1024 to 4096 Reasons for using D3.1 over RFoG:

Unleashing Fiber Capacity by Jointly Optimizing D3.1 and RFoG Parameters

A Technical Paper prepared for SCTE/ISBE by

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1. Introduction

DOCSIS® 3.1 (D3.1) offers exceptional capabilities for broadband service providers to enhance capacity and throughput both in the downstream (DS) and upstream (US) directions. While there has already been considerable activity in deploying D3.1 in the downstream, operators are in the early phases of rolling out D3.1 in the upstream.

While sharing many similarities with DOCSIS®3.0 (D3.0), D3.1 standards differ in important aspects – OFDMA operation, higher orders of modulation, increased flexibility in channel width, and most notably in burst upstream operation. There are many new things to consider in D3.1 including basic parameters such as Cyclic Prefix (CP), Roll-off Period (RP), OFDMA FFT size, minimum performance requirements, and encompassed spectrum. While D3.1 allows for a large encompassed spectrum affording significantly increased capacity, it also allows for very small mini-slots thus leading to a rather large dynamic range of RF inputs to existing RFoG ONUs. It is therefore an appropriate time to understand the capability of currently deployed RFoG plant and endeavor to jointly optimize D3.1 and RFoG parameters to ensure robust throughput in the downstream *and* the upstream.

In this paper, we describe relevant D3.1 parameters and link them to physical characteristics of an RFoG network. We examine performance of individual ONUs using stand-alone D3.1 test equipment as well as analyze D3.1 initial range and register protocols in a realistic D3.1 CMTS environment. We next consider a complete multi-ONU RFoG environment with multiple simultaneously transmitting cable modems and ONUs and introduce a new way for analyzing ranges of error free operation windows of D3.1 upstream systems. We conclude with a discussion of real world application of analysis presented in this paper for legacy deployed RFoG systems and offer practical suggestions for green-field D3.1 RFoG deployments.

2. A Word about OBI and D3.1

Optical Beat Interference (OBI) is a profound issue in RFoG reverse path (Mutalik, Schemmann, Maricevic, and Ulm – 2015 INTX NCTA Spring Technical Forum) and affects the system in debilitating ways. The subject of OBI and of its effects on cable systems as well as methods to mitigate and eliminate its deleterious effects has been extensively reported in the context of D3.0 over RFoG (ZorluOzer, Mutalik, Vieira, and Chrostowski – SCTE Cable-Tec Expo 2015). While mitigating OBI could have been argued to be adequate for D3.0 systems, an effective elimination of OBI is a requirement for D3.1 systems, as will be made clear in subsequent sections of this paper. Briefly, typical bonded D3.0 upstream (US) systems have at most 4 cable modems (CMs) that can transmit simultaneously, whereas in D3.1 systems, up to 40 CMs could transmit simultaneously. In this environment, the probability of OBI is vastly increased leading to significant impairments in system throughput (packet loss). Packet losses affect TCP/IP throughput quite profoundly, thus affecting efficiency of the network and with a drastic limitation on capacity.

Fortunately over the years, the cable industry has developed two very effective solutions for the elimination of OBI.

2.1. Wavelength Selective ONUs (WSO Option)

OBI occurs when two or more ONUs, at near identical wavelengths (WLs), transmit simultaneously and reach the same upstream receiver. Since US transmission is in burst mode, ONU lasers typically exhibit wavelength drift at laser start up, which can significantly increase the OBI occurrence. Therefore, selecting WLs of ONUs that do not intersect even if all ONUs are in burst mode would effectively eliminate OBI. Furthermore, this would enable the use of passive optical splitters as originally envisioned in RFoG deployments. Furthermore, this concept allows for distributed splits in the field thus providing substantial flexibility in the plant. However, in this approach, the passive loss and the potential for additional noise at the headend receiver from a larger number of simultaneously transmitting ONUs could limit available SNR and thus limit capacity. These effects are however a part and parcel of the D3.1 environment, and are described in detail in subsequent sections. Innovative ways of building the ONU and the headend receivers and configuring of the RFoG network would help alleviate some of these concerns. In this paper, this option is referred to as the WSO option.

2.2. Multi Diode Receivers (MDR Option)

OBI can also be eliminated by restricting the light of each ONU to an individual photo-diode (PD). Thus multiple ONUs can transmit simultaneously with no opportunity for OBI to occur. With innovative optical and electronic design techniques, these MDRs can also be designed to fully support PON wavelengths. Since the MDRs are placed at the location of a traditional RFoG splitter, the light levels entering the individual PDs from the ONUs are quite high, and thus when retransmitted to the headend receiver provide a substantial SNR advantage, potentially allowing one to take advantage of higher order QAM modulation.

However, MDRs by their nature are active devices and require powering at their locations and cabinet or strand accommodations. Oftentimes, since powering is provided, these MDRs also include optical amplification to extend the link and/or provide higher power levels in the DS to the ONUs. This is referred to as the MDR option.

In this paper, we assume the elimination of OBI and now proceed to describe D3.1 parameters, compare these to D3.0, and describe their interplay with established RFoG standards in the cable industry such as the SCTE IPS 174.

3. D3.1 Numerology Upstream and Downstream

D3.1 uses Orthogonal Frequency Division Multiplexing (OFDM) in the DS and the US, whereas D3.0 used Single Carrier QAM (SC-QAM), Furthermore, while D3.0 was capped to SC-QAM256 in the DS and SC-QAM64 in the US, D3.1 allows for much more complexity of modulation, all the way up to OFDM4096. Thus, unlike in the D3.0 environment where the capacity is capped for a given RF spectrum, a higher MER in the D3.1 environment can enable higher modulation formats and therefore meaningfully increase capacity of the network. This is a paradigm shift in that higher MER for D3.0 served to provide performance margin, higher MER for D3.1 provides increased capacity (provided a higher modulation format can be achieved).

In the DS, D3.1 operates in 4K or 8K FFT modes, affording channel bandwidths that can span 24 MHz to 192 MHz. The subcarrier spacing for the 4K mode is 50 kHz, and for the 8K mode is 25 kHz, while the symbol duration is 20us for the former and 40us for the latter. These parameters and the performance requirements for various OFDM constellations are summarized in the table below.

Table 1 – D3.1 DS and US Numerology

D3.1 Downstream Parameters Summarized (from CM-SP-PHYv3.1)		
Mode	4k	8k
Channel BWs	24MHz to 192MHz	
Subcarrier spacing	50kHz	25kHz
Symbol duration	20us	40us
Cyclic Prefix	0.9375, 1.25, 2.5, 3.75, 5us	
Rolloff Period	0, 0.3125, 6.25, 0.9375, 1.25us	
OFDM Constellation	CNR AWGN 1GHz	CNR AWGN 1-1.2GHz
4096	41.0	41.5
2048	37.0	37.5
1024	34.0	34.0
512	30.5	30.5
256	27.0	27.0
128	24.0	24.0
64	21.0	21.0
16	15.0	15.0

D3.1 Upstream Parameters Summarized (from CM-SP-PHYv3.1)		
Mode	2k	4k
Channel BWs	10MHz-96MHz	6.4MHz - 96MHz
Subcarrier spacing	50kHz	25kHz
Symbol duration	20us	40us
Cyclic Prefix	0.9375, 1.25, 1.5625, 1.875, 2.1875, 2.5, 2.8125, 3.125, 3.75, 5.0, 6.25 us	
Rolloff Period	0, 0.3125, 0.625, 0.9375, 1.25, 1.5625, 1.875, 2.1875 us	
OFDMA Constellation	CNR AWGN	
4096	43.0	
2048	39.0	
1024	35.5	
512	32.5	
256	29.0	
128	26.0	
64	23.0	
32	20.0	
16	17.0	
8	14.0	
QPSK	11.0	

For the US, 2K or 4K FFT mode can be selected, which respectively have carriers spaced 50kHz or 25kHz apart and with symbol durations of 20us and 40us.

3.1. Time and Frequency Scheduling: Role of the mini-slot

In D3.1, multiple subcarriers are joined together to create a mini-slot. For the US, 8 of the 50kHz subcarriers in the 2k mode, or 16 of the subcarriers in the 4k mode, which in either case amounts to 400 kHz wide frequency spectrum, is considered as a mini-slot. All D3.1 operations (save a few which do not affect our discussion) are done in multiples of the 400 kHz mini-slots. Thus 400 KHz represents the minimum amount of RF spectrum that may be present at the RF input of the ONU in RFoG operation. Depending upon the traffic utilization, the D3.1 CMTS scheduler allots RF spectrum on a case-by case basis in the time and frequency domain to the various CMs for transmission. This spectrum is always allotted in 400 kHz bandwidth increments.

In the time domain, the D3.1 standard allows for multiple symbols to be joined together in a frame; just how many symbols can form a frame depends upon the encompassed spectrum and other modes of operation. The CMTS allots slots for transmission to the CMs in duration of frame sizes. Since the CMTS schedules in real time, the CMs generally turn off per frame and turn on again at a frequency spot that the CMTS allots them. While the frame sizes can vary from 6 to 32 symbols per frame, the frame size is chosen so as to optimize throughput and latency.

Thus, the 400 kHz mini-slot in the frequency domain, along with the consecutive set of symbols that comprise a Frame, in the time domain, form a unit of well-defined entity that carries data in the D3.1 protocol.

3.2. Cyclic Prefix and Rolloff Period

The HFC plant is a significant asset of the MSOs, but is comprised of many cascaded active and passive devices. Each of these connections in the plant is a potential source for reflections and when many such reflection points exist, they can degrade upstream transmission quality. To minimize the effects of these reflections, D3.1 standard uses the Cyclic Prefix (CP). A part of the end of each symbol is prepended to the start of the same symbol (and a part of the start of the symbol is appended to the same symbol) thus ensconcing the symbol within its own parts. At the CMTS, the main signal from the CM and all of its echoes are received and are auto-correlated with the redundant parts discarded and the main symbol information utilized for demodulation.

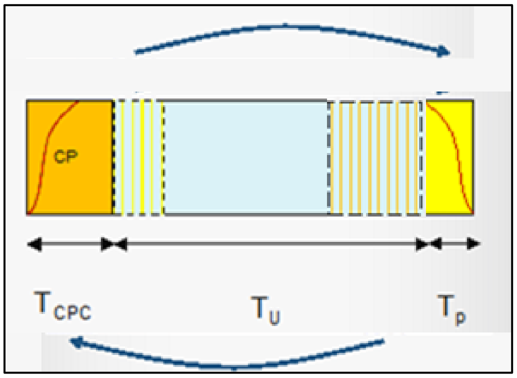


Figure 1 – Illustrating the D3.1 US Symbol and CP, RP

The design and implementation of the CMTS receiver is a source of innovation and has a direct effect on the CP needed. It should be noted here that a large CP would enable resilience to large amounts of reflection; the time dwelled on CP is essentially 'dead-time-on-the-wire' and directly reduces efficiency. This is all the more important since the CP is appended to *each* symbol. Thus the efficiency in real terms is

Efficiency = Symbol Time / (Symbol Time + Cyclic Prefix)

The graph below shows the drop in efficiency with Cyclic Prefix for the 2k and 4k modes for the US D3.1 transmission.

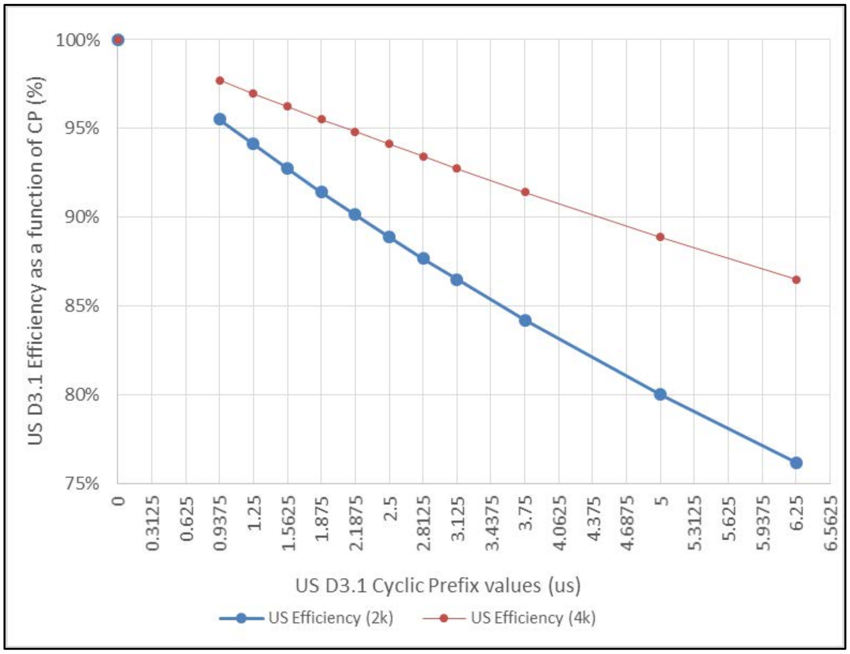


Figure 2 – US D3.1 Efficiency as a function of Cyclic Prefix

While typical HFC networks have reflections at such a magnitude that they require a CP, of say 2.5us, the fiber plant of RFoG is relatively clean, with minimal reflections implying that it may require a shorter CP duration than the HFC plant, thus affording higher efficiencies. In reality this may not be the case as we will explain in subsequent sections. Briefly, this has to do with the laser turn on time as provided by current standards for the RFoG ONU. In any case, reducing the CP has a direct effect on the efficiency, almost as much as an increase in the order of modulation. There is a case to be made for viewing the CP values as mediating the MER values that are normally used to establish modulation order and capacity.

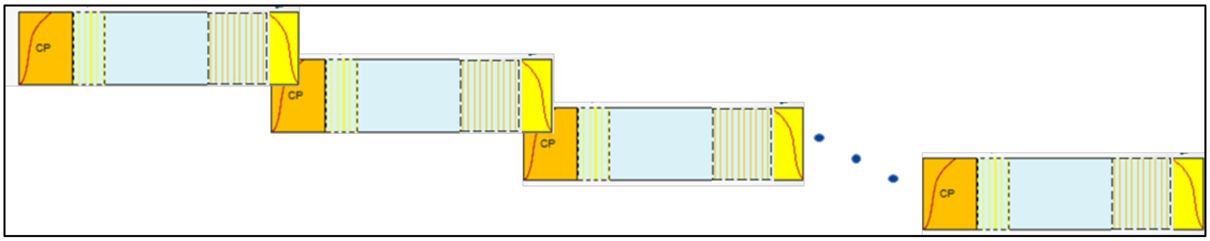


Figure 3 – Illustrating a D3.1 Frame: Note the Overlaid RPs

In addition to the Cyclic Prefix explained above, there is a Rolloff Period (window size), RP, within the CP which gently ramps the data up at the symbol start and ramps it down at the symbol end thus shaping the symbol in the time domain and maximizing channel capacity by sharpening the edges of spectrum of the OFDMA signal. The RP is always less than the CP and has to follow the values listed in Table 1. Generally, the next symbol has its RP coexistent with the current RP, thus introducing only the net CP value as the appendage factor that determines efficiency. Just as the RP does not affect efficiency, neither does the frame size, because the CP affects each symbol regardless of the frame size. The total Frame Length is thus

Frame Length = (Symbol Time+ CP)(Symbols/Frame)*

In the current paper, we have used the 2k mode (symbol length of 20us) and various CP and RP values. However, by way of example, a CP of 1.875us with an RP of 0.9375us with a frame length of 8 symbols/frame has been a common configuration. This configuration would have yielded and efficiency of 91% and a frame length of 175us.

3.3. The Dizzying Choices of D3.1

With the myriad of customizable options listed above, beginning with the mode of operation (2K/4K for the US and 4K/8K for the DS), the choice of the encompassed spectrum (7.4MHz to 96 MHz for the US and 24MHz to 192MHz for the DS), the modulation formats (up to 4096QAM for US and DS) and the CP choices (0.9375-5.0us for DS and 0.9375-6.25us for the US) and the RP choices (0-1.25us for DS and 0-2.1875us for US), it is clear the D3.1 offers a dizzying array of choices for the operators. For this paper, however, we have been selective in our approach to analyze performance of D3.1 over RFoG. We begin with understanding the current RFoG spec and how the role of 400 kHz mini-slot affects the laser turn on operation. Then we analyze the choice of CP and RP and how they affect turn on timing of the US laser. Then with this understanding, we choose CP and RP, and the RF levels that would enable transmission of D3.1 over RFoG and evaluate the dynamic ranges of operation for the WSO and MDR options. Finally, we offer practical suggestions on enhancing the capacity of D3.1 over RFoG systems making full use of the fiber asset deployed.

4. The Basics: Putting D3.1 and RFoG Together

As indicated earlier in the paper, the industry standard for RFoG is defined in the SCTE IPS 174. This standard, first conceived around 2005 defines various aspects of the ONU, such as US and DS WL ranges, ONU laser output wavelength and power, ONU Laser turn-on and turn-off RF levels and various timing specifications. It is critical to understand the current RFoG standard and its interplay with D3.1 parameters to enable robust D3.1 over RFoG. We begin with a quick summary of the interplay of D3.0 and the current RFoG standard.

4.1. D2.0, D3.0 and the SCTE IPS 174

The current SCTE standard worked well in the D2.0 environment where there was no significant system impairment due to the effects of OBI, but in the D3.0 mode, OBI severely impacted the performance resulting in the proliferation of WSO or the MDR options described earlier. The current standard is summarized below.

Table 2 – RFoG Standard Table Summarized

Simplified Summary of RFoG SCTE IPS 174	
ONU DS WL Range	1540-1565 nm
ONU US WL Ranges	1610+/-10 nm
ONU Laser P on	3+/-1.5 dBm
ONU Laser P off	<-30 dBm
ONU Laser Turn-On time	<1.3 us
ONU Laser Turn-Off time	<1.6 us
ONU Laser Turn-On RF	+7 to +16 dBmV
ONU Laser Turn-Off RF	+1 to -8 dBmV
OMI at Total Power	35% +/-3dB @39dBmV
Nominal RF Input Level/6.4MHz	33 dBmV (17.5% OMI)
Nominal Number of RF Channels	4

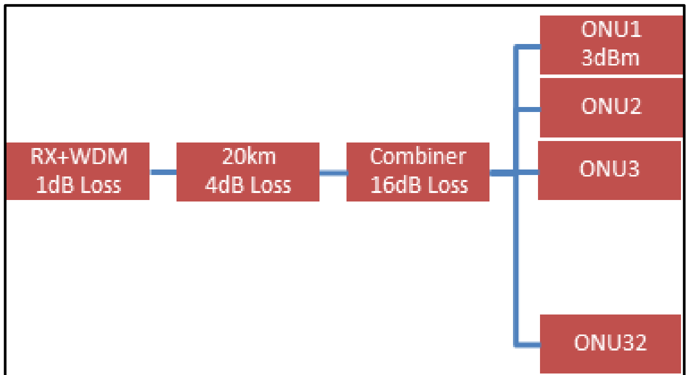
Since D3.0 begins its preamble transmission 1.5us after the initiation of ramp up, the 1.3us timing introduced by the standard continued to be adequate after the elimination of OBI. Furthermore, the RF levels were chosen so that the ONU would be triggered by legitimate signals, but stop ingress and spurious noise from erroneously turning on the ONU. Since the RFoG standard requires a rather high nominal RF input at 33dBmV/6.4MHz, the turn-on trigger remains quite high (although the standard specifies +7 to +16dBmV as turn-on threshold, most ONUs commonly have a 13dBmV +/-3dB as their turn-on threshold). Additionally, D3.0 operates in burst mode with up to 4 bonded SC-QAM64 RF channels, each typically set to 6.4MHz of encompassed spectrum. Thus the total RF load is normally less than 26MHz and requires a rather modest MER to support 64QAM upstream operation. Finally, only a maximum of 4 ONUs are likely to transmit simultaneously, and with OBI elimination, the turn-on timing, the turn-on level, and the modest SNR requirement enables fair transmission of D3.0 over the current standard.

4.2. Understanding D3.1, D3.0 and the SCTE IPS 174

A move to D3.1 requires a finer understanding of the RFoG standard and how it impacts the system. At its heart, we need to understand and resolve the three dynamic ranges simultaneously. These are described next.

4.2.1. Optical Receiver Dynamic Range

Typical RFoG optical receivers are designed with low noise, high sensitivity and high gain since the optical input can be quite low. In typical D3.0 applications, the optical input to the headend receiver is around -19 dBm/ONU and even if all 4 ONUs turn on simultaneously, the optical input does not exceed -13dBm in total. Typical RFoG receivers can handle up to -10dBm of optical input but higher optical level could overload the receiver and cause unwanted effects.



RFoG Loss	22dB
ONUs ON	P(dBm) in Rx
1	-19
4	-13
16	-7
32	-4

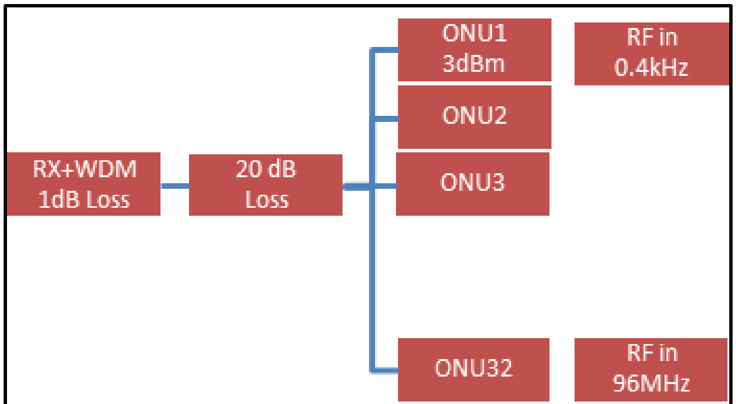
Figure 4 – Illustrating Optical Rx Dynamic Range

In a D3.1 environment the same -19dBm/ONU of power could result in up to -7dBm of power for 16 ONUS on simultaneously and up to -4dBm of power if all 32 ONUs turn on simultaneously. These power levels introduce the risk of overloading typical RFoG receivers. Of course, the optical level overall could be decreased, but that would lead to a lower operational MER resulting in reduced system performance.

There are two ways to overcome this effect. One way would use standard (non-RFoG specific) return receivers. Even though these have slightly higher EIN and lower gain, their lower sensitivity enables a higher optical power and ensures an operational dynamic range. Alternatively, we would use an MDR in the continuous mode. In this case, the optical level to the headend receiver is independent of the optical level at each of the MDR distribution ports and thus ensures a wide operational dynamic range.

4.2.2. ONU RF Input Dynamic Range

The operational range of an ONU is a significant determining factor of the overall dynamic range in the system. At the low RF input levels, it is limited by the SNR or MER availability and at high RF input levels it is limited by the ONU laser clipping. In a D3.0 environment where there are typically only 4 RF SC-QAM channels, the total RF level is only 6dB higher than the RF level of each individual SC-QAM.



RF nom	OMI nom	MHz
33	17.5%	6.4
RF(MHz)	RF(dBmV)	OMI(%)
0.4	21	4%
1.6	27	9%
6.4	33	18%
25.6	39	35%
48	42	48%
96	45	68%

Figure 5 – Illustrating ONU RF Input Dynamic Range

However, for D3.1, the RF transmission occurs in mini-slot sizes of 400 kHz, therefore the smallest RF input can be at 400 kHz wide and the largest RF signal could occupy the entire 96 MHz band. The implications of this are that the total RF level at the ONU RF input may be 24dB higher than the RF level of a 400 kHz mini-slot. This is illustrated in the figure below:

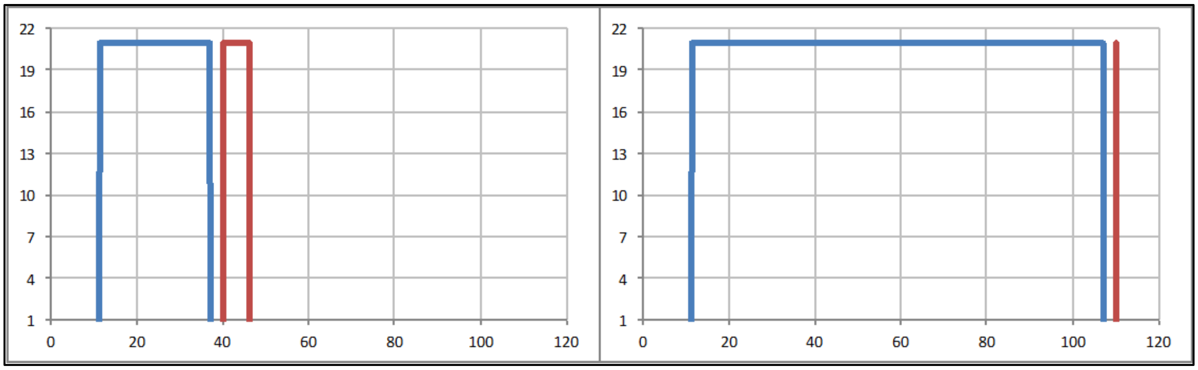


Figure 6 – Illustrating Typical RF Levels: D3.0 left and D3.1 right

Note however that practical US systems today are limited to 42MHz for the low splits, 85MHz for mid-splits and 204MHz for high split applications. Therefore the RF levels depicted here are for illustration purposes and the exact RF dynamic range is determined by specific encompassed spectrum in each system.

Recall that the typical implementation of the RF turn-on level is 13+/-3dBmV. As a result, we would need at least 16dBmV in 400kHz to turn the ONU Laser on. However, if all 96 MHz (note that in a 204MHz upstream, there may be up to two 96MHz OFDMA channels) of available spectrum were utilized, the total power would be 40dBmV, which is close to the onset of clipping. Notice that in 400 kHz case, the system performance is not limited by the available SNR or MER, which likely would be more than sufficient at RF levels below 16dBmV/400kHz, but that it is limited primarily by the laser turn on itself. Overall, this is a potential limitation that could substantially limit system operational range.

There are two possible ways to handle the wide RF range requirement. In the first way, we would limit the total RF encompassed spectrum. Limiting the spectrum to 25.6 MHz for example as is currently the case, the RF level range is 18dB and therefore affords 6 dB additional operational dynamic range. The other way would be to let the ONUs run in Continuous mode (CTM). Note here that only the ONU laser is always on, but the CM is still operating in burst mode. This will radically open up the dynamic range since the laser is always on; there is no requirement to limit operation to 16dBmV minimum RF. As mentioned earlier, systems would provide sufficient SNR or MER below 16dBmV/400kHz. This is illustrated in the NPR curve below.

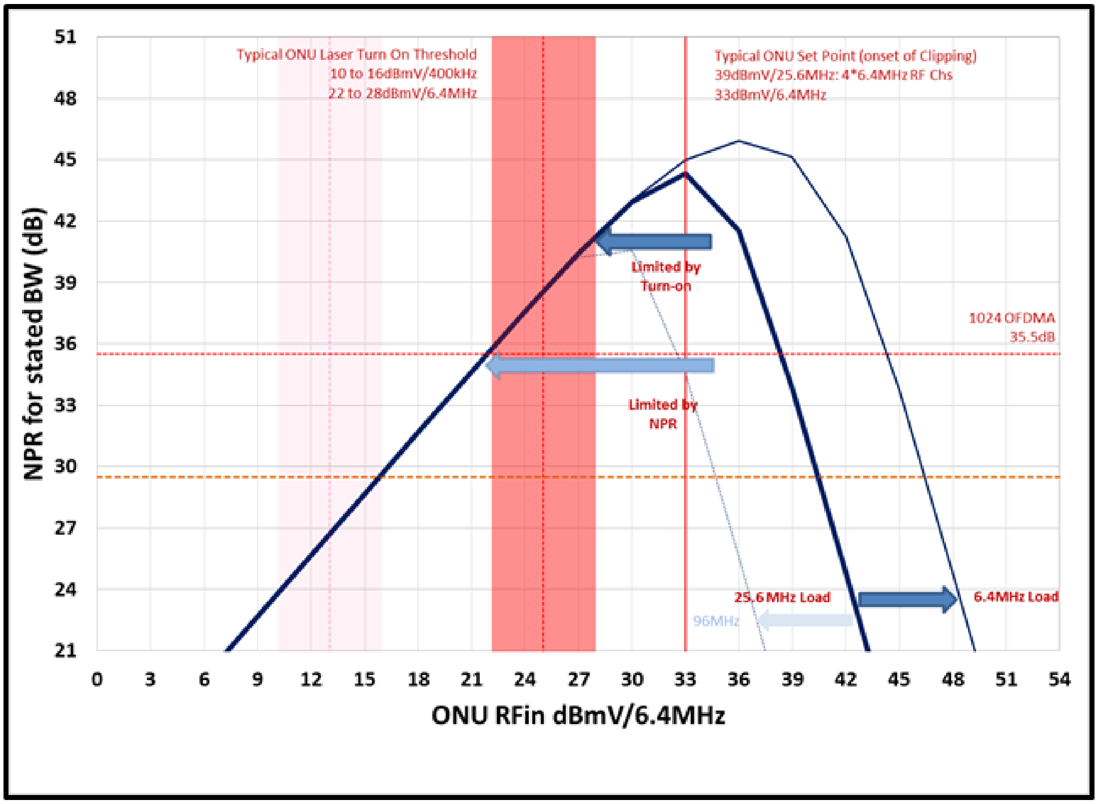
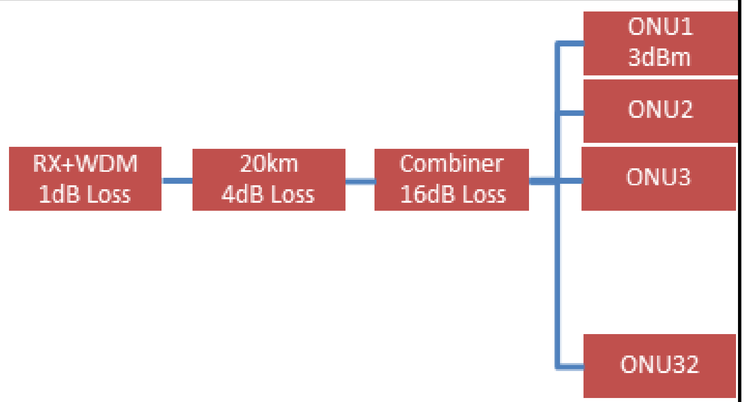


Figure 7 – Illustrating a Typical NPR curve and RF Turn-On Levels

The figure above illustrates a typical NPR curve of an ONU with -19dBm input at the headend receiver with RF levels represented per 6.4MHz bandwidth. The shaded red box illustrates the 13+/-3dBmV/400kHz laser turn-on level prorated to a 6.4MHz bandwidth. It is clear that the RF input could be lower than the lowest RF laser turn on level and the ONU would still have produced sufficient SNR to resolve 1024QAM signals. If 256QAM were required, the system could have gone even lower. However, following the SCTE standard results in a dynamic range that is rather limiting.

4.2.3. The MER-BER Dynamic Range



RFoG Loss	22dB	WSO Option
ONUs ON	P(dBm) Total	Est NPR(dB)
1	-19	44
4	-13	41
16	-7	38
32	-4	35

Figure 8 – Illustrating the MER-BER Dynamic Range

While the above section makes a compelling case for a continuous mode operation, if all ONUs operated in the continuous mode (CTM), then it could result in a substantial increase in the overall noise level at the headend receiver. As we have shown in earlier sections, with 16 ONUs simultaneously on, the optical level increases by 12 dB, bringing with it an increase in the noise floor due to the additional shot and RIN noise of individual ONUs, thus affecting the left side of the NPR curve shown in Figure 7. In practice the RF dynamic range improvement obtained by operating in continuous mode could be tempered by this additional noise. However, one thing to note here is that D3.1 uses the powerful low density parity check (LDPC) codes that work exceptionally well in AWGN environments (not so much in clipping), so that the system may function even below the specific performance levels specified in the D3.1 standard subject to the CMTS implementations. In other words, faced with a choice of dynamic range limitations due to laser clipping or the noise floor, one would always want to choose to operate closer to the noise floor and take potential advantage of LDPC.

5. The Single ONU Simulated D3.1 Tests

Testing a new protocol such as D3.1 with its dizzying array of customizations in a multi-ONU CMTS setting is fraught with choices. It was necessary to find a way to accomplish a large set of tests to help establish the operational parameters that could then be used in a multi-ONU CMTS test bed. Therefore, we began our testing with a single ONU in a test bed with Rohde & Schwarz CLGD-FSW test gear. Briefly, the Cable Load Generator (CLGD) can generate frames of burst US OFDMA test signals with various CP and RP values. When the CLGD is connected to the FSW signal analyzer thru the ONU and a

Headend Receiver, the FSW can read the incoming burst mode signal and provide MER values (but no BER values at this time).

5.1. CLGD-FSW Test Configuration

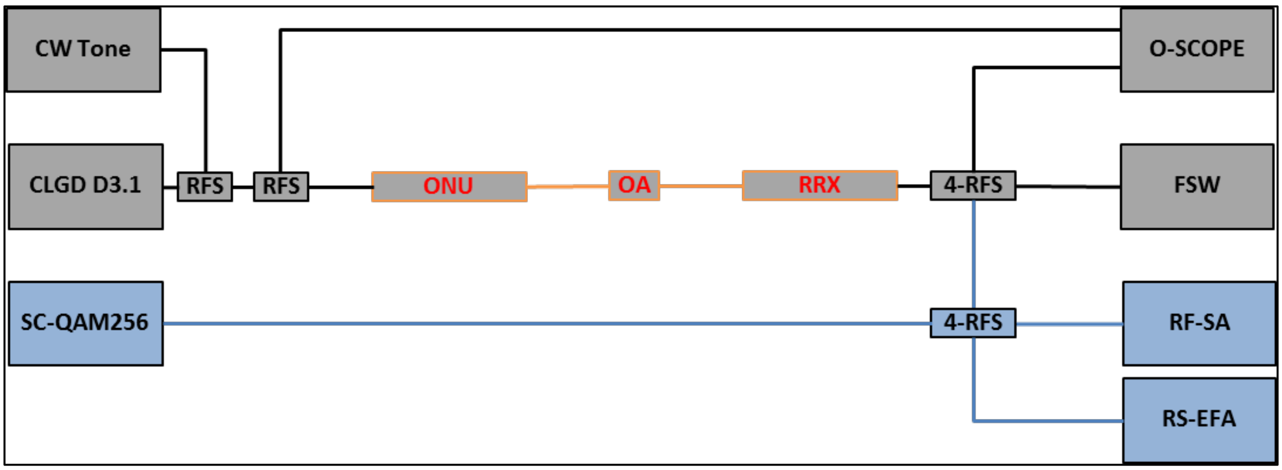


Figure 9 – CLGD-FSW Single ONU Test Setp

The test bed comprised a CW tone generator that was coupled in with the CLGD so that we could enable CTM operation of the ONU when needed. A part of the input signal was available on an O-Scope for time domain analysis. The RF level out of the headend receiver was split and was made available to the O-Scope and to the FSW. We also had a known SC-QAM256 'probe' channel for reference, one that combined with the output of the headend receiver so that we could compare the D3.1 burst signals to a known continuous signal as the experiment progressed.

The CLGD would create 5000 frames of US data and send them thru the ONU while the FSW would record the mean MER as well as the maximum and minimum MER values. One could then vary the encompassed spectrum, the RF level, the OFDMA profiles, the FFT modes, the CP, and the RP via CLGD commands. In total, over 50 files were created that could simulate the set of options that D3.1 provides.

Furthermore, the CW tone could enable the ONU to be in BTM or CTM mode of operation. Finally, the ONU was customizable and the turn on timing could be adjusted as needed. Each of these settings would then be tested using the options described above. All in all, we tested hundreds of combinations to understand the operational set for D3.1 testing over multiple ONUs and over a real CMTS.

The first set of tests used a standard SCTE IPS 174 compliant ONU, with a turn-on time around 1.3us. The CP was increased from 0.9375 all the way to 6.25us as specified by the D3.1 spec. In each case, the RP value was set to 0.3125us. The ONU was then set to the CTM with the CW tone and the CLGD passed the frames across the ONU to the receiver and were analyzed by the FSW. As expected, the mean, maximum and minimum MER values in each test were very close to each other indicating that the performance was unaffected by the choice of a CP.

However, when the ONU operated in a burst mode, the minimum MER value fell quite dramatically each time the test was run with a CP value less than the laser turn on time. Even with the CP value well above the laser turn on time, the FSW continued to show a small reduction in the minimum MER relative to the mean MER. The reduction in minimum MER even with large CP values indicates that the laser turn-on process itself impacts performance and is briefly examined in a subsequent section. Changes in RP did not seem to affect the performance significantly.

5.2. Single ONU Measured Results

27dBmV/35MHz	MER Continuous Mode ONU			MER Burst Mode ONU (1.3us)		
CP	Mean	Max	Min	**Mean**	**Max**	**Min**
0.9375	44.2	44.5	43.8	**44.0**	**44.6**	**31.9**
1.5625	44.0	44.4	43.6	**44.0**	**44.5**	**35.1**
3.1250	44.0	44.4	43.5	**43.9**	**44.4**	**39.2**
6.2500	44.2	44.6	43.8	**44.1**	**44.6**	**40.8**
Rolloff Parameter does not affect performance significantly						
CP must exceed the Laser Turn-on time for adequate performance, Continuous Mode performance impervious to CP values						

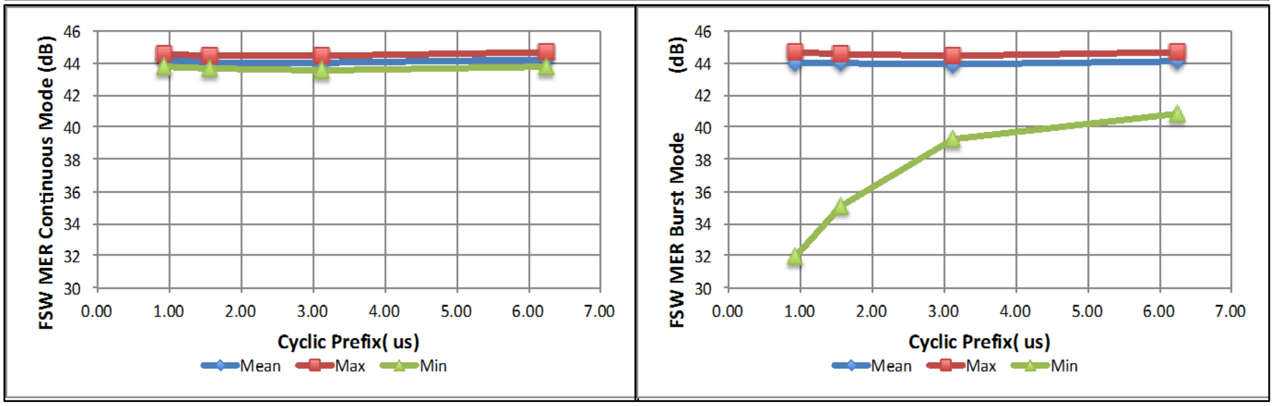


Figure 10 – Measured MER for Single ONU using the CLGD and FSW Test Equipment

The results above indicate that the CP values for standard SCTE IPS 174 ONUs that operate in the BTM must be chosen above 1.5us, preferably at least 1.875us to accommodate the laser turn-on and turn-off requirements. No such restrictions need be observed in the case of ONUs that operate in CTM. As explained earlier, larger CP values reduce throughput efficiency, therefore values of CP between 1.875 to 2.5us may be a tradeoff for robust and efficient systems.

6. Additional Considerations

6.1. Initial Range and Register

Initial Ranging and Registering in D3.1 differs slightly from the same process in D3.0. In D3.0, the range and register signals are of a lower modulation format and require a lower MER than the data signals themselves. In D3.1, the range and register signals use the same modulation profile as the data signals and therefore, adequate MER must be established before the ranging & registering process can be completed. It is therefore critical that the system robustly support the required MER before the CMs are set to range and register.

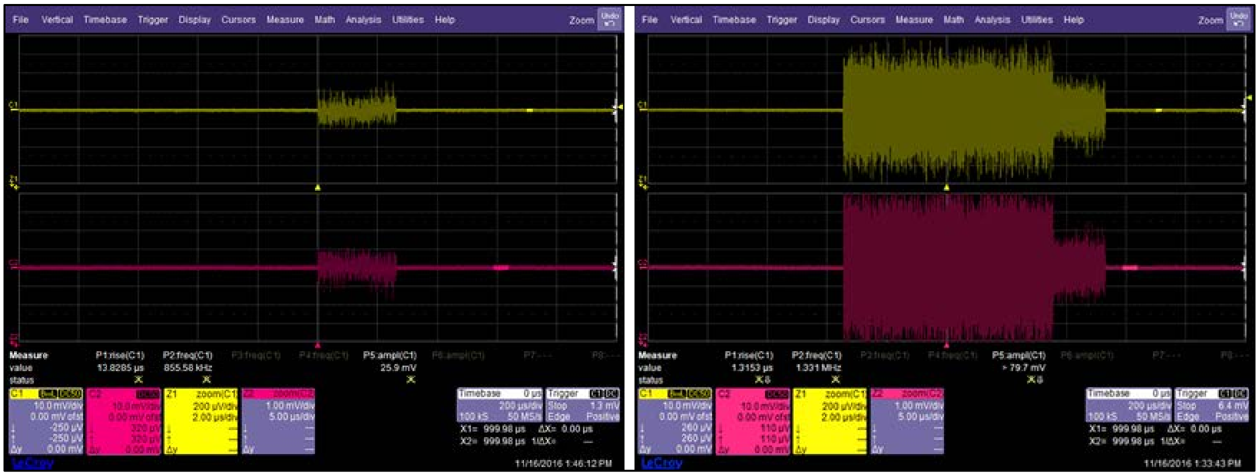


Figure 11 – Time Domain Captures of Range and Register Signal and Signals at 50Mbps

While ranging and registering is a multi-step process, different than the one used to transmit data signals, the CM still uses the ranging signals in the 400 kHz mini-slot. Presented above is a time domain capture of the range and register signal on the left. As can be seen, the signal amplitude is rather limited when compared to a burst of 50Mbps of traffic which has been captured in the time domain graph shown on the right. Therefore, the RF levels into the ONU must feature an RF level which is high enough within 400kHz to trigger the ONU laser on for successful range and registering. Range and register signals are sent periodically in addition to station maintenance, therefore the MER of the system must be maintained to prevent time out conditions.

6.2. Laser Turn on Effects: CP, RP and OMI

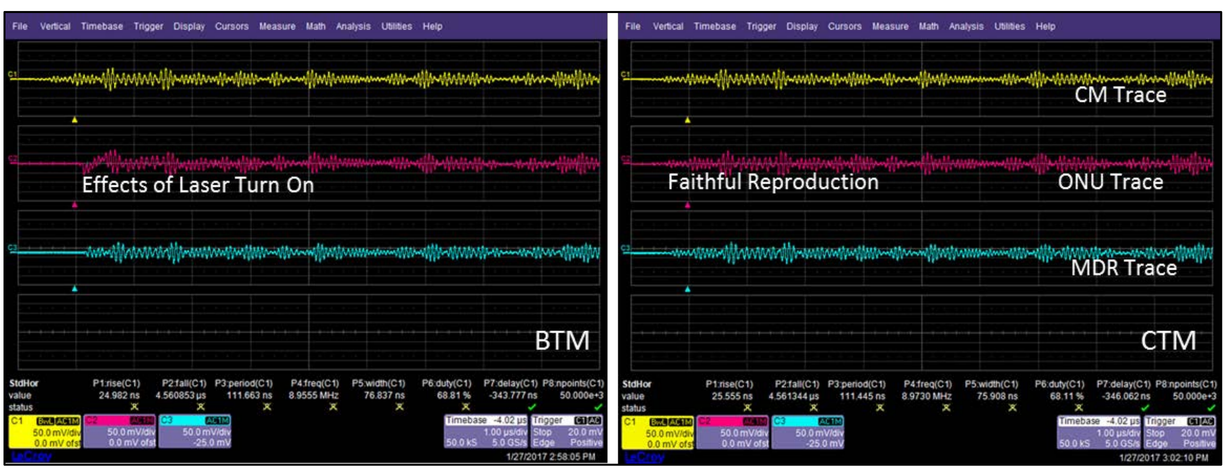


Figure 12 – Time domain capture of the effects of the Laser turn on

Presented above are time domain captures that zoom in on the initial few micro-seconds of the ranging signal. We configured the O-scope to provide outputs of the time domain signal from the CM, the ONU directly connected to the receiver and the ONU thru a coupler to the MDR (with the output of the MDR connected to a receiver). On the left is the time domain capture with the ONU in the BTM and on the right is the same time domain capture but with the ONU in the CTM. The effects of laser startup are visible in the figure on the left. It is seen here that a part of the signal is cut off and a part of the signal is experiencing RF level variation consistent with laser turn on.

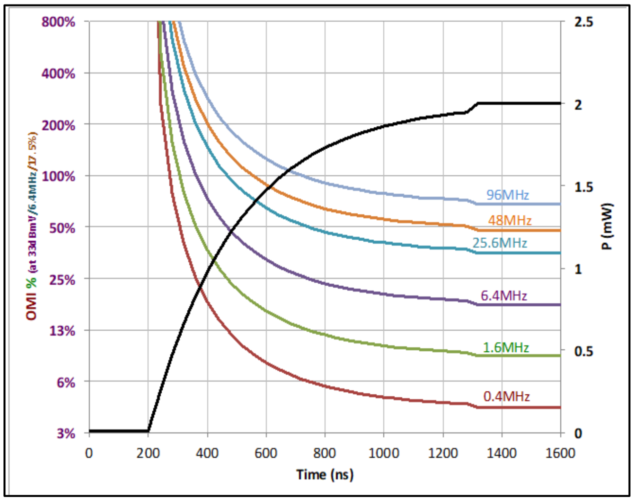


Figure 13 – OMI of an ONU at Turn-on and potential for Collateral Clipping

There is a time delay (100-500ns) before the laser begins the process of turning on. From initial laser turn on to maturity (90% of stated output power), the laser experiences a very high OMI. While this high level of OMI is experienced only for a short period of time (500 – 1000ns), the laser experiences significant clipping during this turn-on time (note that the RP may mitigate this effect to a small extent). If the CP exceeds the laser turn on time, then the CMTS is still able to lock to the symbol and get information within the frame. However, if the laser turn on time exceeds the CP, then substantial packet loss is observed.

Since all ONUs share the same headend receiver, if one laser is clipping, a different laser that fully turned on (and otherwise not clipping itself), could experience packet losses due to the collateral effects of the other ONU(s) with lasers in the initial turn-on process. This effect also occurs in D3.0 RFoG systems, but could happen more frequently in D3.1 RFoG systems due to the possibility of a higher number of ONUs turning on and off. Effects of collateral clipping are difficult to detect, in systems that are already noise and OBI prone, but must be accounted for in multi-CM environments.

6.2.1. A word about CTM: Ingress and CP

Ingress can be a significant concern. Whereas the burst mode operation of the ONU and the RF input level threshold limit ingress, we have seen that these also limit dynamic ranges. One way to potentially resolve this would be to reduce the laser turn-on threshold as a means to increase operational dynamic range. However even with said decrease in the laser turn-on levels, there is a fair amount of low frequency noise laser clipping that could inherently limit the operational range. Readers are urged to contemplate the benefits and constraints described here in the context of their own networks in deciding upon CTM or BTM operation.

We have seen earlier that appropriate selection of Cyclic Prefix values are required for the smooth operation of D3.1. However, we have also seen that large values of CP are 'dead-time-on-the-wire' and limit efficiency.

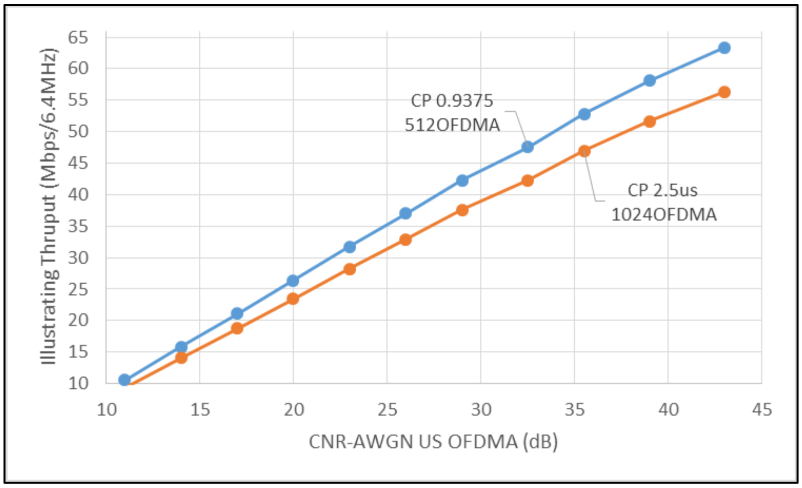


Figure 14 – Illustrating the Role of CP in enabling throughput

As can be seen in the chart above, a lower value of CP would enable a higher throughput at lower SNR or MER. Alternatively, at the same SNR, one could achieve higher throughput. In the above example, the ability to migrate from 2.5us CP to 0.9375 CP could result in a half order of improvement in modulation profile. We anticipate that HFC systems will generally need a higher CP value set to accommodate the multiple reflections present in the HFC plant. However, in an RFoG environment where these reflections are minimized, operating in CTM may allow for the use of lower CP values thus providing additional throughput if needed.

Table 3 – Trade Off Analysis of BTM and CTM Operation

Effects	ONUs in BTM	ONUs in CTM
Ingress, Noise Funneling Observed	No	Yes
Noise Floor Rise Observed	No	Yes
Laser Turn On Clipping	Yes	No
Collateral Clipping	Yes	No
CP Values Restricted: Laser Turn On Time	Yes	No
Dynamic Range Restricted: Laser Turn On Level	Yes	No

Notice that since an ONU in CTM will always transmit a mature optical signal, the performance is independent of the CP length, the laser does not suffer turn on clipping and does not exhibit the effects of collateral clipping. As mentioned once before, and indicated in the table above, these trade-offs must be contemplated in the context of ingress mitigation before a decision for the CTM or BTM mode transmission is made.

7. System Tests

7.1. Test Configuration

After understanding single CM/ONU performance, we now move to test in the multi-CM/ONU environment.

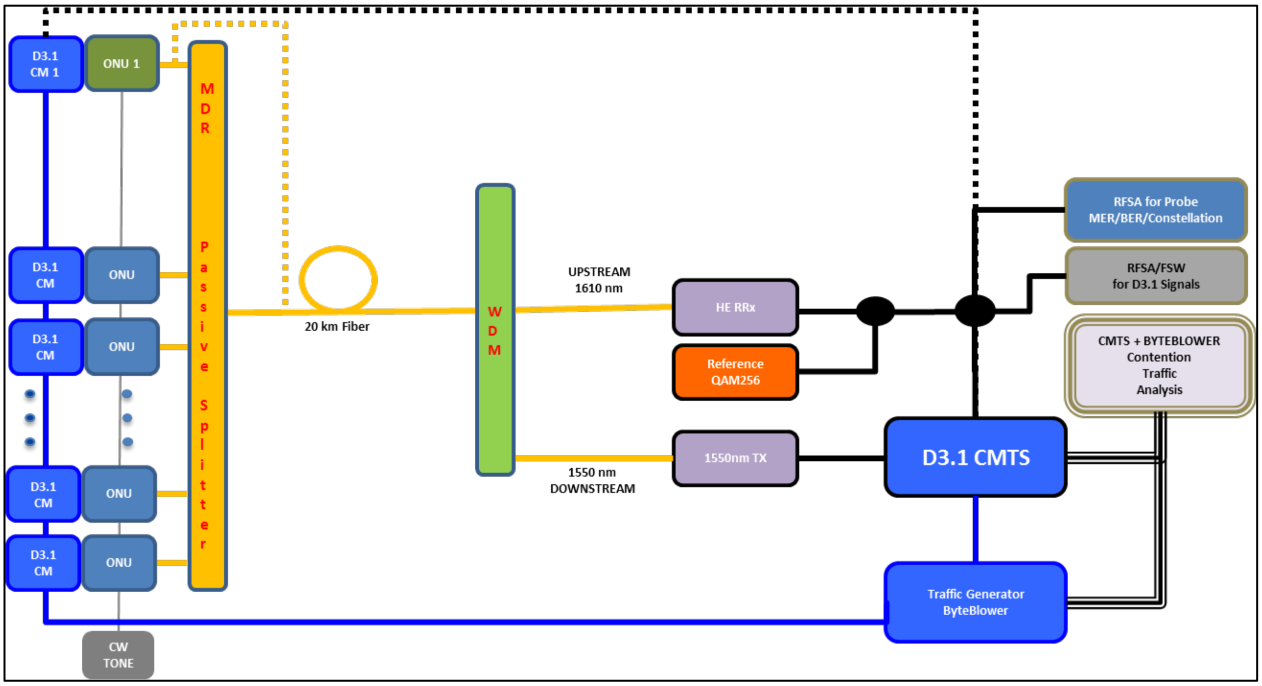


Figure 15 – 16 CM/ONUSystem Configuration

Presented above is the test configuration used for testing. We used the SB8200 D3.1 compatible CMs for our tests, with wavelength selective CP801TU for the ONUs. The ONUs selected all have a laser turn-on level of around 13dBmV. Each ONU optical output was split by a 3dB splitter that enabled an MDR and a regular optical splitter to be accommodated. The output of the MDR or the splitter traversed 20 km and passed thru a Wavelength Division Multiplexer (WDM) to reach the regular HFC upstream headend optical receiver. The output of the receiver was split with one output going to a set of displays and another entering the UCAM card of the E6 D3.1 CMTS. We also introduced a steady probe channel of SC-QAM256 at the output of the receiver so that we may evaluate RF levels and also identify egregious clipping events as they occurred during test. The DCAM card of the E6 CMTS was connected to a Directly Modulated 1550nm transmitter and connected to the WDM thus completing the two way link.

A CW tone generator was filtered and split so that each ONU would receive a steady RF signal to force it in CTM as needed. This steady tone was then combined with the D3.1 output as presented as input to the ONU. A ByteBlower traffic generator supplied traffic to the set of CMs thru a switch and also analyzed the traffic as it came back to the CMTS for frame loss and other information. The entire information was fed to an Excel based analysis engine that would then determine the maximum, minimum frame losses of each ONU to determine if the said test was successful, the criteria of success being a less than 1% maximum frame loss over any ONU under test. The CMTS itself can provide a set of diagnostic information, most importantly the RF levels out of the CMs for the initial setup and continued operation of the ONUs.

7.2. System Simulations

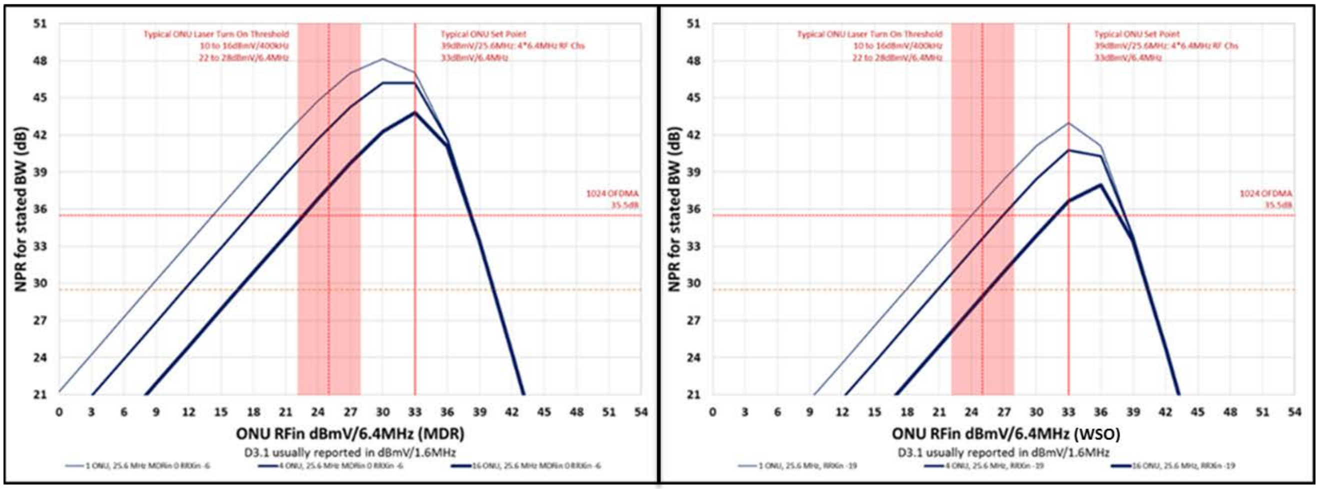


Figure 16 – Illustrating NPR estimates for the MDR and WSO cases

Presented above are NPR simulations for the MDR and WSO options. These simulations are presented for cases of 1, 4 and 16 ONUs transmitting simultaneously. Recall that the WSO option is completely passive while the MDR option requires powering at the MDR location, and that both options eliminate OBI. It is seen here that the NPR decreases with more ONUs simultaneously operating. While more ONUs reduce NPR, the statistics might suggest that the time duration of simultaneous operation may be quite limited and it might be more likely that fewer than the maximum number of ONUs are on generally in the BTM operation. Note however that we have not taken into account in this NPR simulation any of the other effects we have discussed in previous sections such as self or collateral clipping.

In all of the tests below, we have used a maximum of 16 CM/ONUs, this is because current state of the art allows for 16 WL options for the WSO option. However, we have allowed for a 32 way splitter (both for the MDR and WSO) test bed in anticipation of higher quantities of tests as technology evolves. The optical input to each MDR port is 0dBm, while the optical input to the headend receiver is -6dBm, leading to a total link estimate of 29dB. In the WSO case, the output of the splitter traverses 20 km and reaches the headend receiver at -19dBm, thus leading to a 22dB link.

There are two dashed horizontal lines, one is at 35.5dB and identified as for OFDMA1024 operation, the other dashed line 6dB below is for the OFDMA256 operation. Note that on the noise side, if the ONUs were operated in the BTM, the performance may be limited by laser turn-on levels rather than by the availability of signal to noise margin. Thus the familiar improvement in the NPR dynamic range that would accrue by reducing the NPR requirement from OFDMA1024 to OFDMA256 would not result in an improvement in operational margin for a real system because the ONU would not have turned on below the RF level. However, in the CTM case, even with a reduction in NPR as more ONUs are added, since the ONUs are always On, even with the increase in noise floor, the RF levels that were previously not available due to turn-on level limitations would now operate and provide sufficient NPR to enable wider dynamic ranges. Remember that this is a lab environment without the presence of ingress and therefore the observed dynamic range may be optimistic. To that end, additional tests would be required to obtain more rounded evaluation of the CTM and BTM systems.

For US tests in this section, we used 22MHz of encompassed spectrum from 20MHz to 42MHz. The mode used was the 2k FFT, with a CP value of 1.875us and an RP value of 0.9375us. The frame size was with 8 symbols and 175us in duration. The traffic used was UDP/IP with uniformly distributed 64-1500 Byte packets. This was chosen to simulate the type of traffic encountered with 64 Byte packets simulating TCP 'acks' for OTT content like Netflix and 1500 Byte packets simulating YouTube uploads.

7.3. Measured Results

7.3.1. RF Levels in the 16CM/ONU System

Table 4 – RF Levels into the ONUs for the MDR and WSO Systems

RF Levels dBmV/1.6MHz	MDR System ONU RF in	WSO System ONU RF in
CM-ONU 1	*27.5*	*27.0*
CM-ONU 2	*27.0*	*26.5*
CM-ONU 3	*25.3*	*24.8*
CM-ONU 4	*28.3*	*28.3*
CM-ONU 5	28.3	27.8
CM-ONU 6	27.3	27.3
CM-ONU 7	27.5	27.0
CM-ONU 8	28.0	27.8
CM-ONU 9	27.3	26.8
CM-ONU 10	26.3	25.8
CM-ONU 11	25.3	25.0
CM-ONU 12	26.8	26.3
CM-ONU 13	26.5	26.5
CM-ONU 14	29.0	28.8
CM-ONU 15	23.8	24.0
CM-ONU 16	28.3	28.3
Mean RF	27.0	26.7
Max RF	29.0	28.8
Min RF	23.8	24.0
SD	1.4	1.3
Max-Min	5.3	4.8
Mean RF 4	*27.0*	*26.6*
Max-Min 4	*3.0*	*3.5*

When the CMTS is connected and the CMs are allowed to range and register after establishing DS and US MER, the CMTS diagnostic RF levels into each ONU are tabulated as shown above. It is common to see around 6 dB of variation in RF levels across the ONUs. This is due to ONU unit to unit variations, link variations for individual ONUs to the CMTS, and the resolution of the CMTS long loop ALC itself.

This variation is further enhanced when temperature and aging effects are taken into account. These variations cause the NPR curves of individual ONUs to be offset horizontally and vertically, and sometimes to shift continually in response to environmental factors. Therefore, the effective range of operation of the system could be considerably reduced from what would appear to be the dynamic range of an individual ONU.

7.3.2. Dynamic Sliver and Dynamic Range

In this paper, we introduce the concept of a ‘Dynamic Sliver’ to take into account the above mentioned variations. The Dynamic Sliver is defined as the range of attenuation that may be applied at the CMTS input that enables all individual CMs and ONUs to operate with essentially no frame loss. With this understanding, we tested a 16 CM RFoG configuration over a 20 km link and into a D3.1 CMTS. A 16 CM option was chosen because it allows for both the WSO and MDR options to be tested.

7.3.3. Detailed Test Scenarios

As part of the analysis, we tested the following 16 conditions

1. 1024OFDMA with 10Mbps/CM leading to total of 160Mbps traffic for 16 ONUs
    a. MDR with ONUs in CTM operation
    b. MDR with ONUs in BTM operation
    c. WSO with ONUs in CTM operation
    d. WSO with ONUs in BTM operation
2. 256OFDMA with 8Mbps/CM leading to a total of 128Mbps traffic for 16 ONUs
    a. MDR with ONUs in CTM operation
    b. MDR with ONUs in BTM operation
    c. WSO with ONUs in CTM operation
    d. WSO with ONUs in BTM operation
3. 1024OFDMA with 1Mbps/CM to simulate a lightly loaded system for 16 ONUs
    a. MDR with ONUs in CTM operation
    b. MDR with ONUs in BTM operation
    c. WSO with ONUs in CTM operation
    d. WSO with ONUs in BTM operation
4. 1024OFDMA with 10Mbps/CM with 4 ONUs simulating an RFoG system with minimal penetration
    a. MDR with ONUs in CTM operation
    b. MDR with ONUs in BTM operation
    c. WSO with ONUs in CTM operation
    d. WSO with ONUs in BTM operation

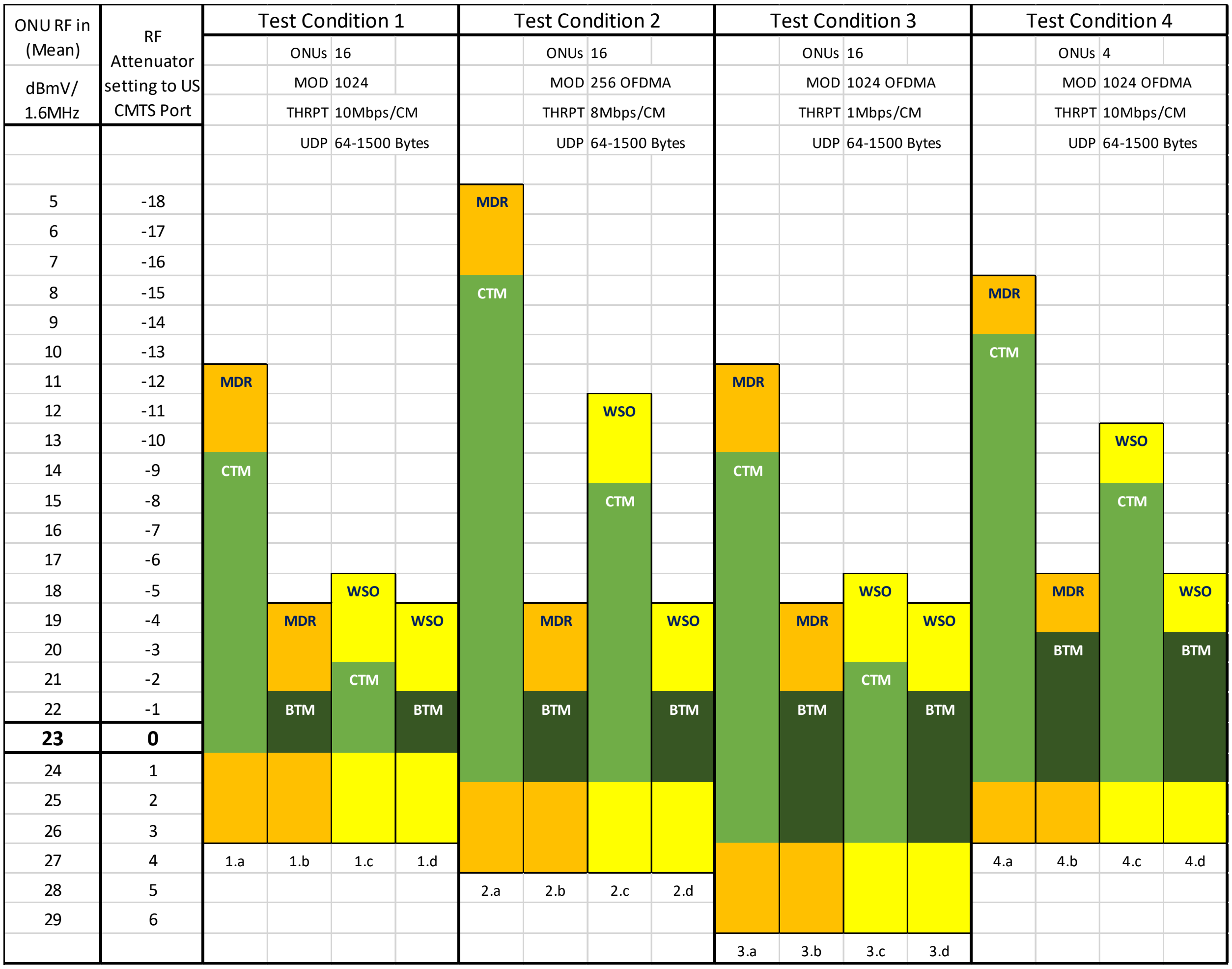


Figure 17 – Measured System Dynamic Slivers and Dynamic Ranges

7.3.4. Discussion of Test Results

Presented above is a visual summary of the collated test results. As indicated, the point of reference is the attenuator setting just prior to the CMTS. An increase in attenuation results in the RF levels to the ONUs to increase and vice-versa. With this understanding, it is noted here that the ranges represented in hues of Green refer to the 'Dynamic Sliver' that is available for the 16 ONU system, whereas the additional Yellow hues represent what would have been the dynamic range had a single ONU been used with data traffic but with all other ONUs transmitting light.

By way of example, in test condition 1.a, all 16 ONUs are operational in CTM, but only one ONU is passing traffic, and therefore that ONU would have perceived the dynamic range as wide as from the attenuator setting of -12 to +3, a full 16dB Dynamic Range. However, in a system, due to the RF level variation described earlier, all ONUs together have an error free operational range of the CMTS attenuator setting of -9 to 0dB, thus indicating only a 10dB of usable dynamic range. As fewer ONUs are operating, the available Dynamic Range increases.

Test Condition 1 indicates that the on-set of clipping for 1024OFDMA with 10Mbps loading has occurred at the attenuator setting of 3, which corresponds to an RF level of 26dBmV/1.6MHz. This translates to 32dBmV/6.4MHz, and 38dBmV/25.6 MHz, fairly close to the onset of clipping as seen by previously measuring pre FEC BER with SC-QAM256 testing for this ONU. Furthermore, from observing results from 1.b, which indicates BTM operation, it is seen that the ONUs did not turn on until the RF input level reached 19dBmV/1.6MHz of power, this is equal to 13dBmV/400kHz, which is the specified RF input level required to turn on these ONUs. It is seen here that the CMTS Dynamic Sliver is drastically reduced for BTM operation primarily due to the SCTE IPS 174 spec that specifies the laser turn-on parameters. In the 1.c test case, the wavelength selective ONUs in CTM operation have a naturally lower dynamic range and consequently a smaller Dynamic Sliver. However, the dynamic sliver in the 1.c case still exceeds the 1.d case, which is limited by the laser turn-on.

When 256OFDMA is used, it is observed that the maximum throughput is reduced slightly from 10Mbps to 8Mbps, with a slight improvement in the clipping performance of the system. While the CTM operated ONUs are able to take advantage of the lower operational NPR needed for OFDMA256 operation relative to the OFDMA1024 operation, the ONUs in the BTM operation are unable to take advantage of this due to the RF turn-on level restrictions and as a result have a rather restricted Dynamic Range and Dynamic Sliver. The effect of CTM operation can be more important as the modulation complexity decreases.

For test condition 3, it is noted that as the utilization decreases and the traffic becomes lighter, the onset of clipping is delayed by a few dB, since the ONUs are generally transmitting less RF spectrum (please see Figure 7). However, there is no improvement observed on the noise side consistent with the NPR curves and our earlier discussion. Thus the improvement in Dynamic Range and consequently of the Dynamic Sliver is all due to the delayed onset of clipping as a result of lower utilization and the more robust nature of 256OFDMA relative to 1024OFDMA.

Finally for test condition 4, we see that as we reduce the number of ONUs to simulate a very lightly penetrated system, the Dynamic Range of the CTM system becomes better due to an improvement in signal to noise with lesser number of ONUs (please see Figure 16). The Dynamic Sliver also improves, because of reduced link variations using these 4 ONUs selected for test (in this example). Note however, as expected, there is no improvement in the onset of clipping and of the laser turn-on.

It is anticipated that this set of tests may be augmented in the future with a larger set of ONUs and with expanded test conditions.

8. Conclusions

This paper represents the first step towards gaining a complete and full understanding of the implications of supporting D3.1 US capability in existing and to be deployed RFoG Systems. The discussion in this paper and the set of test results presented are very important beginnings of establishing D3.1 performance standards over RFoG.

The increased performance requirements characteristic of D3.1 along with the ability of a significantly higher number of CMs to transmit simultaneously make the matter of OBI elimination a much more urgent matter. While D3.0 and existing RFoG standards have been a good match, D3.1 and its many different aspects such as OFDMA operation, higher orders of modulation, increased flexibility in channel width, Cyclic Prefix, Roll-off Period, OFDMA FFT size, minimum performance requirements, and encompassed spectrum, call for the operator to carefully consider complex tradeoffs to optimize operating conditions for their RFoG networks.

In this paper, we described relevant D3.1 parameters and linked them to the physical characteristics of an RFoG network. We examined performance of individual ONUs under various D3.1 parameters to understand optimum operating conditions of ONUs in burst mode. We then utilized two well-known methods of OBI elimination in a complete multi-ONU RFoG environment which was subjected to the vast array of D3.1 parameters, and we observed performance in the BTM and CTM ONU modes of operation.

D3.1 enables the industry to enhance its capacity and flexibility, while RFoG presents a way for Cable operators to continually push fiber deeper into their networks. In support of this goal, it is anticipated that this set of tests may be augmented in the future with a larger set of ONUs and with expanded test conditions.

9. Acknowledgments

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10. Abbreviations

4-RFS	4 Way RF Splitter
AGC	Automatic Gain Control
ALC	Automatic Level Control
BER	Bit Error Rate
BTM	Burst Mode Operation
CLGD	DOCSIS® Cable Load Generator
CMTS	Cable Modem Termination System
CMTS	Cable Modem
CP	Cyclic Prefix
CTM	Continuous Mode Operation
CW	Carrier Wave
D2.0	DOCSIS® 2.0
D3.0	DOCSIS® 3.0
D3.1	DOCSIS® 3.1
dBm	Decibels relative to one milli-watt
dBmV	Decibels relative to one milli-volt
DS	Downstream
EIN	Equivalent Input Noise
FFT	Fast Fourier Transform
GHz	Gigahertz
HFC	Hybrid Fiber Coax
IPS	Interface Practices Subcommittee
kHz	Kilohertz
LDPC	Low Density Parity Check
Mbps	Megabits per Second
MDR	Multi-Diode Receiver

MER	Modulation Error Ratio
MOD	Modulation
MHz	Megahertz
NPR	Noise Power Ratio
ns	Nanoseconds
OA	Optical Amplifier
OBI	Optical Beat Interference
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OMI	Optical Modulation Index
ONU	Optical Network Unit
O-Scope	Oscilloscope
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
RF-SA	RF Spectrum Analyzer
RFoG	RF over Glass
RP	Roll-off Period
RRx	Return Receiver
RS-EFA	Rohde & Schwarz EFA Test Receiver
Rx	Receiver
SC-QAM	Single Carrier Quadrature Amplitude Modulation
SNR	Signal to Noise Ratio
UDP	User Datagram Protocol
US	Upstream
us	Microseconds
WDM	Wavelength Division Multiplexer
WL	Wavelength
WSO	Wavelength Selectable ONU

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