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**Radio Frequency over Glass
Fiber-to-the-Home (RFoG) Specification
Extension**

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Table of Contents

Title	Page Number
NOTICE _____	2
1. Introduction _____	6
1.1. Executive Summary _____	6
1.2. Scope _____	6
1.3. Benefits _____	6
1.4. Intended Audience _____	6
1.5. Areas for Further Investigation or to be Added in Future Revisions _____	6
2. Normative References _____	7
2.1. SCTE References _____	7
2.2. Standards from Other Organizations _____	7
2.3. Published Materials _____	7
3. Informative References _____	7
3.1. SCTE References _____	7
3.2. Standards from Other Organizations _____	8
3.3. Published Materials _____	8
4. Compliance Notation _____	8
5. Abbreviations and Definitions _____	8
5.1. Abbreviations _____	8
5.2. Definitions _____	9
6. Reference Architecture _____	11
6.1. System _____	11
6.2. RFoG Optical Network Unit (R-ONU) _____	12
6.3. Embedded R-ONU _____	13
6.4. Upstream Wavelength, λ_{up} _____	13
7. Common Optical Specifications _____	14
7.1. Optical Requirements _____	14
7.2. Optional PON Pass Thru Filter _____	15
8. System Specifications _____	16
9. Downstream R-ONU Specifications _____	17
10. Upstream R-ONU Specifications _____	18
10.1. Wavelength and Power _____	18
10.2. Turn-On and Turn-Off Characteristics _____	19

10.3.	AM System Input Level and Response	22
11.	R-ONU Power	23
12.	Physical and Environmental	24
12.1.	R-ONU Common Requirements	24
12.2.	Marking	24
12.2.1.	Operating Temperature	24
12.2.2.	Operating Relative Humidity	24
12.2.3.	Cooling and Ventilation	24
12.2.4.	Indicators	24
12.2.5.	RFI integrity	24
12.2.6.	Coaxial Ports	25
12.2.7.	Optical Connector	25
12.2.8.	Shock	25
12.2.9.	Grounding	25
12.3.	R-ONU Outdoor Requirements	25
12.3.1.	Outdoor Temperature	26
12.4.	R-ONU Indoor Requirements	26
13.	Implementation Notes	26
14.	Appendix A: System Loss Specification (Informative)	29
14.1.	Downstream Considerations	29
14.2.	Upstream Considerations	30
15.	Appendix B: Considerations Involved in an Adaptive Threshold Approach to R-ONU Laser Turn-On and Turn-Off (informative)	30
16.	Appendix C: Upstream Optical Receiver Performance	32
17.	Appendix D: Optical Beat Interference (Informative)	33

List of Figures

Title	Page Number
FIGURE 1 - OMI DEFINITION	10
FIGURE 2 - RFOG REFERENCE ARCHITECTURE	12
FIGURE 3 - RFOG ONU REFERENCE ARCHITECTURE	13
FIGURE 4 - ISOLATION BLOCK DIAGRAM	14
FIGURE 5 - OPTIONAL PON PASS THROUGH FILTER BLOCK DIAGRAM	15
FIGURE 6 - R-ONU TURN-ON AND TURN-OFF DIAGRAM	22
FIGURE 7 - PLACEMENT OF ATTENUATORS WHEN SYSTEM LOSS IS TOO LOW	28

List of Tables

Title	Page Number
TABLE 1 - OPTICAL SPECIFICATIONS APPLYING TO THE R-ONU AND SYSTEM	14
TABLE 2 - OPTICAL SPECIFICATIONS APPLYING AT THE OPTICAL HUB	15
TABLE 3 - OPTICAL SPECIFICATIONS FOR OPTIONAL PON PASS THROUGH FILTER	15
TABLE 4 - ODN SPECIFICATIONS FOR AM SYSTEMS	16
TABLE 5 - RF FREQUENCIES	17
TABLE 6 - DOWNSTREAM R-ONU SPECIFICATIONS	18
TABLE 7 - UPSTREAM R-ONU SPECIFICATIONS SPECIFIC TO WAVELENGTH AND POWER	19
TABLE 8 - R-ONU TURN-ON AND TURN-OFF SPECIFICATIONS	19
TABLE 9 - AM UPSTREAM R-ONU INPUT LEVEL AND RESPONSE SPECIFICATIONS	22
TABLE 10 - R-ONU POWERING SPECIFICATIONS	24

1. Introduction

1.1. Executive Summary

This document defines a fiber-to-the-home system optimized for compatibility with hybrid fiber-coax (HFC) plant, using the same end equipment at both the home and at the headend or hub. The RFoG system is defined to begin where the plant becomes passive, extending from that point to the home. This interface is referred to as the Optical Hub. There are many possible variations on the structure of the optical hub, depending on the needs of the system. The RFoG system is defined to terminate at the subscriber-side interface of an RFoG Optical Network Unit (R-ONU) at the home.

1.2. Scope

The specifications in this document define the performance requirements that apply to the R-ONU and are designed to allow interoperability between R-ONUs from various manufacturers.

The following system parameters and devices are NOT specified by this document:

- Downstream transmitter and optical amplifier
- Upstream receiver
- System carrier-to-noise and distortion

Additionally, the following items are not specified for the R-ONU. The user is cautioned that there *may* well be variations between manufacturers.

- Physical mounting arrangement
- Weight
- Fiber management
- Element management
- Service disconnect
- Extended reach

1.3. Benefits

The benefits of this standard are:

- Defines the performance of the R-ONU so equipment manufacturers have a guideline for the requirements and design of the R-ONU
- Allows for interoperability between equipment manufacturers
- Describes the overall RFoG System and provides guidelines for system design and performance
- Discusses Optical Beat Interference (OBI) and means of mitigating OBI

1.4. Intended Audience

The intended audiences for this standard are equipment manufacturers, service providers, design engineers, system engineers and system integrators.

1.5. Areas for Further Investigation or to be Added in Future Revisions

This document provides specifications or procedures for frequencies up to 1218 MHz. DOCSIS 3.1 specifications include operation at frequencies up to 1218 MHz, and optionally, to 1794 MHz. Specifications or procedures for frequencies above 1218 MHz should be considered in a future revision of this document.

Future revisions of this document should also include frequency splits of 204/254 MHz and review the R-ONU turn on/off RF levels and timing for full DOCSIS 3.1 and OFDM compatibility.

2. Normative References

The following documents contain provisions, which, through reference in this text, constitute provisions of this document. At the time of Subcommittee approval, the editions indicated were valid. All documents are subject to revision; and while parties to any agreement based on this document are encouraged to investigate the possibility of applying the most recent editions of the documents listed below, they are reminded that newer editions of those documents might not be compatible with the referenced version.

2.1. SCTE References

- ANSI/SCTE 01 2015, Specification for “F” Port, Female, Outdoor
- ANSI/SCTE 02 2015, Specification for “F” Port, Female, Indoor
- ANSI/SCTE 119 2011, Measurement Procedure for Noise Power Ratio

2.2. Standards from Other Organizations

- 47CFR15.109 2012 Radio Frequency Devices, Unintentional Radiators, Radiated Emission Limits
- 47CFR76.605(12) 2012, Code of Federal Regulations, Multichannel Video and Cable Television Service, Technical Standards
- 47 CFR76.609(h) 2012 Code of Federal Regulations, Multichannel Video and Cable Television Service, Measurements
- 47CFR76.614 2012 Code of Federal Regulations, Multichannel Video and Cable Television Service, Cable Television System regular monitoring
- ANSI C63.4, 2003-2009 Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz
- GR-326-CORE, Issue 4, Generic Requirements for Single-Mode Optical Connectors and Jumper Assemblies
- GR-3120-CORE, Issue 2, Generic Requirements for Hardened Fiber Optic Connectors (HFOCs) and Hardened Fiber Optic Adapters (HFOAs)
- IEEE C62.41-1991, IEEE Recommended Practice for Surge Voltages in Low-Voltage AC Power Circuits
- ITU-T G.652d, Characteristics of a Single-Mode Optical Fibre Cable
- TIA-604-3-B FOCIS-3, Fiber Optic Connector Intermateability Standard, Type SC and SC-APC

2.3. Published Materials

- No normative references are applicable.

3. Informative References

The following documents might provide valuable information to the reader but are not required when complying with this document.

3.1. SCTE References

- ANSI/SCTE 96 2013, Cable Telecommunications Testing Guidelines
- ANSI/SCTE 81 2012, Surge Withstand Test Procedure

3.2. Standards from Other Organizations

- IEEE Standard 802.3-2012, Carrier sense multiple access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications (Includes the EPON standard). See also subsequent corrigenda.
- ITU-T G.984, Gigabit-capable passive optical networks (GPON)
- ITU-T G.987, 10-Gigabit-capable passive optical network (XG-PON) systems
- ITU-T G.652, Characteristics of a single-mode optical fibre cable
- ITU-T G.657, Characteristics of a bend-loss insensitive single-mode optical fibre and cable for the access network

3.3. Published Materials

- GR-49-CORE, Issue 2, Generic Requirements for Outdoor Telephone Network Interface Devices
- GR-487-CORE, Issue 3, Generic Requirements for Electronic Equipment Cabinets
- Multimedia over Coax Alliance (MoCA), <http://www.mocalliance.org>

4. Compliance Notation

<i>Shall</i>	This word or the adjective “ <i>required</i> ” means that the item is an absolute requirement of this specification.
<i>shall not</i>	This phrase means that the item is an absolute prohibition of this specification.
<i>Forbidden</i>	This word means the value specified shall never be used.
<i>Should</i>	This word or the adjective “ <i>recommended</i> ” means that there may exist valid reasons in particular circumstances to ignore this item, but the full implications should be understood and the case carefully weighted before choosing a different course.
<i>should not</i>	This phrase means that there may exist valid reasons in particular circumstances when the listed behavior is acceptable or even useful, but the full implications should be understood and the case carefully weighed before implementing any behavior described with this label.
<i>May</i>	This word or the adjective “ <i>optional</i> ” means that this item is truly optional. One vendor may choose to include the item because a particular marketplace requires it or because it enhances the product, for example; another vendor may omit the same item.
<i>deprecated</i>	Use is permissible for legacy purposes only. Deprecated features may be removed from future versions of the standard. Implementations should avoid use of deprecated features.

5. Abbreviations and Definitions

5.1. Abbreviations

CNR	carrier-to-noise ratio
NPR	noise power ratio
ODN	optical distribution network
OMI	optical modulation index
ONU	optical network unit
ONT	optical network terminal
PON	passive optical network

RFoG	rf over glass
R-ONU	rfog optical network unit
SBS	stimulated brillouin scattering
WDM	wave division multiplexer

5.2. Definitions

noise power ratio	The ratio of the signal power density to the power density of the combined noise and intermodulation distortion in the channel. Essentially, NPR is the depth of notch. The signal power density is defined with the entire passband filled with energy. The power density of the noise and intermodulation distortion <i>shall</i> be measured by removing signal power from a range of frequencies with a notch filter while maintaining constant total signal power at the DUT input.
nominal	Specifications or values in this document that have the word “nominal” in them are approximate and designate a suggested or theoretical value. Items noted with the word “nominal” are not normative requirements.
optical modulation index (omi):	The amount that the instantaneous power of the optical carrier varies around the average power of that optical carrier. In this specification, OMI is used only for the amplitude modulation of an optical carrier by an RF signal and is generally expressed as a percent. OMI is defined to be 100% when the peak of a single sine wave that is amplitude modulated onto an optical carrier modulates the instantaneous power of that carrier from zero power to twice the average power.
optical power	Unless otherwise specified, “optical power” refers to the average power of an optical carrier. If the optical power is gated on and off, the optical power is defined as the average power during the burst, not including turn-on and turn-off transitions. Optical power measurements <i>shall</i> be averaged sufficiently to assure that any changes to content that is modulated onto the laser does not affect the measurement.
Crosstalk	The ratio of a desired signal to an undesired signal, measured at a defined point in a system. Note that it is expressed as a positive number. Normally it is applied in the electrical domain.
Isolation	The ratio of a signal in a desired direction, to the same signal in a defined undesired direction. It is expressed as a positive number, and it <i>shall</i> be clear whether it is measured in the electrical or optical domain.

Figure 1 shows the relationship between the laser optical power and the modulating current.

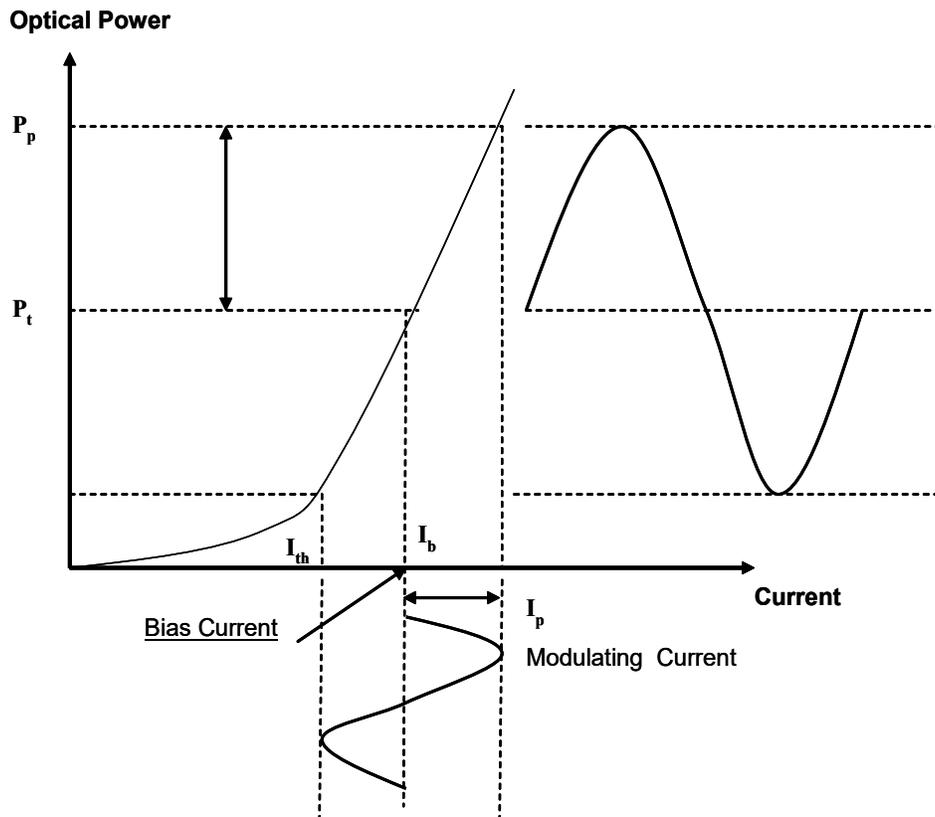


Figure 1 - OMI Definition

In the optical domain, the OMI is defined as:

$OMI = (P_p - P_t) / P_t$, where

- P_p is the peak optical output power of the laser
- P_t is the optical power at the bias current

In the electrical domain, the OMI is defined as:

$OMI = I_p / (I_b - I_{th})$, where

- I_{th} is the threshold current of the laser
- I_b is bias current
- I_p is the peak modulating current

The optical and electrical definitions are equivalent.

The definition of OMI involves the peak of the signal and is easiest to measure with a simple sinusoidal signal. The OMI of any other modulating signal, $m(t)$, is defined to be the OMI that would be produced if a single sine wave of identical average RF power to $m(t)$ were modulated onto the optical carrier. In other words, with a complex modulating signal, the exact peak is no longer referenced. The average power of the complex signal is measured and is said to have the same OMI as would be produced if that signal were replaced with a sine wave of equivalent average power.

OMI *should* always be measured with a CW carrier that has the same average power as the desired signal.

Unless specified as a per-channel value, OMI always refers to the modulation index of the entire RF signal.

Verification Example for both equations with a laser with a slope efficiency of .1W/A:

$$I_{th} = 10 \text{ mA}$$

$$I_b = 30 \text{ mA}$$

$$I_p = 1 \text{ mA}$$

$$P_p = 2.1 \text{ mW}$$

$$P_t = 2.0 \text{ mW}$$

In the optical domain: $OMI = (P_p - P_t) / P_t$

$$OMI = (2.1 - 2.0) / 2.0 = 0.05$$

In the electrical domain: $OMI = I_p / (I_b - I_{th})$

$$OMI = 1 / (30 - 10) = 0.05$$

6. Reference Architecture

Reference architectures for the RFoG system and for the R-ONU are shown in this section. The terminology R-ONU, for *RFoG Optical Network Unit*, is used to differentiate the RFoG ONU from ONUs adhering to other specifications, which typically include a digital transmitter and receiver independent of any RF components. This reference architecture comprises the minimum commonality of the system. Nothing precludes a vendor from offering additional features, but they *may* or *may not* be compatible with components from other vendors. Compatibility is limited to the issues covered in this document.

6.1. System

Figure 2 illustrates the reference architecture of the system. In the reference architecture, the optical hub, the start of the RFoG system, comprises a downstream optical transmitter operating nominally on 1550 nm, optical amplification and splitting as appropriate, and an upstream optical receiver which receives upstream optical signals on λ_{up} nm (defined below), and converts them to RF form. The wave division multiplexer used to combine and separate the two wavelengths is part of the ODN, consistent with the ODN definition in EPON and GPON.

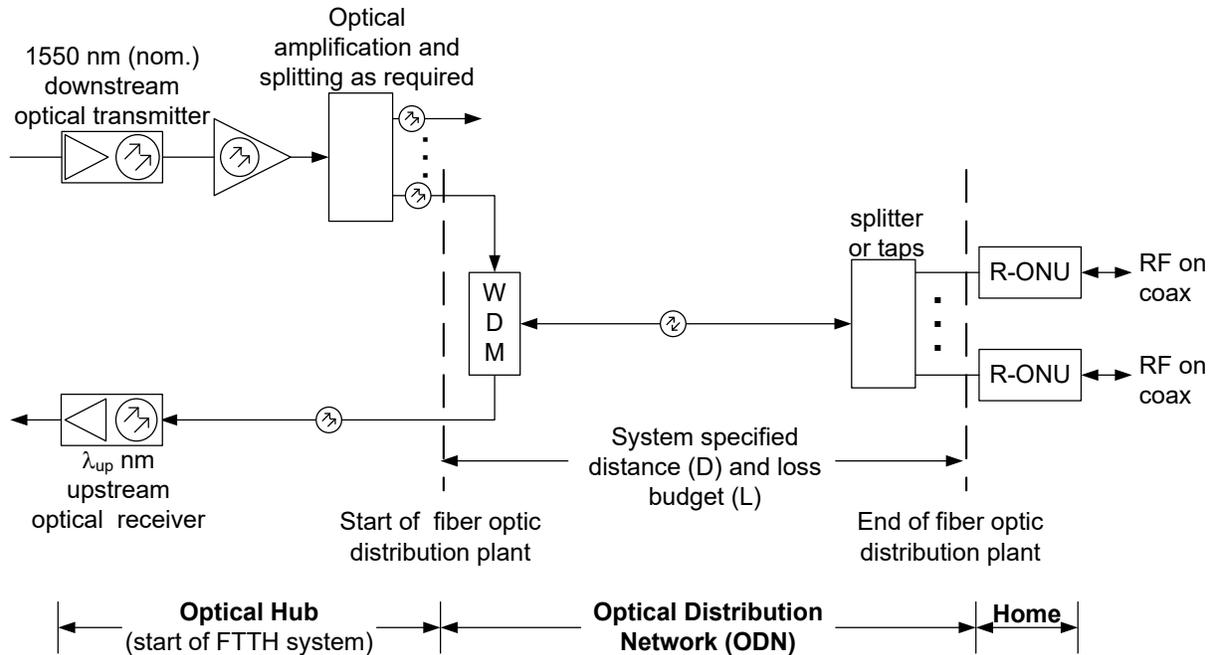


Figure 2 - RFoG Reference Architecture

The Optical Hub *may* take on many other forms according to the needs of the system. For example, it *may* comprise only optical amplification and splitting in the downstream direction, with optical combining and demodulation followed by digital conversion in the upstream direction. The form of the optical hub is not controlled by this document. Specifications contained herein apply only between the start of the optical distribution network (ODN) and the RF coax output from the R-ONU. The system designer is responsible for making sure that the effects of any signal degradation at the Optical Hub or upstream of it, are properly accounted in the network design. Upstream system performance will vary by choice of Upstream Optical Receiver hardware. Receiver noise performance and technology choice determines interoperability. The ODN is defined to start at the input to the WDM at the optical hub and to end at the pigtail on the R-ONU at the home.

The ODN is shown with a single point splitter. The ODN *may* also be implemented as a series of optical taps or as a multi-layer splitter, such as a 1:4 split followed by a set of 1:8 splitters at a different location. So long as the maximum distance, loss budget, and split ratio are respected, the architecture of the splitting is at the discretion of the operator.

6.2. RFoG Optical Network Unit (R-ONU)

Figure 3 illustrates the ONU reference architecture. The ONU comprises a wave division multiplexer (WDM) which separates the downstream optical signal at 1550 nm nominal and the upstream optical signal at λ_{up} nm. The WDM optionally passes optical signals to and from the PON port for connection to an ONT. The downstream receiver recovers RF downstream signals from the 1550 nm (nominal) downstream optical carrier and supplies them to the output via a diplexer.

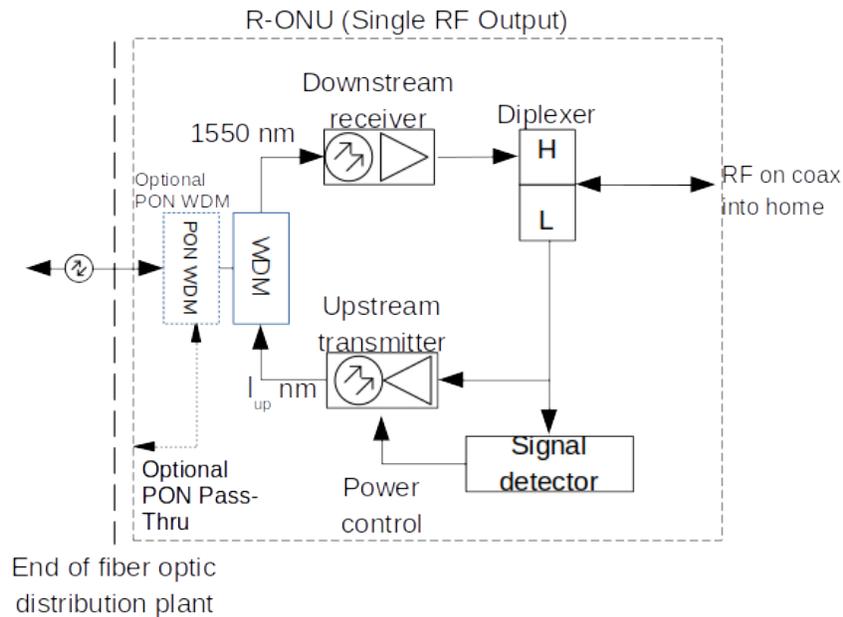


Figure 3 - RFoG ONU Reference Architecture

The low port of the diplexer supplies upstream signals to an upstream transmitter whose output is at λ_{up} nm. It also supplies signals to a signal detector, whose job it is to turn on the upstream transmitter when RF signals in the upstream band are detected at a level exceeding a specified minimum threshold.

6.3. Embedded R-ONU

An Embedded R-ONU is an R-ONU that is an integral part of a larger product supplied by the cable operator, and which complies with the intent of this specification so far as practicable given the function of the overall product. In some cases, the completed product will not literally meet one or more specifications in this document as a necessary result of the way the combined product works. However, so long as it can be shown that the completed product will interoperate with other RFoG products and that the completed product meets the intent of this specification, the manufacturer is not precluded from advertising it as conforming to this specification.

6.4. Upstream Wavelength, λ_{up}

λ_{up} . One permitted wavelength is 1310 nm nominal, and the other is 1610 nm nominal. Use of 1610 nm permits an optional overlay of an RFoG system with either an IEEE 802.3-2012 (EPON) system or an ITU G.984 / ITU G.987 (GPON) system, both of which use 1310 ± 50 nm or lower wavelengths for upstream data communications. Both upstream wavelengths will work with the same physical network. Note that if the 1310 nm upstream wavelength is used for RFoG, then neither EPON nor GPON will coexist in the same physical passive optical network.

For compatibility with 10G-EPON or XG-PON systems, the 1610 nm upstream option *should* be used,

7. Common Optical Specifications

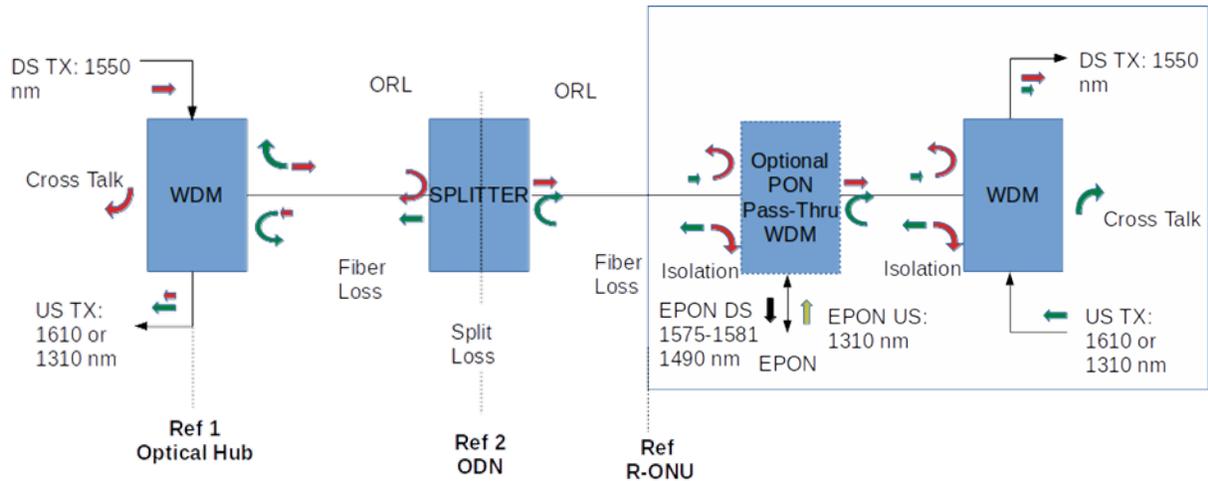


Figure 4 - Isolation Block Diagram

7.1. Optical Requirements

This section contains worst-case optical specifications. Unless otherwise noted, specifications apply to the optical domain, not the electrical domain.

Table 1 - Optical Specifications Applying to the R-ONU and System

Specification	Supports	Value
Optical return loss for each component in the system	Should	40 dB
Cumulative optical return loss	Shall	If any components in the RFoG system have an optical return loss of less than 40 dB, then the system operator or system integrator <i>shall</i> verify that the cumulative round-trip optical return loss is at least 32 dB.
Isolation, upstream transmitter to downstream receiver	Should	27 dB (see note 1-1)
1575-1581 nm wavelength rejection	Shall	25 dB (see note 1-2)

Note 1-1: (informative): There could be up to 0.3 dB loss of CNR when a +6 dBm transmitter is used.

Note 1-2: (informative): This requirement is for the 1610 nm wavelength R-ONU and allows for operation with 10Gb/s PON systems.

Note that these are worst-case specifications; better specifications are acceptable.

Table 2 - Optical Specifications Applying at the Optical Hub

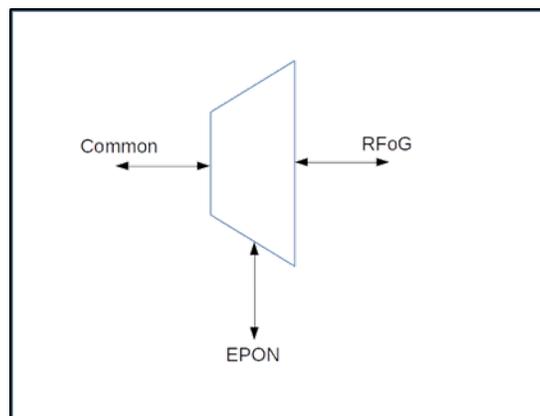
Specification	Supports	Value
Isolation, WDM common port to upstream receiver, measured at 1540 – 1565 nm. See note 2-1 below	Should	24 dB
Isolation, downstream transmitter into upstream receiver	Should	45 dB min. (See note 2-2)

Note 2-1: (informative): The isolation *may* be achieved in a wave division multiplexer(s) in the upstream signal path, in combination with filtering in the upstream receiver. The total isolation *should* meet this specification, but this specification doesn't control where the isolation is achieved.

Note 2-2: (informative): The isolation shown is sufficient to produce no more than 0.1 dB degradation of CNR margin for a 64QAM upstream signal. If 256-QAM is used in the upstream direction, then 47 dB of isolation could produce up to 0.5 dB degradation in CNR margin.

7.2. Optional PON Pass Thru Filter

A PON pass thru filter is required for operation with EPON or GPON systems. The PON pass thru filter can be an external filter, or incorporated into the R-ONU. The topology and requirements for the PON pass thru filter are shown in Figure 5 and Table 3.

**Figure 5 - Optional PON Pass Through Filter Block Diagram****Table 3 - Optical Specifications for Optional PON Pass Through Filter**

Specification	Supports	Value
1. RFoG Passband (Common-RFoG)	Shall	US: 1600-1620 nm DS: 1540-1565 nm
2. EPON Passband (Common-EPON)	Shall	US: 1310 (+/-50) nm DS: 1575-1580 nm and 1490 (+/- 10) nm
3. RFoG Maximum Signal Insertion Loss (Common-RFoG)	Shall	<= 1.0 dB

Specification	Supports	Value
4. EPON Maximum Signal Insertion Loss (Common-EPON)	Shall	≤ 0.8 dB
5. RFoG Minimum Isolation (Reflection port isolation (RFoG leakage into EPON Port))	Shall	13 dB
6. EPON Minimum Isolation (Passthrough port isolation, 1310, 1270, 1577nm leakage into RFoG port)	Shall	25 dB
7. RFoG Ripple	Should	≤ 0.5 dB
8. Minimum Directivity (EPON-RFG and RFoG-EPON Ports)	Shall	≥ 50 dB
9. Minimum Return Loss (All Ports)	Shall	≥ 40 dB
10. Maximum Polarization Dependent Loss (All Ports)	Shall	≤ 0.2 dB
11. Insertion Loss Thermal Stability	Should	≤ 0.006 dB/Degrees Celsius

8. System Specifications

The Optical Distribution Network *shall* meet the requirements in Table 4.

Table 4 - ODN Specifications for AM Systems

Specification	Value
Operating distance, optical hub to R-ONU (D) for 1:32 split ratio. (See notes 4-1 and 4-2)	0 - 20 km
Highest loss budget under which the system <i>shall</i> operate (L)	25 dB (See note 4-3)
Loss budget differential (The delta between the highest loss budget and the lowest loss budget for system operation)	5 dB lower than the highest loss.
Lowest loss budget under which the system <i>shall</i> operate	If the system design has loss that is too low (e.g., if the split ratio is low) then the system design <i>shall</i> make up the loss. See Section 13, "Implementation Notes", for a discussion of the minimum loss budget.

Specification	Value
Assumed optical fiber type	ITU G.652 B or later, or ITU G.657

Note 4-1: Longer distances *may* be possible, but the designer *should* keep the distance limits and interactions of EPON and GPON in mind if migration to either standard is contemplated.

Note 4-2: Any split ratio *may* be used so long as the total loss budget is respected. Depending on the splitting architecture, Stimulated Brillouin Scattering (SBS) *may* limit operation to a lower split ratio (See Section 14.1, “Downstream Considerations”, for more information). Typical PON implementations normally use split ratios of 32 and, rarely, 64, limited by available optics, so using a higher split ratio *may* make use of those standards infeasible unless an intermediate interface is used.

Note 4-3: The system *shall* operate with losses up to and including the values specified in Table 4. Design and operation with loss budgets greater than specified is optional. See Section 14, “Appendix A: System Loss Specification”, for a discussion.

The crossover between upstream and downstream RF frequencies *shall* meet the requirements of one of the options in Table 5. The frequencies given in Table 5 are the values that the R-ONU *shall* be specified to support. The inequalities are given to allow for R-ONU implementations that are manufacturer-specified to include a maximum upstream and/or minimum downstream frequency that provides a wider passband than the listed value.

Table 5 - RF Frequencies

Option	Maximum Upstream Frequency F_{US-Max}	Minimum Downstream Frequency F_{DS-Min}	Maximum Downstream Frequency F_{DS-Max}
Option 42/54/1002	≥ 42 MHz	≤ 54 MHz	≥ 1002 MHz
Option 65/85/1002	≥ 65 MHz	≤ 85 MHz	≥ 1002 MHz
Option 85/102/1002	≥ 85 MHz	≤ 102 MHz	≥ 1002 MHz
Option 42/54/1218 (Note 5-2)	≥ 42 MHz	≤ 54 MHz	≥ 1218 MHz
Option 65/85/1218	≥ 65 MHz	≤ 85 MHz	≥ 1218 MHz
Option 85/102/1218	≥ 85 MHz	≤ 102 MHz	≥ 1218 MHz

Note 5-1: Other crossover frequency plans *may* be used by mutual agreement between the equipment supplier and the operator.

Note 5-2: For options 42/54/1002 and 42/54/1218, the maximum upstream frequency may be extended to 45 MHz.

9. Downstream R-ONU Specifications

R-ONUs are used in Single Dwelling Unit (SDU) and Multiple Dwelling Unit (MDU) applications. In MDU applications there is typically more loss at the output of the R-ONU and the R-ONU needs to accommodate these higher losses to maintain the same system performance. The R-ONU *shall* meet all the requirements in Table 6 for SDU and MDU applications.

Table 6 - Downstream R-ONU Specifications

Specification	Value (SDU)	Value (MDU)
Optical carrier wavelength	1540-1565 nm	1540-1565 nm
Received optical power over which RF output level, tilt, and frequency response specifications <i>shall</i> be met	-6 to 0 dBm	-6 to 0 dBm
Received optical power over which there <i>shall</i> be no optical power alarms and the RF output <i>shall</i> be present	-13 to +1 dBm	-13 to +1 dBm
Output impedance	75 ohms	75 ohms
RF output reference level as measured with a CW test signal at 860 MHz, OMI = 3.5% (See note 6-1)	+17 dBmV \pm 3 dB	+38 dBmV \pm 3 dB
Output Tilt (54 to 1002 MHz)	+5 \pm 2 dB	+7 \pm 2 dB
Frequency response (Option 1002)	\pm 2 dB deviation from tilt, F _{DS-Min} to 860 MHz +2/-4 dB deviation from tilt, 860 MHz-1002 MHz	\pm 2 dB deviation from tilt, F _{DS-Min} to 860 MHz +2/-4 dB deviation from tilt, 860 MHz-1002 MHz
Frequency response (Option 1218)	\pm 2 dB deviation from tilt, F _{DS-Min} to 860 MHz +2/-5 dB deviation from tilt, 860 MHz-1218 MHz	\pm 2 dB deviation from tilt, F _{DS-Min} to 860 MHz +2/-5 dB deviation from tilt, 860 MHz-1218 MHz

Note 6-1: At optical powers below -6 dBm, AGC *may* not be effective. Thus, the RF output level is allowed to decrease 2 dB for every 1 dB decrease in optical power below -6 dBm. At -13 dBm optical power, the RF output level *may* be as low as +3 \pm 3 dBmV for an OMI of 3.5%. This specification does not prohibit implementations that maintain the +17 dBmV RF output reference level at optical powers below -6 dBm.

10. Upstream R-ONU Specifications

10.1. Wavelength and Power

Two wavelength options are provided in the upstream direction. The upstream wavelength *may* be 1310 nm for maximum cost effectiveness, or 1610 nm in order to allow the same PON to be used for RFoG and GPON or EPON applications. A WDM and upstream receiver corresponding to the upstream wavelength *shall* be used at the Optical Hub.

The R-ONU *shall* meet one of the columns of requirements in Table 7.

Table 7 - Upstream R-ONU Specifications Specific to Wavelength and Power

	$\lambda_{up}=1310$ nm	$\lambda_{up}=1610$ nm	
	$P_{up} =$ <u>3 dBm</u>	$P_{up} =$ <u>3 dBm</u>	$P_{up} =$ <u>6 dBm</u>
Application	Secondary wavelength, only for systems not needing compatibility with EPON or GPON	Primary wavelength, compatible with EPON or GPON or 10Gb/s PON	
Optical output power, standard temperature range	+3.0 dBm \pm 1.0 dB	+3.0 dBm \pm 1.0 dB	+6.0 dBm \pm 1.0 dB
Optical output power, outdoor temperature range	+3.0 dBm \pm 1.5 dB	+3.0 dBm \pm 1.5 dB	+6.0 dBm \pm 1.5 dB
Maximum “off state” optical power	-30 dBm	-30 dBm	
Wavelength tolerance (includes effects of temperature) (See note 8-1)	\pm 50 nm	\pm 10 nm	
Coexistence with EPON or GPON	None	All specifications <i>shall</i> be met when the same fiber is carrying either EPON or GPON signaling, including 10 Gb/s systems	

Note 8-1: The wavelength *shall* be within the wavelength tolerance specified when the R-ONU is operated over one of the appropriate operating temperature ranges specified in Section 12.

10.2. Turn-On and Turn-Off Characteristics

The R-ONU *shall* meet the turn-on and turn-off characteristics specified in Table 8. The characteristics are illustrated in Figure 6. The turn-on and turn-off characteristics *shall* be tested with a single continuous wave (CW) RF carrier.

Table 8 - R-ONU Turn-On and Turn-Off Specifications

Interval	Specification	Value (SDU)	Value (MDU)
N/A	Power at which R-ONU <i>shall not</i> turn on	$\leq +7$ dBmV	$\leq +2$ dBmV
N/A	Power at which R-ONU <i>shall</i> turn on (See note 9-1)	$\geq +16$ dBmV	≥ 8 dBmV
N/A	Power at which R-ONU <i>should</i> turn on (See note 9-1)	$\geq +13$ dBmV	≥ 5 dBmV
N/A	Power of “on” level at which R-ONU laser <i>shall not</i> turn on with pulsed on/off RF input (50% duty cycle, 100 ns period)	$\leq +10$ dBmV	≤ 5 dBmV

Interval	Specification	Value (SDU)	Value (MDU)
N/A	Power of “on” level at which the R-ONU laser <i>should</i> turn on within time T1 (defined below and in Figure 6), when tested using a pulsed on/off RF input (50% duty cycle, 100 ns period)	$\geq +16$ dBmV	≥ 8 dBmV
N/A	Power at which R-ONU <i>shall not</i> turn off (See note 9-2)	≥ 5 dBmV	≥ -2 dBmV
N/A	Power at which R-ONU <i>should not</i> turn off (See note 9-2)	≥ 0 dBmV	≥ -7 dBmV
N/A	Power at which R-ONU <i>shall</i> turn off	≤ -8 dBmV	≤ -15 dBmV
T1: Don’t turn on too late	Maximum time from application of RF to 90% optical power (read to late-side mask)	1.3 μ s	1.3 μ s
T2: Don’t turn on too fast	Minimum 10-90% optical power rise time (read from late-side mask 10% to early-side mask 90%)	100 ns	100 ns
T3: Don’t turn on too slow	Maximum optical power rise time (read from early-side mask 10% to late-side mask 90%). If there is overshoot on the optical power, use the value after the overshoot has dissipated.	1.0 μ s	1.0 μ s
Don’t turn on by mistake	Power at which a <u>single isolated pulse</u> ≤ 90 nanoseconds long <i>should not</i> turn on the laser	$\leq +65$ dBmV	$\leq +54$ dBmV
T11: Don’t turn off too late	Maximum time from removal of RF (defined as RF dropping to -8 dBmV) to the time the optical carrier falls to 10% of its steady-state amplitude (read to late-side mask)	1.6 μ s	1.6 μ s
T12: Don’t turn off too fast	Minimum 90-10% optical power fall time	100 ns	100 ns
T13: Don’t turn off too slow	Maximum 90-10% optical power fall time	1.0 μ s	1.0 μ s

Interval	Specification	Value (SDU)	Value (MDU)
T14: Don't turn off by mistake	<p>When turn-off threshold is > -2 dBmV, the R-ONU shall not drop laser power below 90% for a sudden drop in RF input power to ≤ -8 dBmV that lasts ≤ 600 ns. For the same turn-off threshold, the R-ONU <i>may</i> allow the laser power to remain above 90% for a sudden drop in RF input power to ≤ -8 dBmV that lasts > 600 ns.</p> <p>When turn-off threshold is ≤ -2 dBmV, the R-ONU shall not drop laser power below 90% for a sudden drop in RF input power to ≤ -8 dBmV that lasts ≤ 400 ns. For the same turn-off threshold, the R-ONU <i>may</i> allow the laser power to remain above 90% for a sudden drop in RF input power to ≤ -8 dBmV that lasts > 400 ns. (See note 7-3)</p>	N/A	N/A
<i>Should</i> Maintain Turn On with Ramp Up Input	Upon reaching 90% optical power during turn on, subsequent time during which optical power <i>should not</i> drop below 90% of its steady-state amplitude	$\leq 12 \mu\text{s}$	$\leq 12 \mu\text{s}$
<i>Should</i> Reach and Maintain Steady-State Stability Upon Turn On	Maximum time after application of a valid turn on RF input in which optical modulator <i>should</i> achieve and maintain RF signal level stability within ± 0.1 dB, observed at the output of a reference optical-to-electrical converter (also reach and maintain NPR required performance)	1.3 μs	1.3 μs

Note 9-1: To allow flexibility in the laser activation implementation and provide greater noise immunity in the RFoG system, the “**shall** turn on” level *may* be increased by up to 3 dB relative to the “*should* turn on” level. This will delay the absolute start of laser activation by less than 1/3 of a symbol period.

Note 9-2: To allow flexibility in the laser de-activation implementation and provide greater noise immunity in the RFoG system, the “**shall** not turn off” level *may* be increased by up to 3 dB relative to the “*should not* turn off” level.

Note 9-3: For a sudden drop in RF input power to -8 dBmV, a valid input signal will remain below the higher threshold (+1 dBmV) for more time than below the lower threshold (-2 dBmV).

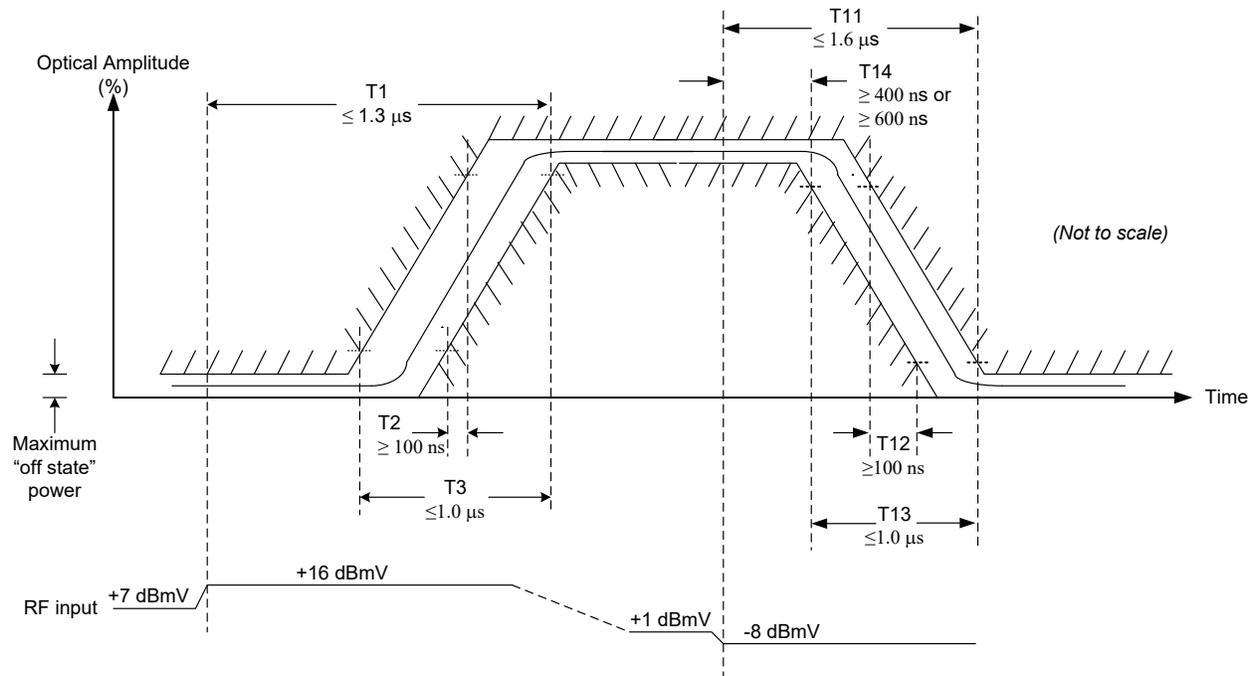


Figure 6 - R-ONU Turn-On and Turn-Off Diagram

Note that the turn-on and turn-off characteristics shown in Figure 6 apply for transitions between any RF power within the “Off” power range and any RF power within the normal operating range of the R-ONU.

10.3. AM System Input Level and Response

The table below details the RF performance characteristics of the AM R-ONU.

Table 9 - AM Upstream R-ONU Input Level and Response Specifications

Specification	Value (SDU)	Value (MDU)
Nominal channel capacity (See note 10-1)	Four 6.4 MHz wide channels	Four 6.4 MHz wide channels
Nominal RF input level per channel (upstream RF into R-ONU) (See note 10-1)	+33 dBmV per carrier	+22 dBmV per carrier
Frequency response	± 2 dB, 5 to F_{US-Max} MHz	± 2 dB, 5 to F_{US-Max} MHz
OMI at total power, over full rated temperature range (See note 10-2)	35% ± 1 dB @ carrier amplitude of +39 dBmV	35% ± 1 dB @ carrier amplitude of +28 dBmV
Noise Power Ratio (NPR) (42/54/1002), 42/54/1218) (See note 10-3, 10-4)	≥ 38 dB over a ≥ 10 dB dynamic range centered appropriately for the nominal input level	≥ 38 dB over a ≥ 10 dB dynamic range centered appropriately for the nominal input level

Specification	Value (SDU)	Value (MDU)
Noise Power Ratio (NPR) (65/85/1002), 65/85/1218) (See note 10-3,10-5)	≥ 36 dB over a ≥ 10 dB dynamic range centered appropriately for the nominal input level	≥ 36 dB over a ≥ 10 dB dynamic range centered appropriately for the nominal input level
Noise Power Ratio (NPR) (85/102/1002), 85/102/1218) (See note 10-3,10-6)	≥ 35 dB over a ≥ 10 dB dynamic range centered appropriately for the nominal input level	≥ 35 dB over a ≥ 10 dB dynamic range centered appropriately for the nominal input level
Maximum power level (total power, continuous, no damage)	+60 dBmV	+60 dBmV

Note 10-1: The nominal channel capacity is used to derive the nominal RF input level per channel specification and to estimate the performance of an upstream channel in a typical deployment. These values are suggested and are not mandatory. R-ONUs *may* be used with as few as one upstream channel, and in that case, the nominal RF level *may* be set higher, to accommodate (for example) more optical upstream combining. R-ONUs *should* function with higher channel loads, but performance *may* be reduced. See Section 13, “Implementation Notes”, for guidance on channel characteristics and additional considerations.

Note 10-2: The OMI is measured with a CW carrier inserted at the specified carrier amplitude. The specified OMI and carrier amplitude are the recommended design level for total composite RF power at the R-ONU coaxial port when fully loaded. The If four channel operation is assumed, the level of each channel at the R-ONU coaxial port will be 6 dB lower. See Section 13, “Implementation Notes”, for guidance on channel characteristics.

This OMI is specific to Amplitude Modulated solutions and *may* be different for alternative technology choices such as Frequency Modulation.

Note 10-3: R-ONU upstream NPR cannot easily be measured in a link with high optical loss. To measure NPR, it is necessary to use a link with relatively low optical loss. NPR *shall* be tested with 20 km of fiber and additional attenuation resulting in -10 dBm optical power into the test receiver. The test receiver *shall* have an EINC over the return band being measured of no greater than $2.5 \text{ pA}\sqrt{\text{Hz}}$ and two tone IM2 and IM3 products better than -60 dBc @ 20% OMI per tone and 0 dBm total optical received power. The test setup *should* have the optical attenuation placed between the transmitter and the fiber.

Note 10-4: The noise loading for the NPR test *shall* be 37 MHz of broadband noise from 5 MHz to 42 MHz with a nominally centered notch.

Note 10-5: The noise loading for the NPR test *shall* be 60 MHz of broadband noise from 5 MHz to 65 MHz with a nominally centered notch.

Note 10-6: The noise loading for the NPR test *shall* be 80 MHz of broadband noise from 5 MHz to 85 MHz with a nominally centered notch.

11. R-ONU Power

The R-ONU *shall* be powered from 12 Vdc (nominal) and *shall* meet the requirements in Table 10. The R-ONU *shall* operate correctly when presented with the maximum specified input voltage ripple. Standby battery power is not required, but *may* be provided in an external power supply if desired.

Table 10 - R-ONU Powering Specifications

Specification	Value
Operational Input Voltage Range	+10.5 to 18.0 volts dc (12 V nominal)
Input Current	400 mA max (SDU Version) 600 mA max (MDU Version)
Input Voltage Ripple, 50-120 Hz	500 mV _{RMS}
Input Voltage Ripple, 121 Hz - 1 MHz	500 mV _{p-p}
Power Connection Method	F connector combined with RF. Center conductor to be positive with respect to ground. Note 11-1.

Note 11-1: Additional power connection methods maybe supplied, but this one *shall* be supplied. All other specifications *shall* be met regardless of the connection method.

12. Physical and Environmental

12.1. R-ONU Common Requirements

The requirements in this section apply to all R-ONUs.

12.2. Marking

R-ONUs that do not meet the R-ONU specification in Section 12.3, “R-ONU Outdoor Requirements”, *shall* be labeled with the statement “Standard Temperature Only” and the products *shall* be prominently and permanently labeled “For 0 to +50° C use only”.

12.2.1. Operating Temperature

The standard temperature range R-ONU *shall* meet all specifications when operated in an ambient temperature ranging from 0 to +50 degrees Celsius (+32 to +122 degrees Fahrenheit). The extended temperature range R-ONU *shall* meet all specifications when operated in an ambient temperature ranging from -40 to +60 degrees Celsius (-40 to +140 degrees Fahrenheit).

12.2.2. Operating Relative Humidity

The R-ONU *shall* meet all specifications when operated in relative humidity from 5 to 95%, non-condensing.

12.2.3. Cooling and Ventilation

If a heat sink is used, it *should not* be positioned so as to interfere with mounting the unit.

12.2.4. Indicators

The R-ONU *shall* provide visual indication of the presence of DC power and of downstream optical power.

The visual indication of downstream optical power *shall* be ON at levels above -13 dBm.

12.2.5. RFI integrity

The shielding integrity of an R-ONU when measured in accordance with 47CFR76.609(h) *shall* be such that measured values comply with limits set forth in 47CFR76.605(12) and 47CFR76.614. Unintentional

emissions greater than 400 MHz when measured in accordance with ANSI C63.4, 2003-2009 *shall* comply with limits appearing in 47CFR15.109. The test *shall* be made with the exciting signal modulating the downstream optical transmitter to +3.5% OMI and the downstream optical signal level at the R-ONU *shall* be 0 dBm. The RF output *shall* be terminated with a 75 ohm terminator.

12.2.6. Coaxial Ports

All coaxial ports on the R-ONU *shall* be type F and *shall* conform to the requirements of ANSI/SCTE 02 2006 (Specification for “F” Port, Female, Indoor). Optionally, for improved moisture rejection, the coaxial ports of the R-ONU *should* be designed to meet the requirements of ANSI/SCTE 01 2006 (Specification for “F” Port, Female, Outdoor).

12.2.7. Optical Connector

Preferred R-ONU optical interfaces *shall* be based on the SC/APC single-mode connector using either (a) or (b), as follows:

a) Standard SC/APC connectors, as defined by

- i) Intermateability: TIA/EIA FOCIS 3 (TIA/EIA-604-3B)
- ii) Geometry, Loss, Reflectance: GR-326-CORE, Issue 4, Feb 2010

b) Hardened fiber optic connectors (HFOCs) based on and which can mate to the SC/APC connector, as defined by appropriate sections of GR-3120, Issue 2, April 2010.

Both standard SC/APC connectors and hardened (weather-resistant) connectors are preferred optical interfaces. The choice of connector interface (non-hardened or hardened) will depend on the intended deployment scenario for the R-ONU. Standard connectors generally require some measure of environmental protection, whereas hardened connectors generally do not. Intermateability between standard SC/APC connectors and hardened connectors permits standard SC/APC connectors to be used inside the R-ONU while, with the proper bulkhead adapters, standard or hardened connectors *may* be connected from outside.

Other interfaces *may* be used by mutual agreement between the equipment supplier and the operator so long as the optical return losses specified herein are met. If a manufacturer wishes to use an optical connector other than an SC/APC, this *shall* be prominently stated in sales literature and/or on a Purchase Order. Lacking such a statement, SC/APC connectors are to be assumed.

12.2.8. Shock

The R-ONU *shall* meet all specifications after being subjected to three drops from a height of three feet onto concrete, once in each axis. Connector damage is allowed, but the R-ONU *shall* meet all specifications after damage is repaired.

12.2.9. Grounding

In order to meet possible interpretations of the National Electrical Code, R-ONUs shall provide for attachment of an AWG #8 ground wire.

12.3. R-ONU Outdoor Requirements

R-ONUs *may* be deployed inside weather-resistant housings for the purpose of environmental/physical protection as well as to store cable slack, prevent tampering, facilitate access for network testing and the like. Housings used for this purpose *should* follow these guidelines:

Minimum Features:

- The housing *should* be designed to prevent the ingress of water, wind-driven rain, sand and dust, according to Telcordia GR-487 CORE section 3.31.1 “Wind-driven Rain” and Telcordia GR-49 section 5.9, “Sand and Dust”.
- The standard entry/exit port size *should* accommodate optical drop cables as well as electrical power, optical, and coaxial cables run to/from the customer premises.
- The housing *should* allow for a minimum bend radius of 10 times the fiber cable outside diameter, or as recommended by the cable manufacturer.
- The housing *should* provide a suitable means (such as a backplane or substrate) for mounting and securing the R-ONU.

Additional Features:

- The housing *may* permit storage of drop cable slack.
- The housing *may* support pigtail splicing and/or optical adapters necessary to interconnect the drop cable and the R-ONU or inside optical cables to the drop or R-ONU.
- The housing *may* allow for coaxial splitters, power inserters and similar devices needed to complete the installation.

12.3.1. Outdoor Temperature

Unless the climate is moderate, a R-ONU *shall* meet all specifications when operated in an ambient temperature ranging from -40 to +60 degrees Celsius (-40 to +140 degrees Fahrenheit).

12.4. R-ONU Indoor Requirements

An R-ONU intended to be used indoors *should* be mounted in a housing that is attractive for use in residential environments. Indoor units *shall* meet all specifications from 0 to 50 degrees Celsius.

13. Implementation Notes

1. It is possible that, on the same PON or a group of PONs combined to one upstream optical receiver, a cable modem in one home will transmit at the same time a set top transmits in another home. If this happens, two optical transmitters will turn on at the same time. If they happen to be close enough in wavelength, it is possible that the two will generate Optical Beat Interference (OBI) at the upstream receiver, and neither transmission may get through. See Appendix D for a discussion on OBI and OBI mitigation techniques.
2. Cable modems preferably *should* be restricted by the CMTS such that only one cable modem in a headend optical receiver group is transmitting at any given time. If several ODNs are combined to a single optical receiver, then the restriction *should* apply to all cable modems in the combined group. This restriction *may* be accomplished by operating all modems from a common scheduler in the CMTS. A single cable modem *may* transmit on multiple bonded channels if desired.
3. For RFoG operation with burst profiles using 64-QAM modulation, preamble lengths of 32 symbols or more *may* be required. For lower orders of modulation, shorter preambles *may* work acceptably, but the CMTS vendor *should* be consulted. If CMTS default values of preamble length are to be changed, the CMTS vendor *should* be consulted.
4. DOCSIS upstream operation *should* use an upstream symbol rate of 1280 ksps or greater. Standard practice of operating SCTE 55-1 upstream uses the symbol rate of 128 ksps, and standard practice of operating SCTE 55-2 upstream uses the symbol rate of 772 ksps even though SCTE 55-1 and 55-2 allow for other options. Therefore, with an RFoG system, SCTE 55-1 systems *should* operate with an upstream symbol rate of 128 ksps, and SCTE 55-2 systems *should* operate at 772 ksps.

To assure proper operation of the R-ONU, the operating level of the SCTE 55-1 or SCTE 55-2 signal at the R-ONU *should* be equal to the level of a DOCSIS channel.

5. If an upstream wavelength of 1310 nm is chosen, then it will not be possible to share the physical passive optical network with either an EPON or GPON standard network, as EPON and GPON both use 1310 nm for upstream signaling.
6. The R-ONU is compatible with 10 Gb/s PON due to the inclusion of the 1575-1581 nm blocking filter.
7. Blocking filters *may* also be required if an optical carrier at any wavelength other than 1310 ± 50 , 1490 ± 10 , $1540 - 1565$, or 1610 ± 10 nm is used in the same fiber.
8. The minimum loss budget for any PON is set as 5 dB less loss than the maximum loss budget. The primary purpose is to minimize the variation in upstream performance. In mixed RFoG and PON systems, there is an additional consideration of crosstalk from the PON into RFoG. If loss *shall* be added to an RFoG system, it *may* be added in the RFoG system only in the upstream signal path. The downstream *may* be accommodated by simply supplying a lower amplitude 1550 nm downstream optical carrier. For mixed RFoG and PON systems, additional loss *may* need to be added in the PON interface. See Figure 7 for an explanation of where to add attenuation in order to place the entire plant within specification. Note that WDM loss is included in the system loss budget. Also note that Figure 7 covers two cases, with and without an xPON (either EPON or GPON). The 1310 nm wavelength (if used) is handled in different ways with and without xPON.
9. The upstream channel capacity is assumed to be four 6.4 MHz wide DOCSIS channels. Note that the per-carrier level is 6 dB lower than the total power level. This accounts for the assumption that the system is loaded with four channels. The link loss and performance assumptions are based on four-channel operation. One could design the system for operation with fewer channels, which would result in a higher OMI and CNR for each channel, but less upstream data capacity for the system. Alternatively, one could design the system for operation with more channels, which would result in a lower OMI and CNR for each channel, but allow for more capacity in the system. The “Nominal channel capacity” and “Nominal RF input level per channel” are not mandatory specifications. The “OMI at total power” specification is a normative requirement. However, one *shall* be careful to not deviate too far from the Nominal RF input level per channel specification or the turn-on and turn-off thresholds of the R-ONU *may* not operate correctly with the actual channel level.
10. The Turn-On and Turn-Off characteristics specified in Section 10.2, “Turn-On and Turn-Off Characteristics”, are measured with a CW signal. The actual laser turn-on and turn-off times will be different when the R-ONU is fed actual DOCSIS traffic. When consecutive bursts from different cable modems behind different R-ONUs exist with the minimum guard times allowed in the DOCSIS 3.0 specification, the specifications in Section 10.2, “Turn-On and Turn-Off Characteristics”, allow a second R-ONU to turn on before the first R-ONU is off, thus allowing for the possibility of optical beat interference (though not at a time when data is being transmitted).
11. The CMTS or other long loop AGC controller will command the upstream RF transmitters in the premise to raise or lower their transmit level until the proper level is achieved at the input to the CMTS or other controller. It is important to align the RFoG upstream network such that the RF level into the R-ONU is at the proper level when the input to the CMTS or other controller is also at the proper level.

It is recommended that the alignment be conducted on an R-ONU with high optical loss between it and the upstream receiver because R-ONUs that feed high optical loss budgets will require high RF input levels to compensate. As a result, R-ONUs with lower optical loss budgets will be driven with lower RF levels. If alignment were instead conducted on an R-ONU with a low optical loss budget, the RF input to R-ONUs with a high optical loss budget will have their upstream transmitters driven into clipping. R-ONUs with a high optical loss budget will have lower than average NPR at the nominal RF input level but

will be driven by higher than nominal RF levels. R-ONUs with a low optical loss budget will have a higher than average NPR at the nominal RF input level but will be driven by lower than normal RF levels.

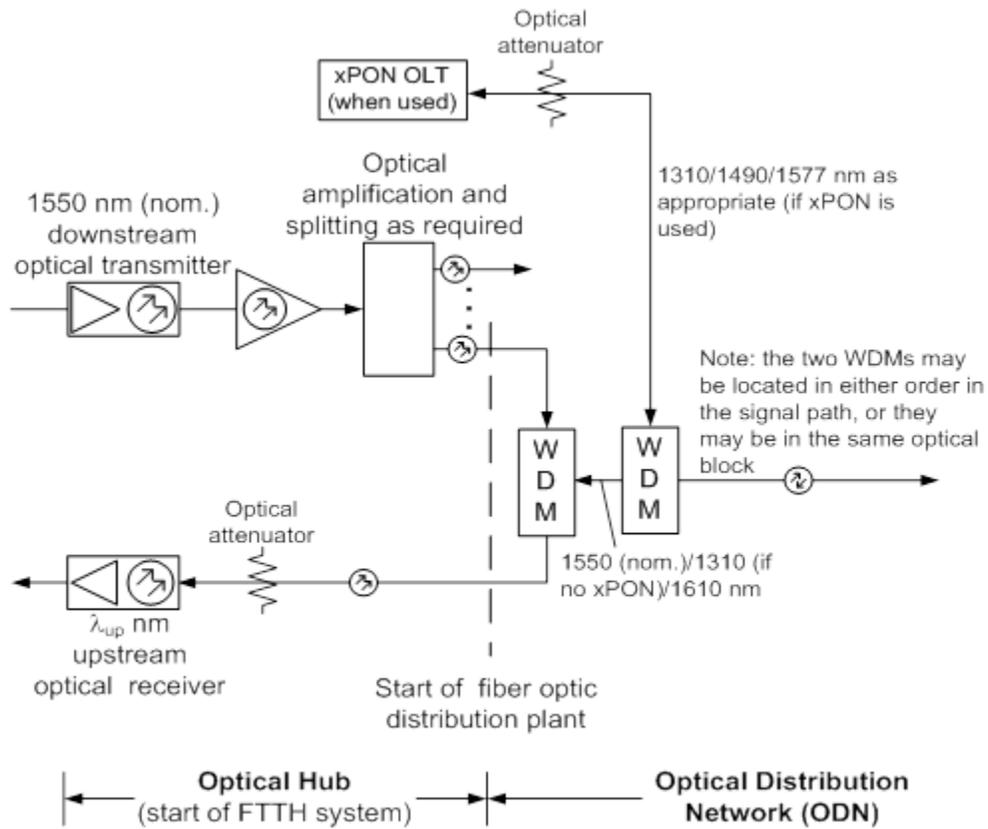


Figure 7 - Placement of attenuators when system loss is too low

14. Appendix A: System Loss Specification (Informative)

The RFoG system *shall* operate with a system loss in either direction of at least 25 dB. Note from Figure 2 that this (downstream) loss is defined from the input to the WDM that combines the upstream and downstream optical signals, to the input of any R-ONU. The RFoG system *may* work at higher loss levels. This section is intended to provide guidance concerning the loss that can be tolerated. Both upstream and downstream directions *shall* be considered, as either *may* be the limiting factor. Besides other considerations, one *may* want to keep in mind an ultimate conversion or overlay (to coexist with RFoG) to some other form of PON, looking at the loss budgets it will tolerate. One factor to be considered in an overlay would include additional system loss due to added WDM devices (added to or substituted for the original devices) and the potential impact on both the RFoG and PON system.

14.1. Downstream Considerations

In the downstream direction, the maximum loss tolerable is determined by the minimum optical signal needed at the R-ONU, and by the maximum launch signal at the headend. The maximum launch signal is usually set by SBS (Stimulated Brillouin Scattering) limitations in the fiber. When setting optical power into the fiber, it is very important to assure that the optical power meter is properly calibrated and adjusted to measure 1550 nm signals. If the optical power into the fiber is too high, SBS *may* result. With the current state of the art, the minimum received optical power at the R-ONU that produces a satisfactory carrier-to-noise ratio (C/N) is about -5 dBm for analog channels. Common practice is to operate analog carriers with an optical modulation index (OMI) into the optical transmitter of 3.5% per carrier, and this is assumed. Digital carriers (256-QAM) are by convention operated -6 dB from analog carriers, and when all-digital transmission is used, lower optical levels will usually produce satisfactory results. Thus, the minimum optical input of -5 dBm applies when analog carriers are transmitted, but if all-digital transmission is used, lower levels *may* be used without violating this standard.

Using conventional HFC optical transmitters, the maximum launch power into a long fiber might be +16 dBm, resulting in a tolerable loss budget of $16 - (-5) = 21$ dB, less than required. However, there are several things an operator can do in order to improve the loss budget:

1. Many optical transmitters today employ SBS-mitigating strategies, resulting in higher output power without encountering the SBS threshold. Typically the SBS threshold might be raised by up to 4 dB, just getting to the 25 dB loss budget.
2. Shorter lengths of fiber permit higher launch powers. For example, if the distance from the headend to the splitter is 5 km, then the launch power can be approximately 4 dB higher than the launch power for a 20 km PON. (Note that in calculating the effect on SBS, one need only include the fiber distance to the first split, as power usually will drop enough at that point to not be much of a problem. Also, note that the PON is defined to include the WDM, and typically the WDM is located so close to the transmitter that the launch power contributing to SBS is the optical power after the loss of the WDM. Thus, the power you would use in calculating SBS effects will be 1 dB or so lower than the actual launch power, reduced by the loss in the WDM.)
3. Newer fiber types offer improved SBS limitation, so if you are installing new fiber from the headend, you *may* want to consider using this fiber in order to improve performance.

Note that at higher optical power levels there *may* be additional safety regulations which *shall* be observed. Also, there are additional possibilities for damage to connectors and other components. A service provider contemplating operation at higher optical levels *shall* be cognizant of these issues.

Of course, if digital-only transmission is planned over the RFoG network, then the optical power at the R-ONU *may* be lower, and the above considerations modified accordingly. In this case it *may* be possible to reduce the optical power by 3-5 dB compared with that needed if analog signals are carried. Such operation does not represent a violation of this standard.

14.2. Upstream Considerations

In the upstream direction, the maximum tolerable loss is determined by the launch power of the R-ONU, the type of modulation of the upstream carriers, the number of upstream carriers, and the sensitivity of the upstream receiver. Note that the tolerable upstream loss budget is different from the calculation of upstream levels from the RF sources in the home. Once the upstream optical loss is set for a particular PON, the expected receive level at the headend *shall* be chosen such that the OMI of the upstream transmitter is “correct,” as defined elsewhere in this document.

As an example, consider an upstream minimum launch power of +2 dBm, four 64-QAM signals, and a receiver that can provide 28 dB C/N (the minimum considered acceptable for 64-QAM) at an input level of -23 dBm. This yields a maximum system loss of 25 dB as suggested. There *may* be some ways to improve the loss, however:

1. Some manufacturers are providing optical receivers with greater sensitivity.
2. If you only plan to operate two upstream carriers rather than four, you might be able to design for 3 dB higher OMI at the R-ONU, improving your loss budget.
3. Optical amplifiers could be strategically placed in the plant.
4. Use of the higher-powered 1610 nm option will permit more system loss.

You *may* decide to use some combination of these methods to allow for optically combining two upstream PONs, thus saving upstream receivers. But you *shall* allow for a number of possible degrading issues:

1. System loss *may* turn out to be higher than anticipated after a break that is repaired under adverse conditions. Standard design techniques provide a “repair margin” (at least 1 dB and up to 3 dB) to allow for this. This means that 25 dB available loss would allow the designer 24 dB of day-one loss.
2. There could be up to 1 dB degradation in optical budget due to dispersion issues in the plant.
3. There can be several decibels of variation in OMI at the home, depending on actual losses in the system, receiver output, loss between the receiver and the CMTS, accuracy of the CMTS level setting, etc.

15. Appendix B: Considerations Involved in an Adaptive Threshold Approach to R-ONU Laser Turn-On and Turn-Off (informative)

This standards document contains R-ONU requirements for upstream laser turn-on and turn-off in Section 10.2. The requirements include specifications for input RF signal levels and input RF burst durations that *shall* trigger or not trigger laser turn-on and that *shall* trigger or not trigger laser turn-off. The requirements are succinctly captured in Table 8, and various turn-on and turn-off characteristics are illustrated in Figure 6.

The thresholds for signal levels and burst durations in the turn-on and turn-off requirements are absolute thresholds. They are not relative thresholds. Within the SCTE IPS Working Group 5, use of adaptive thresholds was thoroughly discussed and an algorithm was presented. In this appendix, the rationale for adaptive thresholds is discussed. In addition, some of the reasons for not incorporating adaptive thresholds in the standard are mentioned. In the end, this appendix serves as a brief presentation of information pertaining to adaptive turn-on and turn-off thresholds, and perhaps in the future, operation with adaptive thresholds will be incorporated into normative statements in this standards document.

As discussed in this standards document, the primary communication signals in the upstream that *shall* be considered in the R-ONU RF signal detection and laser turn-on and turn-off are the following:

- DOCSIS burst transmissions
- SCTE 55-1 Return Out-of-Band burst transmissions
- SCTE 55-2 Return Out of Band burst transmissions

There are several other legacy upstream transmissions that have been used on cable access networks, but many of these proprietary signals were supported by equipment that is now obsolete due to replacement by equipment based on available standards (e.g., the ANSI/SCTE 135 series of standards based on CableLabs DOCSIS specifications).

The Implementation Notes in Section 13 make specific recommendations to only run DOCSIS upstream symbol rates at 1.28 Msps and higher, to run SCTE 55-1 upstream OOB at 128 ksps, to run SCTE 55-2 upstream OOB only at 772 ksps QPSK, and to operate upstream SCTE 55-1 and 55-2 signal levels at the same level as a DOCSIS channel as seen at the RF input on the R-ONU. These recommendations are helpful to upstream signal detection at the R-ONU and reliable laser turn-on and turn-off, and the specific turn-on and turn-off requirements with fixed thresholds were established while considering these recommendations.

Adaptive thresholds would provide additional performance for reliable turn-on and turn-off that could better handle the following considerations:

- More efficient network operation due to smaller gap time between DOCSIS upstream burst transmissions
- Large dynamic range of input signal levels
- Dynamic range of highest to lowest power symbols in high density constellations
- Peaks and valleys during symbol transitions at low symbol rates

Within the SCTE Interface Practices Subcommittee Working Group 5, a specific approach and algorithm for adaptive turn-on and turn-off was contributed and discussed. This approach defined a Burst Transmission Level, which corresponds to an average power level of a burst longer than 12 microseconds. It also defined a Final Burst Transmission Level, which is the Burst Transmission Level when the turn-off decision is made for a signal burst. Finally, it defined a Qualified Signal Threshold, which is derived from the Final Burst Transmission Level of recent upstream bursts and adjusted downward as a function of the amount of time that has elapsed since the most recent laser turn-off time. The longer the amount of time since the last laser turn-off, the more the Qualified Signal Threshold is decremented until some minimum threshold level is reached. The actual turn-on and turn-off thresholds are based on the Qualified Signal Threshold when it is defined. In the case when the Qualified Signal Threshold is not defined within the algorithm, a defined absolute threshold applies.

Though an adaptive threshold approach was considered for the Generation 2 version of the RFoG specification, it was not deemed a necessity by R-ONU vendors, and some did not want to implement an algorithm that perhaps would require a microprocessor in the R-ONU. In addition, some R-ONU manufacturers still have to gain experience with the fixed threshold requirements for turn-on and turn-off and thus are not ready to consider further enhancement of turn-on or turn-off that make this function higher-performance and more reliable. Actual operation has shown that long gap times between burst transmissions are needed at some R-ONUs, compared to typical DOCSIS upstream burst profiles. Adaptive turn-on and turn-off capability *may* provide significant increase in efficiency by reducing the long gaps currently required in some plants.

The dynamic range of the RF input to the R-ONU is impacted by variation of optical path losses in the network (as one factor among several) because of the closed-loop transmit power control within the ranging operation. The absolute turn-on and turn-off thresholds in the standard have to be low enough to provide high-reliability triggering for the lowest R-ONU input RF signal levels. The result is that for the high level RF inputs to the R-ONU, the time of the ramp-up and the ramp-down of a DOCSIS upstream burst to reach below the absolute thresholds is relatively long. The DOCSIS burst profiles used for an RFoG access network then *shall* have sufficient gap time to allow the longest duration ramp-up and ramp-down to affect laser turn-on and turn-off to avoid transmissions from two R-ONUs on the segment simultaneously, as contrasted with DOCSIS over HFC which allows some overlap of ramp-up of one burst with ramp-down of another. By using turn-on and turn-off thresholds adapted to recent inputs to

each individual R-ONU, the long time span for ramp-up and ramp-down between a high power RF transmission and the low level absolute thresholds is avoided. Then DOCSIS burst profiles for the RFoG access network can use smaller gap times similar to typical DOCSIS upstream operation in hybrid fiber coax (HFC) plants, and thus the access network efficiency in these situations is improved.

16. Appendix C: Upstream Optical Receiver Performance

This section includes suggested upstream receiver parameters. In certain cases, other parameters *may* be more appropriate and are not prohibited.

This section describes an optical receiver that, when used, provides proper operation of the RFoG network for an AM system. The parameters are set up assuming that one will operate DOCSIS 3.x modems with four simultaneous upstream carriers from one home, using the highest density modulation formats permitted under the DOCSIS 3.x specification.

Table 11 - AM Upstream Receiver Performance

Specification	Value
Optical input level range	-21 to -12 dBm
Detector responsivity (1310 nm and 1610 nm)	> 0.8 A/W
Frequency response	± 1 dB, 5 to F_{US-MAX}
Output impedance	75 ohms
RF output level (OMI= 17.5%, $P_{opt,in} = -21$ dBm)	>10 dBmV
Equivalent input noise current density(See note 11-1)	< 2.5 pA/ \sqrt{Hz}
Receiver turn-on (measured from when the optical input first reaches nominal value to when the electrical output reaches 90% of its steady-state value)	< 0.25 μ s

Note 11-1: The stated performance represents a typical receiver. To obtain the 25 dB loss budget required in Table 4 a 6.0 dBm transmitter will be required. For lower loss budgets, 3.0 dBm transmitters *may* be sufficient to provide -21 dBm minimum optical input power.

Table 12 - AM Upstream Receiver Performance for Extended Reach

Specification	Value
Optical input level range	-25 to -16 dBm
Detector responsivity (1310nm and 1610nm)	> 0.8 A/W
Frequency response	± 1 dB, 5 to F_{US-MAX}
Output impedance	75 ohms
RF output level (OMI= 17.5%, $P_{opt,in} = -25$ dBm)	>10 dBmV
Equivalent input noise current density (See note 12-1)	< 1.0 pA/ \sqrt{Hz}
Receiver turn-on (measured from when the optical input first reaches nominal value to when the electrical output reaches 90% of its steady-state value)	< 0.25 μ s

Note 12-1: The stated performance represents a receiver for extended reach and/or reduced optical output power transmitter.

17. Appendix D: Optical Beat Interference (Informative)

Point-to-Multipoint access networks accomplish multiple access by scheduling transmissions that are orthogonal in time, frequency, wavelength, or by correlation code. Most native fiber PON systems employ Time Division Multiple Access (TDMA), while DOCSIS typically employs both time and Frequency Division Multiple Access (FDMA) by scheduling (or provisioning) transmissions across different channels in DOCSIS 3.0 and across groups of OFDM carriers (channels and mini-slots) in DOCSIS 3.1.¹ When using DOCSIS over RFoG, FDMA can generate simultaneous transmissions from multiple RFoG ONUs (R-ONUs). While these FDMA transmissions are separated in frequency and thus orthogonal in the RF signal, with RFoG, the RF signal is used to modulate the intensity of the laser, and the resulting optical signal is recovered using a direct detection receiver. Since the laser wavelength is not precisely controlled in this process, it is possible that two R-ONUs can transmit simultaneously using lasers that are close enough together that the (non-linear) direct detection process generates optical intermodulation products that are within the bandwidth of the receiver. This phenomenon is known as Optical Beat Interference (OBI).

OBI is only generated when two factors are present: 1) 2 or more R-ONUs are simultaneously transmitting and 2) the wavelengths of those transmissions are sufficiently close together that the resulting intermodulation products are within bandwidth of the receiving photodiode. The combination of these two factors can make the presence of OBI appear random since the actual transmit wavelength (and linewidth) of a given R-ONU is typically not easily observable (through the standard performance monitoring data collection process) and varies with environmental conditions.²

The wavelength of a particular ONU transmission will vary within the allowed wavelength range due to unit-to-unit variations, environmental temperature, and short term heating of the laser during transmission times. The laser will also exhibit a linewidth, which is influenced by the Lorentzian noise of the laser, the chirp of the laser and the modulator signal bandwidth. Several studies have modeled and measured OBI with directly modulated DFB lasers, indicating that wavelength separation from 0.1 to 0.8 nm is sufficient to avoid OBI, depending on how well the temperature of the laser is controlled.

OBI Mitigation Techniques

OBI mitigation techniques have been developed to reduce or eliminate the occurrence of OBI in RFoG deployments. These techniques can be classified into two general categories:

- 1) Prevent wavelengths from overlapping in the receiver
- 2) Prevent transmission times from overlapping

Techniques for preventing the wavelengths from overlapping in the receiver include separating the wavelengths, either with static or dynamic wavelength assignment, and using one optical receiver per R-ONU. Overlapping transmission times are avoided through the use of scheduling at the CMTS, either statically, where no R-ONUs are allowed to transmit simultaneously, or dynamically, where the R-ONUs pairs that cause OBI are learned so that the scheduler can avoid overlapped transmissions of just those R-ONUs which would cause OBI.

¹ OBI also can result from simultaneous transmission of out-of-band (OOB) and DOCSIS transmissions from different ONUs on the same ODN. However, since the amount of OOB transmissions is small relative to DOCSIS transmissions, the presence of OBI is more likely due to multiple simultaneous DOCSIS transmissions.

² While OBI can occur during normal operation, it can also appear as an artifact in fault conditions, when a defective R-ONU fails to completely turn off its laser.

OBI's impact on DOCSIS Performance

OBI causes intermittent noise in the received upstream signal when two R-ONUs transmit at the same time on overlapping wavelengths. The noise is increased as the phase noise of the lasers is converted to intensity noise through the (non-linear) direct detection process. The amount of noise is determined by the optical spectra of the modulated lasers, the amount of overlap in their optical spectra and the relative states of polarization of the received signals.[1] If the transmit wavelength is not controlled, it will vary due to unit-to-unit variations, ambient temperature changes and short-term heating of the laser during a burst transmission.

While OBI can come and go based on ambient temperature variation and varying traffic patterns, once a set of R-ONUs is deployed, the set of nominal wavelengths is typically fixed, which can make OBI more likely in some PONs than others. Furthermore, if the nominal wavelengths and ambient temperatures of two R-ONUs on the same PON are similar, the probability of experiencing OBI can increase dramatically and occur over long time periods, creating a chronic condition.

The dependence of OBI on the nominal wavelengths of the selected R-ONUs also makes it difficult to reproduce field issues in the lab, where typically only a single PON's worth of R-ONUs are tested. It is therefore difficult to know whether a lab test is representative of what will be seen in the field or a sampling near one or the other extreme. Only with careful measurement of the wavelength of each R-ONU and comparing the distribution of the units under test to the more general distribution of nominal wavelengths and temperature variations seen in the field can confidence in laboratory testing be gained.

References:

[1] T. H. Wood and N. K. Shankaranarayanan, "Operation of a Passive Optical Network with Subcarrier Multiplexing in the Presence of Optical Beat Interference," *Journal of Lightwave Technology*, vol. 11, no. 10, October 1993