Characterization of Spectrum Resource Scheduling in FDX DOCSIS

A Technical Paper prepared for SCTE•ISBE by

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Introduction

Prior to Full Duplex (FDX) DOCSIS, the downstream (DS) and the upstream (US) were scheduled independently, as the DS and the US transmissions were isolated from each other in frequency. In FDX DOCSIS however, the DS and the US operate at the same frequency and at the same time. Coordinated DS and US scheduling is required to avoid interference and to balance the bi-directional traffic need. Fundamentally, FDX spectrum is directionally fluid with a unique set of constraints that confines the DS and US scheduling decisions. How to manage the FDX spectrum resource, maximize the DS and US throughput and maintain fairness is a big design and deployment challenge faced by both Cable Modem Termination System (CMTS) vendors and operators.

In this paper, we tackle this problem by studying the characteristics unique to the FDX spectrum, quantify the optimization objectives, and identify scheduling options to maximize both spectral efficiencies and fairness. The rest of the paper is organized as follows. Section 1 overviews the FDX operation principles and the scheduling constraints. Section 2 then examines the correlations between the DS and the US spectral efficiencies. Section 3 characterizes the FDX spectrum directional assignment and its impact on system throughput. Section 4 quantifies the FDX spectrum capacity gain with respect to the FDD spectrum capacity. Section 5 discusses fairness in the context of the FDX spectrum resource distribution hierarchy. Section 6 provides an illustrative example to demonstrate the FDX spectrum resource scheduling framework. A summary is provided at the end to conclude the paper.

Content

1. FDX DOCSIS: Potential and Challenges

FDX DOCSIS is targeted at significantly increasing the US capacity without sacrificing the DS capacity by enabling simultaneous bidirectional transmissions in a frequency band between 108 MHz and 608 MHz[1][5][6]. Within this band, the RF spectrum allocated for FDX operations is organized in sub-bands, with each sub-band containing one FDX DS channel and one or two FDX US channels, as shown in Figure 1.

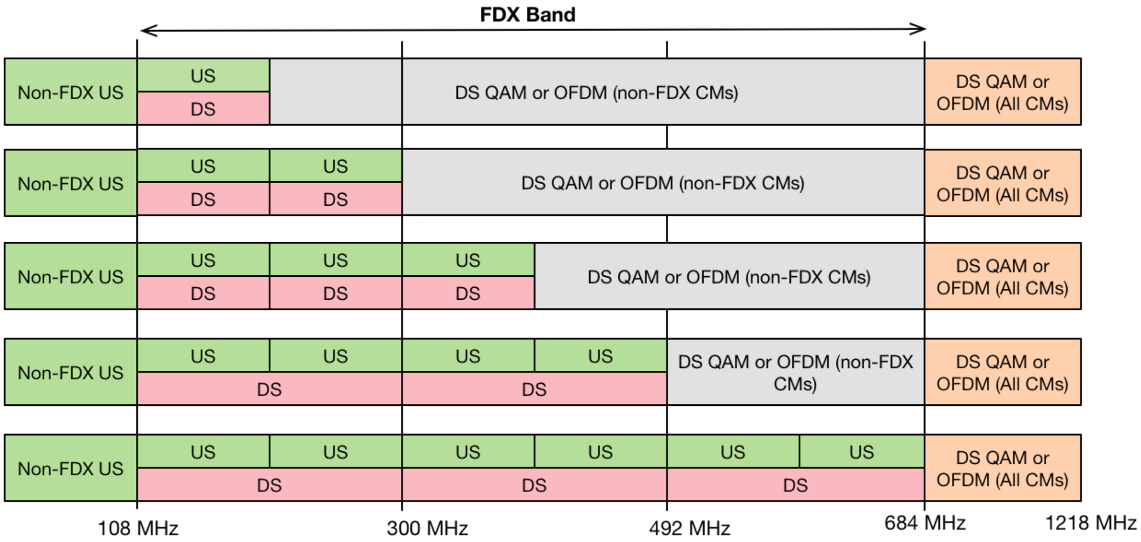


Figure 1- FDX Resource Block and Allocated Spectrum Options

The biggest challenge to enable FDX is the interference from transmitter to receiver at the CMTS (DS to US interference) and among cable modems (CM)s (US to DS interference), as described below.

1.1. DS to US Interference

At an FDX remote PHY device (RPD) node the transmitted DS signal, which has a much higher signal level than the received US signal, can be echoed back to the US receive path through the internal and external coupling. Such interference will completely wipe out the received US signal if there is not sufficient isolation between the transmitter and the receiver. Normally, a diplexer filter is used to keep the DS signal from entering the US receive path. However, the FDX RPD Node will not have a diplexer in order for it to receive the US signal in the same spectrum sent by the CMs. Instead, an echo canceller (EC) is used to suppress the interference sourced from the DS transmissions and thus provide the required isolation[3]. The EC removes the interference by reconstructing the echoes from the transmitted DS signals based on a proper estimation of the echo channel characteristics, as shown in Figure 2.

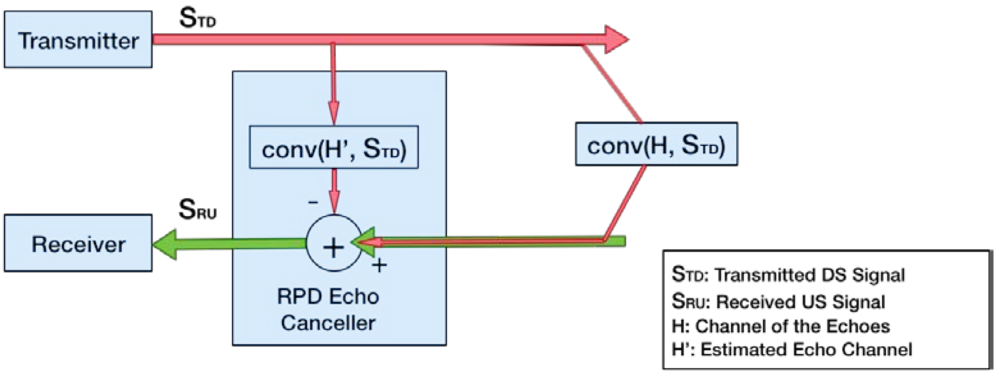


Figure 2 DS to US Interference and Echo Cancellation at the FDX RPD Node

1.2. US to DS Interference

From the CM perspective, the FDX spectrum will still appear to be frequency division duplexed (FDD), in the sense that, a sub-band can only be used by the CM in either DS or US direction at a given time. FDX is achieved by assigning one set of CMs to use the sub-band for US at the same time that a different set of CMs is being assigned to use that sub-band for DS. The main sources of the US to DS interference experienced by a CM are internal, from its own US transmission in an adjacent sub-band, and external, from neighboring CMs US transmissions. While the echo cancellation technique can remove the internal self-interference, it cannot be used to mitigate the external interference, as the source of the interference is unknown to the receiving CM.

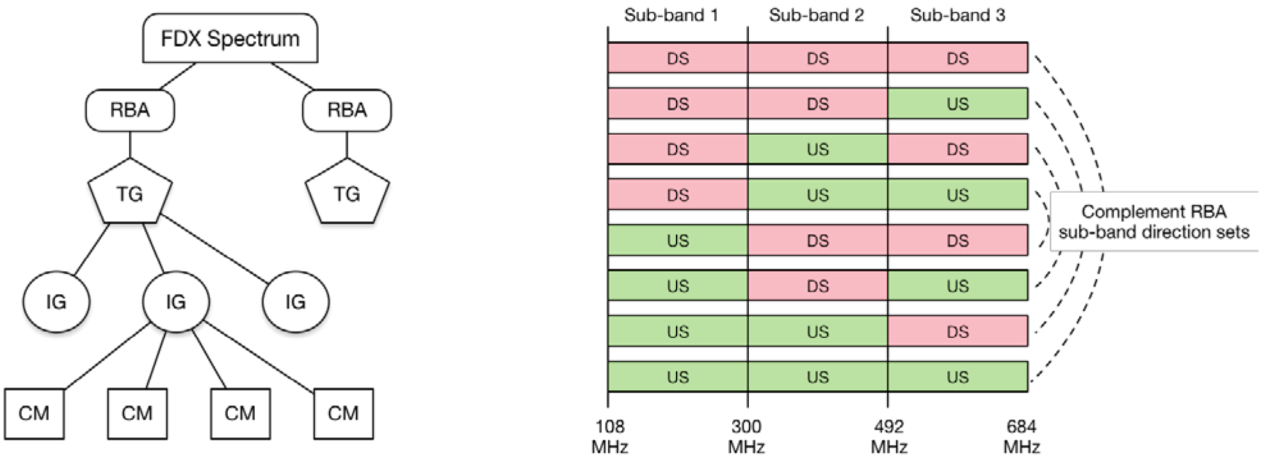
The external CM to CM interference is due to the imperfect isolation in the cable plant. if one CM is transmitting in the US in one sub-band while another CM is trying to receive in that same sub-band, energy from the first CM’s US transmission can, in some cases, leak into the location of the second CM and prevent it from successfully receiving the DS transmissions. Such interference can be avoided with proper scheduling such that CMs that interfere with each other will not transmit and receive at the same time and at the same frequency. This mechanism is referred as the “simplex-duplex” rule required for FDX operation. Specifically, FDX DOCSIS separates a CM’s neighboring CMs into two categories based on the CM’s interference group (IG)[2][4]:

1. CMs within the IG, which need to operate in simplex mode (uni-directional at any particular point of time and frequency) with the respect to the CM to avoid co-channel interference;
2. CMs outside the IG, which have an isolation above the IG’s boundary (a threshold that bounds the isolation among CMs inside the IG) and can operate in full duplex mode with respect to the CM.

In this nomenclature, simplex refers to a unidirectional path at a given instance of time and frequency, and duplex refers to a bidirectional path at a given instance of time and frequency.

In FDX DOCSIS, the “simplex-duplex” operation rule is enforced via the IG-TG-RBA mapping hierarchy as shown in Figure 3. IGs are grouped into different transmission group (TG)s for scheduling purposes. Each TG is associated with a resource block assignment (RBA) that enforces FDD with in the TG. Different RBAs enable bidirectional use of the FDX spectrum.

Figure 3-b shows the RBA directional assignment options with three FDX sub-bands. RBAs with complement DS and US assignment form the minimum RBA sub-band direction sets that fully assign the spectrum in both directions. When more than two TGs are used, a sub-band will have at least two TGs sharing the sub-band in the same direction.



(a) CM-IG-TG mapping and RBA assignment

(b) RBA options for a 3-subband resource block

Figure 3 Mitigating CM to CM Interference with Simplex-Duplex Rule

1.3. FDX Spectrum Resource Scheduling Challenges

The FDX operation imposes a unique set of challenges to spectrum resource scheduling. First, as described in more detail in Section 2, the DS and US spectral efficiencies can no longer be separately controlled, as the intended transmit signal of one direction is the source of the interference to the other direction. Second, the DS and US resource blocks accessible by a CM are constrained by the simplex-duplex rule through a multi-level resource distribution chain. Third, the IG based spectrum sharing may conflict with the ability to maintain service level agreement (SLA) goals, as the interference environment is independent to the traffic distribution and service offerings.

Due to the DS to US correlation, and the conflicting optimization goals of efficiency and fairness, FDX spectrum resource scheduling becomes a highly integrated problem set with multiple sub-problems that need to be individually analyzed.

2. FDX Spectral Efficiency

The objective of this section is to analyze the achievable DS and US spectral efficiencies when the interference is a dominating factor affecting system performance. Due to the path loss of the coax plant, the DS and US transmit power ends being much higher than the converse receive power, resulting in a high level of interference at the receiver. When interference is a dominating factor impacting system performance, we can use signal to interference ratio (SIR) to evaluate the spectral efficiency. If the background noise is not negligible, the SIR serves as an upper bound of the achievable spectral efficiency.

2.1. Interference-Limited Network Model

To analyze the impact of the interference, we model the FDX system as a two-port (a kind of four-terminal) network connecting the transmitters and the receivers of both the DS and US directions, as shown in Figure 4. The directional connections of the DS and US signals and the interference paths in between can be characterized with the following parameters:

- Plant Path Loss

This is the path loss along the intended DS or US transmission path through the coax plant. For a N+0 network, the plant loss is reciprocal between the DS and the US.

- DS to US Isolation

This is the total isolation from the DS transmitter to the US receiver at the FDX RPD node. It combines the passive DS to US coupling loss, X_{DU}, and the DS echo return loss, G, provided by the EC.

- US to DS Isolation

This is the isolation between a pair of CMs attached to the same coax plant. In FDX operation, the IG boundary is the lower bound of the US to DS isolations, X_{UD} for its member CMs with respect to rest of the CM population.

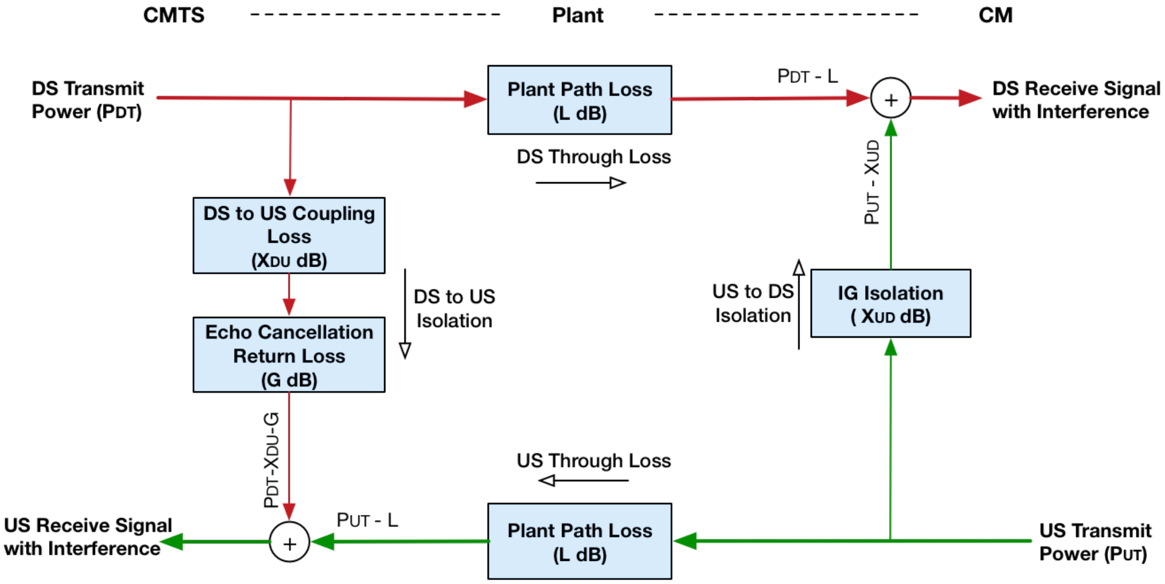


Figure 4 Interference-Limited Network Model for FDX Operation

2.2. FDX DS and US SIRs

Based on the network model, the DS and US SIR can be easily setup using logarithmic power units (dB) as below:

$$SIR_U = P_{UT} - L - P_{DT} + X_{DU} + G \tag*{$Eq\ 1$}$$

$$SIR_D = P_{DT} - L - P_{UT} + X_{UD} \tag*{$Eq\ 2$}$$

Where,

P_{UT}: US transmit power per 6 MHz in dBmV

P_{DT}: DS transmit power per 6 MHz in dBmV

X_{DU}: DS to US isolation in dB

X_{UD}: US to DS isolation in dB

G: DS echo return loss in dB

L: DS or US path loss in dB

Eq1 and Eq2 reveal the correlation between the DS and the US spectral efficiencies in terms of SIRs. To visualize this correlation, the DS and the US SIR values are plotted in Figure 5 as the DS transmit and US receive power change. Other parameters assumed are listed below:

X_{DU}: DS to US isolation = 20 dB

X_{UD}: US to DS isolation = 65 dB

G: DS echo return loss = 50 dB

L: DS or US signal propagation loss = 33 dB

Note that the above values are illustrative only.

From Figure 5, we can observe that as the US transmit power increases, the US SIR improves, but the DS SIR declines; and as the DS transmit power increases, dB by dB, the DS SIR increases, the US SIR decreases. The sum of the DS SIR and US SIR however remains constant regardless of the power level.

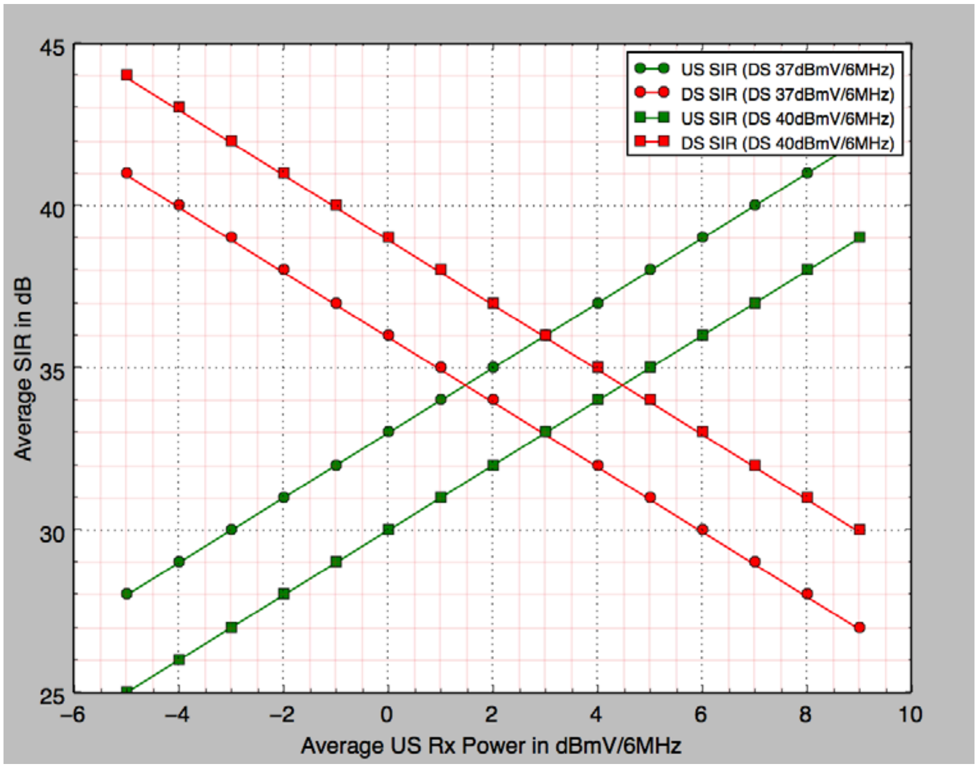


Figure 5 Correlation Between the DS SIR and US SIR in FDX Spectrum

2.3. Interference-Limited Spectrum Resource Characteristics

When the system operates in the interference limited regime, the FDX spectrum efficiency exhibits following properties:

- Monotonicity

When the transmit power increases in one direction, the spectral efficiency decreases in the opposite direction. This implies that we can trade off the DS spectral efficiency against the US spectral efficiency with proper transmit power adjustment in either direction.

- Exchangeability

Adjustments are exchangeable among elements affecting the spectral efficiency. For example, as shown below, increasing US transmit power is equivalent to decreasing the DS transmit power with respect to the US SIR; increasing the DS transmit power is equivalent to increasing the IG isolation boundary with respect to the DS SIR,

$$SIR_U = P_{UT} \uparrow - P_{DT} \downarrow + X_{DU} + G - L$$

$$\mathrm{SIR_D} = \mathrm{P_{DT}} \uparrow - \mathrm{P_{UT}} + \mathrm{X_{UD}} \uparrow - \mathrm{L}$$

This property provides the flexibility required to achieve the spectral efficiency target under certain operational constraints. For example if the DS transmit power is limited, a larger IG can be used to get to the higher DS SIR desired.

- Conservation

Conservation is a direct result of the monotonicity. For given signal path loss and isolation loss between the DS and the US, the sum of the DS and US SIR remains constant. This can be seen by adding *Eq1* with *Eq2* as below:

$$SIR_U + SIR_D = X_{UD} + X_{DU} + G - 2L \qquad Eq\ 3$$

Eq3 makes sense intuitively. When the interference dominates, less signal loss and better isolation result in better spectral efficiency.

3. Sub-band Directional Assignment

In FDX operation, the DS or US sub-band direction assignment must follow the “simplex-duplex” rule such that a sub-band is only used in a single direction for a particular TG. Between the TGs, however, there are no direction restrictions, so when one TG uses a sub-band for US operation, a different TG can simultaneously use the same sub-band for DS operation, doubling the usage of the spectrum.

In FDX DOCSIS, the sub-band direction assignment is done through RBA to TG mapping and at any given time a TG can only be associated with one RBA. To examine the impact of sub-band direction assignment on system performance, we derive the maximum achievable FDX DS and US throughput as below.

Assuming there are M TGs sharing N sub-bands, we model the per TG per sub-band direction assignment as a MxN matrix for each direction shown as below, where A^D denotes the DS assignment and A^U denotes the US assignment, a_{ij}^D and a_{ij}^U are the directional assignment coefficients for TG_i in jth sub-band of the corresponding US and DS directions.

$$\text{Assignment of the DS: } A^D = \begin{array}{cc} \xrightarrow{N\text{ Sub-bands}} & M\text{ TGs} \\ \begin{bmatrix} a_{11}^D & \cdots & a_{1N}^D \\ \vdots & \ddots & \vdots \\ a_{M1}^D & \cdots & a_{MN}^D \end{bmatrix} & \Bigg\downarrow \end{array}$$

$$\text{Assignment of the US: } A^U = \begin{array}{cc} \xrightarrow{N\text{ Sub-bands}} & \\ \begin{bmatrix} a_{11}^U & \cdots & a_{1N}^U \\ \vdots & \ddots & \vdots \\ a_{M1}^U & \cdots & a_{MN}^U \end{bmatrix} & \Bigg\downarrow \quad M\text{ TGs} \end{array}$$

The direction assignment coefficient varies between 0 and 1, representing different assignment scenarios described below:

- 0 : The given TG is not assigned to use the given sub-band in the given direction
- 1: The given TG is assigned to use the full sub-band in the given direction
- Between 0 and 1: The given TG is assigned to use the a fraction of the given sub-band in the given direction. This will be the case when multiple TGs share the same sub-band in the same direction.

The following restrictions apply to the sub-band direction assignment:

- A sub-band cannot be used for both DS and US for a given TG at the same time. This implies the entry wise product (also known as the Hadamard product) of the DS and US assignment matrices is zero:

$$a_{ij}^{D} .* a_{ij}^{U} = 0 \qquad \text{Eq4-1}$$

- The sum of the assignments of a sub-band in a given direction across all TGs cannot exceed 100% of the sub-band spectrum in the corresponding direction. The sub-band is claimed to be fully assigned in both DS and US directions if the following conditions are met:

$$\sum_{i=1}^{M} a_{ij}^{D} = 1; \qquad \text{Eq4-2}$$

$$\sum_{i=1}^{M} a_{ij}^{U} = 1; \qquad \text{Eq4-3}$$

Eq4-1 to Eq4-3 imply that a minimum of two TGs ($M \geq 2$) are required for a sub-band to be fully utilized in the FDX operation. For the special case of two TGs, the directional assignment coefficients a_{ij}^{D} and a_{ij}^{U} are either 1s or 0s, and the sub-band direction sets of the two TG need to be complement to each other for each sub-band to be fully assigned. Figure 6 shows the two TG and three TG mapping examples that have the three sub-bands fully assigned.

	Sub-band 1	Sub-band 2	Sub-band 3
TG1	DS	DS	US
TG2	US	US	DS

(a) Example: Incomparable RBA Sub-band Direction Sets With 2 TGs over 3 Sub-bands

	Sub-band 1	Sub-band 2	Sub-band 3
TG1	DS	DS	US
TG2	US	DS	DS
TG3	DS	US	DS

(b) Example: Comparable RBA Sub-band Direction Sets With 3 TGs over 3 Sub-bands

Figure 6 Comparable vs. Incomparable Fully Assigned RBA Sub-band Direction Sets

An additional observation is that when there is an odd number of sub-bands fully assigned to two TGs, the numbers of the DS and US sub-bands are incomparable between the TGs. For example, in Figure 6-a, TG1 has two DS sub-bands and one US sub-bands, while TG2 has two US sub-bands and one DS sub-bands. For the three sub-band case, comparable directional assignment can be achieved however with three TGs instead, with each sub-band shared by at most two TGs in each direction. An example of the comparable directional assignment is shown in Figure 6-b.

4. FDX Spectrum Capacity Gain

The FDX spectrum capacity is defined here as the aggregate DS and US throughput achievable across all TGs over the allocated FDX spectrum. For an individual TG, denote the achievable DS and US throughput across the N sub-bands as,

DS max throughput set for TG_i: $D_i = [d_{i1}, .., d_{iN}]$, for $i = 1, .. M$

US max throughout set for TG_i: $U_i = [u_{i1}, .., u_{iN}]$, for $i = 1, .. M$

where d_{ij} and u_{ij} are determined by the DS and US spectral efficiencies of the member IGs included in TG_i and the sub-band width.

After applying RBAs, the FDX spectrum capacity collectively achievable with M TGs can then be expressed as:

$$\text{FDX Spectrum Capacity } = \sum_{i=1}^{M}(A_i^D \cdot D_i + A_i^U \cdot U_i) \qquad \textit{Eq5}$$

where, A_i^U and A_i^D denote the ith row of the RBA direction assignment matrices A^U and A^D.

We then define the FDD spectrum capacity as a reference to evaluate the FDX spectrum capacity gain. Assuming the maximum DS or US throughput in the non-FDX mode across the spectrum span of the N sub-band as:

DS max throughput when spectrum is used in DS only: $D_0 = [d_{01}, .., d_{0N}]$

US max throughput when spectrum is used in US only: $U_0 = [u_{01}, .., u_{0N}]$

Further assuming an even split of the DS and US spectrum in FDD, the FDD spectrum capacity is:

$$\text{FDD Spectrum Capacity } = \sum_{j=1}^{N}(d_{0j} + u_{0j})/2 \qquad \textit{Eq6}$$

Hence, the FDX spectrum capacity gain is:

$$\text{FDX Spectrum Capacity Gain} = \frac{\sum_{i=1}^{M}(A_i^D \cdot D_i + A_i^U \cdot U_i)}{\sum_{j=1}^{N}(d_{0j} + u_{0j})/2} \qquad \textit{Eq7}$$

Eq7 can serve as a benchmark to evaluate an FDX system performance. Maximizing it combines the FDX spectral efficiency optimization with the RBA sub-band directional assignment optimization. However, maximizing Eq7 alone will result in biased spectrum allocations in favor of the less interfered users, fairness also needs to be considered as discussed below.

5. FDX Fairness

A typical dilemma in resource scheduling is the conflicting optimization objectives between throughput and fairness. In FDX DOCSIS, maximizing the throughput alone does not necessarily translate into the maximum value for the operators, as it may favor the least interfered subscribers who may not be subscribed to the highest service levels. Fairness is needed to retain happy customers with an allocation proportional to the SLAs.

Service level fairness is a global goal irrelevant to the localized constraints or scheduling decisions. The fewer constraints or the fewer local scheduling points, the easier it is to achieve fairness. FDX DOCSIS, however, has many localized scheduling points along the resource distribution hierarchy. Achieving fairness requires resource or traffic balancing at each of the branching point. As shown in Figure 7, from bottom up, the following options can be used to optimize fairness:

- A CM can have a different spectral efficiency in a direction by adjusting the transmit power or shrinking / extending its IG boundary. The spectral efficiency change results in different DS and/or US data profile settings.

- By shrinking the IG boundary to a lower spectral efficiency, an IG can split into smaller IGs, which can then be mapped into different TGs for load balancing purposes.
- A TG can be associated with a different RBA in order to achieve a different DS to US capacity ratio.
- The legacy DS and US spectrum resource, accessible to all the CMs, can be used as a fluid resource to improve fairness across the system.

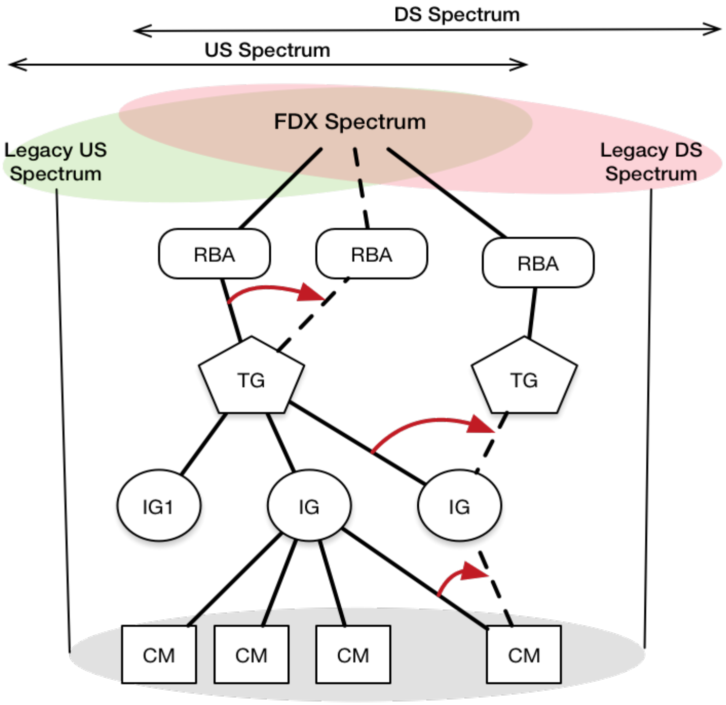


Figure 7 Spectrum Resource Distribution Hierarchy and Load Balancing Options

To evaluate fairness, a proper fairness measure is required. Choices of the fairness measure may include throughput, latency, or a quantifier expressing the subscribers' quality of experiences. More study is required in this area to identify a proper fairness measure for the high-end FDX users, as new applications may appear to take advantage of the FDX spectrum. When best effort service and uniform traffic distribution are assumed, Jain's fairness index [7] can be used to describe the relative equality of the average allocation per user, quoted below:

$$f(x) = \frac{[\sum_{i=1}^{n} x_i]^2}{n\sum_{i=1}^{n} x_i^2} \qquad x_i \geq 0 \qquad Eq8$$

where $f(x)$ is the fairness index, ranging from 1/n (worst case) to 1 (best case), and the parameter x is the average throughput per user. The fairness index is maximum when all users receive the same allocation.

6. An Illustrative Example

In this section, we put everything together with an example to illustrate the FDX spectrum resource scheduling framework.

6.1. Physical and RF Topologies

Without loss of generality, we use a single leg N+0 network as shown in Figure 8. The FDX RPD Node has one port connected to 24 FDX CMs evenly across 6 taps. Other legs can of course present, but not considered to be significant for the purpose of this example.

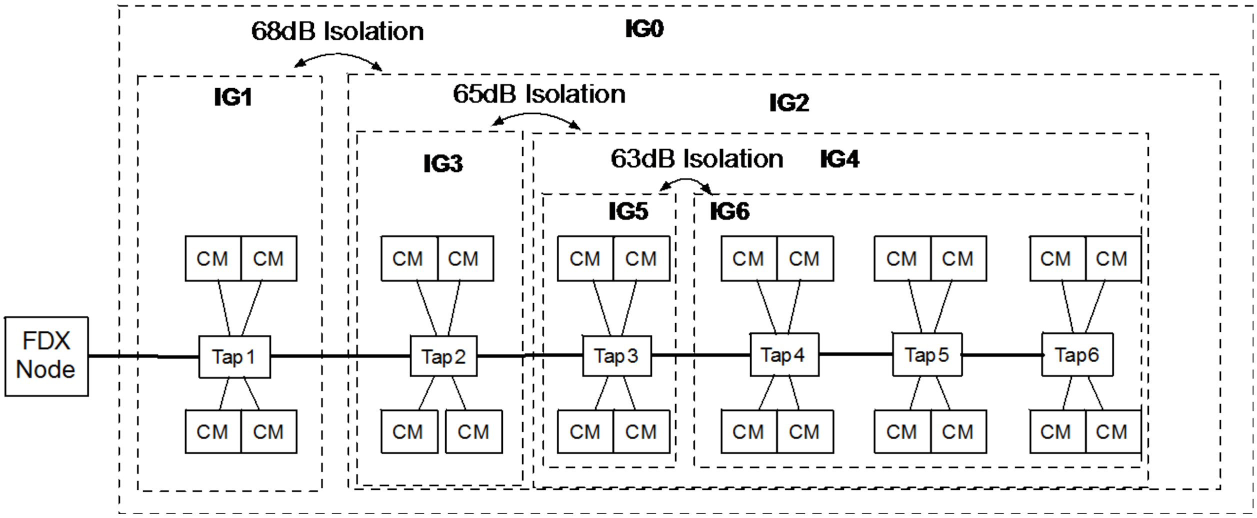


Figure 8 Example - FDX System Physical and RF Topologies

The 24 CMs are separated into 4 IGs, namely IG1, IG3, IG5 and IG6 as marked in Figure8. Note that the IG selection is part of the scheduling decision intended to optimize both throughput and fairness. Table 1 lists all IG options available.

Table 1 Example - IG Options

IG Index	**IG Scope**	**DS Spectral Efficiency (bits/subcarrier)**		
		Sub-band 1	**Sub-band 2**	**Sub-band 3**
IG0	Tap1 to Tap6	11.5	10.5	9.5
IG1	Tap1	11	10	9
IG2	Tap2 to Tap6			
IG3	Tap2	10	9	8
IG4	Tap3 to Tap6			
IG5	Tap3	9	8	7
IG6	Tap4 to Tap6			

The available DS and US spectrum include:

- Legacy upstream 5-85 MHz, estimated around 400 Mbps with a mix of single carrier quadrature amplitude modulation (SC-QAM) and orthogonal frequency division multiplexing with multiple access (OFDMA) channels, around 400Mbps
- FDX Spectrum 108 – 684 MHz, with 3 sub-bands of 192MHz width. The maximum directional capacity is estimated around 4.8 Gbps if entire band is used for DS operation or US operation.
- Legacy downstream above 684 MHz, estimated around 2Gbps with a mix of SC-QAM and orthogonal frequency division multiplexing (OFDM) channels.

6.2. DS and US Spectral Efficiencies

The DS and the US spectral efficiencies are listed in Table 2, together with other performance impacting parameters. To make the example more interesting, the DS and the US transmit power levels are up-tilted to compensate the increasing path loss across the three sub-bands.. In this example, the background noise is assumed to cause a 3dB degradation to the spectral efficiency with respect to the SIR in either DS or US direction. Note that, in actual FDX operation, the DS and US spectral efficiencies can be determined based on the receive modulation error ratio (RxMER) measurements, during and after IG discovery.

Table 2 Example - DS and US Spectral Efficiencies

	Operation Parameters	**Sub-band 1**	**Sub-band 2**	**Sub-band 3**
Common to all IGs	US Tx Power (dBMv/6MHz)	33	36	39
	DS Tx Power (dBMv/6MHz)	34	37	40
	Path Loss (dB)	30	33	36
	DS to US Coupling Loss (dB)	20	20	20
	DS Echo Processing Loss (dB)	50	50	50
IG1, IG2	IG Boundary (dB)	68	68	68
	DS SIR (dB)	39	36	33
	US SIR (dB)	39	36	33
	DS Spectral Efficiency (Bits/subc)	11	10	9
	US Spectral Efficiency (Bits/subc)	11	10	9
IG3, IG4	IG Boundary (dB)	65	65	65
	DS SIR (dB)	36	33	30
	US SIR (dB)	39	36	33
	DS Spectral Efficiency (Bits/subc)	10	9	8
	US Spectral Efficiency (Bits/subc)	11	10	9
IG5, IG6	IG Boundary (dB)	62	62	62
	DS SIR (dB)	33	30	27
	US SIR (dB)	39	36	33
	DS Spectral Efficiency (Bits/subc)	9	8	7
	US Spectral Efficiency (Bits/subc)	11	10	9

6.3. Scheduling Decisions

In this example, best effort service is offered to all 24 subscribers in both the DS and US directions. All 24 CMs are active with even traffic distributions. Per CM peak rate is limited to 3 Gbps for the DS and 1 Gbps for the US. All CMs are active with even traffic distributions.

Figure 9 shows a snapshot of the resource distribution hierarchy with the set scheduling decisions described below:

- IG1, IG3, IG5 and IG6 are selected with the DS and the US data profiles set to the achievable FDX DS and US spectral efficiencies.
- IG1 and IG3 are included in TG1 with a total of 8 CMs. IG5 is included in TG2 with a total of 4 CMS, and IG5 is included in TG3 with a total of 12 CMs.
- A set of symmetrical RBA sub-band direction sets are selected with respect to the three TGs, with 2 DS sub-bands and 1 US sub-bands allocated to each TG as shown in Figure 9. This arrangement together with legacy spectrum will allow the FDX system to meet the 3 Gbps DS and 1 Gbps US SLA requirements.

  The average RBA directional allocation coefficients are listed below. Note that for the US direction, each sub-band is used exclusively by one TG; while for the DS direction, each sub-band is shared by two TGs. The DS assignment coefficients used in this example are based on proportional scheduling and the assumption of uniform traffic distribution across all CMs in all TGs.

  $$\text{Average US Assignment Coefficient}: \ A^U = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

  $$\text{Average DS Assignment Coefficient}: \ A^D = \begin{bmatrix} 2/3 & 0 & 2/5 \\ 1/3 & 1/4 & 0 \\ 0 & 3/4 & 3/5 \end{bmatrix}$$

- The legacy DS and US spectrums are used in this example to balance the FDX spectrum capacity allocation differences among the TGs.

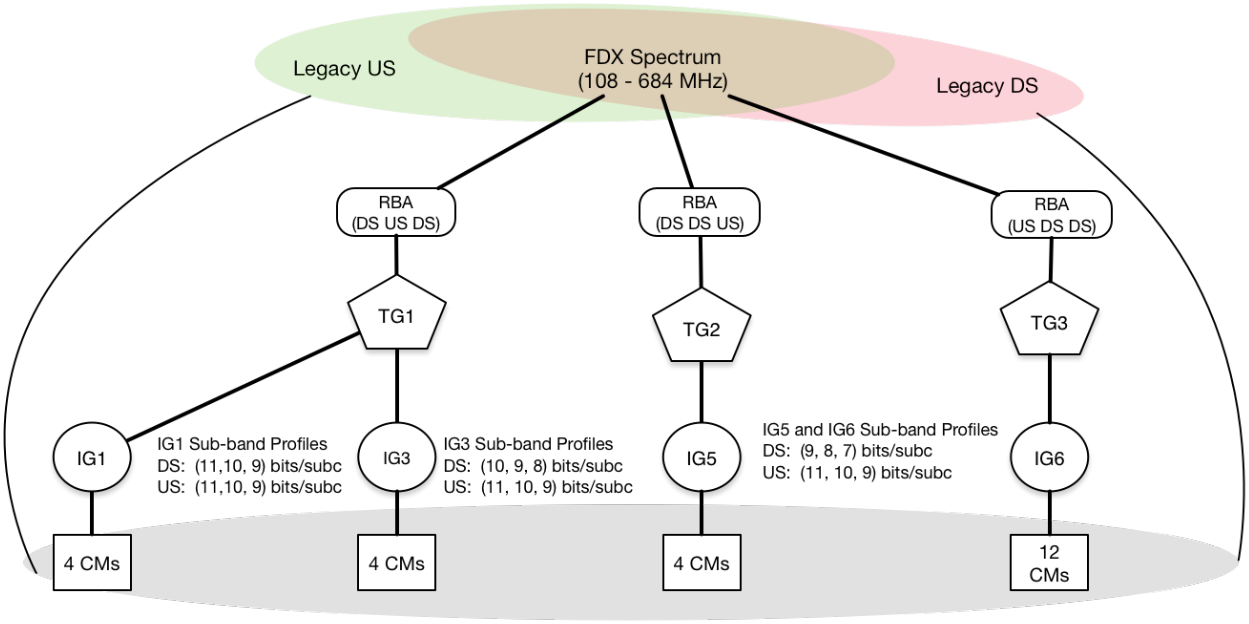


Figure 9 Example - Resource Distribution Hierarchy

6.4. Scheduling Performance

The scheduling performance in terms of throughput and fairness are calculated based on the above scheduling decisions. The FDX spectrum capacity gain (Eq7) is used to evaluate the overall FDX throughput performance, where the FDD spectrum capacity is calculated by assuming the FDD DS or US spectral efficiency is 0.5 dB higher than the FDX DS or US spectral efficiency.

The fairness performance is evaluated with Jain's fairness index (Eq8) with respect to the per CM average DS and US throughput. As indicated in Table 3, the US is less fairly shared due to the unbalanced CM population among the IGs, and the common spectrum resource, in this case legacy US spectrum, is insufficient to compensate the resultant traffic load differences.

Table 3 Example - Scheduling Performance

		TG1	TG2	TG3
Per TG Average FDX Capacity (Gbps)	DS	2.06	0.77	1.57
	US	1.54	1.38	1.69
FDX Spectrum Capacity Gain		1.86		
Legacy Capacity (Gbps)	DS	2		
	US	0.4		
Per TG Max Capacity (Gbps)	DS	4.9	4.60	4.3
	US	1.9	1.8	2
Per TG CM Average (Mbps)	DS	241	234	247
	US	192	345	174
Jain's Fairness Index	DS	0.99		
	US	0.91		

Conclusion

An optimal FDX spectrum scheduler maximizes the FDX spectrum capacity while maintaining fairness among subscribers based on the DS and US SLAs. It balances the DS and the US capacities with traffic loads by adjusting the DS and US spectral efficiencies, the DS and US spectrum widths, and the competing CM population. To do this, it must follow the FDX spectrum resource distribution hierarchy enforced by the FDX DOCSIS operation, which involves RBA, TG, IG and data profile assignments. Essentially, the FDX spectrum scheduling is a process to identify the best paths along the distribution hierarchy connecting the spectrum resource to the CMs that achieve the optimization objectives.

This paper characterizes the FDX spectrum scheduling by analyzing the bidirectional spectrum capacity, the resource sharing constraints, the optimization objectives and the delivery mechanism. We observed that when system is interference limited, the DS and US spectral efficiency is inversely related, and the combined spectral efficiency remains constant relative to the passive plant topology and the active processing gain for interference suppression. We showed how this property can be used to balance the DS and US performance under various operation constraints. We further modeled the FDX spectrum resource sharing mechanism as a single rooted scheduling tree, and revealed the resource sharing fluidity between the DS and the US, and among all the distribution points. We explained how the utilities defined in FDX DOCSIS can be applied for the resource sharing purpose, including RBA allocation, TG assignment, IG discovery and data profile settings. We also defined a set of performance metrics that could be used to evaluate system performance and guide optimization. An example was present at the end to illustrate the FDX spectrum resource scheduling process.

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Abbreviations

CM	cable modem
CMTS	Cable Modem Termination System
DS	downstream
FDD	frequency division duplexed
FDX	full duplex
IG	interference group
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiplexing with multiple access
RBA	resource block assignment
RxMER	receive modulation error ratio
SC-QAM	single carrier quadrature amplitude modulation
SIR	signal to interference ratio
SLA	service level agreement
TG	transmission group

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