US SCHEDULING IN THE DOCSIS 3.1 ERA: POTENTIAL & CHALLENGES

A TECHNICAL PAPER PREPARED FOR THE SOCIETY OF CABLE TELECOMMUNICATIONS ENGINEERS

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ABSTRACT

The paper provides an overview for the various upstream (US) scheduling schemes that are available in the DOCSIS 3.1 era. These include Time Division (TD), Frequency Division (FD), Hybrid TD-FD, and Time and Frequency Division (TaFD) US scheduling schemes. The article analyzes the overhead, multiplexing latency, capacity, advantages, and disadvantages of the above schemes. US channel bonding is also discussed in light of the above scheduling architectures. Finally, a DOCSIS 3.1 network migration strategy that takes US scheduling into consideration is proposed.

INTRODUCTION

For the past two decades, Multiple Service Operators (MSOs) showed continuous offerings of faster service over time which yielded higher peak rates year over year. The need to offer higher peak rates every year is due to customer demand and competition as shown in Fig. 1 [1]. Observe that the peak rates that were offered by the telco industry in 2012/2013 were significantly higher than the peak rates offered by most of cable MSOs. Therefore, Cable MSOs continued to offer higher peak rates to address competition and accommodate the every-increasing subscribers' demand.

The data in Fig. 1 was used to predict the Cumulative Annual Growth Rate (CAGR) for the Downstream (DS) and Upstream (US) peak rates. The analysis covered multiple cable MSOs including CableVision, Charter, Comcast, Cox, and TWC. It was found that the average CAGR over all of those MSOs to be approximately 53% and 59% for the DS and US peak rates, respectively. Observe that the US CAGR is relatively high and is expected to slow down (e.g., 30%) in the next few years for MSOs who choose to stay with the 5-42 MHz split. For those who will be moving or are in the process of moving to the 5-85 MHz mid-split, the 60% US CAGR may still hold. In any case, the analysis in this paper is based on the 60% US CAGR.

The average GAGR values along with the peak rates for 2013 were used to predict the growth of peak rates for the next few years as shown in Fig. 2. Note that the DS and US peak rates in 2013 were assumed to be 50 Mbps and 10 Mbps, respectively, which are close to the average peak rates in 2013 across all of the above MSOs. These rates and CAGRs yielded 2015 DS and US peak rates of 117 Mbps and 25 Mbps, respectively, which are close to the average peak rates offered across the above MSOs today. Note that although some MSOs offer very high peak rates today (e.g., ~500 Mbps), these peak rates are not always offered via the typical Hybrid Fiber Coaxial (HFC) network and therefore are not the focus of this study. The analysis here is more focused on the 'normal' peak rates that are commonly offered to customers over HFC networks and not

the 'peak' peak rates that are offered over Fiber To The Home (FTTH) network architectures to address competition.

Observe that an US peak rate of ~100 Mbps is needed in 2018 and ~260 Mbps in 2020, which also corresponds to ~1 Gbps DS peak rate in 2020. Note that the required capacity to offer certain peak rate can be up to ~1.2 times that peak rate plus the total average throughput for the service group (i.e., average subscriber throughput times number of subscribers per service group) [2]. To obtain average subscriber throughput statistics, recent MSOs' data were collected and it was found that the CAGR for the average US subscriber average throughput is about ~22%. Moreover, the data showed that the average subscriber throughput in 2015 was about ~60 kbps. Therefore, assuming 250 users per service group, the needed US capacity in 2018 and 2020 is ~150 Mbps (100*1.2+250*0.06*1.22^3) and ~350 Mbps (260*1.2+250*0.06*1.22^5), respectively. Observe that the US capacity of 350 Mbps (required in 2020) corresponds to 1 Gbps DS service offering.

To accommodate the above peak rates, the DOCSIS 3.1 specifications were developed and issued in 2013. DOCSIS 3.1 standard promises a great capacity potential as it extends the spectrum in both DS and US directions, uses a modern PHY technology (i.e., Orthogonal Frequency Division Multiplexing (OFDM)), and utilized improved Forward Error Correction (FEC) technology (i.e., Low Density Parity Check (LDPC) codes).
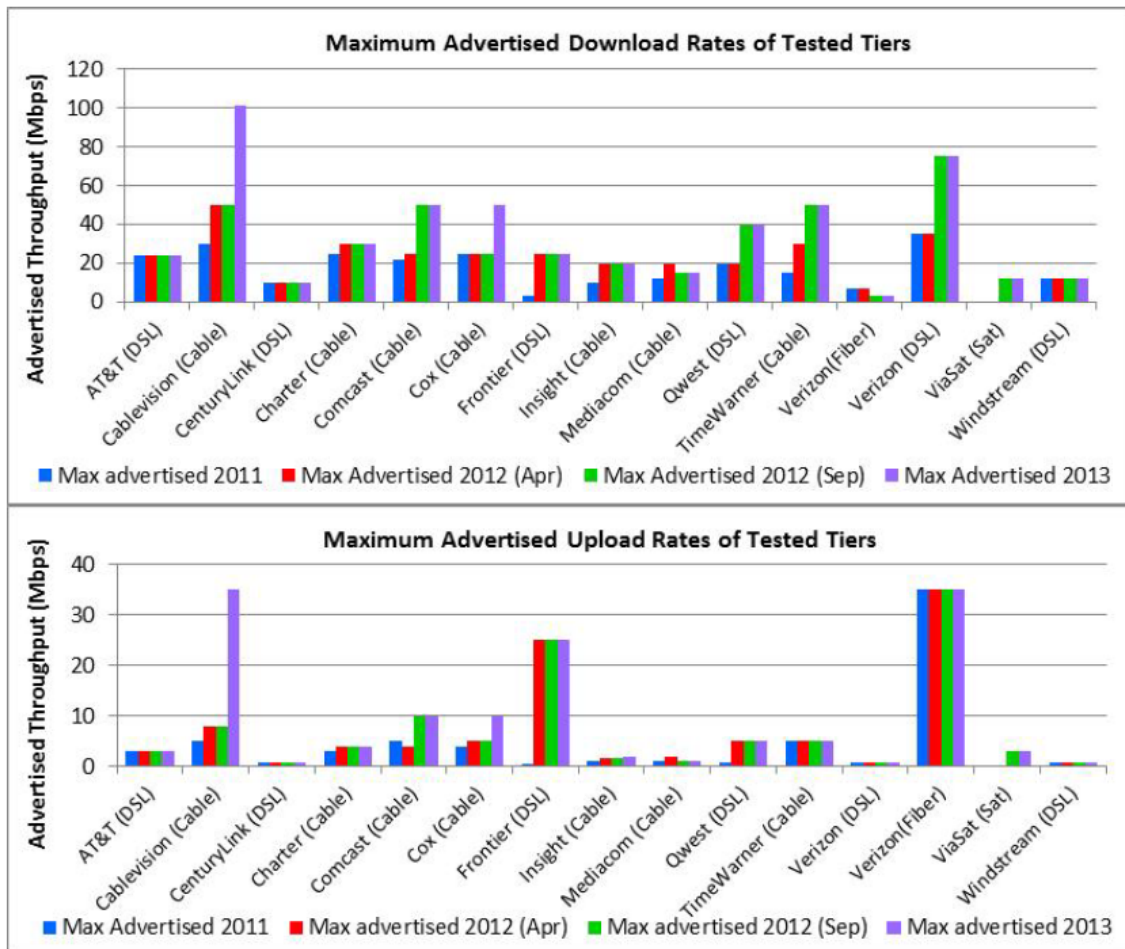
Figure 1 - Maximum advertised DS & US peak rates by cable and telco industries [1].
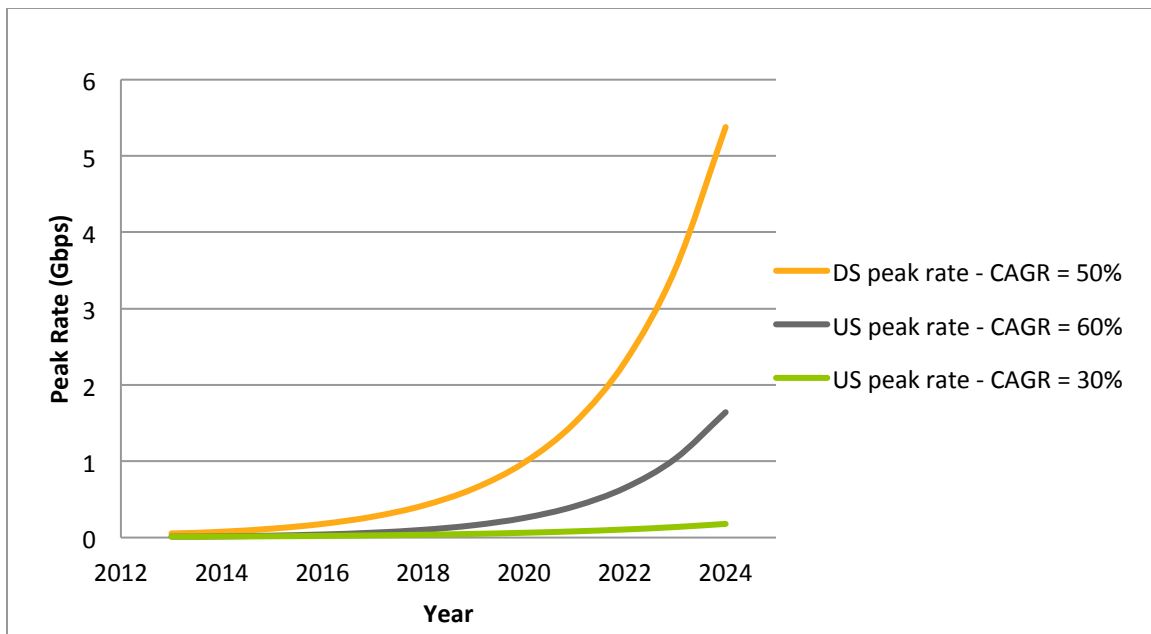
Figure 2 - Growth in DS & US peak rates offered by Cable MSOs based on data in Fig. 1.

The migration to DOCSIS 3.1 can be challenging due to differences in technology from DOCSIS 3.0 to DOCSIS 3.1. The migration in the US can be more challenging than the DS due to the limited available spectrum and the potential spectral overlap for DOCSIS 3.1 OFDM channels and DOCSIS 3.0 Single-Carrier Quadrature Amplitude Modulation (SC-QAM) channels. Moreover, issues in the US direction that affect network migration include noise funneling, distortion, burst transmission, topology resolution, multiple access, etc.

Among the above issues, the limited spectrum, overlapping channels, and the multiple access nature are of specific interest for this article. In particular, the paper focuses on the US scheduler feature, which is a module within the Cable Modem Termination System (CMTS) that coordinates the access to a US channel for all CMs on that channel. The bottom-line function of the US scheduler is to grant access to different CMs and satisfy their Quality of Service (QoS) and Service Level Agreement (SLA) rates given a limited spectrum with overlapping channels.

The US scheduler feature is quite complicated because it has to address multiple challenges including QoS, multiple access for modems, initial ranging, station maintenance, etc. Moreover, there are multiple CMTS features that interact with the US scheduler feature, which include adding/removing flows via Dynamic Service Change (DSX) MAC Management Messages (MMM) and Packet Cable Multimedia (PCMM), Integrated US Agility (IUA), Intelligent Channel Optimizer (ICO), US channel bonding, etc.

This paper will describe the different types of US scheduling and show how they can help with the DOCSIS 3.1 migration. It will be shown how the TaFD US scheduler can

provide a smooth migration path and deliver the required peak rates and satisfy the subscriber QoS constrains. This paper is organized as follows: Section 2 describes the types of US schedulers and analyzes their overhead / multiplexing latency / throughput / advantages / disadvantages/etc. Bonding relationship to different US schedulers is discussed in Section 3. Section 4 describes potential migrations paths taking US scheduling into consideration. Finally, the paper is concluded in Section 5.

OVERVIEW OF US SCHEDULERS

In pre-DOCSIS 3.1 CMTSs, US schedulers for multiple Advanced Time Division Multiple Access (ATDMA) channels run individually and grant access to each channel independently. This may change in DOCSIS 3.1, where the TaFD US scheduling feature is supported and OFDMA channels can overlap with ATDMA channels. In this case, the US scheduler of an OFDMA channel is affected by the scheduler of an ATDMA channel and vice versa mainly because both channels share the same spectrum. Beyond TaFD scheduling, there are other US scheduling schemes that can also be deployed but may offer inferior service to that provided by the TaFD scheduler as will be explain in this section. The next few subsections describe the different types of US schedulers and discuss their overhead, multiplexing latency, capacity, advantages, and disadvantages.

Time Division (TD) US Scheduler

With Time Division (TD) US scheduling, each technology (OFDMA or ATDMA) is allocated access to the whole spectrum at any moment of time. Figure 3 shows a set of ATDMA channels that are granted access to the spectrum simultaneously at time instant T_0, while the OFDMA channel gets access to the whole spectrum at time instant T_1. Grating access for each technology to the whole spectrum at any given instant of time has advantages and disadvantages. On the plus side, higher peak rates can be achieved. On the negative side, spectrum can be wasted – especially if one technology or some channels within that technology are not used due to a low amount of offered traffic.

To start analyzing the TD scheduler, the multiplexing latency is investigated. The multiplexing latency is defined as the time difference between the moment when a certain technology (ATDMA or OFDMA) was last allocated access to the spectrum and the next time when it is allocated access. In other words, it is the time duration over which a technology is not granted access to the spectrum. The multiplexing latency only affects some grants due to the following:

- Some requests may arrive and fit immediately into grants of allocated minislots for that channel

- Other requests may arrive when the channel is quiet and therefore have to wait for the next frame that is allocated to that channel

- Some requests may partially fit and be fragmented which has different latency impact for pre-D3.0 versus Continuous Concatenation and Fragmentation (CCF) piggybacking

Since the multiplexing latency affects only some grants, the increase in average request to grant delay due to the switching is more difficult to calculate.

Observe that the request-grant-cycle includes the following phases:

- Cable Modem (CM) receives packet(s) for transmission and waits for a request opportunity in a MAP. The delay in ability to make a request is impacted by the US scheduling and allocation scheme, bonding, MAP request opportunities, collisions & backoffs, etc.

- CM sends a request to the CMTS which has propagation, processing, and queuing delays which are impacted by hardware, MAP scheduling scheme, bonding scheduling, request processing, etc.

- The scheduler tries to grant the request in subsequent MAPs for the future. The scheduling delay may be impacted by US scheduling and allocation scheme, bonding, MAP scheduling, etc.

- CM transmits the packet(s) in the specific granted minislots. The packet(s) incurs propagation & processing delays including fragment reassembly

- The CM may piggyback or use multiple requests outstanding to reduce the requesting delay

Given the above, no attempt is taken to estimate the request-to-grant latency or end-to-end system latency in this paper because these latencies depend on multiple variables and are not linearly proportional to the multiplexing latency that is analyzed here. Therefore, in order to perform a fair comparison between different scheduling techniques, the study included in this paper is only constrained to the multiplexing latency which is a common parameter across all US is scheduling techniques.
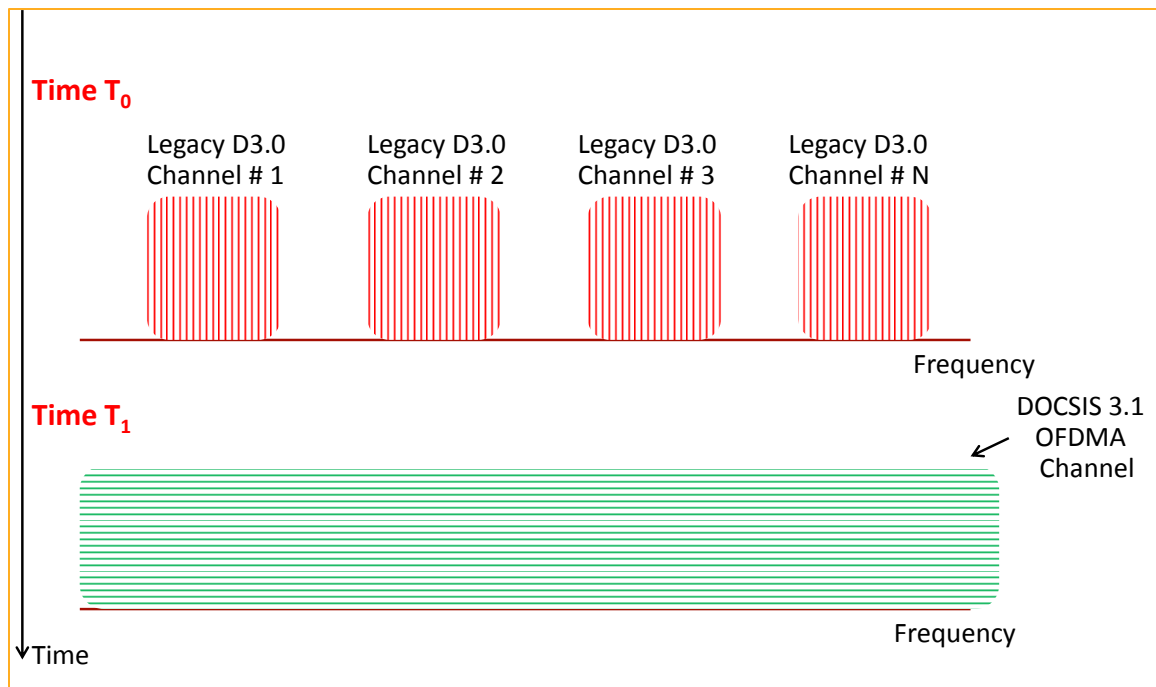
Figure 3 - Time Division US Scheduling – Each technology is allocated access to the whole spectrum for certain time duration.

In order to analyze the multiplexing latency and overhead of the TD scheduling scheme, some examples are considered below. In particular, two examples will be considered where in one example the TD scheduler will incur low overhead but higher multiplexing latency while the other example will show the opposite. For these examples, different parameters are assumed as summarized in Table 1 and described below.

1. 5-85 MHz US spectrum

2. Total of 4 ATDMA channels. Two adjacent 6.4 MHz channels separated by a gap from two adjacent 3.2 MHz channels. One of the 3.2 MHz channels is always on.

   a. Minislot duration is 12.5 usec for 6.4 MHz channels.

   b. Minislot duration is 25 usec for 3.2 MHz channels. Note that a single 3.2 MHz channel minislot is equivalent to two minislots for 6.4 MHz channel.

3. One OFDMA channel covering the available spectrum (80 MHz).

   a. FFT size = 2K, FFT duration = 20 usec.

   b. Cyclic Prefix (CP) duration is 5 usec.

   c. Total OFDMA symbol time = 20 + 5 = 25 usec.

d. OFDMA minislot is 400 kHz. Total OFDMA minislots in 80 MHz is 200.

e. Has a single exclusion zone to accommodate the always-ON 3.2 MHz channel (i.e., 8 OFDMA minislots.)

f. Available OFDMA minislots in 80 MHz is 200-8 = 192 minislots.

g. 8 OFDMA symbols per frame (i.e., per minislot). Frame duration is 200 usec.

h. In each OFDMA frame, there are 16 ATDMA minislots (for 6.4 MHz) and 8 ATDMA minislots (for 3.2 MHz).

4. Map interval = 2.4 msec.

a. There are 12 OFDMA frames per map interval

b. In each map interval, there are 192 ATDMA minislots (for 6.4 MHz) and 96 ATDMA minislots (for 3.2 MHz).

5. Guard time/band

a. Guard time for an ATDMA channel scheduled after an OFDMA grant is 1 ATDMA minislot.

b. Guard band for an OFDMA channel adjacent to an ATDMA channel is ½ OFDMA minislot (200 kHz).

6. ATDMA minislots are in sync with the OFDMA frame boundaries. Switching between the technologies occur at OFDMA frame boundaries.

7. The spectrum is allocated 2/3rd of the time (i.e., 66.7%) for ATDMA and 1/3rd of the time (i.e., 33.3%) for OFDMA.

Table 1 - Assumptions for the Overhead/Multiplexing latency examples

Parameter	Assumption Value
US Spectrum	5-85 MHz
Number of SC-QAM (ATDMA) channels	Total of 4. Two 6.4 MHz channels & two 3.2 MHz channels. One of 3.2 MHz channels is always on
SC-QAM Minislot duration	12.5 usec for 6.4 MHz channels and 25 usec for 3.2 MHz channels
OFDMA FFT Size	4K
OFDMA CP	5 usec
OFDMA symbols per minislot (per frame)	8
Map Interval	2.4 msec
SC-QAM Guard time	1 SC-QAM Minislot
OFDMA guard band (adjacent to SC-QAM)	½ OFDMA Minislot
Synchronization of minislots	SC-QAM Minislots are in sync with OFDMA Minislots boundaries (OFDMA frame boundaries)
Percentage of time allocation for each technology	66.7% for ATDMA & 33.3% for OFDMA

The first example, where the TD scheduler incurs low overhead but high multiplexing latency, is shown in Fig. 4. Observe that the example covers a duration of time that is equals to the duration of 12 OFDMA frames (8 OFDMA frames duration are allocated for ATDMA and 4 OFDMA frames duration are allocated for OFDMA).

In this particular example, the overhead for ATDMA channels is three minislots (2 minislots for 6.4 MHz channels and 1 minislot for the 3.2 MHz channel). Therefore, the percentage of overhead for ATDMA is calculated as

$$\text{\% overhead for ATDMA} = (2*6.4+2*3.2)/(2*16*8*6.4+16*8*3.2) = 0.94\%$$

The overhead for OFMDA channel will be one OFDMA minislot (1/2 minislot on each side of the always on ATDMA channel) when the OFDMA channel is ON. Therefore, the percentage of overhead for OFDMA is calculated as

$$\text{\% overhead for OFDMA} = (1*4)/(192*4) = 0.52\%$$

As for the multiplexing latency, the 3.2 MHz channel that is ON continuously does not incur any latency. On the other hand, for the other channels that get multiplexed, the multiplexing latency can be estimated to be a 4 OFDMA frames and a single ATDMA minislot. This translates to 0.8125 msec for 6.4 MHz channels and 0.825 msec for the 3.2 MHz channel. On the other hand, the multiplexing latency for the OFDMA channel is 8 OFDMA frames or 1.6 msec.
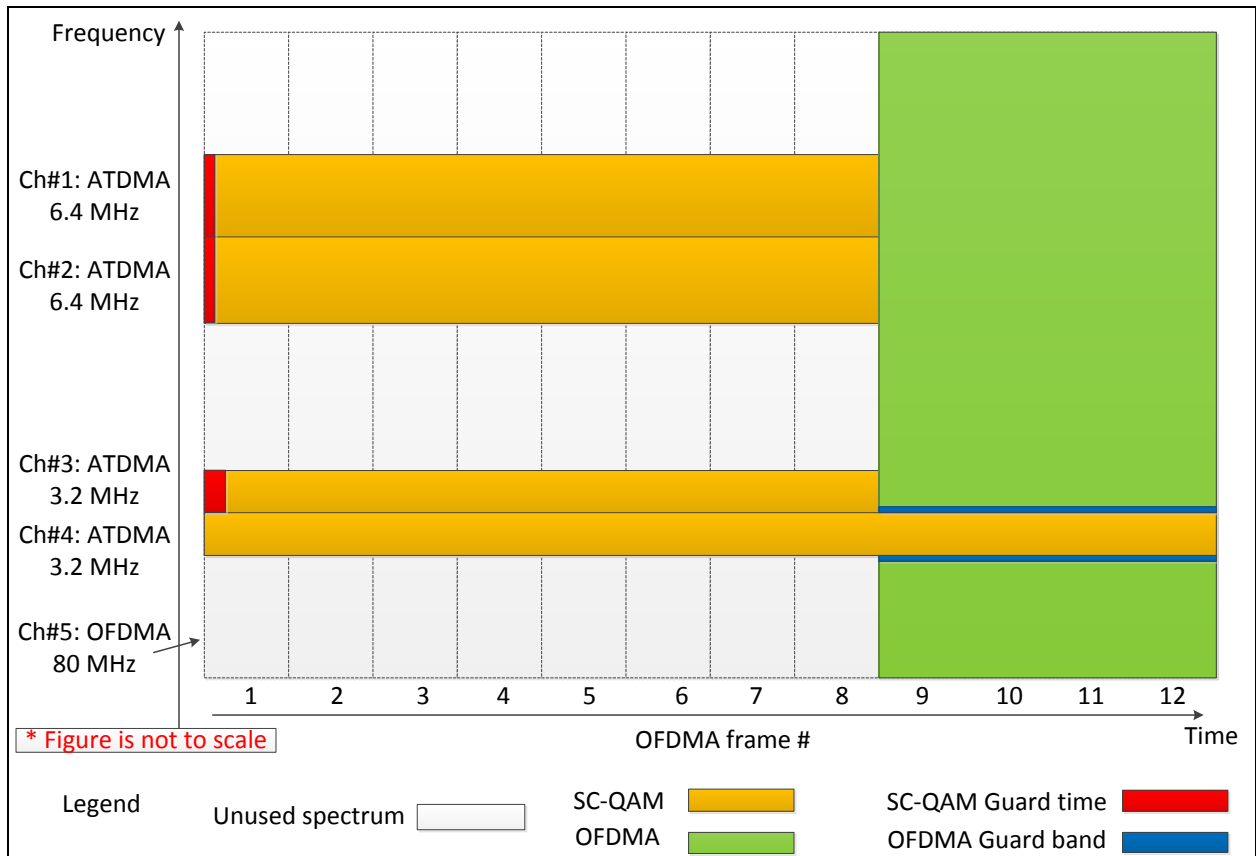
Figure 4 - TD Scheduler – Low overhead and high multiplexing latency.

Another example that shows different performance for the TD scheduler is shown in Fig. 5, where the overhead is high but the multiplexing latency is low. For this example, percentage of overhead for ATDMA channels is calculated as

$$\% \text{ overhead for ATDMA} = (8*6.4+8*3.2)/(2*16*8*6.4+16*8*3.2) = 3.4\%$$

On the other hand, the percentage of overhead for the OFDMA channel is unchanged from the previous example and is calculated as

$$\% \text{ overhead for OFDMA} = (1*4)/(192*4) = 0.52\%$$

As for the multiplexing latency of the example in Fig. 5, ATDMA channels incur a latency of one OFDMA frame and one ATDMA minislot. This translates to 212.5 usec and 225 usec, for 6.4 MHz and 3.2 MHz channels, respectively. As for the OFDMA channel, the multiplexing latency is equivalent to the duration of two OFDMA frames or 400 usec.

Another example is introduced below to analyze the capacity potential of the TD scheduler and check its ability to deliver the 350 Mbps capacities that are required to accommodate the peak rates needed in 2020 as described in Section 1. For this capacity example, multiple assumptions were made as summarized in Table 2 and described below.

1. Spectrum is 5-85 MHz. Available bandwidth is 80 MHz.

2. 8 single Carrier-Quadrature Amplitude Modulation (SC-QAM) ATDMA channels. Seven channels overlap with the OFDMA spectrum (4 6.4 MHz and 3 3.2 MHz channels) and one 6.4 MHz channel is always on and does not share spectrum with the OFDMA and therefore OFDMA exclusions are used to accommodate that. Observe that the number of SC-QAM channels assumed for this analysis is larger than the number of US channels deployed today by most MSOs (3-4 6.4 MHz channels).

3. A small 192 kHz OOB signal is present and OFDMA exclusions are used to accommodate it.

4. SC-QAM channels spectral efficiency is assumed to be 4.15 bps/Hz [3] [4] . On the other hand, the OFDMA channel spectral efficiency is assumed to be 6.55 bps/Hz [3] [4] assuming an MSO operating margin of 2 dB.

5. SC-QAM channels utilization is 60% (i.e., allocated 60% of the time) while the OFDMA channels utilization is 40% (i.e., allocated 40% of the time).

6. The muxing cost is 10%. This includes multiplexing overhead, guard grants, request & ranging opportunities, probes, etc.
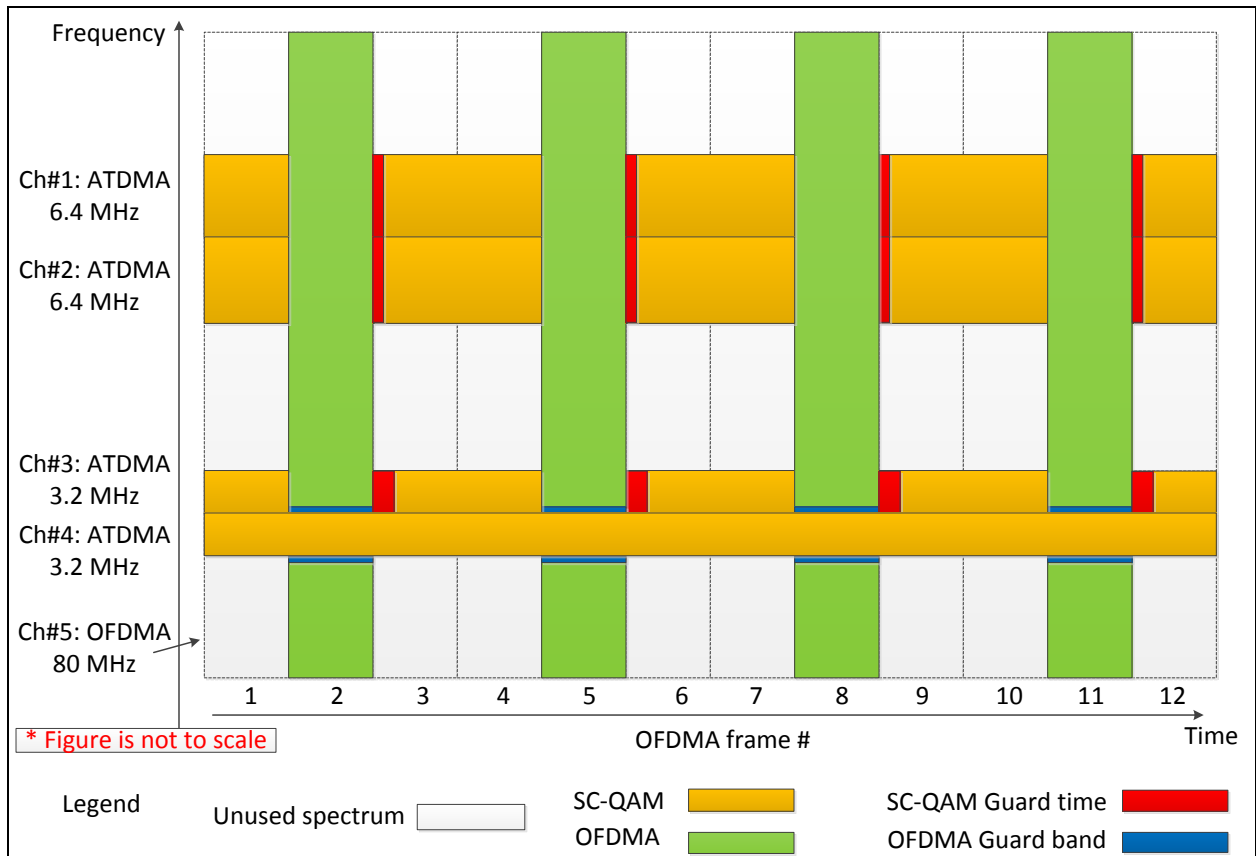
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Figure 5 - TD Scheduler – High overhead and low multiplexing latency.

Table 2 - Assumptions for the capacity analysis

Parameter	Assumption Value
US Spectrum	5-85 MHz
Number of SC-QAM (ATDMA) channels	Total of 8. 7 channels share spectrum with OFDMA (Four 6.4 MHz channels & Three 3.2 MHz channels). One 6.4 MHz channels is always on
SC-QAM Minislot duration	12.5 usec for 6.4 MHz channels and 25 usec for 3.2 MHz channels
OOB signal	One channel of 192 kHz bandwidth
SC-QAM spectral efficiency	4.15 bps/Hz
OFDMA spectral efficiency	6.55 bps/Hz
Percentage of time allocation for each technology	60% for ATDMA & 40% for OFDMA
Muxing cost	10%

The results of the capacity analysis are shown in Fig. 6. Observe that the SC-QAM channels can provide a maximum of about 173 Mbps while the OFDMA channel can

provide a maximum of about 481 Mbps. The average usable channel capacity is about 300 Mbps which are contributed from the SC-QAM channels and OFDMA channel and taking the muxing overhead into consideration. The peak capacity that is offered by the OFDMA channel is adequate to satisfy the 350 Mbps required in 2020 to support peak rates of 260 Mbps.

Total spectrum (MHz)	80						
~TD muxing cost (*)	10%						
SC-QAM spectral eff	4.15	bps/Hz					
OFDMA spectral eff	6.55	bps/Hz					
	overlap SC-QAMs	overlap SC-QAMs	non-ovlp SC-QAMs	non-overlap OOB		overlap OFDMA	non-ovlp OFDMA
numCh	4	3	1	1			
Ch width (MHz)	6.4	3.2	6.4	0.192			
Total BW (MHz)	25.6	9.6	6.4	0.192		35.2	38.208
thruput (Mbps)	106.2	39.8	26.6			230.6	250.3
Peak rate (Mbps)	172.6					480.8	
Fixed Allocation %	60%	60%	100%			40%	40%
Avg technology thruput (Mbps)	57.4	21.5	26.6			83.0	100.1
Total avg tech thruput (Mbps)	105.4					183.1	
Total avg US capacity (Mbps)	288.5						

Figure 6 - TD Scheduler – Capacity analysis.

Frequency Division (FD) US Scheduler

In the Frequency Division (FD) US scheduler, each technology (OFDMA or ATDMA) is allocated certain portion of the spectrum for the whole time. This is illustrated in Fig. 7, where it can be noted that the SC-QAM channels are allocated their spectrum continuously and operate as they do today. Similar is applicable to the OFDMA channel where it can only use the spectrum portions that are not utilized by the SC-QAM channels. If the number of SC-QAM channels is large, then the amount of spectrum left for OFDMA may not have enough to support the required capacities. Nevertheless, the FD scheduling scheme provide zero multiplexing latency because each technology has continuous access to the spectrum.
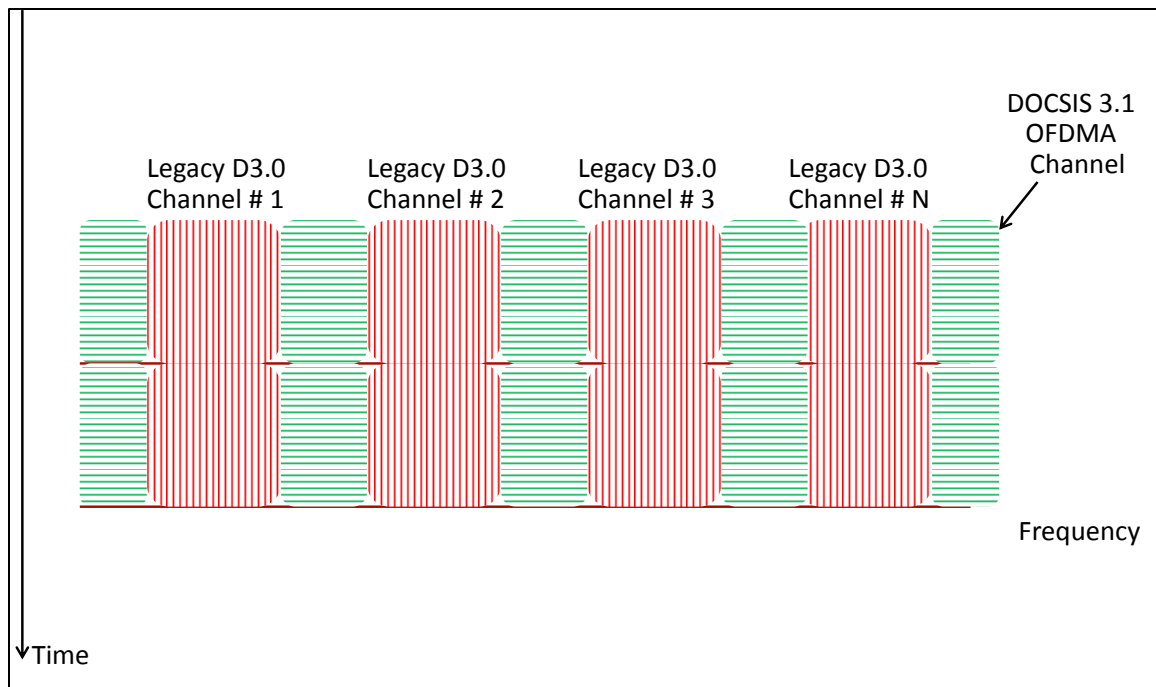
Figure 7 - Frequency Division US Scheduling – Each technology is allocated continuous access to certain portion of the spectrum.

The FD scheduler overhead analysis can be performed via an example as shown in Fig. 8, which assumes the same parameters used in the overhead analysis for the TD scheduler and listed in Table 1.

Note that there is no overhead associated with the SC-QAM ATDMA channels. On the other hand, the percentage of OFDMA overhead is calculated to be (4*0.5)/192 = 1.04%. Recall that none of the ATDMA or OFDMA technologies will incur any multiplexing latency.

As was done for the TD scheduler, an example capacity analysis for the FD scheduler can be performed using the same assumptions presented in Table 2. Observe that the muxing overhead was reduced to 5% because there is actually no spectrum sharing and therefore no overhead because of switching between technologies. However, there are other kinds of overhead. The results are summarized in Fig. 9, where the peak capacity offered by the OFDMA channel is about 250 Mbps while the peak capacity offered by the ATDMA channels is about 173 Mbps. For the average capacity analysis, two cases are presented. In one case, each technology is allocated 100% of the time since the spectra do not overlap and each technology has continuous access to its spectrum. The total average capacity offered by the scheduler is about 408 Mbps. However, for fairness to the TD scheduler, a second case is included where ATDMA channels were allocated 60% of the time and OFDMA is allocated 40% of the time assuming the same number of channels in Table 2. In this case, the total average capacity offered by the scheduler is about 206 Mbps.

It can be argued that the above 60%/40% comparison may not be fair to the FD scheduler because channels are allocated less than 100% of the time although they have got access to their spectra for 100% of the time. Therefore, another scenario is provided in Fig. 10, where the number of channels was adjusted (i.e., reduced) such that the 100% access case provides close capacity to what is actually needed for ATDMA channels from the TD scheduler example (i.e., 105 Mbps). In this case, the number of ATDMA channels was reduced from four 6.4 MHz channels and three 3.2 MHz channels to three 6.4 MHz channels and one 3.1 MHz channels to provide 115 Mbps capacity when the channels have access to their spectrum for 100% of the time. Note it can be argued that this is an optimistic case for the FD scheduler because the utilization on the channel is dynamic and it will not be practical to change the number of channels dynamically as demand changes.
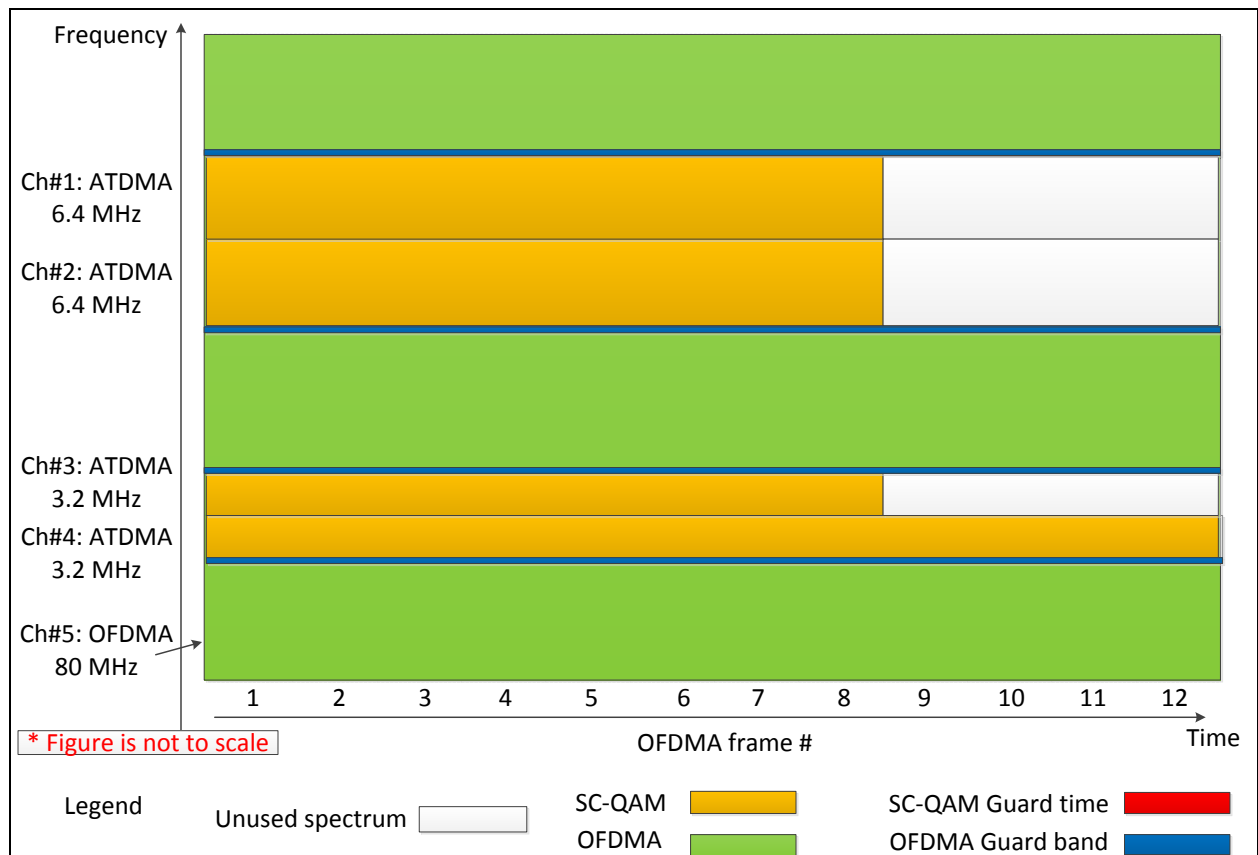
Figure 8 - Overhead analysis for the FD scheduler.

Total spectrum (MHz)	80						
~FD muxing cost (*)	5%						
SC-QAM spectral eff	4.15	bps/Hz					
OFDMA spectral eff	6.55	bps/Hz					
	overlap SC-QAMs	**overlap SC-QAMs**	**non-ovlp SC-QAMs**	**non-overlap OOB**		**overlap OFDMA**	**non-ovlp OFDMA**
numCh	4	3	1	1			
Ch width (MHz)	6.4	3.2	6.4	0.192			
Total BW (MHz)	25.6	9.6	6.4	0.192		35.2	38.208
thruput (Mbps)	106.2	39.8	26.6			0.0	250.3
Peak rate (Mbps)	172.6					250.3	
Fixed Allocation %	60%	60%	100%			0%	40%
Avg technology thruput (Mbps)	60.6	22.7	26.6			0.0	100.1
Total avg tech thruput (Mbps)	109.8					100.1	
Total avg US capacity (Mbps)	209.9						
Fixed Allocation %	100%	100%	100%			0%	100%
Avg technology thruput (Mbps)	100.9	37.8	26.6			0.0	250.3
Total avg tech thruput (Mbps)	165.3					250.3	
Total avg US capacity (Mbps)	415.6						

Figure 9 - FD Scheduler – Capacity analysis (Scenario A: same number of channels as in Table 2).

Total spectrum (MHz)	80						
~FD muxing cost (*)	5%						
SC-QAM spectral eff	4.15	bps/Hz					
OFDMA spectral eff	6.55	bps/Hz					
		overlap SC-QAMs	overlap SC-QAMs	non-ovlp SC-QAMs	non-overlap OOB		overlap OFDMA	non-ovlp OFDMA
numCh		3	1	1	1			
Ch width (MHz)		6.4	3.2	6.4	0.192			
Total BW (MHz)		19.2	3.2	6.4	0.192		22.4	51.008
thruput (Mbps)		79.7	13.3	26.6			0.0	334.1
Peak rate (Mbps)		119.5					334.1	
Fixed Allocation %		60%	60%	100%			0%	40%
Avg technology thruput (Mbps)		45.4	7.6	26.6			0.0	133.6
Total avg tech thruput (Mbps)		79.5					133.6	
Total avg US capacity (Mbps)		213.2						
Fixed Allocation %		100%	100%	100%			0%	100%
Avg technology thruput (Mbps)		75.7	12.6	26.6			0.0	334.1
Total avg tech thruput (Mbps)		114.9					334.1	
Total avg US capacity (Mbps)		449.0						

Figure 10 - FD Scheduler – Capacity analysis (Scenario B: Number of channels was reduced such that the average ATDMA capacity is equal to that needed per the TD scheduler analysis).

Hybrid Time Division and Frequency Division (H-TD-FD) US Scheduler

The Hybrid Time Division and Frequency Division (H-TD-FD) US scheduler is based on the combination of the TD and FD schedulers. In particular, this scheme is similar to the TD scheme with the addition that the OFDMA channel is able to use the portions of the spectrum that are unused by SC-QAM channels when those SC-QAM channels are on. This is illustrated in Fig. 11.

This scheme can provide high peak rates as was the case for the TD scheduler. Moreover, it reduces the multiplexing latency for the OFDMA channel to zero. However, this scheme is still not flexible and may yield wasted capacity and reduced efficiency due to synchronization (i.e., scheduling coordination) between different ATDMA channels. More discussions regarding this are included later in this paper when different US scheduling techniques are compared against each other.
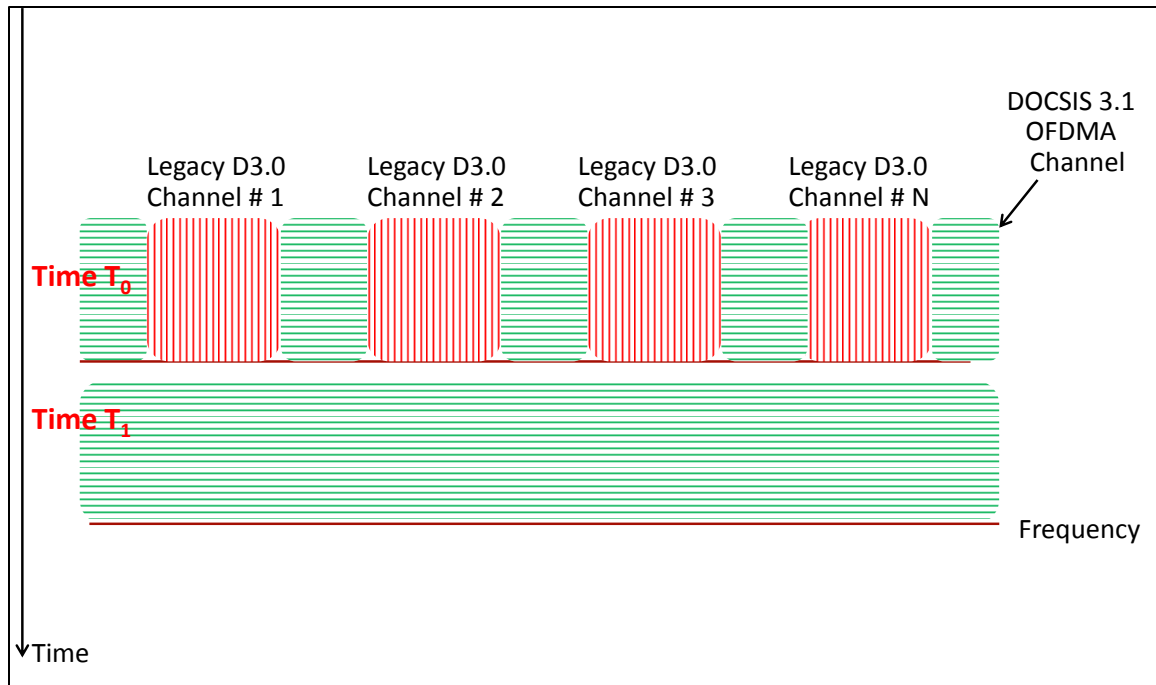
Figure 11 - Hybrid Time Division and Frequency Division US scheduler – Combination of TD and FD schedulers.

Analyzing the overhead and multiplexing latency for the H-TD-FD US scheduler is performed in a similar fashion to the analysis that was done for the TD scheduler. In particular, two examples are shown here where the first example, which is illustrated in Fig. 12, incurs low overhead but high multiplexing latency, while the other example, shown in Fig. 13, exhibits high overhead and low multiplexing latency. The ATDMA overhead for the example in Fig. 12 can be calculated as follows

% overhead for ATDMA = (2*6.4+2*3.2)/(2*16*8*6.4+16*8*3.2) = 0.94%

On the other hand, the percentage of overhead for the OFDMA channel in Fig. 12 is calculated as

% overhead for OFDMA = (2*8+1*4)/(192*8+192*4) = 0.87%

As for the multiplexing latency for the example shown in Fig. 12, the OFDMA channel has no multiplexing latency. On the other hand, the ATDMA channels incur multiplexing latency of 4 OFDMA frames plus one ATDMA minislot, which happens to be 0.8125 msec and 0.825 msec for the 6.4 MHz and 3.2 MHz channels, respectively.

Similarly, the overhead of ATDMA channels in Fig. 13 is calculated as

% overhead for ATDMA = (8*6.4+8*3.2)/(2*16*8*6.4+16*8*3.2) = 3.75%

On the other hand, the percentage of overhead for the OFDMA channel in Fig. 13 is calculated as

% overhead for OFDMA = (2*8+1*4)/(8*(192-2*16-8)+4*192) = 1%

The OFDMA channel in Fig. 13 has no multiplexing latency while the multiplexing latency for the ATDMA channels is equal to a single OFDMA frame and one ATDMA minislot which happens to be 212.5 usec and 225 usec for the 6.4 MHz and 3.2 MHz channels, respectively.
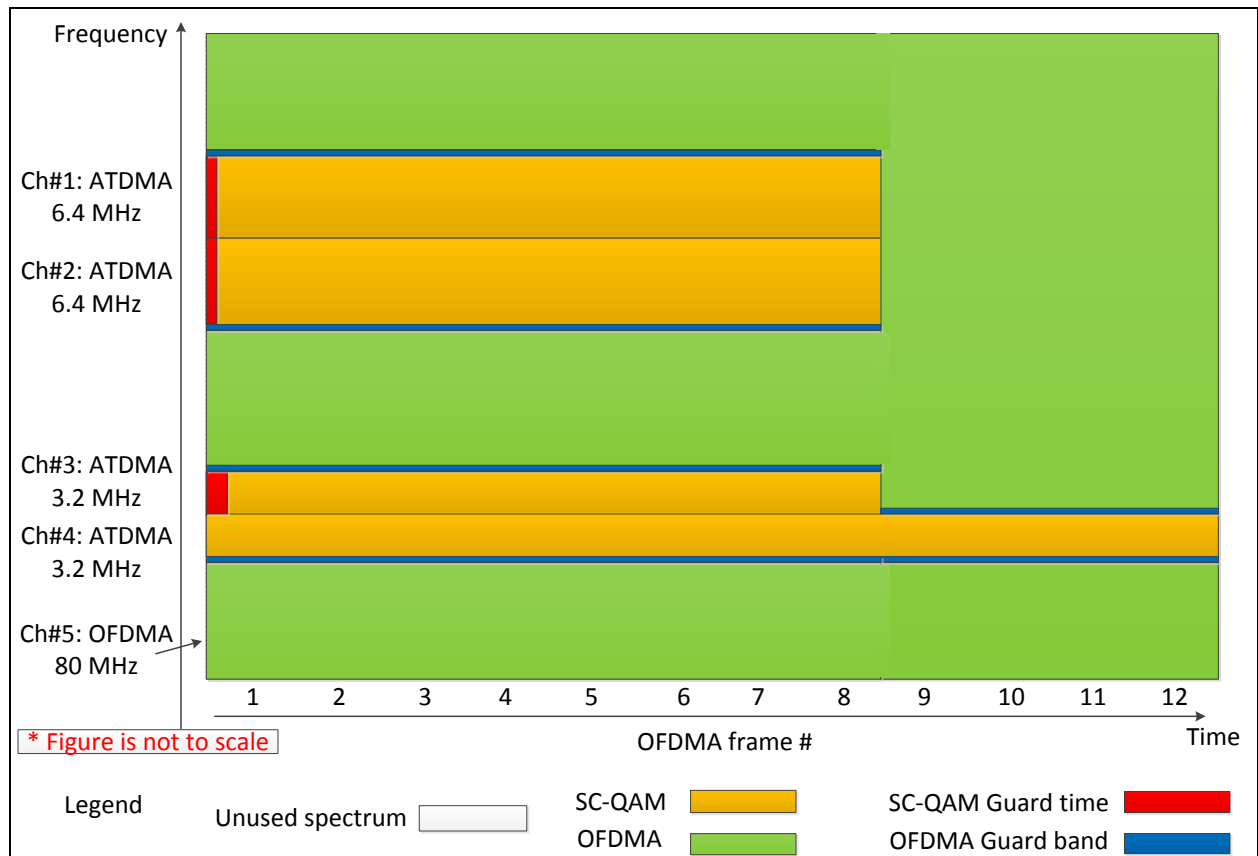

Figure 12 - H-TD-FD Scheduler – Low overhead and high multiplexing latency.
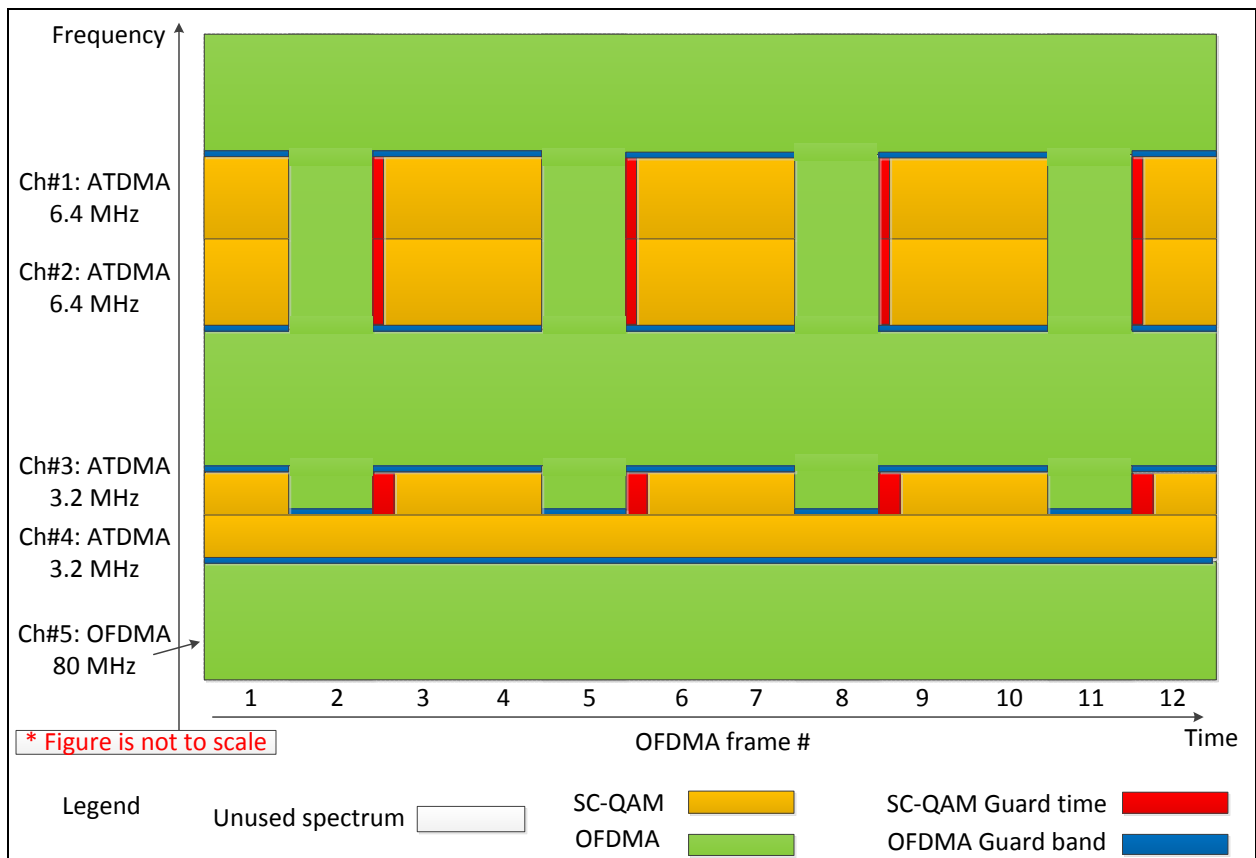
Figure 13 - H-TD-FD Scheduler – High overhead and low multiplexing latency.

As for the capacity analysis, the results are summarized in Fig. 14 for the assumptions that were listed in Table 2. Note that the peak capacity provided by the ATDMA channels is about 173 Mbps while that is offered by the OFDMA channel is about 481 Mbps. The total average capacity offered by the H-TD-FD scheduler is about 439 Mbps. It will be shown later that these capacities are actually equal to those offered by the TaFD which is analyzed in the next subsection. However, the inflexibility of this scheduling architecture, which is similar to that of the TD architecture, makes it inferior to the TaFD scheduler.

Total spectrum (MHz)	80						
~Hybrid TD-FD muxing cost (*)	10%						
SC-QAM spectral eff	4.15	bps/Hz					
OFDMA spectral eff	6.55	bps/Hz					
	overlap	overlap	non-ovlp	non-overlap		overlap	non-ovlp
	SC-QAMs	SC-QAMs	SC-QAMs	OOB		OFDMA	OFDMA
numCh	4	3	1	1			
Ch width (MHz)	6.4	3.2	6.4	0.192			
Total BW (MHz)	25.6	9.6	6.4	0.192		35.2	38.208
thruput (Mbps)	106.2	39.8	26.6			230.6	250.3
Peak rate (Mbps)	172.6					480.8	
Fixed Allocation %	60%	60%	100%			40%	100%
Avg technology thruput (Mbps)	57.4	21.5	26.6			83.0	250.3
Total avg tech thruput (Mbps)	105.4					333.3	
Total avg US capacity (Mbps)	438.7						

Figure 14 - H-TD-FD Scheduler – Capacity analysis.

Time and Frequency Division (TaFD) US Scheduler

The Time and Frequency Division (TaFD) US scheduler is the ultimate US scheduling solution that combines flexibility and efficiency. The catch with this TaFD scheduler which is described by the DOCSIS 3.1 standard [5] is the added development complexity. In this scheduling scheme, the resources within the time-frequency map are allocated between different technologies (ATDMA vs. OFDMA) as needed. Herein, the spectrum between ATDMA and OFDMA channels is shared and gets allocated to either technology, as shown in Fig. 15 and Fig. 16 [5], to accommodate the service requirements. The flexibility yields the combination of less latency, high peak rate, meeting variable traffic demand, and offering better service.

For the overhead and multiplexing latency investigation, the analysis is provided for an example, which illustrated in Fig. 17 and uses the assumptions in Table 1. Observe that the allocation for the shared spectrum was done arbitrarily provided that each ATDMA channel is allocated 66.7% of the time or 8 OFDMA frames out of 12. Therefore, while other arrangements are possible, the analysis performed for this particular example is to illustrate the idea of the TaFD scheduler flexibility.

For this particular example, the ATDMA overhead is calculated as follows

$$\% \text{ overhead for ATDMA} = (7*6.4+8*3.2)/(2*16*8*6.4+16*8*3.2) = 3.4\%$$

On the other hand, the percentage of overhead for the OFDMA channel is calculated as

$$\% \text{ overhead for OFDMA} = (2*10+1*2)/(1*192+1*(192-8)+2*(192-2*16)+4*(192-8-16)+1*(192-16)+3*(192-8-16*2)) = 1.1\%$$

As for the multiplexing latency, the TaFD scheduler is flexible and therefore the multiplexing latency can theoretically be assumed to be zero. While this is true for the OFDMA channel in this particular example, the ATDMA channels incurred some multiplexing latency. In particular, channel 1 (6.4 MHz channel) incurred an average of 1.33 OFDMA frames and 1 ATDMA minislot which is equal to 279 usec. For channel 2 (6.4 MHz channel), the multiplexing latency is 1 OFDMA frame and 1 ATDMA minislot which is equal to 212.5 usec. Similarly, the multiplexing latency for channel 3 (3.2 MHz) is 1 OFDMA frame and 1 ATDMA minislot which is equal to 225 usec.

For the capacity analysis with the assumptions listed in Table 2, the results are summarized in Fig. 18. Note that the peak capacity that is offered by the OFDMA channel is about 481 Mbps while that is offered by the ATDMA channels is about 173 Mbps. The total average capacity offered by the TaFD is about 439 Mbps. Recall that these results are theoretically identical to those provided for the H-TD-FD scheduler. However, in practice, the H-TD-FD scheduler is less flexible and therefore less efficient. More discussions regarding this will be provided in the next section where different US scheduling techniques are contrasted against one other.
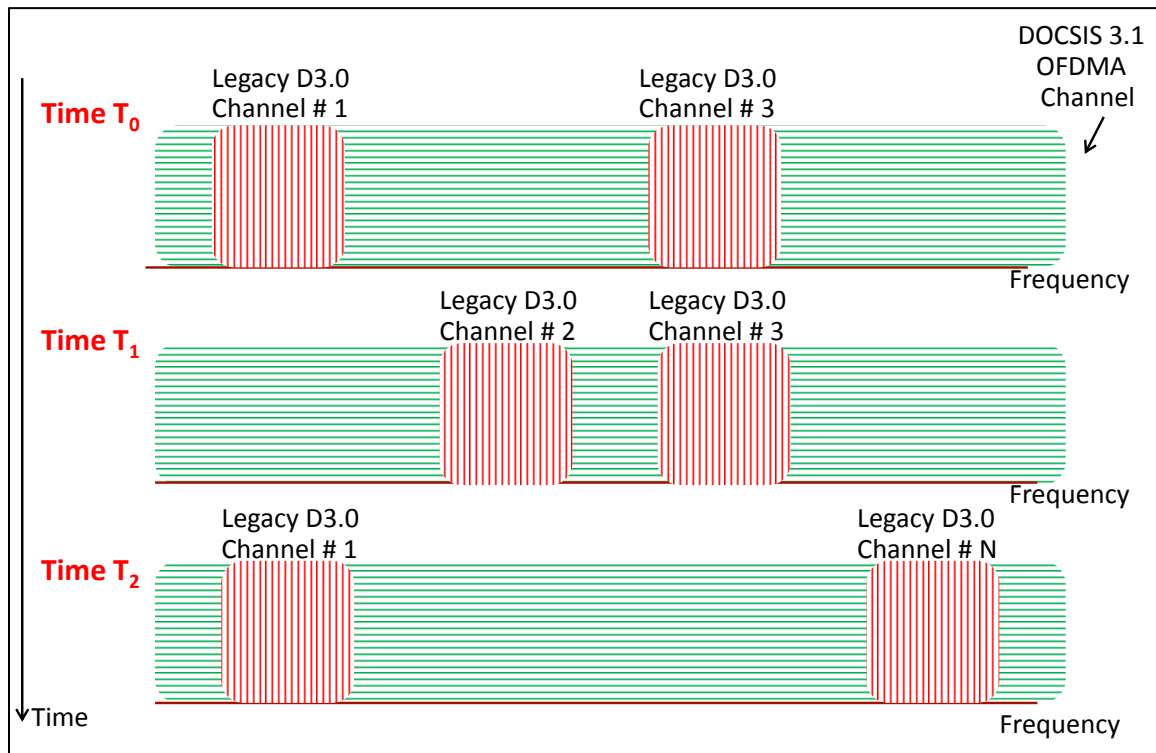

Figure 15 - Time and Frequency Division scheduler – Flexible spectrum assignment to different channels as needed.
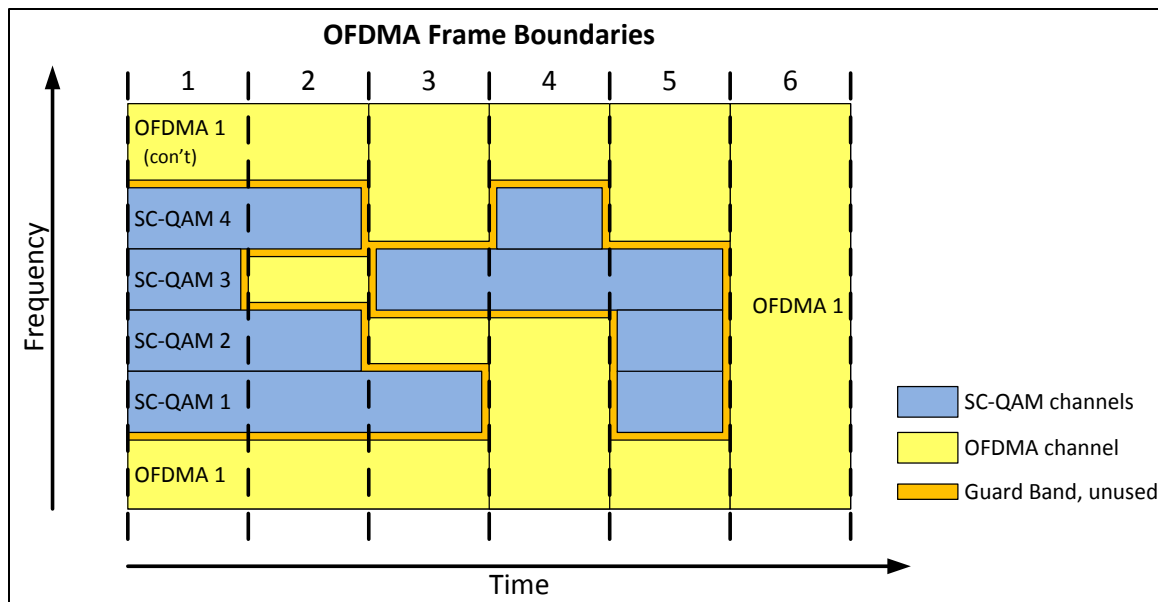
Figure 16 - Time and Frequency Division scheduler [5] – Flexible spectrum assignment to different channels as needed.
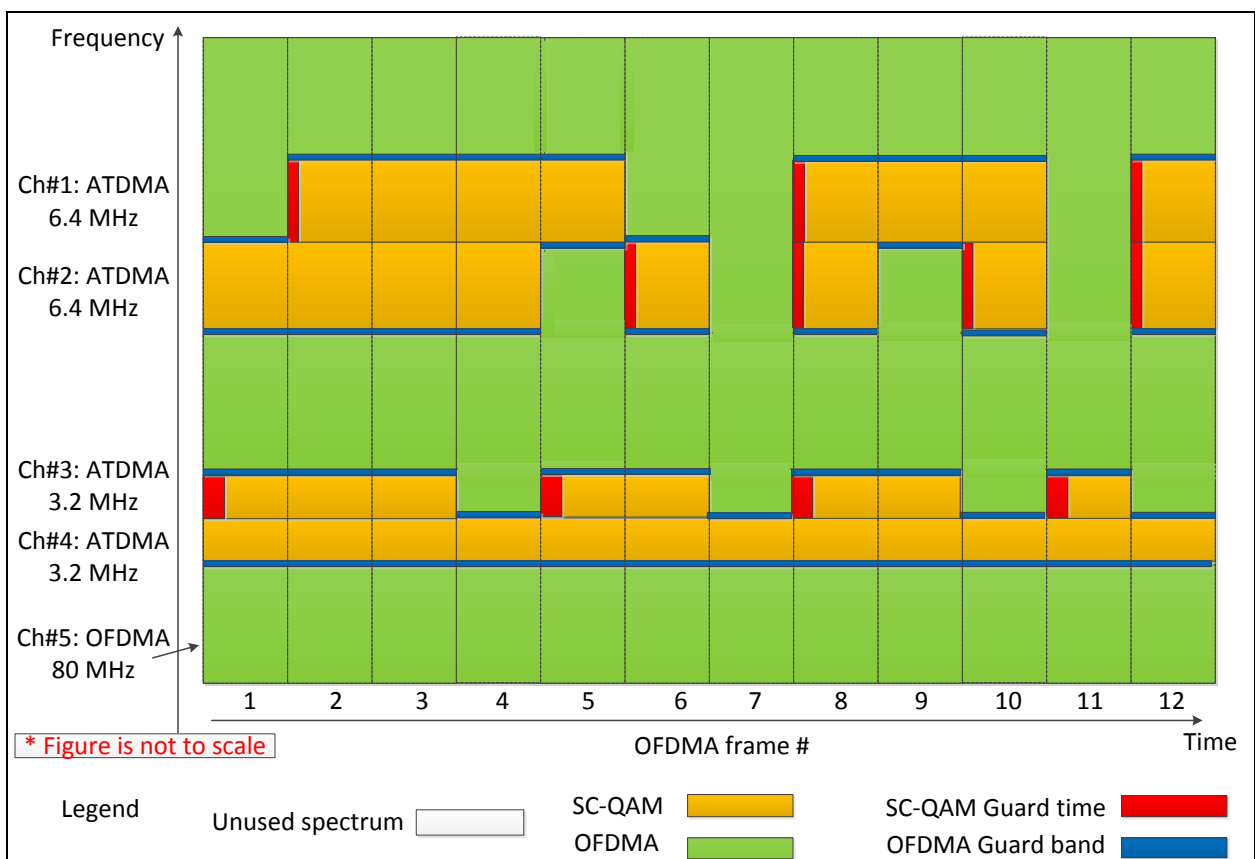

Figure 17 - TaFD Scheduler –overhead and multiplexing latency analysis.

Total spectrum (MHz)	80						
~TaFD muxing cost (*)	10%						
SC-QAM spectral eff	4.15	bps/Hz					
OFDMA spectral eff	6.55	bps/Hz					

	overlap SC-QAMs	overlap SC-QAMs	non-ovlp SC-QAMs	non-overlap OOB		overlap OFDMA	non-ovlp OFDMA
numCh	4	3	1	1			
Ch width (MHz)	6.4	3.2	6.4	0.192			
Total BW (MHz)	25.6	9.6	6.4	0.192		35.2	38.208
thruput (Mbps)	106.2	39.8	26.6			230.6	250.3
Peak rate (Mbps)	172.6					480.8	
Fixed Allocation %	60%	60%	100%			40%	100%
Avg technology thruput (Mbps)	57.4	21.5	26.6			83.0	250.3
Total avg tech thruput (Mbps)	105.4					333.3	
Total avg US capacity (Mbps)	438.7						

Figure 18 - TaFD Scheduler – Capacity analysis.

Comparison of Various US Scheduling Schemes

This section compares the different US scheduling techniques presented above and contrasts their advantages and disadvantages. As for the TD scheduler, the architecture is of moderate complexity where coordination between all ATDMA channels schedulers has to occur such that they are all granted / quieted for the same time duration. However, the TD scheduler has an advantage; it has the ability to accommodate high peak rates. In particular, the peak capacity that is offered by the OFDMA channel is about 481 Mbps which can support the 350 Mbps required capacity needed in 2020. On the flip side, there is always a trade-off between multiplexing latency and overhead with the TD scheduler because it lacks flexibility. This absence of flexibility also leads to some inefficiency and wasted capacity in situations where the technology is scheduled to have access across the whole spectrum and nevertheless there is no or little data available for transmission.

With TD schedulers, some services like Unsolicited Grant Service (UGS), where Service Flows (SFs) have to be granted at a certain rate, may have service and scheduling issues because those services may require a grant rate that may not be achievable with the current spectrum access allocation pattern and/or percentage. Additionally, the hard switch over times from ATDMA to OFDMA will cause complexities with unfragmentable long grants which may have to wait until the next time the ATDMA channels are allocated. Observe that since the spectrum can be used by one technology or another at any given instant of time, it will be required to coordinate the grants on different ATDMA channels and group them together which will add complexity to the scheduler.

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This inflexibility will also lead to reduced total average capacity offered by this scheduling scheme. These issues can only get worse as the utilization of the OFDMA channel increases. As a side note, observe that the presence of one or more ATDMA channels that are on all the time can address some of the multiplexing latency concerns.

Regarding the FD scheduler, it has a simple architecture and has no multiplexing latency issues. However, this scheduling scheme offers low peak rate and low average total capacity. This makes it a less attractive option for network migration where higher peak rates and average capacities are needed. US channel bonding may address some of these concerns as will be described later. Observe that since no spectrum sharing is allowed in this scheduling scheme, the OFDMA channel can only use the leftover spectrum after legacy channels are allocated the needed spectrum. Not only is the spectrum left for the OFDMA channel limited, but part of this the spectrum is located in the lower portion or the US band which tends to be noisy and therefore reduced capacity is obtained.

As for the H-TD-FD scheduler, it has moderate complexity architecture and can *theoretically* offer high peak rates and average capacity that supports the needed capacities in 2020. However, this scheme may have the same inflexibility/fragmentation / UGS / inefficiency issues that the TD scheduler exhibited as described above.

The architecture of the TaFD scheduler is complex because it has to offer multiple subfeatures and functionalities. These include coordinating the scheduling between all overlapping channels, offering flexibility / efficiency / high peak rates, fast burst responsiveness, accommodating time-constrained services like UGS and ranging, offering adequate customer Quality of Experience (QoE), and supporting smooth migration to DOCSIS 3.1. Note that while the flexibility of the TaFD scheduler causes more switching events and therefore more overhead, the TaFD scheduler remains overall more efficient than all other schemes. Due to the complexity of this feature, its delivery will likely be phased over time. The complexity of this scheduler may have implications in some remote gadget architectures. In particular, for the remote MAC-PHY architecture, where the scheduler is placed in the node, more processing might be required to implement this scheduler in the node although it can be argued that the reduced number of subscribers and channels in these architecture can help in regard to these processing concerns,

The different US scheduling schemes can be summarized as described below:

- TD – requires time multiplexing allocation scheduler/scheme
- FD – spectrum allocation scheme, does not require frequency multiplexing allocation scheduler (no spectrum sharing or muxing cost)
- H-TD-FD – requires time & frequency multiplexing allocation scheduler/scheme

- TaFD – requires flexible time & frequency multiplexing allocation scheduler/scheme

Of the above scheduling schemes, TaFD is the ultimate US scheduling technique for the DOCSIS 3.1 migration era, when a DOCSIS 3.1 OFDMA channel has to coexist with legacy DOCSIS 3.0 ATDMA channels. This scheduler can provide a smooth DOCSIS 3.1 migration path that is seamless to subscribers.   The scheduler is architected such that is able to support a wide range of spectrum capacity ranging from all grants to ATDMA channels only to all grants for OFDMA channels only (and various combinations in between).

BONDING FOR US SCHEDULERS

US channel bonding is a critical feature within the DOCSIS 3.0 specifications. Performing bonding between the two technologies (ATDMA and OFDMA) can provide multiple advantages like reducing the multiplexing latency, increasing efficiency, accommodating services with time constraints, load balancing, and smoother network migration operation. Bonding is critical especially for the less complicated US scheduling schemes like TD, FD, H-TD-FD schedulers. In fact, the FD scheduler may not be usable without US channel bonding. As for the flexible TaFD scheduler, bonding is less critical but provides better efficiency at the cost of added scheduler complexity. Therefore, it will likely that US channel bonding will be phased over time if it is combined with the TaFD scheduler because of the inherent complexity that comes with this scheduler.

IMPLICATIONS OF US SCHEDULERS ON DOCSIS 3.1 MIGRATION

The DOCSIS 3.1 specification is different enough from the DOCSIS 3.0 to make the process of network migration an interesting challenge! The network migration in the US can be more challenging than that in the DS because of spectrum scarcity, which can be solved via the US scheduling feature. In particular, the US scheduler feature can help with network migration because this feature impacts channel planning and placement, capacity planning, DOCSIS 3.1 CM seeding, etc. As mentioned earlier, it is important to select an US scheduling architecture that accommodates the required US capacities, which in turn enables 1 Gbps DS service offering.

As described earlier, not all US scheduling schemes can support the required 350 Mbps capacities in 2020. In particular, it was found that while the TD scheduler can provide the required peak capacities and tends to offer lower latency and higher efficiency with US channel bonding, it may have allocation inflexibility and issues supporting services like UGS and long grants for DOCSIS 3.0 CMs. The FD scheduler, on the other hand,

could not provide enough peak capacities. Bonding between ATDMA and OFDMA can help in this case. However, the FD scheme is not very efficient and provided low average channel capacity. The H-TD-FD is a promising scheme but has the same constraints that the TD scheduler exhibits. On the other hand, the flexibility that is provided by the TaFD scheduler presents it as the ultimate DOCSIS 3.1 scheduler where high peak capacities are offered, time-constrained services are accommodated, and coexistence between DOCSIS 3.0 and DOCSIS 3.1 CMs is operated smoothly. In particular, the fluid environment where ATDMA and OFDMA channels are allocated the spectrum dynamically can be critical for coexistence of pre-DOCSIS 3.1 and DOCSIS 3.1 CMs.

The migration process can be broken into multiple phases to make it feasible [6]. The selection of phases changes over time depending on the traffic demand, product and feature availability, and competition. An example migration strategy is proposed below that the MSOs may choose to consider while navigating through the DOCSIS 3.1 era

- Allocate spectrum for one or more pre-DOCSIS 3.1 channels to be on all the time and not shared with DOCSIS 3.1 channels in order to reduce the latency for pre-DOCSIS 3.1 CMs. These channels help in accommodating time-constrained services and features like UGS and ranging, etc.

- Apply the subscriber shedding concept. In this scheme, the top percentage of power subscribers that require high peak rate and/or average throughput are moved to DOCSIS 3.1 [7] [8] [9] [10]. Subscriber shedding reduces the required number of pre-DOCSIS 3.1 channels to support the subscribers on those channels. Therefore, this technique can help in reclaiming multiple pre-DOCSIS 3.1 channels and allocating the reclaimed spectrum to the more efficient DOCSIS 3.1 channels

- Adjust number of pre- DOCSIS 3.1 channels to accommodate pre-DOCSIS 3.1 users

- Reclaim bandwidth and allocate it to OFDMA channel

- Place any new subscriber demanding high peak rate on DOCSIS 3.1 channels. Continue monitoring usage of existing customers and keep shedding heavy/power subscribers to OFDMA

- Optional step: move to 5-85 MHz split

- Optional Step: use FD scheduler with US channel bonding to support coexistence of DOCSIS 3.1 and pre-DOCSIS 3.1 CMs while the TaFD feature is being developed

- Use phased approach for the TaFD scheduler to support coexistence of DOCSIS 3.1 and pre-DOCSIS 3.1 CMs

- Continue adjusting the number of pre-DOCSIS 3.1 channels as necessary

- Increase the US spectrum to 5-85 MHz (or more)

- Once the TaFD scheduler feature is largely developed and supported, combine with US channel bonding for more efficiency

- Increase the US spectrum from 5-85 MHz to 5-204 MHz (or more)

The above potential migration path shows that the combination of DOCSIS 3.1, the TaFD feature, and the concept of subscriber shedding can significantly increase the capacity, efficiency, and flexibility of HFC networks. This will enable the MSOs to meet the traffic demand and address the competition for the next two decades.

CONCLUSIONS AND RECOMMENDATIONS

This paper analyzed the TD, FD, H-TD-FD, and TaFD US scheduling schemes. Most of these schemes, except for TaFD, suffer from one or more combinations of latency, capacity, and efficiency issues. While US channel bonding can help address some of these concerns, the inflexibility exhibited by some of these architectures will still lead to efficiency issues as well as scheduling complexities when scheduling some services and grant types. The TaFD scheduling scheme is the ultimate solution in the DOCSIS 3.1 era because it offers high peak rates, efficiency, and flexibility but at the cost of scheduler complexity. This paper proposed a network migration strategy where pre-DOCSIS 3.1 and DOCSIS 3.1 channels can smoothly coexist using the US scheduling feature.

ACKNOWLEDGMENTS

ABBREVIATIONS

ATDMA	Advanced Time Division Multiple Access
CAGR	Cumulative Annual Growth Rate
CCF	Continuous Concatenation and Fragmentation
CM	Cable Modem
CMTS	Cable Modem Termination System
DS	Downstream
DSX	MAC Management Message that stands for Dynamic Service "X" where the X can be Add/Change/Delete which is used for dynamically modifying SFs between the CM and CMTS
FEC	Forward Error Correction
FD	Frequency Division
FTTH	Fiber To The Home
HFC	Hybrid Fiber Coax
H-TD-FD	Hybrid Time Division Frequency Division
ICO	Intelligent Channel Optimizer
IUA	Integrated US Agility
LDPC	Low Density Parity Check
MMM	MAC Management Messages
msec	Milliseconds
MSOs	Multiple Service Operators
OFDM	Orthogonal Division Multiplexing
OFDMA	Orthogonal Division Multiple Access
PCMM	Packet Cable Multimedia
QoE	Quality of Experience
QoS	Quality of Service
SC-QAM	Single Carrier Quadrature Amplitude Modulation
SF	Service Flow
SLA	Service Level Agreement
TaFD	Time and Frequency Division
TD	Time Division
UGS	Unsolicited Grant Service
usec	Microseconds
US	Upstream

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