specifies a minimum region of minislots containing the subcarrier locations of one or multiple CWTs for a duration required for the Measurer CMs to measure the RxMER while the CWTs are being transmitted. Given a CWT may cause the inter-carrier interferences (ICI) to adjacent US data subcarriers, a CWT Transmission Opportunity needs to include certain guard subcarriers on each side of the CWTs and a guard time to allow proper ramping at both the start and the end of the CWT transmission.

Table 1 – CWT Sounding Size

Component	Calculation	Value
K	number of symbols per frame	36
Upstream Elementary Period Rate	(Tsu) = 1/ Upstream Sampling Rate	1/102.4 MHz
Symbol size	4096*Tsu	40 µs
Cyclic Prefix Size	192*Tsu	1.875 µs
Frame size	K* (symbol size + CP size)	1.508 ms
CWT ramp size	(128 * 8192 * Tsu / K) * 2 ramps	14.22 frames
CWT duration	Chosen by CMTS	525 US frames
Total Total CWT Time US	(CWT ramp size + CWT duration) * Frame size	812.7 ms
Total CWT Time DS	20 % overhead on either side of CWT to co-ordinate ramp, RxMER measurements etc. (1.4* Total CWT Time US)	1138 ms

The CMTS allocates a CWT Transmission Opportunity for the whole duration of the intended CWT transmissions rounded up to the OFDMA frame boundary, including the headroom to cover the ambiguity of the CWT-REQ propagation delay and processing time. The CMTS also ensures sufficient CWT transmission time to allow all the Measurer CMs participating in sounding to measure and report RxMER. The table above shows the calculations needs to compute the CWT total duration.

A CWT Interference Region defines the DS spectrum in time and frequency that may be impacted by a CWT transmission in sounding. The CMTS uses zero-bit loading at the DS subcarriers corresponding to the CWT frequency locations and includes a number of guard subcarriers on each side of the CWTs to avoid ICI to adjacent DS data subcarriers.

The table below shows the overhead of the Periodic Sounding process using the CWT method. The assumption is the CMTS will ask the CM to transmit a CWT in a sub-set of minislots across the channel. This could be for example one CWT for every minislot in the channel, which equates to 237 CWTs. (There are 237 minislots in a 95 Mhz OFDMA channel.) The CMTS could ask the CM to transmit multiple CWTs within a minislot, and a subset of minislots across the channel. Another example would be to use 50 minislots for one CM's CWT transmission (with say 3-4 CWTs within each minislot). The below table calculates the overhead for Sounding. As one CM uses less of the channel, the reminder of the channel can be used by other CMs to complete the sounding process sooner.

Table 2 – CWT Sounding Overhead

Number Minislots consumed by CWTs from each test CM	**Part of channel occupied by each Test CM (out of 237 Minislots)**	**CWT Sounding Time for Each CM** (ms)	**CWT Sounding Time for All CMs** (Seconds)	**Overhead w Sounding Cycle = 3600 secs**	**Overhead w Sounding Cycle = 10800 secs**
237	100%	1138	72.834	2.02%	0.67%
200	84%	960.362	61.463	1.71%	0.57%
150	63%	720.271	46.097	1.28%	0.43%
100	42%	480.181	30.732	0.85%	0.28%
50	21%	240.090	15.366	0.43%	0.14%
Number of CMs 64					

2.5. OUDP Sounding Overhead

The CMTS allocates an OUDP Test Signal Interference Region for the whole duration of the OUDP Test Bursts Transmission Opportunity with an addition of the ambiguity of the propagation delay difference in between farthest and closest CMs on the plant and frames misalignment between two upstream channels of the sub-band and downstream channel recovery time. The CMTS allocates this region fully composed of zero-bit loaded corresponding DS data subcarriers. The allocated recovery time is based on the longest value of the t-ds-reacquisition capability on the MAC domain. The away time, in this case, is a time between the start of the first transmitted upstream symbol to the end of the last transmitted upstream symbol on a sub-band. The below table shows the calculation steps to compute the OUDP sounding duration.

Table 3 – OUDP Sounding Size

Component	Calculation	Value
K	number of symbols per frame	36
US Elementary Period Rate	(Tsu) = 1/ Upstream Sampling Rate	1/102.4 MHz
Symbol size	4096*Tsu	40 µs
Cyclic Prefix Size	192*Tsu	1.875 µs
Frame size	K* (symbol size + CP size)	1.508 ms
OUDP duration	Chosen by CMTS	50 US frames
OUDP Time	OUDP frame duration * frame time	75.375 ms
Ambiguity Offset	2 * Frame time	3.015 ms
Recovery Time	2* Ambiguity Offset	6.030 ms
Total OUDP Time (US)	OUDP Time + Ambiguity Offset + Recovery Time	84.420 ms

The CMTS does not grant OUDP Test Burst Transmission Opportunity to more than one test CM, to ensure that the source of the interference introduced by a particular test CM can be uniquely identified. For the OUDP sounding, a sounding test opportunity covers the entire FDX channel width in frequency and lasts about 60 to 80 milliseconds in time. Thus, no spectrum can be used for traffic when the OUDP sounding burst is present on the FDX channel under test.

Table 4 – OUDP Sounding Overhead

Part of channel Occupied by each Test CM	OUDP Sounding Time for Each CM	OUDP Sounding Time for All CMs	Overhead w Sounding Cycle = 3600 secs	Overhead w Sounding Cycle = 10800 secs
100%	84.420 ms	5.40 secs	0.15%	0.05%
Number of CMs = 64				

3. FDX Echo Cancellation

3.1. FDX Echo Cancellation at Node

To ensure proper operation of FDX at the Node, the interference resulting from FDX operation needs to be suppressed, via echo cancellation at the Node. Two types of EC techniques can be implemented in an RPD node to cancel or suppress the echoes. Analog EC cancels out the echoes in the analog domain before the ADC. Conventionally analog EC will take a copy of the DS signal, and manipulate its phase and magnitude to generate a canceling signal that is then added to the receiver path to cancel out the echo. 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 DS reference signal with the proper magnitude and phase and subtracted from the received signal.

To cancel out the echo, the canceling signal is generated from the reference signal and needs to have the proper magnitude and phase. These EC coefficients are computed over a time period by comparing and tracking the magnitude and phase difference between the reference and echoes embedded in the received signal. The procedure with which the EC coefficients are computed/tracked is called EC training, and the time period over the EC training period. The FDX node will schedule periods where it can complete EC training.

3.2. FDX Echo Cancellation at CM

Echo cancellation is used to improve FDX CM receiver performance by cancelling Adjacent Leakage Interference (ALI) and Adjacent Channel Interference (ACI) resulting from upstream transmissions. Echo Cancellation is required for each RBA in which there is at least one sub-band in the upstream direction and at least one sub-band in the downstream direction. The CM determines echo canceller training success. Until the Echo Canceller (EC) has converged the RBA sub-band direction set is not usable by the CM for anything but upstream maintenance, sounding, and EC training transmissions.

Prior to the CM's Echo Canceller being trained, the CMTS cannot request a CM to make an RxMER measurement in one sub-band while it is transmitting upstream in another sub-band. Hence, prior to its Echo Canceller being trained, an FDX CM cannot be a test CM in one sub-band while being a measurer CM in another sub-band at that same time.

3.2.1. Foreground and Background Training

The FDX CM uses two different methods to perform Echo Canceller Training, Foreground Training and Background Training.

In Foreground Training, the FDX CM transmits at regular power levels in the sub-bands that are in the upstream direction in the RBA sub-band direction set. Upstream bandwidth is dedicated via ECT probe allocations for all upstream channels in upstream sub-bands in the RBA. Foreground training may include zero bit loading (ZBL) on the downstream sub-bands in the RBA.

In Background Training, no upstream bandwidth is consumed. Instead, the FDX CM sends a low-level signal on the sub-band(s) that are downstream direction in the RBA. Background training does not require the use of probe allocations but does require assignment of a training window because the CMTS is responsible for limiting the number of CMs performing background EC training at the same time in order to manage the total emissions on the plant.

The FDX CM may require multiple EC training methods. Foreground training with ZBL is the only method that can be used for the cancellation of both ALI and ACI. Background training can be used for the cancellation of ALI, but not for the cancellation of ACI and foreground training without ZBL can be used for the cancellation of ACI, but not for the cancellation of ALI.

3.2.2. Initial vs Periodic Training

There are two phases to Echo Cancellation Training: initial and periodic. Initial EC Training is used to initially train the Echo Canceller for a given RBA sub-band direction set. Once the FDX CM has achieved sufficient convergence on an RBA sub-band direction set, periodic EC training is used to maintain sufficient convergence of the FDX CM's Echo Canceller for that RBA sub-band direction set.

3.3. EC Training & Overhead

For a CM, the recommended EC retraining period due to thermal drift is about 10 ~15 sec or as requested from the CM. The maximum number of symbols needed for training at a given time is estimated at a maximum up to 128 symbols (upper bound). For background training the number of symbols needed is in the order of a few thousand symbols (~5000).

For initial training the table below calculates the time taken for ECT in various stages. For Initial training, the overhead is not meaningful as it happens one time at FDX initialization. Periodic training, is the main ECT to calculate the overhead for. Foreground training needs ECT probe allocations. Foreground training, if it uses ZBL on the Downstream, will also take away bandwidth from the downstream. Background ECT without ZBL doesn't take away active bandwidth but the CMTS needs to schedule these training windows for the CM.

ECT time is calculated as the Number of Symbols (for ECT) * symbol time * number of channels. For 2 US channels (in an RBA), a 40 µs symbol time, and a CM which needs 128 symbols to EC train, will have a total EC time of (128*2*40=) 1024 µs. The below table describes the values for case where the RBA has 2 US & 1 DS or 2 DS & 1 US sub-bands, for foreground training and for background training. The overhead is calculated as the (ECT time for all CMs) / EC periodicity.

Table 5 – EC training Overhead

Num Symbols needed for ECT	Num US Channels	Num DS Channels	EC time US (ms)	EC time DS (ms)	Total ECT time US (ms)	Total ECT time DS (ms)	US OverHead	DS OverHead (if ECT is with DS ZBL)
Symbol time = 40 µs, EC Periodicity = 15 seconds, Number of CMs = 64								
Foreground ECT w ZBL (Initial)								
128	2	1	10.24	5.12	655	328	NA	
128	1	2	5.12	10.24	328	655		
Foreground ECT w ZBL (Periodic)								
32	2	1	2.56	1.28	164	82	1.09%	0.55%
32	1	2	1.28	2.56	82	164	0.55%	1.09%
Background ECT wo ZBL (Initial or Periodic)								
5000	2	1	400	200	25600	12800	NA	
5000	1	2	200	400	12800	25600		

For Periodic training, the Training Expiration Times are the amount of time that the FDX CM is able to maintain EC training sufficient convergence when performing Foreground and Background training. This can be in multiples of the Training Periodicity.

4. FDX Resource Block Allocation

FDX operation is full duplex from the perspective of the CMTS but frequency division duplex (FDD) from the perspective of the CM. The FDX band is divided into sub-bands and the CMTS assigns which sub-band(s) each CM is to use for upstream FDX operation and which sub-band(s) each is to use for downstream FDX operation. This assignment is referred to as a resource block assignment (RBA). The sub-band is the atomic unit of allocation meaning that the entire sub-band is either assigned to be used for downstream traffic or upstream traffic. It is recognized that different CMs will have different bandwidth demand for both the upstream and downstream directions and that this demand can change dynamically. FDX allows resource assignment to be changed dynamically and this is known as Dynamic FDD.

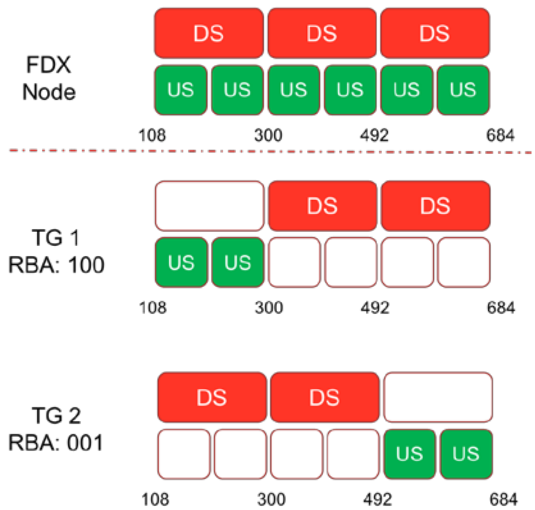


Figure 4 – RBA Example

The CMTS periodically sends the RBA message to describe the current or upcoming RBA mapping. RBAs are associated with TGs and CMs are assigned to TGs. The above figure shows 2 TGs which are assigned different resource block assignments, TG1 (up,down,down) and TG2 (down, down, up).

4.1. Fast and Slow RBA Switching

Switching is defined as a change in the RBA for the TG. RBA switching has been designed to support a range of implementations all the way from static systems to highly dynamic systems. This provides operators with a tool set with which FDX deployments can be tuned to specific needs. RBA switching needs to account for channel acquisition and tracking processes that are dependent upon channel attributes which are time varying. Processes include channel acquisition and echo cancellation tracking. The duration since a sub-band last had an identical direction assignment determines if an RBA switch is 'fast' or 'slow'. The 'Away Time' can be defined as the amount of time a CM spends away from a certain direction and in the opposite direction for a particular sub-band, before it returns to the original direction. The CMTS determines if a switch is fast or slow based upon the duration of the away time and CM capabilities. The switching procedure is the same for both fast and slow switching, the difference is the duration a CMTS waits before sending or scheduling PDUs after a sub-band direction change.

When switching a sub-band assignment to the downstream direction, the CMTS waits for at least the downstream switching reacquisition time prior to sending traffic to a CM on a downstream channel in the sub-band. Likewise, when switching a sub-band to the upstream direction, the CMTS re-ranges and allows a CM to re-train echo cancellation prior to providing grants if the away time has been greater than that specified by the CM capabilities.

RBAs can change regularly and quickly. Thus, the rate at which RBAs are sent could possibly become taxing to FDX-L CMs if each message had to be processed by the CMs CPU. To prevent this, RBA messages are of two types a hardware friendly version and a software friendly version. FDX-L CMs are expected to process software-based RBAs and to drop the hardware-based RBAs. This allows a CMTS to send hardware based RBAs at a very high rate without impacting FDX-L CMs. The CMTS will inform FDX-capable CMs which type of RBA message to utilize based on CM capabilities.

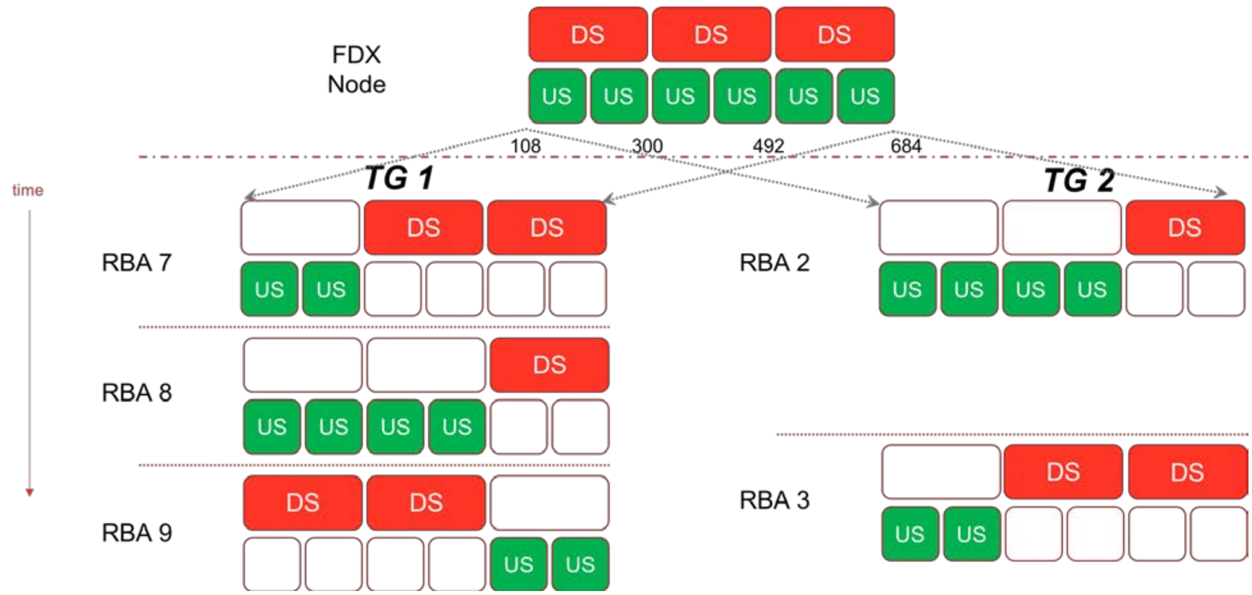


Figure 5 – RBA Switch in different TGs

To avoid CM-to-CM interference, in a given FDX sub-band, the CMTS makes sure all CMs in the same TG (group of IGs) are operating in the same direction at the same time, each TG is assigned an RBA. The figure above shows the RBA sequence changing independently across two TGs.

4.2. RBA Switching Use cases

There are many reasons an CMTS would want to allocate or change RBAs in the FDX band. The way the operator would change the RBA depends on the deployment scenarios and the bandwidth to offer the customers. Some of the reasons why an operator may want to switch RBAs are as follows:

Load Balancing across the plant: E.g., diurnal cycles: There could be more activity from business users during the day, home users in the evening. An operator may choose to run the FDX band to be more symmetrical (with more upstream bandwidth) during the day for business but favoring downstream bandwidth in the evening for home users.

Activity patterns across the plant: At any given time, a particular TG may have many active users, while some other TG have many idle CMs. An operator may choose to set the FDX band to address different activity patterns in specific TGs

Immediate bandwidth demand changes across the plant. At a given time one user doing a large upload is filling most of the upstream sub-bands assigned to that TG, and then as a second user begins an upload, the TG requires more upstream bandwidth. In this case the operator may configure the CMTS to respond to such immediate changes in demand.

The following are the different configurations of RBA settings an operator could use to meet the various use cases.

Static RBA: In this case the operator, needs a certain amount of bandwidth in each direction. As an example, the operator may need US bandwidth equivalent to 2 FDX sub-bands. In this case the operator could set the RBA for the TG (or all TGs) with 2 US sub-bands. e.g. an RBA configuration of 110 (US, US, DS).

Duty Cycle RBA: In this case the operator, needs a certain amount of bandwidth in each direction which fluctuates over a time period. As an example, the operator may need US bandwidth equivalent to 2 FDX sub-bands during the day and DS bandwidth equivalent to 2 FDX sub-bands during the day. In this case the operator could set the RBA for the TG (or all TGs) to switch between a couple of RBAs over some time period e.g. an RBA configuration of 100 (US, DS, DS) ←→ 110 (US, US, DS) which could change at a rate chosen by the operator (could be on the order of hours or minutes).

Dynamic RBA: In this case the operator, configures the CMTS (or an external application) to drive the RBA configuration and let it decide how to set RBAs based on current demand. In this case the CMTS could set the RBA for the TG (or all TGs) to switch between any possible RBA combinations (could be on the order of 100 ms) as per the demand on the network.

4.3. RBA switching & Overhead

When the CMTS changes RBAs, it coordinates the sending and scheduling of traffic such that all traffic is sent or received by a CM on a channel that is in the CM's TG's RBA and is valid for that CM at the time the traffic is sent or received. When the CM is switching the RBAs there is a period of time which the CM needs to change state from one direction to another. This budget to make changes along with other network parameters will be used by the CMTS to determine when it can schedule or send traffic from or to each CM that is affected by a change in the RBA.

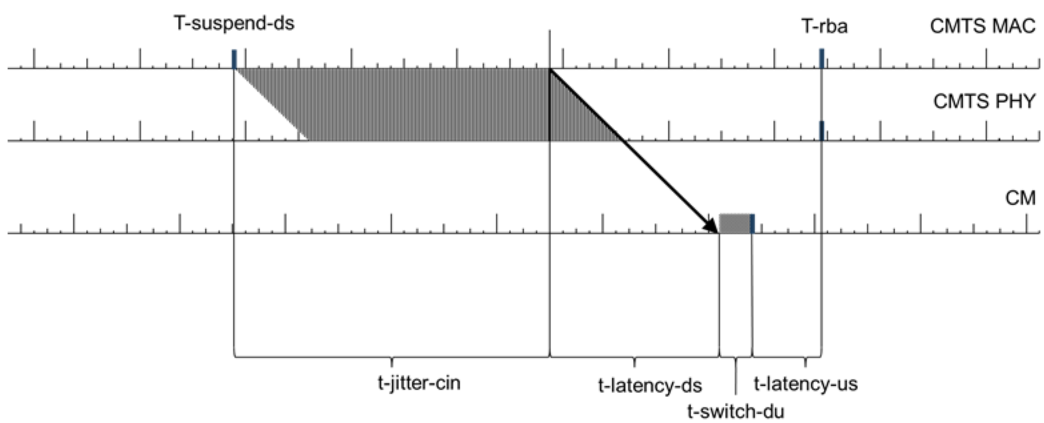


Figure 6 – RBA Switching Time Calculation

The Figues above shows the component in computing the time it takes to change the direction of a sub-band from one direction to the other. In this figure the sub-band is in the downstream direction prior to T-Suspend-ds and switches to upstream after T-rba. The labels are explained below.

- T-rba: The time the new RBA becomes active (from the perspective of the CMTS).
- CM Switch Time (t-switch-xx): The maximum duration it takes for a CM to enact an RBA change from DS to US (t-switch-du), or from US to DS (t-switch-ud):
- t-cm-rba-proc: This is the minimum time that a CMTS allows for a CM to process RBA messages in advance of the time that a CM will begin to enact the RBA.
- Downstream Latency (t-latency-ds): The time it takes for a PDU to travel from the CMTS to the CM. It includes any time-interleaving, D3.1 convergence layer processing, and CIN Latency.
- CIN Jitter (t-jitter-cin): The maximum variance in CIN Latency a PDU could take to traverse the CIN between the CCAP Core and the RPD in the RPHY architecture. (In a CMTS architecture with co-located MAC & PHY, the CIN Jitter will approach zero.)

- Upstream Latency (t-latency-us): The time it takes for a PDU to travel from the CM to the CMTS burst receiver (within the CMTS PHY).
- T-suspend-ds: The CMTS ensures that no PDUs arrive at a transitioning CM after the CM has switched that spectrum from DS to US.

The following numbers will describe the components of the RBA Switch Time.

Table 6 – RBA OverHead

Delay Component	Calculation	Value
DS PHY layer propagation delay	5 µs per KM → 8 km distance	40 µs
DS Interleaving Delay	(M-1) * Symbol time = (3-1) * 22.5 µs	45 µs
DS pipeline delay	3 * DS symbol size = 3 * 22.5 µs	67.5 µs
RPD Forwarding Latency	200 µs	200 µs
t-latency-ds	Propagation delay + Interleaving delay + Pipeline delay + RPD Fwd latency	352.5 µs
US PHY layer propagation delay	5 µs per KM → 8 km distance	40 µs
US pipeline delay	(3 * Frame Size)	405 µs
t-latency-us	Propagation delay + Pipeline delay	445 µs
t-switch-du	Depends on the capability of the new FDX silicon. Somewhere in the range of 10 µs to 1000µs	10 µs, 500 µs or 1000 µs
t-jitter-cin	Depends on the CIN network designed by the operator	1ms to 8ms
Total Pause Time for FDX channel	t-latency-us + t-switch-du + t-latency-ds + t-jitter-cin	~Range from 1.8 ms to 9.7 ms

The figure below shows the RBA switch time (pause time) for an FDX channel as a function of the CIN jitter, which is the biggest contributing factor as seen in the table above. Each curve in the figure is for a different CM Switch time (which is a CM capability) from 10 µs to 1000 µs.

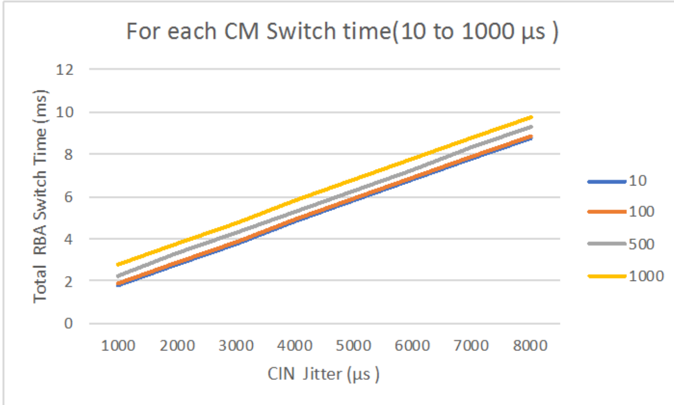


Figure 7 – CM RBA Switch/Channel Pause Time

The figure below shows an FDX Sub-band changing from upstream to downstream and back to upstream. During each of these RBA changes there is sometime went to CMTS pauses transmission on channel.

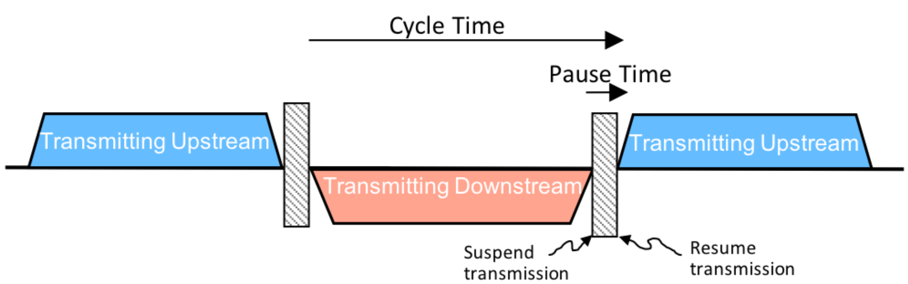


Figure 8 – RBA Overhead

The overhead is defined as the "pause" time during which transmissions are halted divided by the "cycle time" (time data being transmitted + switching time). For a given FDX channel: Overhead = Pause Time / cycle time. If the FDX sub-band is in the downstream direction (cycle time) for 100 ms and the switch time is 1.8 ms, the RBA Change Time Overhead is 1.8%. The below graph shows the overhead in RBA switching as the FDX direction cycle time ranges from 100 milliseconds to a 1000 ms. Each curve is for a CM's RBA switch time from 1.8 ms to ~10 ms. For RBA switch cycles greater than 400 ms the overhead is less than 2%, and as the cycle time is greater than a second the overhead is less than 1%

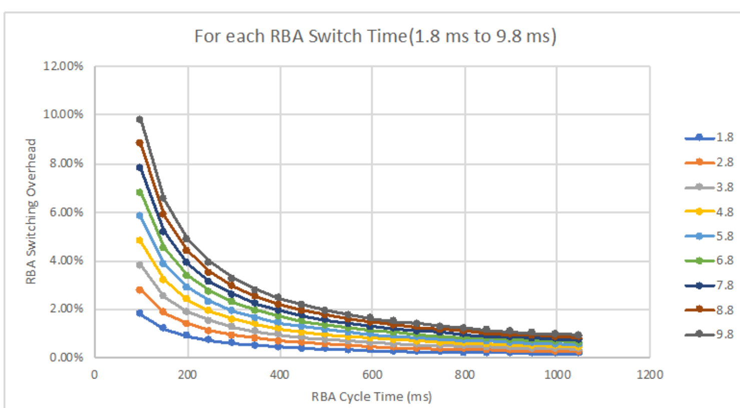


Figure 9 – FDX Channel Pause/Cycle Time (Overhead)

FDX Scenarios

5. FDX Capacity Basics

5.1. FDX Modulation orders

The following table shows the RxMER (dB) level needed at a CM to be able to receive data traffic at a certain modulation order.

Table 7 – RxMER needed for Modulation orders

Constellation	D3.1 DS MER(db)	FDX DS *	D3.1 US	FDX US
QPSK			11	12.5
8-QAM			14	15.5
16-QAM	15	16.5 (17/17)	17	18.5
32-QAM			20	22
64-QAM	21	22.5 (23/23)	23	25.5
128-QAM	24	25.5 (26/25.5)	26	29
256-QAM	27	28.5 (29/29)	29	32
512-QAM	30.5	31.5 (33/32)	32.5	36
1024-QAM	34	35 (42/36)	35.5	44
2048-QAM	37	40 (NA/44.5)	39	
4096-QAM	41		43	
8192-QAM	46			
16384-QAM	52			

** The FDX DS values are from the tables for the External ACI Test and the values in the (parentheses) are from the Self ACI Test as defined in the [D3.1 PHY Spec].*

5.2. FDX TG formation

The FDX architecture provides two-way signal transmission within the same spectral band. This requires a passive architecture without amplifiers. In this case, the fiber node connects to a single series of multiport taps. An example of one coaxial branch of a fiber deep node + 0 architecture is shown figure below. Here is an IG Discovery example using the RxMER measurement data listed in Table below.

Table 8 – CM-to-CM Interference Levels and Interference Groups

MER(dB)		Transmit					
		Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
Receive	Tap 1	6	39.9	39.9	39.9	39.9	39.9
	Tap 2	39.9	9.8	37.5	37.5	37.5	37.5
	Tap 3	39.9	37.5	9.8	34.5	34.5	34.5
	Tap 4	39.6	37.5	34.5	13.2	31	31
	Tap 5	39.9	37.5	34.5	31	15.8	27
	Tap 6	39.6	37.5	34.5	31	27	15.8

Modulation Order		Transmit					
		Tap 1	**Tap 2**	**Tap 3**	**Tap 4**	**Tap 5**	**Tap 6**
Receive	**Tap 1**	0	11.5	11.5	11.5	11.5	11.5
	Tap 2	11.5	0	11	11	11	11
	Tap 3	11.5	11	0	10	10	10
	Tap 4	11.5	11	10	0	9	9
	Tap 5	11.5	11	10	9	0	8
	Tap 6	11.5	11	10	9	8	0

The measured interference allows the CMTS to sort CMs into IGs per FDX sub-band. For a given IG, the CCI experienced by any CM in the IG due to the transmission from any other CM in the IG is greater than the desired design limit, and the CCI experienced by any CM outside the IG due to the transmission from a CM inside the IG is less than the desired design limit. The different colored cells show the potential IG groupings. This translates to 4 different IGs showns in the figure below.

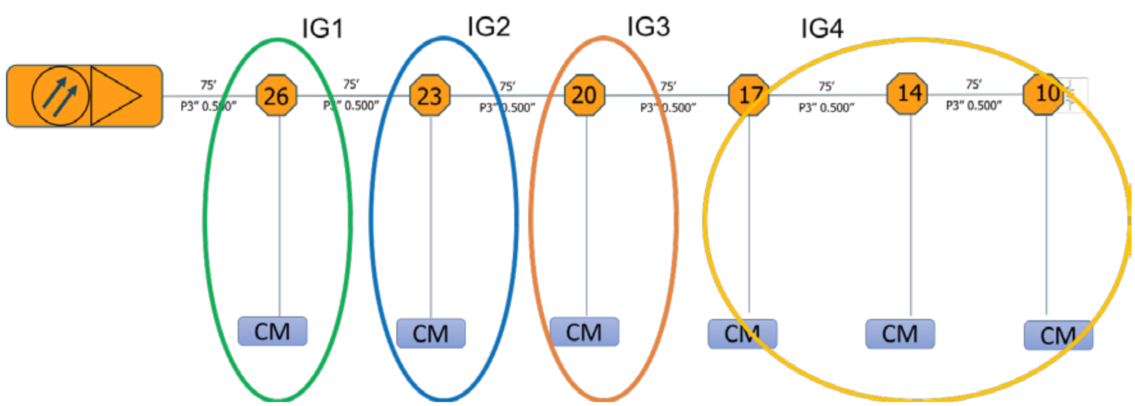


Figure 10 - CM-to-CM Interference Levels and Interference Groups

Since the path loss, which determines the interference between a Test CM and a Measurer pair, could vary significantly over frequency, a Test CM may be required to send test signals at multiple subcarrier locations for IG discovery within the FDX sub-band. Consequently, the CCI limit of an IG can be represented as a function of frequency, for example, as a list of threshold values corresponding to different frequency locations in the FDX sub-band under test.

5.3. FDX Node, FDX CM & FDX-L CM Capacity

The FDX Node supports the FDX sub-bands and the channels in both directions at the same time i.e. it simultaneously receives & transmits in same FDX spectrum. The FDX Node performs echo cancellation to make sure that the transmitted signal does not interfere with the received signal. For the same amount of spectrum, the FDX Node is passing double the number of bits. This is in contrast with the CM that either receives or transmits in the same FDX spectrum at a given time.

The FDX system is essentially Full Duplex from perspective of CMTS and Frequency Division Duplex from perspective of CM. As the RxMER levels obtained are different across each Interference Group, each TG will have a different capacity as per the modulation orders/profiles which can be used by that

TG. The FDX CM capacity at a given time is limited to the RBA setting for its TG. The FDX Node capacity is not per TG, it is per MAC Domain as all the FDX channels are shared by all the TGs.

5.4. CM Channel Support

As discussed in the introduction, the following tables summarize the capabilities of an FDX CM and an FDX-L CM (A software upgraded D3.1 CM)

Table 9 – FDX Channel Support

Channel	Device	OFDM/OFDMA	SC-QAM
FDX			
Downstream	CM	4 OFDM Channels (3 FDX) (5 Optional)	32
Downstream	CMTS	6 OFDM Channels (3 FDX)	32
Upstream	CM	7 OFDMA Channel, (6 FDX, 2 Non-FDX)	4 (8 Optional)
Upstream	CMTS	8 OFDMA Channels (6 FDX, 2 Non-FDX)	4 (8) Optional)
FDX-L (D3.1)			
Downstream	CM	2 OFDM Channels	32
Downstream	CMTS	2 OFDM Channels	32
Upstream	CM	2 OFDMA Channels	8
Upstream	CMTS	2 OFDMA Channels	8

5.5. FDX MER and Capacity assumptions

The following table describes the OFDM/A channel capacities for various bit loading, after considering the overhead (PLC, NCP, FEC, pilots, pilot patterns, frame size etc). This calculation has been described in other papers, the values below assume a somewhat aggressive setting (of cyclic prefixes, pilots, pilot patterns) to get the more bits per sec in both upstream and downstream.

Table 10 – D3.1 Bit Loading and Channel Capacities

Bit Loading	DS Mbps	US Mbps
D3.1	**OFDM**	**OFDMA**
8	634	737
9	711.5	815
10	790.5	906
11	863	994
12	953.5	1072
D3.0	**SC-QAM**	**SC-QAM**
256 SCQAM	38.81	(not used in examples)

For the calculations in the series of figures (describing RBA configurations) in the next chapter, this paper assumes an average bit loading/modulation order of 12 for the an OFDM channel, a 11 for an FDX DS channel. Similarly, in the Upstream, it assumes an average bit loading/modulation order of 11 to be achievable for the an OFDMA channel, a 10 for an FDX US channel. Based these assumptions the following table shows the calculated bandwidth (MBps) for the different types of channels used in chapter 6,7.

Table 11 – D3.1/FDX Bit Loading and Channel Capacities

Channel Type	Bandwidth (MBps)
FDX DS-192	1726
FDX DS	863
FDX US	906
D-192-OFDM	1907
D-150-OFDM	1489.8
U-96-OFDMA	994
U-80-OFDMA	828.3
SCQAM-32	1241.92
SCQAM-24	931.44

6. FDX RBA configurations

The following section describes the various RBA configurations which an operator can use, and the bandwidth provided by each configuration.

6.1. 5 Sub-band configurations

The following figure illustrates all the possible sub-band configurations within FDX. The FDX spectrum begins from 108 MHz and extends two 684 MHz. The following figure displays Spectrum in 96 MHz chunks. The downstream sub bands/channels are marked as "FDX DS" or "FDX DS-192" in red, while the upstream sub bands/channels are marked as "FDX US" in Green. The values on the right give the total MBps bandwidth as seen by the FDX CM.

	FDX BAND										
108	204	300	396	492	588	684		FDX CM (MBps)		FDX Node (MBps)	
			FDX				MHz	DS	US	DS	US
	FDX DS						96	863	0	863	906
	FDX US							0	906		
	FDX DS	FDX DS					192	1726	0	1726	1812
	FDX DS	FDX US						863	906		
	FDX US	FDX DS						863	906		
	FDX US	FDX US						0	1812		
	FDX DS	FDX DS	FDX DS				288	2589	0	2589	2718
	FDX DS	FDX DS	FDX US					1726	906		
	FDX DS	FDX US	FDX DS					1726	906		
	FDX DS	FDX US	FDX US					863	1812		
	FDX US	FDX DS	FDX DS					1726	906		
	FDX US	FDX DS	FDX US					863	1812		
	FDX US	FDX US	FDX DS					863	1812		
	FDX US	FDX US	FDX US					0	2718		
	FDX DS-192		FDX DS-192				384	3452	0	3452	3624
	FDX DS-192		FDX US	FDX US				1726	1812		
	FDX US	FDX US	FDX DS-192					1726	1812		
	FDX US	FDX US	FDX US	FDX US				0	3624		
	FDX DS-192		FDX DS-192		FDX DS-192		576	5178	0	5178	5436
	FDX DS-192		FDX DS-192		FDX US	FDX US		3452	1812		
	FDX DS-192		FDX US	FDX US	FDX DS-192			3452	1812		
	FDX DS-192		FDX US	FDX US	FDX US	FDX US		1726	3624		
	FDX US	FDX US	FDX DS-192		FDX DS-192			3452	1812		
	FDX US	FDX US	FDX DS-192		FDX US	FDX US		1726	3624		
	FDX US	FDX US	FDX US	FDX US	FDX DS-192			1726	3624		
	FDX US	FDX US	FDX US	FDX US	FDX US	FDX US		0	5436		
	96	192	288	384		576					

Figure 11 – RBA SubBand Configurations & Capacity

6.1. Static US & DS

The static US/DS case is likely the initial deployment strategy for operators who want to increase upstream bandwidth. The following figure illustrates again the possible sub-band configurations within FDX, this time re-arranged to show the static upstream case and the static downstream case. It also groups the other RBA configurations to show the various levels of bandwidth with the different RBA configurations, in the order of increasing US bandwidth.

Mhz								
108	204	300	396	492	588	684	MBps	
							DS	US
	FDX DS						863	0
	FDX DS	FDX DS					1726	0
	FDX DS	FDX DS	FDX DS				2589	0
	FDX DS-192		FDX DS-192				3452	0
	FDX DS-192		FDX DS-192		FDX DS-192		5178	0
	FDX US						0	906
	FDX US	FDX US					0	1812
	FDX US	FDX US	FDX US				0	2718
	FDX US	FDX US	FDX US	FDX US			0	3624
	FDX US	FDX US	FDX US	FDX US	FDX US	FDX US	0	5436
	FDX DS	FDX US					863	906
	FDX US	FDX DS					863	906
	FDX DS	FDX DS	FDX US				1726	906
	FDX DS	FDX US	FDX DS				1726	906
	FDX US	FDX DS	FDX DS				1726	906
	FDX DS	FDX US	FDX US				863	1812
	FDX US	FDX DS	FDX US				863	1812
	FDX US	FDX US	FDX DS				863	1812
	FDX DS-192		FDX US	FDX US			1726	1812
	FDX US	FDX US	FDX DS-192				1726	1812
	FDX DS-192		FDX DS-192		FDX US	FDX US	3452	1812
	FDX DS-192		FDX US	FDX US	FDX DS-192		3452	1812
	FDX US	FDX US	FDX DS-192		FDX DS-192		3452	1812
	FDX DS-192		FDX US	FDX US	FDX US	FDX US	1726	3624
	FDX US	FDX US	FDX DS-192		FDX US	FDX US	1726	3624
	FDX US	FDX US	FDX US	FDX US	FDX DS-192		1726	3624

Figure 12 – Different view of the RBA capacities

6.2. Duty Cycle RBAs

The following figures show different examples of the possible US and D bandwidths for different RBA configurations. In each of these configurations the CMTS switches each TG from one RBA to another RBA, for a set amount of time, i.e. the CMTS is maintain a certain duty cycle for each RBA. RBAs which used have a value of ½ or 1/3 in the 'RBA Fraction' column indicating the CMTS is switching RBAs (at a certain rate) between those RBAs, and RBAs which are not used have a value of 0

108	204	300	396	492	588	684							
									Node (MBps)			Effective Data Rate	
	FDX						DS	US	DS	US	RBA Fraction	DS	US
TG1	FDX DS						863	0			1/2	431.50	453.00
	FDX US						0	906			1/2		
									863	906			
TG2	FDX DS						863	0			1/2	431.50	453.00
	FDX US						0	906			1/2		
												863.00	906.00

Figure 13 – Duty Cycle RBA example 96 MHz FDX Band

In the above example of a 96 MHz FDX band, with a TG Switching RBA's between downstream (1/2 the time) and upstream (1/2 the time) gets an effective bandwidth (431.5, 453) which is half of what each RBA would be achieve by itself.

108	204	300	396	492	588	684							
									Node (MBps)			Effective Data Rate	
	FDX						DS	US	DS	US	RBA Fraction	DS	US
TG1	FDX DS	FDX DS					1726	0			0		
	FDX DS	FDX US					863	906			0		
	FDX US	FDX DS					863	906			1/3	287.67	1510.00
	FDX US	FDX US					0	1812			2/3		
									1726	1812			
TG2	FDX DS	FDX DS					1726	0			0		
	FDX DS	FDX US					863	906			0		
	FDX US	FDX DS					863	906			2/3	575.33	1208.00
	FDX US	FDX US					0	1812			1/3		
												863.00	2718.00

Figure 14 – Duty Cycle RBA example 192 MHz FDX Band

In the above example of a 192 MHz FDX band, With TG1 switching RBA's between RBA 10 (up,down) 1/3rd of the time and RBA 11 (up,up) 2/3rd the time, gets an effective bandwidth (287.67, 453) for that TG. For TG2 switching RBA's between RBA 10 (up,down) 2/3rd of the time and RBA 11 (up,up) 1/3rd the time, gets an effective bandwidth (575.33, 1208) for that TG.

Now summing up the effective data rates across the TG's gives (863,2718), which is greater than the node capacity (1726,1812)in the upstream and less in the downstream. This means that the downstream's on the node are being underutilized and the upstreams are being oversubscribed. This means that if a single user is using the peak upstream rate on one TG, another user on a different TG may not be able to use the upstream rate provided by the channel at the same time.

108	204	300	396	492	588	684							
									Node (MBps)			Effective Data Rate	
	FDX						DS	US	DS	US	RBA Fraction	DS	US
	FDX DS	FDX DS	FDX DS				2589	0			0		
	FDX DS	FDX DS	FDX US				1726	906			0		
	FDX DS	FDX US	FDX DS				1726	906			0		
TG1	FDX DS	FDX US	FDX US				863	1812			0	0.00	2718.00
	FDX US	FDX DS	FDX DS				1726	906					
	FDX US	FDX DS	FDX US				863	1812			0		
	FDX US	FDX US	FDX DS				863	1812			0		
	FDX US	FDX US	FDX US				0	2718			1		
	FDX DS	FDX DS	FDX DS				2589	0			0		
	FDX DS	FDX DS	FDX US				1726	906			0		
	FDX DS	FDX US	FDX DS				1726	906			0		
TG2	FDX DS	FDX US	FDX US				863	1812			0	1294.50	1359.00
	FDX US	FDX DS	FDX DS				1726	906			1/2		
	FDX US	FDX DS	FDX US				863	1812			0		
	FDX US	FDX US	FDX DS				863	1812			1/2		
	FDX US	FDX US	FDX US				0	2718			0		
									2589	2718			
	FDX DS	FDX DS	FDX DS				2589	0			0		
	FDX DS	FDX DS	FDX US				1726	906			0		
	FDX DS	FDX US	FDX DS				1726	906			0		
TG3	FDX DS	FDX US	FDX US				863	1812			0	1294.50	1359.00
	FDX US	FDX DS	FDX DS				1726	906			1/2		
	FDX US	FDX DS	FDX US				863	1812			0		
	FDX US	FDX US	FDX DS				863	1812			1/2		
	FDX US	FDX US	FDX US				0	2718			0		
	FDX DS	FDX DS	FDX DS				2589	0			1/3		
	FDX DS	FDX DS	FDX US				1726	906			0		
	FDX DS	FDX US	FDX DS				1726	906			1/3		
TG4	FDX DS	FDX US	FDX US				863	1812			1/3	1726.00	906.00
	FDX US	FDX DS	FDX DS				1726	906			0		
	FDX US	FDX DS	FDX US				863	1812			0		
	FDX US	FDX US	FDX DS				863	1812			0		
	FDX US	FDX US	FDX US				0	2718			0		
												4315.00	6342.00

Figure 15 – Duty Cycle RBA example 288 MHz FDX Band

In the above example of a 288 MHz FDX band, we have 4 TGs. With TG1, there is no switching RBA's , it is always assigned to use RBA 111 (up,up,up) all of the time, so it gets an effective bandwidth of (0, 2718) for that TG. For TG2, TG3, the CMTS is switching RBA's between RBA 100 (up,down,down) 1/2 of the time and RBA 110 (up,up,down) 1/2 the time, gets an effective bandwidth (1294.5, 1359) for those TG. For TG4 switches RBA's between RBA 000 (down,down,down) 1/3rd of the time, RBA 010 (down,up,down) 1/3rd the time, RBA 011 (down,up,up) 1/3rd the time, to get an effective bandwidth (1726,906) for those TG.

Now summing up the effective data rates across the TG's gives (4315,6342) which is greater than the node capacity (2589,2718), in the upstream and in the downstream. This means that both the downstream channels and the upstream channels are being oversubscribed. This means that if a single user is using the peak rate on one TG, another user on a different TG may not be able to use the rate provided by the channel at the same time.

108	204	300	396	492	588	684							
									Node (MBps)			Effective Data Rate	
	FDX						DS	US	DS	US	RBA Fraction	DS	US
	FDX DS-192		FDX DS-192				3452	0			1/4		
TG1	FDX DS-192		FDX US	FDX US			1726	1812	3452	3624	0		
	FDX US	FDX US	FDX DS-192				1726	1812			3/8	1510.25	2038.50
	FDX US	FDX US	FDX US	FDX US			0	3624			3/8		
												1510.25	2038.50

Figure 16 – Duty Cycle RBA example 384 MHz FDX Band

In the above example of a 384 MHz FDX band, we have just 1 TG. For TG1, the CMTS switches RBA's between RBA 00 (down, down) 1/4th of the time, RBA 01 (up, down) 3/8th the time, RBA 11 (up, up) 3/8th of the time, to get an effective bandwidth (1510,2038) for those TG.

Now summing up the effective data rates across the TG's, since there is only one TG here, gives (1510,2038) which is less than the node capacity (3452,3624) , in the upstream and in the downstream. This means that both the downstream channels and the upstream channels are being underutilized.

108	204	300	396	492	588	684							
								Node (MBps)				Effective Data Rate	
	FDX						DS	US	DS	US	RBA Fraction	DS	US
	FDX DS-192		FDX DS-192		FDX DS-192		5178	0			0		
	FDX DS-192		FDX DS-192		FDX US	FDX US	3452	1812			0		
	FDX DS-192		FDX US	FDX US	FDX DS-192		3452	1812			0		
TG1	FDX DS-192		FDX US	FDX US	FDX US	FDX US	1726	3624			0	2589.00	2718.00
	FDX US	FDX US	FDX DS-192		FDX DS-192		3452	1812			1/2		
	FDX US	FDX US	FDX DS-192		FDX US	FDX US	1726	3624			0		
	FDX US	FDX US	FDX US	FDX US	FDX DS-192		1726	3624			1/2		
	FDX US	FDX US	FDX US	FDX US	FDX US	FDX US	0	5436			0		
	FDX DS-192		FDX DS-192		FDX DS-192		5178	0			0		
	FDX DS-192		FDX DS-192		FDX US	FDX US	3452	1812			1/2		
	FDX DS-192		FDX US	FDX US	FDX DS-192		3452	1812			0		
TG2	FDX DS-192		FDX US	FDX US	FDX US	FDX US	1726	3624			1/2	2589.00	2718.00
	FDX US	FDX US	FDX DS-192		FDX DS-192		3452	1812			0		
	FDX US	FDX US	FDX DS-192		FDX US	FDX US	1726	3624			0		
	FDX US	FDX US	FDX US	FDX US	FDX DS-192		1726	3624			0		
	FDX US	FDX US	FDX US	FDX US	FDX US	FDX US	0	5436			0		
									5178	5436			
	FDX DS-192		FDX DS-192		FDX DS-192		5178	0			0		
	FDX DS-192		FDX DS-192		FDX US	FDX US	3452	1812			1/2		
	FDX DS-192		FDX US	FDX US	FDX DS-192		3452	1812			1/2		
TG3	FDX DS-192		FDX US	FDX US	FDX US	FDX US	1726	3624			0	3452.00	1812.00
	FDX US	FDX US	FDX DS-192		FDX DS-192		3452	1812			0		
	FDX US	FDX US	FDX DS-192		FDX US	FDX US	1726	3624			0		
	FDX US	FDX US	FDX US	FDX US	FDX DS-192		1726	3624			0		
	FDX US	FDX US	FDX US	FDX US	FDX US	FDX US	0	5436			0		
	FDX DS-192		FDX DS-192		FDX DS-192		5178	0			0		
	FDX DS-192		FDX DS-192		FDX US	FDX US	3452	1812			0		
	FDX DS-192		FDX US	FDX US	FDX DS-192		3452	1812			0		
TG4	FDX DS-192		FDX US	FDX US	FDX US	FDX US	1726	3624			0	863.00	4530.00
	FDX US	FDX US	FDX DS-192		FDX DS-192		3452	1812			0		
	FDX US	FDX US	FDX DS-192		FDX US	FDX US	1726	3624			0		
	FDX US	FDX US	FDX US	FDX US	FDX DS-192		1726	3624			1/2		
	FDX US	FDX US	FDX US	FDX US	FDX US	FDX US	0	5436			1/2		
												9493.00	11778.00

Figure 17 – Duty Cycle RBA example 576 MHz FDX Band

In the above example of a 576 MHz FDX band, we have 4 TGs.

For TG1, the CMTS is switching RBA's between RBA 100 (up,down,down) ½ of the time and RBA 110 (up,up,down) ½ the time, gets an effective bandwidth (2589, 2718) for the TG.

For TG2, the CMTS is switching RBA's between RBA 001 (down,down,up) 1/2 of the time and RBA 011 (down,up, up) 1/2 the time, getting the same effective bandwidth as TG1 , (2589, 2718) for the TG 2.

For TG3, the CMTS is switching RBA's between RBA 001 (down,down,up) 1/2 of the time and RBA 010 (down,up, down) 1/2 the time, getting the effective bandwidth of (3452, 1812) for TG3.

For TG4, is more upstream heavy, and it switches RBA's between RBA 110 (up,up,down) ½ of the time, RBA 111 (up,up,up) ½ the time, to get an effective bandwidth (863,4530) for those TG.

Now summing up the effective data rates across the TG's gives (9493,11778) which is greater than the node capacity (5178,5436), in the upstream and in the downstream. This means that both the downstream channels and the upstream channels are being oversubscribed. This means that if a single user is using the peak rate on one TG, another user on a different TG may not be able to use the rate provided by the channel at the same time.

6.3. Dynamic RBAs and the Need for RBA Management

Giving the examples seen above, one can see that setting RBA's for the set of TGs and the set of CMs in each TG, can quickly become complicated. The RBA setting depends on the service level of an individual user, the aggregate service needs across CM's in a TG, and the aggregate service needs across all TGs.

An operator for initial FDX deployments, can start with static RBA settings (this could be different static RBA's for the different TG's, based on the needs of each TG). A second step would be simple duty cycle RBA settings, to get finer granularity of FDX upstream and downstream bandwidth capabilities.

Once an operator moves past static RBA settings and simple duty cycle RBA settings, the goal would be to set RBAs dynamically based on the needs in the plant. This means tracking the aggregate upstream and downstream usage on a TG basis, and predicting the appropriate RBA setting needed to best meet the service level agreements and performance on the FTX channels

D3.1 introduced the need for dynamic profile management across an OFDM/OFDMA channel. This has become an application external to the CMTS which can create profiles and push them into the CMTS. In a similar fashion one can imagine RBA management application combined with profile management for the FDX channels becoming a necessity to manage bandwidth across the FDX band effectively

7. FDX + D3.1 Channel Capacity

Now that we are familiar with the capacity provided by FDX channels, in this section we look to understand maximum data rates which can be provided by an FDX and an FDX– L CM.

In addition to the FDX band of channels, based on the D3.1 and FDX CM capabilities, the assumption here is as follows. For the downstream, CMs can tune to 32 SC QAMs, and a D3.1 OFDM channel(192Mhz) outside of the FDX band and use OFDMA channels for the Upstream. The Channel capacity scenarios, in the figures below shows the CM using the FDX band and in addition shows the CM being able to use the upstream from 5-85 MHz and non-FDX DS from 684 to1218 MHz.

Now FDX CM cannot receive non-FDX channels (SC-QAM or OFDM) within the FDX band (108-684 MHz). So even if the occupied FDX band is say 108 to 300 MHz, the FDX-CM cannot receive non-FDX channels in the 300-684 Mhz zone. This drives the placement of the 192 MHz OFDM channel, and the 32 SCQAM channels above 684 MHz. For the upstream the CM could receive SCQAM or OFDMA channels, or both using Time and Frequency division multiplexing, but for simplicity the assumption is an OFDMA channel across the usable upstream spectrum. The capacity of the channels is calculated based on the table defined in section 5.5.

7.1. FDX CM Common Use case (Use Case 1)

In this scenario, the operator introduces the FDX band for use with FDX channels. In addition, the operator introduces a (non-FDX) 192 MHz OFDM channel (684-876 zone), and adds 32 SC-QAM channels in the 876-1068 zone. The CM is also receiving an 80 MHz OFDMA upstream in the legacy band.

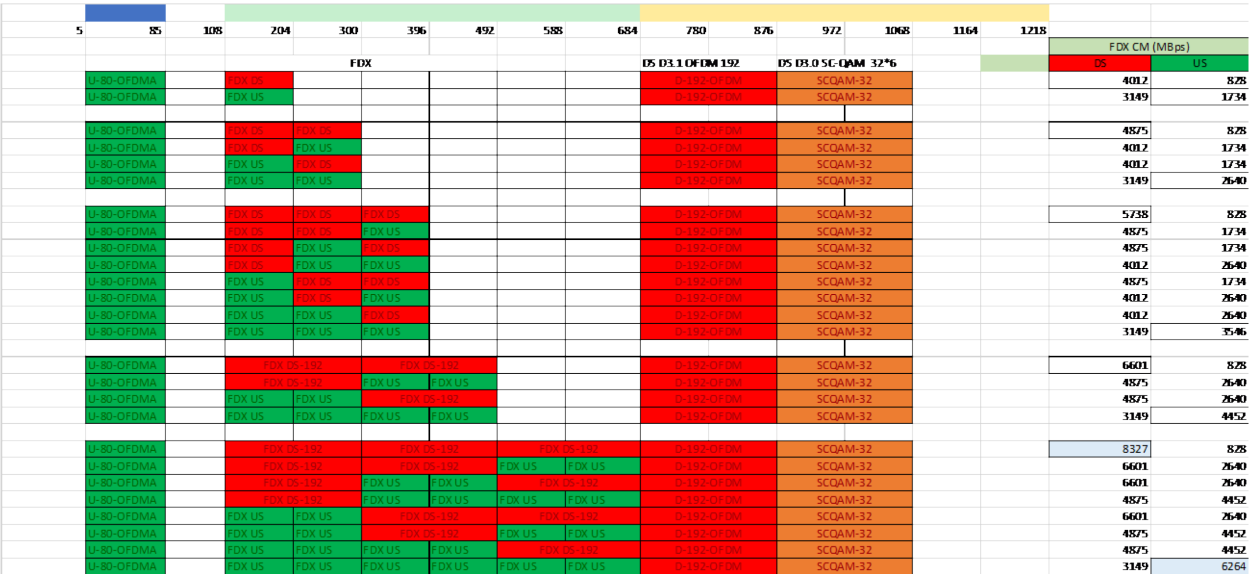


Figure 18 – FDX CM Total channel Capacity- Use Case 1

The channel capacity Use Case 1, in the figure above: per the capacity numbers on the right edge of the figure above, as the size of the FDX band increases, the maximum downstream capacity increases, from about 4 Gbps to 8.3 Gbps, and the upstream capacity ranges from 1.7 Gbps to 6.2 Gbps

7.2. Additional OFDM channel for 1 or 2 FDX sub-band (Use case-2)

An FDX CM can receive up to four OFDM channels. In this Use case, for the scenarios in which the FDX bands which are 92 MHz, 192 MHz and 384 MHz, the FDX CM has an extra OFDM receiver which can be put to use. In this scenario, the operator introduces an additional 192 MHz OFDM channel, and moves the SC-QAM channels to the 1068-1218 zone, this also reduces the number of SC-QAM channels from 32 to 24.

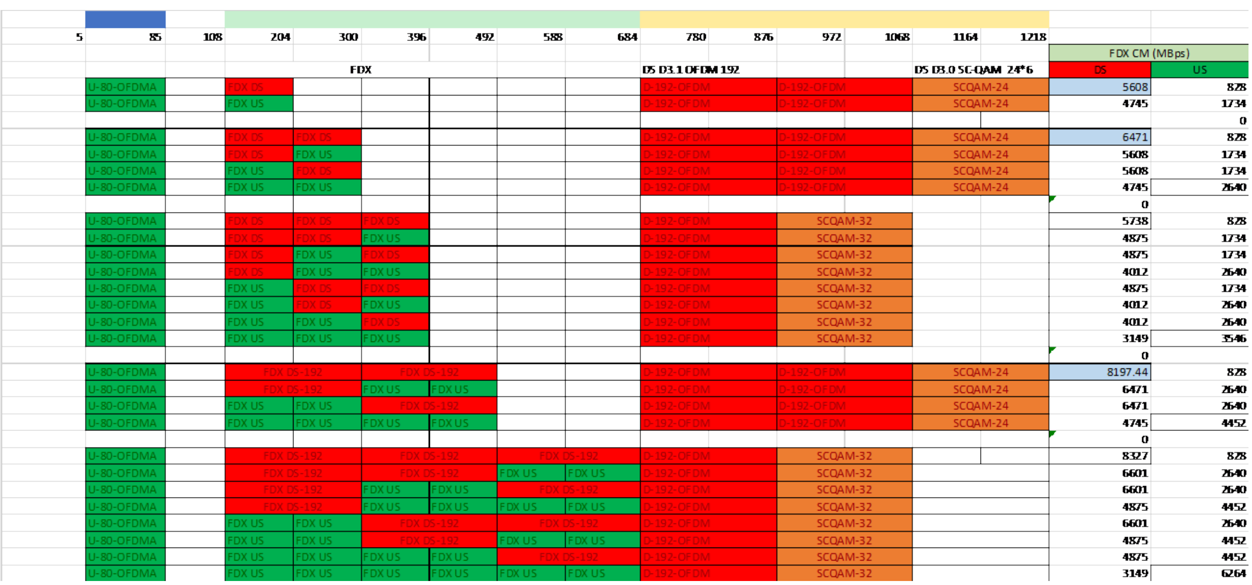
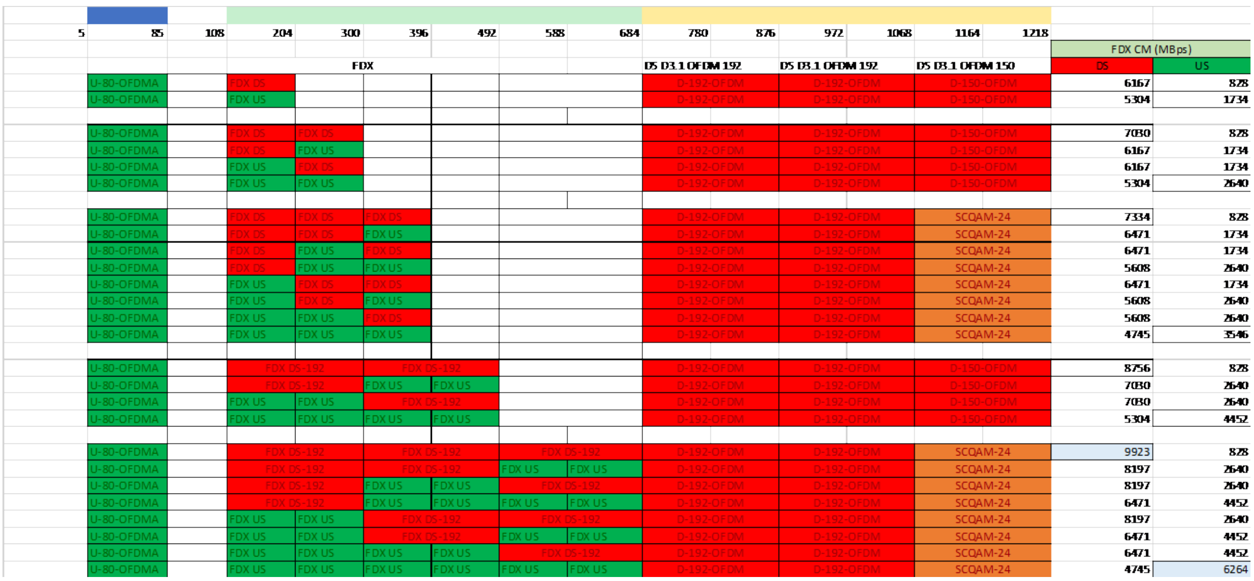


Figure 19 – FDX Total CM channel Capacity- Use Case 2

The channel capacity Use Case 2, in the figure above: per the capacity numbers on the right edge of the figure above, this use case is the same for the 288,576 MHz FDX-Band scenarios. But for the 96,192 and 384 MHz Scenarios the maximum downstream capacity increases, from about 4 Gbps to 5.6 Gbps, about 4.8 Gbps to 6.4 Gbps, and about 6.6 Gbps to 8.1 Gbps,

7.3. Additional Optional OFDM channel Support (Use case-3)

An FDX CM can receive up to four OFDM channels and optionally it could support one additional FDX Channel. In this scenario, the assumption is the CM can support 5 OFDM channels. In this scenario, the operator introduces an additional 192 MHz OFDM channel, and moves the SC-QAM channels to the 1068-1218 zone, this also reduces the number of SC-QAM channels from 32 to 24. For the 96, 192, 384 MHz FDX Bands (2 sub-band Use cases) the operator can replace the SC-QAM with a more efficient OFDM Channel (150 MHz from 1068 to 1218 MHz), since an OFDM Tuner will be available.



5 85 108 204 300 396 492 588 684 780 876 972 1068 1164 1218

		FDX						DS D3.1 OFDM 192	DS D3.1 OFDM 192	DS D3.1 OFDM 150	FDX CM (MBps) DS	FDX CM (MBps) US
U-80-OFDMA		FDX DS						D-192-OFDM	D-192-OFDM	D-150-OFDM	6167	828
U-80-OFDMA		FDX US						D-192-OFDM	D-192-OFDM	D-150-OFDM	5304	1734
U-80-OFDMA		FDX DS	FDX DS					D-192-OFDM	D-192-OFDM	D-150-OFDM	7030	828
U-80-OFDMA		FDX DS	FDX US					D-192-OFDM	D-192-OFDM	D-150-OFDM	6167	1734
U-80-OFDMA		FDX US	FDX DS					D-192-OFDM	D-192-OFDM	D-150-OFDM	6167	1734
U-80-OFDMA		FDX US	FDX US					D-192-OFDM	D-192-OFDM	D-150-OFDM	5304	2640
U-80-OFDMA		FDX DS	FDX DS	FDX DS				D-192-OFDM	D-192-OFDM	SCQAM-24	7334	828
U-80-OFDMA		FDX DS	FDX DS	FDX US				D-192-OFDM	D-192-OFDM	SCQAM-24	6471	1734
U-80-OFDMA		FDX DS	FDX US	FDX DS				D-192-OFDM	D-192-OFDM	SCQAM-24	6471	1734
U-80-OFDMA		FDX DS	FDX US	FDX US				D-192-OFDM	D-192-OFDM	SCQAM-24	5608	2640
U-80-OFDMA		FDX US	FDX DS	FDX DS				D-192-OFDM	D-192-OFDM	SCQAM-24	6471	1734
U-80-OFDMA		FDX US	FDX DS	FDX US				D-192-OFDM	D-192-OFDM	SCQAM-24	5608	2640
U-80-OFDMA		FDX US	FDX US	FDX DS				D-192-OFDM	D-192-OFDM	SCQAM-24	5608	2640
U-80-OFDMA		FDX US	FDX US	FDX US				D-192-OFDM	D-192-OFDM	SCQAM-24	4745	3546
U-80-OFDMA		FDX DS-192		FDX DS-192				D-192-OFDM	D-192-OFDM	D-150-OFDM	8756	828
U-80-OFDMA		FDX DS-192		FDX US	FDX US			D-192-OFDM	D-192-OFDM	D-150-OFDM	7030	2640
U-80-OFDMA		FDX US	FDX US	FDX DS-192				D-192-OFDM	D-192-OFDM	D-150-OFDM	7030	2640
U-80-OFDMA		FDX US	FDX US	FDX US	FDX US			D-192-OFDM	D-192-OFDM	D-150-OFDM	5304	4452
U-80-OFDMA		FDX DS-192		FDX DS-192		FDX DS-192		D-192-OFDM	D-192-OFDM	SCQAM-24	9923	828
U-80-OFDMA		FDX DS-192		FDX DS-192		FDX US	FDX US	D-192-OFDM	D-192-OFDM	SCQAM-24	8197	2640
U-80-OFDMA		FDX DS-192		FDX US	FDX US	FDX DS-192		D-192-OFDM	D-192-OFDM	SCQAM-24	8197	2640
U-80-OFDMA		FDX DS-192		FDX US	FDX US	FDX US	FDX US	D-192-OFDM	D-192-OFDM	SCQAM-24	6471	4452
U-80-OFDMA		FDX US	FDX US	FDX DS-192		FDX DS-192		D-192-OFDM	D-192-OFDM	SCQAM-24	8197	2640
U-80-OFDMA		FDX US	FDX US	FDX DS-192		FDX US	FDX US	D-192-OFDM	D-192-OFDM	SCQAM-24	6471	4452
U-80-OFDMA		FDX US	FDX US	FDX US	FDX US	FDX DS-192		D-192-OFDM	D-192-OFDM	SCQAM-24	6471	4452
U-80-OFDMA		FDX US	FDX US	FDX US	FDX US	FDX US	FDX US	D-192-OFDM	D-192-OFDM	SCQAM-24	4745	6264

Figure 20 – FDX Total CM channel Capacity- Use Case 3

The channel capacity Use Case 3, in the figure above: per the capacity numbers on the right edge of the figure above, the maximum downstream capacity is from about 6.1 Gbps to 9.9 Gbps, and the upstream capacity stays the same, ranging from 1.7 Gbps to 6.2 Gbps

7.4. FDX-L CM (Use case-4)

An FDX-L CM can receive two OFDM channels and two OFDMA Channels.

In this scenario, the operator uses a192 MHz OFDM channel outside of the FDX band, and uses the SC-QAM channels within the FDX band 108-684 when possible, for the 96, 192, 288, 384 MHz FDX Bands use cases the operator, for the 576 MHz FDX band use case, the operator can move the SC-QAM to the 876-1068 MHz range.

FDX CMs are purpose built CMs designed with hardware and software capable of supporting FDX functionality. FDX-L CMs are D3.1 CMs with limited capabilities for operating within the FDX Band.

The figure below uses the term FDX-L-H for D3.1 High-split CMs which have been software upgrade to use the FDX Band, and the term FDX-L-M for D3.1 Mid-split CMs which have been software upgrade to use the FDX Band. The D3.1 CM supports a downstream lower band edge of 258 MHz. This would apply to FDX-L-H and FDX-L-M CMs. The D.1 CM optionally supports a downstream lower band edge of 108 MHz when the CM is configured to use an upstream upper band edge of 85 MHz or less. This means an FDX-L-M (D3.1 Mid Split CM) may be able to use (FDX) Downstream channels starting at 108 Mhz.

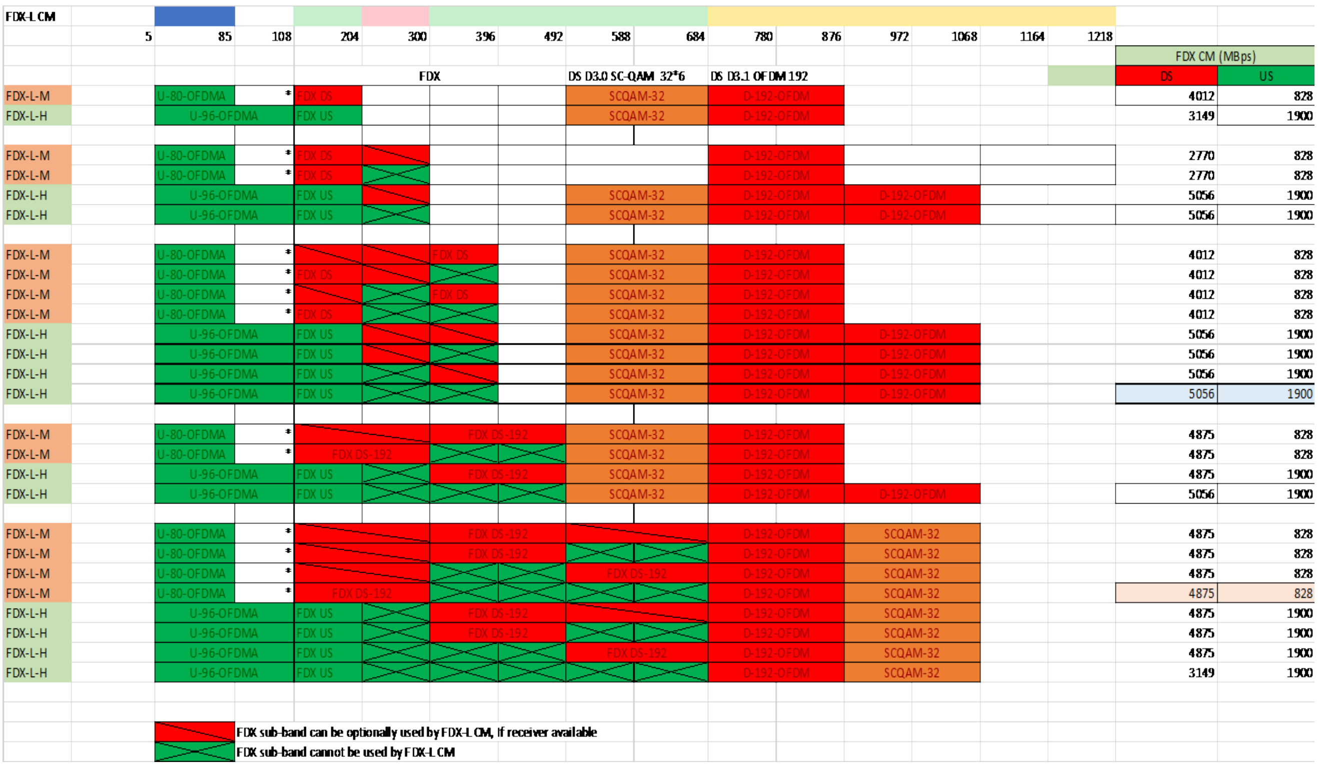


Figure 21 – FDX-L CM CM channel Capacity- Use Case 4

The channel capacity Use Case 4, in the figure above: per the capacity numbers on the right edge of the figure above, the maximum capacity for FDX-L CMs is similar to D3.1 CMs, but with the benefit that an operator may be able to reuse the FDX capacity for currently deployed D3.1 CMs. The downstream capacity ranges from about 4 to 5 Gbps, and the upstream capacity is at ~0.8 Gbps for FDX-L-M CMs (Mid- Split D3.1 CMs) to 1.9 Gbps for FDX-L-H (High Split D3.1 CMs)

Conclusion

Full duplex DOCSIS is a game changing advance in DOCSIS access network technology. It enables a lot more upstream capacity in the network and also allows the operator to dynamically match the customer demand in both the upstream and downstream direction. Each transmission group within the FDX band, gets assigned a unique resource block assignment, to best match the demand from the CMs. The assignment of RBA's has the potential to be complicated and may need to be managed independently. FDX bandwidth along with the legacy(D3.1) downstream and upstream bandwidth easily enables Multi Gigabit service offerings.

Abbreviations

bps	bits per second
ACI	Adjacent Channel Interference
ALI	Adjacent Leakage Interference
CCI	Co-channel interference
CWT	Continuous Wave Tone
D3.1	DOCSIS 3.1
DS	Downstream
ECT	Echo Cancellation Training
FEC	forward error correction
FDX	Full Duplex DOCSIS 3.1
FDX-L	FDX-Limited (functionality)
HFC	hybrid fiber-coax
Hz	hertz
IG	Interference group
RBA	Resource Block Assignment
RxMER	Receive Modulation Error Ratio
SCTE	Society of Cable Telecommunications Engineers
TG	Transmission Group
US	Upstream
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OUDP	OFDM Upstream Data Profile
ZBL	Zero Bit Loading

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