DOCSIS 3.1 Configurations for HFC and RFoG

A Technical Paper prepared for SCTE/ISBE by

Doug Jones
Principal Architect
CableLabs®
858 Coal Creek Circle
Louisville, CO 80027 USA
303-641-6563
d.jones@cablelabs.com

Table of Contents

List of Figures

List of Tables

Introduction

The use of DOCSIS® 3.1 technology on a Radio Frequency over Glass (RFoG) network (SCTE 174) [1], requires special attention because the DOCSIS 3.1 upstream technology can increase the likelihood of optical beat interference (OBI) which can interrupt communication on the return path.

An RFoG network uses an RFoG optical network unit (R-ONU) with an upstream laser to transmit DOCSIS signals over the fiber network. OBI is caused on an RFoG network when two conditions are met: 1) two or more R-ONUs operate at substantially the same wavelength, and 2) those R-ONUs simultaneously transmit. Preliminary testing and analysis completed at CableLabs shows that the highly efficient DOCSIS 3.1 upstream can increase the occurrence of OBI because of how many cable modems (CMs) (e.g., R-ONUs) can simultaneously transmit.

The DOCSIS 3.1 upstream introduces a new technology called orthogonal frequency division multiple access (OFDMA) which supports multiple CMs transmitting at once in order to make more efficient use of upstream spectrum. CableLabs has observed in laboratory testing that both usability and efficiency of the DOCSIS 3.1 upstream is directly impacted by OBI. Further, observations have confirmed that the DOCSIS 3.1 downstream configuration requires no modification because of how RFoG technology operates; there is a single laser transmitter in the downstream therefore OBI will not be generated.

Content

1. A Brief History of RFoG

RFoG allows a cable system to use existing headend infrastructure and consumer-premises equipment while putting an all-fiber network solution in place for future services. Around 2005 there was a competitive push for fiber-to-the-home (FTTH) networks and RFoG was devised to allow an FTTH network option for cable operators.

The SCTE started the RFoG technology standardization process in 2007, with the introduction of the project authorization request (PAR) for a specification which eventually became SCTE 174. The work was undertaken in the SCTE interface practices subcommittee (IPS) working group 5 and resulted in a standard in 2010.

As things turned out, cable continued to innovate and to this day the cable network remains competitive. However, the cable industry found another reason to use RFoG technology, that being lower construction cost for rural environments as compared to a hybrid fiber/coax (HFC) network. In areas where the drop cable exceeded 500 feet or so, an amplifier would be needed at the start of the driveway just to get the signal to a subscriber's home making for relatively more expensive HFC network construction costs as compared to an RFoG network.

In today's market, cable is still looking toward extending fiber deeper as well as constructing greenfield FTTH networks. And there is continued discussion about the latest generation of DOCSIS 3.1 technology running over an RFoG network.

An example RFoG network is shown in Figure 1 where a traditional coax-based cable headend is fed into an outside plant that is all fiber optic cable, and then inside the home the signal is returned to coax cable. What allows this is the R-ONU in the home that converts between fiber optic cable and coax cable.

Figure 1 also shows multiple R-ONUs connecting to the fiber optic network. Traditionally the number or R-ONUs is up to 32 per network which is based on both the optical power levels and loss associated with a 32-way optical splitter in the FTTH network. An interesting consequence of inserting this FTTH network into the middle of what is otherwise a traditional cable network is the cable components on either side do not need to be aware of the RFoG technology. That is, the cable operator does not need to make adjustments in either the headend or in the home in order to use an RFoG network.

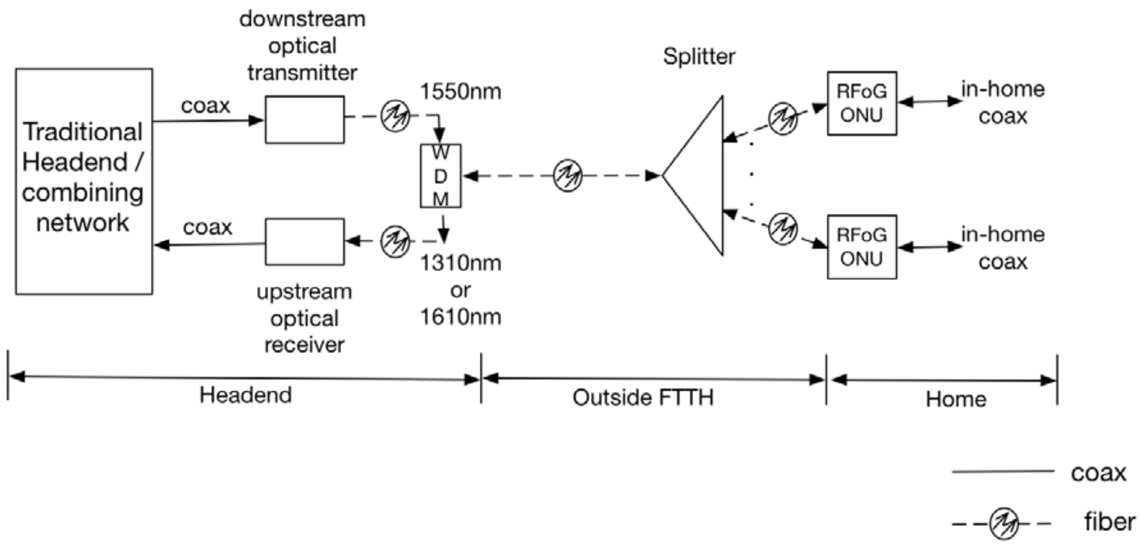

Figure 1 – Typical RFoG Network

RFoG technology is specified in SCTE 174 which places requirements on the R-ONU customer equipment. SCTE 174 includes an introduction to optical beat interference (OBI).

2. Optical Beat Interference

OBI is not specific to RFoG technology, and rather is a general optical phenomenon that occurs at a photodetector when two optical signals that overlap in wavelength are received. In this case, OBI is a beat note, i.e., a signal at the difference of those two optical wavelengths, and in an RFoG network has the effect of raising the upstream noise floor and impacting upstream communications.

In an RFoG network, OBI is an upstream phenomenon; OBI does not occur on the downstream. As shown in Figure 2, OBI is generated in the upstream optical receiver and appears on the coax that feeds the upstream combining network and can impact all upstream signals from any R-ONU transmitting at that time when the OBI is generated. With OBI, all that matters are the upstream wavelengths of the R-ONU lasers. The RF signals being generated in the home do not matter, just that at least two R-ONU return lasers are on at the same time and two of those optical wavelengths are close enough to generate "optical beating" in the photodetector, the physical and mathematical basis of which will be addressed in the next section.

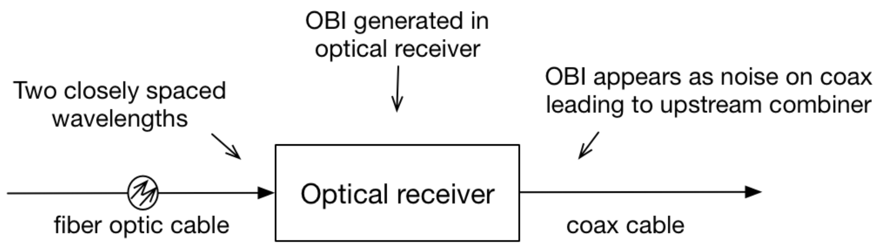

Figure 2 – OBI generation

If the optical signals simultaneously hitting the optical receiver are far enough apart in wavelength, there won't be beating. But if the optical signals are close enough in wavelength, beating occurs. Regular manufacturing tolerances of the upstream lasers can be enough to either have OBI or not have OBI on any particular RFoG network. Since the laser wavelength changes when the temperature changes, OBI and come and go throughout the day as temperatures change.

Upstream transmissions on cable plant can come from a couple of different sources, and any of these can cause the R-ONU optical laser to turn on. Common sources of return signals on the cable plant are:

- DOCSIS cable modems
- Legacy set-top boxes (e.g., SCTE 55-1 [2] and SCTE 55-2 [3])
- Legacy Cable Phone (e.g., Arris Cornerstone® Voice Port™ technology)

Any of these return RF signals on the coax can cause the R-ONU laser to activate to send an optical signal to the optical receiver.

3. Heterodyne and Beat Signals

Heterodynes and beats are related phenomenon and are technologies that have been beneficially used in communications networks, including cable TV, for decades. Beats and heterodynes are created by a frequency mixer, which is a nonlinear electrical circuit that creates new signals from the two signals applied to it. In its most common application, two signals are applied to a mixer and it produces new signals at the sum and difference of the original frequencies. Other frequency components may also be produced in a practical frequency mixer.

Heterodyning is a signal processing technique that creates new signals by combining two known signals in a mixer. Heterodyning can be a very useful technology and has been used for years in cable systems. Included in the references section is a 1967 paper [4] given at the NCTA conference about the use of heterodyning in CATV channel processing. Heterodyne production is generally very controlled in a precise circuit by applying both the input signal and a precisely controlled local oscillator signal to a mixer, and using filtering and amplification to produce the desired new signal.

Beats are also caused by applying two input signals to a mixer, however the process is generally not controlled. It is a naturally occurring phenomena related to the physical capabilities of the mixer. A photodiodes used in an optical receiver can act as and is what causes OBI in an RFoG network.

A schematic for a typical mixer is shown in Figure 3. The input to the mixer are two signals at different frequencies where sometimes $frequency_2$ is shown as a local oscillator (LO). The output signals are called heterodynes and consist of one or more signals at different frequencies than the input signals.

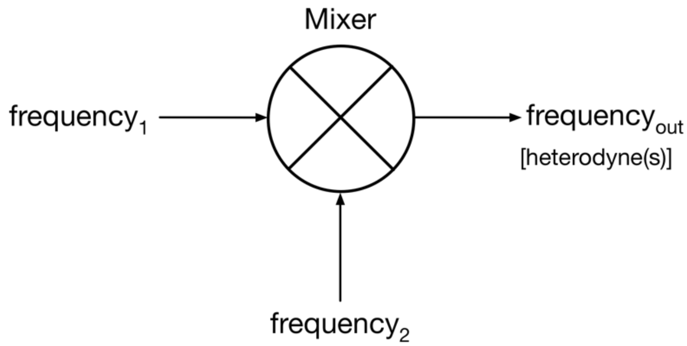

Figure 3 – Typical Mixer

Heterodyning within the mixer is based on the trigonometric identity:

$$\sin(A)\sin(B) = \frac{1}{2}\cos(A-B) - \frac{1}{2}\cos(A+B) \tag{1}$$

On the left-hand side of the equation are the two input signals at different frequencies, A and B, which are "mixed" to create the two new signals at frequencies (A-B) and (A+B), on the right-hand side of the equation. The new signals at frequencies (A-B) and (A+B) are called heterodynes.

Mixers vary and are classified by their functionality:

- An unbalanced mixer, in addition to producing the heterodyne signals, allows both input signals to pass through and appear at the output.
- A single-balanced mixer is designed such that either one or the other of the input signals is available at the output (but not both) as well as the heterodynes.
- A double-balanced mixer is designed such that neither of the input signals and only the heterodyne signals appear at the output.

Products using mixer and heterodyne technology are used for channel frequency conversions are generally carefully constructed, including detailed filters and amplifiers to protect against unwanted signals and only the desired signal is at the output.

Cable uses mixer / heterodyne technology, for example, in channel upconverters. A coaxial cable used by a cable television system can carry many television or QAM channels all at the same time because each channel is given a different frequency, i.e., EIA channel, so they don't interfere with one another. At the cable headend, upconverters move an incoming television channel (or QAM signal) to a different carrier frequency to fit within the channel plan on the coax. Channel upconverters do this by mixing the television signal frequency, f_{CH} with a local oscillator at a different frequency f_{LO}, creating a heterodyne at the sum $f_{CH} + f_{LO}$, which is combined onto the cable.

4. OBI as a Beat Noise

In RFoG networks the optical receiver, typically a photodiode, acts as an unbalanced mixer which can cause the creation of optical beat products when it gets hit simultaneously by two R-ONU lasers whose wavelengths are close enough to each other. The beats that cause OBI are a result of unintentional and uncontrolled heterodyning in the optical receiver that raises the noise floor of the return path which can wipe out the return path for as long as the two R-ONUs are transmitting together.

A schematic for a typical unbalanced mixer is shown in Figure 4.

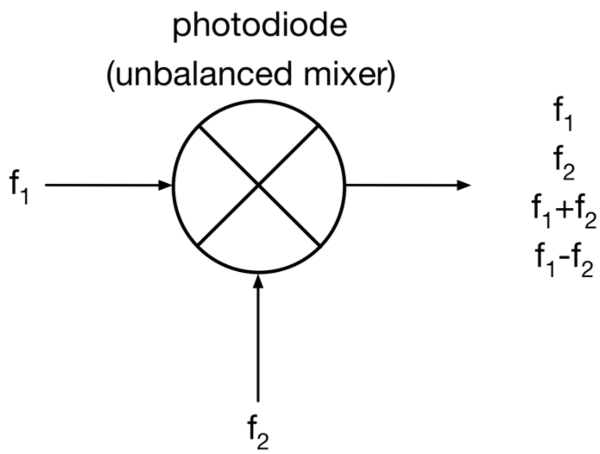

Figure 4 – Unbanalced Mixer

In this case, the wavelengths of the optical signal are sourced from the R-ONUs and when converted to frequency are in the hundreds of Terahertz (THz), or a million times the MHz used on cable systems.

The equations to convert between frequency and wavelength are:

$$f = \frac{c}{\lambda} \tag{2}$$

$$\lambda = \frac{c}{f} \tag{3}$$

where:

$f =$ the frequency of the signal in Hz.
$\lambda =$the wavelength of the signal in meters.
$c =$the speed of light in a vacuum (299,792,458 meters/second).

A signal with wavelength of 1610 nm (1610 x 10^{-9} meters) has an approximate wavelength of 186 THz.

The OBI is the difference product, or (f_1 - f_2). The sum product, (f_1 + f_2) will be in the THz range which will not cause interference in the MHz range. However, subtracting a THz from a THz, when those values are very close, can result in a number in the MHz, and that is the OBI signal that causes degradation to the RF signals. Since the OBI signal is at the output of the optical mixer, that noise is carried through the rest of the optical receiver circuitry and is present on the coax that goes to the upstream combining network.

5. The Physics of Photodiode OBI Generation

This section goes into the detail of deriving equation 1, and shows how a photodiode can create beats.

A diode can be used to create a simple unbalanced mixer that produces both the original frequencies and their sum and difference heterodynes. The derivation begins with the Shockley diode equation which shows the current through an ideal diode as a function of the voltage, V_D, across it. The Shockley diode equation is:

$$I = I_s\left(e^{\frac{V_D}{nV_T}} - 1\right) \tag{4}$$

where:

I is the diode current.
I_s is the diode reverse bias saturation current (essentially a constant, depends on temperature).
V_D is the voltage across the diode.
V_T is the thermal voltage (essentially constant, depends on temperature).
n is the ideality factor of the diode (a constant).
e is a mathematical constant, sometimes known as Euler's number.

It is important to note that the current and voltage are not linearly related, rather, that the voltage is raised as an exponential to e meaning the diode is a nonlinear device. Voltage and current through a diode are not linear, rather, they are related exponentially.

When deriving how the beats are created, it's not important to know these values, rather the equation with be manipulated to show how a pair of input sine waves (signals) will result in new sine waves at the sum and different frequencies.

The exponential function of the Shockley diode equation can be expanded into a Taylor series as shown below:

$$e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!} \tag{5}$$

Which can be approximated by the first few terms of the series:

$$e^x = \left(\frac{x^0}{0!}\right) + \left(\frac{x^1}{1!}\right) + \left(\frac{x^2}{2!}\right) + \left(\frac{x^3}{3!}\right) + \cdots \tag{6}$$

On the right-hand side of the equation, in the first term both numerator and denominator, x^0 and 0! are equal to one therefore the first term on the right-hand side of the equation is equal to one. Using this equation 6 can be simplified as:

$$e^x = 1 + x + \frac{x^2}{2} + \frac{x^3}{6} + \cdots \tag{7}$$

Which can be rearranged as:

$$(e^x - 1) = x + \frac{x^2}{2} + \frac{x^3}{6} + \cdots \tag{8}$$

Now the parenthetical on the left side of the equation is in the form of the parenthetical on right-hand side of the original Shockley diode equation (equation 4). From equation 4 ignoring the three constants $I_S, V_T,$ and n, the original Shockley equation can be approximated as:

$$I = \left(x + \frac{x^2}{2} + \frac{x^3}{6} + \cdots\right) \tag{9}$$

Now assume that diode is in a circuit with a resistor in series with it, and the current, I, will generate an output voltage, the output voltage will have the form:

$$v_0 = \left(x + \frac{x^2}{2} + \frac{x^3}{6} + \cdots\right) \tag{10}$$

Now the derivation is in final form, and assume two input voltages, $v_1 + v_2$ (from the two R-ONUs), are applied to the diode. The output voltage can be approximated as:

$$v_0 = (v_1 + v_2) + \frac{1}{2}(v_1 + v_2)^2 + \frac{1}{6}(v_1 + v_2)^3 + \cdots \tag{11}$$

If those two voltages are sinusoids of different frequencies:

$$v_1 = \sin(A) \tag{12}$$

$$v_2 = \sin(B) \tag{13}$$

Substituting these signals into the equation yields:

$$v_0 = (\sin(A) + \sin(B)) + \frac{1}{2}(\sin(A) + \sin(B))^2 + \frac{1}{6}(\sin(A) + \sin(B))^3 + \cdots \tag{14}$$

To show the creation of new frequencies, the analysis will just look at the term on the right-hand of the equation that is raised to the second power.

$$(\sin(A) + \sin(B))^2 = \sin^2(A) + 2\sin(A)\sin(B) + \sin^2(B) \tag{15}$$

To finish the analysis, notice that on the right hand of the equation, the middle term is essentially the same as equation 1 which is repeated here.

$$\sin(A)\sin(B) = \frac{1}{2}\cos(A - B) - \frac{1}{2}\cos(A + B) \tag{16}$$

Manipulating the Shockley diode equation shows how new frequencies can be created when two sine waves, the outputs of the R-ONUs, are mixed at the photodiode in the headend optical receiver. And based on equation 14 it can be seen that the creation of new frequencies is not “clean”, rather, multiple new frequencies can be created based on the squared, cubed, and the following terms raised to higher exponents that will generate multiple new frequencies which is the noise that is called OBI. Additionally, with RFoG technology it is possible to have more than two sine waves hitting the optical receiver. With upstream channel bonding in DOCSIS 3.0, a typical return path has up to four carriers, meaning four R-

ONUs can transmit at once. In the next section will be a discussion of the OFDMA upstream available in DOCSIS 3.1 and how even more R-ONUs can be transmitting at once. This result is not comparable to what happens in a channel upconverter, where complex circuitry makes for the precise generation of heterodynes. Rather, with RFoG, the heterodyning process within the photodiode is uncontrolled and just creates noise.

6. Lab Setup and Analysis

6.1. Lab Setup

The lab setup is diagramed in Figure 5 and includes an FTTH network with thirty-two R-ONUs, each with a single DOCSIS 3.1 CM attached. Various R-ONUs were used in the analysis; however, never more than thirty-two at once. For each R-ONU, the wavelength of the return laser was found using an optical spectrum analyzer and within the group of thirty-two R-ONUs there were several within close range of each other, capable of generating OBI.

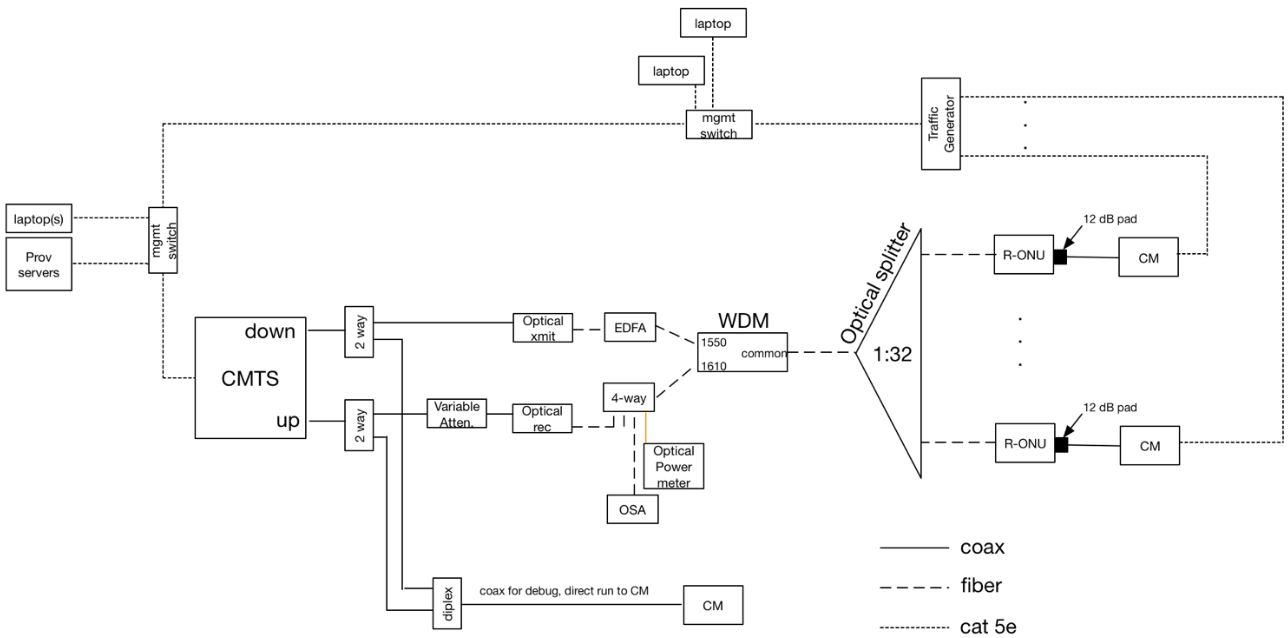

Figure 5 – RFoG Lab Setup

DOCSIS 3.1 CMs are capable of both OFDMA and ATDMA return. When in ATDMA mode, four carriers were used; each 6.4 MHz wide; modulated at 64 QAM; and centered at 17.3 MHz, 23.7 MHz, 30.1 MHz, and 36.5 MHz.

When in OFDMA mode, two channel widths were used; 10 MHz and 24 MHz. Modulations were varied between 64 QAM and 1024 QAM; however, most work was done with 64 QAM as the focus was on reliable communication so errors could be attributable to OBI.

Table 1 lists the nominal upstream laser wavelengths of the thirty-two R-ONUs used in the testing, from low to high wavelength

Table 1 – R-ONU Wavelengths

R-ONU	Laser Wavelength
1	1609.99
2	1610.71
3	1610.83
4	1610.95
5	1611.08
6	1611.34
7	1611.53
8	1611.55
9	1612.01
10	1612.40
11	1612.51
12	1612.56
13	1612.80
14	1612.83
15	1612.87
16	1612.89
17	1612.89
18	1613.10
19	1613.20
20	1613.30
21	1613.52
22	1613.60
23	1613.64
24	1613.72
25	1613.74
26	1613.85
27	1613.93
28	1614.11
29	1614.15
30	1614.98
31	1615.08
32	1615.58

Figure 6 graphically shows the distribution of the R-ONU upstream wavelengths.

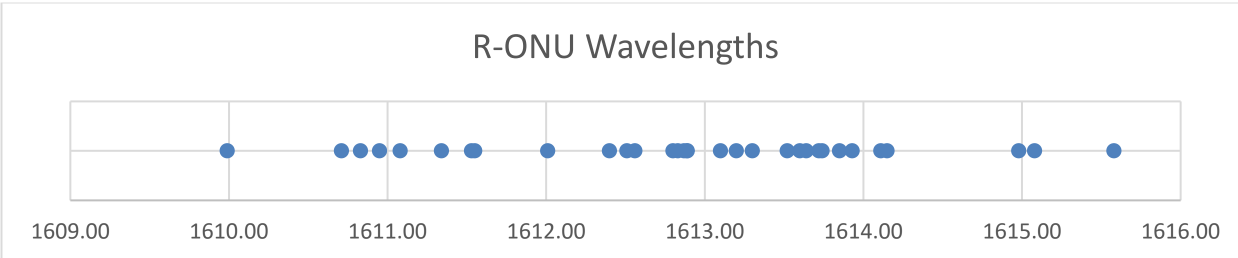

Figure 6 – R-ONU Wavelengths

There is a distribution, due to normal manufacturing variation, of approximately 5.5 nm in the upstream lasers (1610 nm through 1615.58nm). The R-ONU wavelengths that are close together are candidates to cause OBI. Specifically, there is a group of five wavelengths that overlap at 1612.80 nm and 1612.89 nm, as well as a couple other groups of two wavelengths closely spaced together. Note that the wavelengths are not static; they can change with time and temperature. The creation of OBI is hard to predict and can be even harder to troubleshoot.

6.2. OBI and DOCSIS Analysis

When testing with DOCSIS equipment, the presence of OBI was tied to the occurrence of uncorrectable Forward Error Correction (FEC) codewords as reported by the CMTS. An uncorrectable codeword is one which cannot be corrected by the FEC; the assumption that OBI has caused so much noise on the return path that the codewords have been corrupted beyond the ability of the FEC to recover them. The traffic generator also reported packet loss; however, the lab analysis is based on uncorrectable codewords.

With DOCSIS 3.0 trying to induce OBI, specifically with 4 ATDMA carriers over a range of packet sizes and data rates, uncorrectable codewords ranged from 4 – 6% of the traffic under a wide range of scenarios.

With DOCSIS 3.1 trying to induce OBI, under specific conditions up to 80% uncorrectable codewords were observed. The worst case of OBI was observed when both the DOCSIS return channel and the traffic generator were purposely configured to maximize the possibility of multiple simultaneous upstream transmissions. The configuration consisted of OFDMA frames supporting 60 simultaneous minislots, the minislots large enough to carry a 64 Byte packet, and all modems sending upstream 64 Byte packets aligned on the same time interval. This is not a common traffic pattern, specifically aligning packet transmission on the same time interval.

Generally upper layer protocols can recover. Specifically, TCP transport enables re-transmissions of data. Hence, in the presence of a small percentage of data loss (uncorrectable codewords), there is a possibility that customers may not notice OBI. However, UDP will be affected, and Voice over IP (VoIP) phone calls use UDP transport. In the presence of OBI customers may hear drop-outs or stuttering on their VoIP calls. Also, some gaming applications can use UDP transport and OBI would impact performance of gaming.

6.3. Inducing OBI

Figure 7 shows a lab setup that was used to induce OBI. Note there are no CMs or CMTS needed to induce OBI which is just a result of closely spaced optical wavelengths hitting a photodiode on the upstream portion of the optical path.

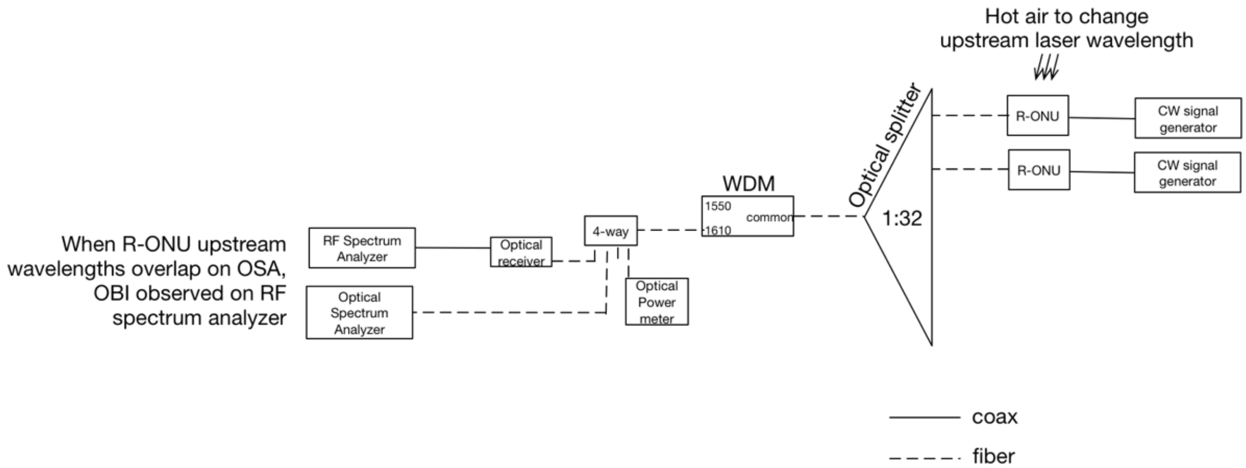

Figure 7 – OBI Lab Setup

In the OBI lab setup, just two R-ONUs were used and were chosen to have upstream laser wavelengths that were close together. A hair dryer was used to change the temperature of one of the R-ONUs to make its laser change wavelength and overlap with the other R-ONU. When the wavelengths overlap, then OBI is created in the optical receiver and can be observed on the RF spectrum analyzer. The results were captured on both an RF spectrum analyzer and an optical spectrum analyzer.

Figure 8 shows both RF and optical spectrum analyzer screenshots before the R-ONU wavelengths were induced to overlap. On the RF spectrum analyzer, one R-ONU has a CW carrier at 10 MHz and the other R-ONU has a CW carrier at 40 MHz. Note that OBI has nothing to do with the RF frequency on the coax, just the overlapping wavelengths at the optical receiver. In this figure, no OBI is observed in on the RF spectrum analyzer. On the optical spectrum analyzer, note how close the two wavelengths are; however, that they do not overlap.

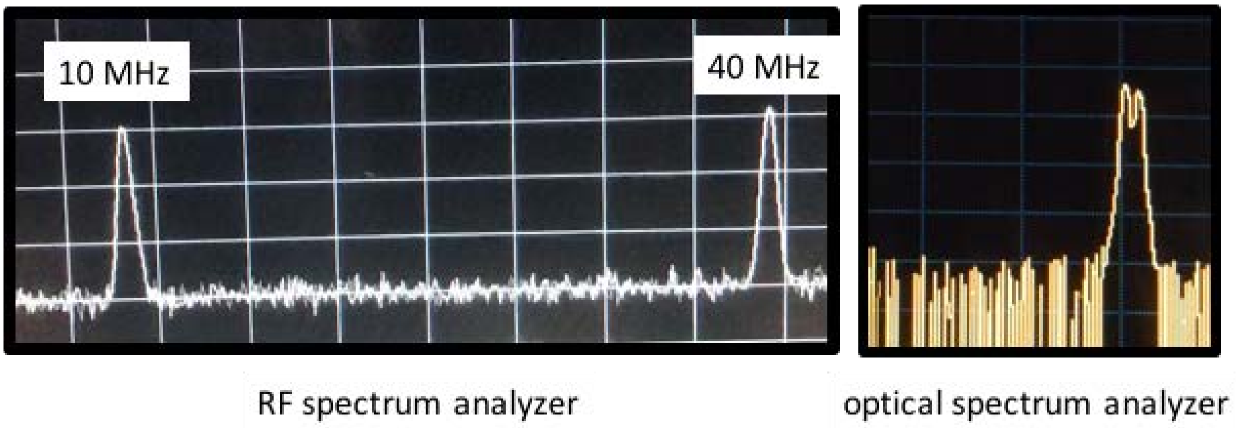

Figure 8 – Wavelengths close, no OBI

Figure 9 shows that same setup a few seconds later as the wavelengths of the R-ONUs overlap and OBI is created at the optical receiver. On the RF spectrum analyzer, the peaks at 10 MHz and 40MHz are still visible, however, the noise floor has risen approximately 25 dB.

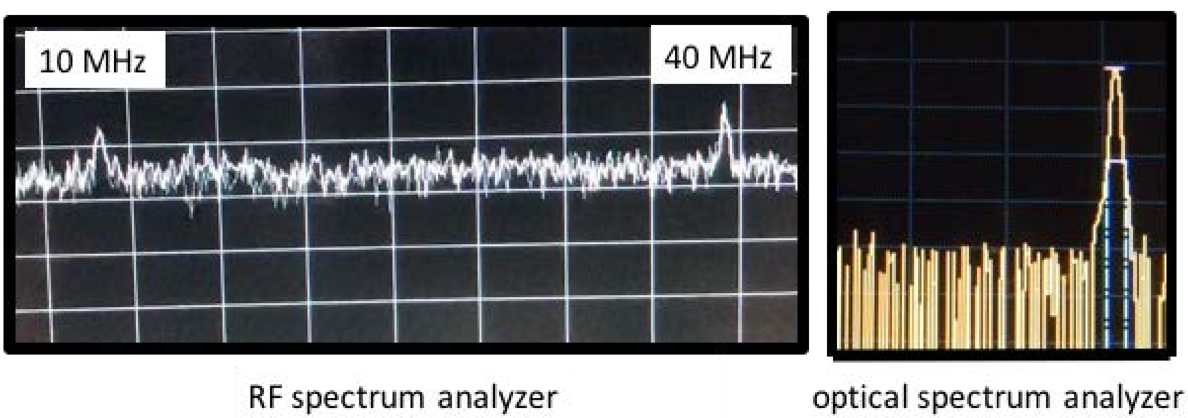

Figure 9 – Wavelengths overlap, OBI present

Note the broad spectrum of the noise caused by the OBI which impacts the entire return path (in this case, 5 – 42 MHz). It only takes two simultaneously transmitting R-ONUs to generate OBI at the optical receiver; however, data would be lost from any other CMs transmitting at the same time even though those R-ONU wavelengths are far enough apart to otherwise not cause OBI.

6.4. Aggregate Optical Receive Power

An issue that may become important with DOCSIS 3.1 upstream over an RFoG networks is the aggregate transmit power if multiple R-ONUs are simultaneously operating. Using log math, and assuming each R-

ONU outputs +3 dBm (several output levels are allowed, check SCTE 174), then the aggregate power of multiple transmitting R-ONUs is shown in Table 2.

Table 2 – R-ONU Aggregate Transmit Power

Number of R-ONU's transmitting	Aggregate Power
1	3 dBm
2	6 dBm
4	9 dBm
8	12 dBm
16	15 dBm
32	18 dBm

On a typical North American return path (5 – 42 MHz) with four DOCSIS 3.0 carriers and the possibility of 4 R-ONUs simultaneously transmitting, the RFoG network had to be designed assuming an aggregate transmit power of +9 dBm. With a DOCSIS 3.1 upstream where it is possible that more than four R-ONUs are simultaneously transmitting, the aggregate power can be higher. The network design should take this into account to ensure the aggregate optical transmit power from multiple simultaneously transmitting R-ONUs is not overloading the optical receiver.

7. DOCSIS and Simultaneous CM Transmissions

As discussed in previous sections, OBI is caused by two (or more) R-ONUs simultaneously transmitting at essentially the same wavelength. Two R-ONUs can transmit at the same time when multiple two-way services are operating. DOCSIS technology has supported multiple upstream carriers since the DOCSIS 1.0 specification, and in addition, there can be both legacy set-top box return channels and legacy cable phone systems. These various upstream services can lead to two R-ONUs transmitting at the same time.

Cable data service has been evolving, and it has been the continued increase of cable data speeds over the last few years that has really driven the deployment of multiple upstream DOCSIS channels. DOCSIS 3.0 technology introduced upstream channel bonding and drove wide adoption of multiple upstream DOCSIS channels. The first DOCSIS 3.0 modem deployments in North America began in early 2008, about the same time as when the SCTE effort to standardize RFoG technology was getting underway.

While DOCSIS technology has allowed multiple upstream carriers for years, there is still a limit of one CM transmitting at a time on a DOCSIS carrier. For example, according to the DOCSIS 3.0 MULPI specification [5], each DOCSIS 3.0 upstream carrier has an associated Upstream Bandwidth Allocation Map (MAP) that describes all upstream transmission opportunities on that carrier. The MAP message allows only one CM to transmit at a time on a carrier.

The first DOCSIS 3.0 modem deployments in North America began in early 2008, about the same time as when the SCTE effort to specify RFoG was gaining steam. The first DOCSIS 3.0 CM certifications happened at CableLabs Wave 58. Note that a DOCSIS 3.0 CMTS can schedule a single CM to transmit on more than one DOCSIS carrier at a time.

The DOCSIS 3.1 specification [6] introduces orthogonal frequency division multiple access (OFDMA) technology on the upstream, and the number of modems that can simultaneously transmit can increase dramatically. In lab testing with 32 CMs on an optical splitter, it was possible to get over 20 modems (and their associated R-ONUs) to simultaneously transmit though the exact number depends on the CMTS scheduling algorithm. OFDMA as used in DOCSIS 3.1 is fundamentally different as compared to upstream QAM used DOCSIS 3.0 and earlier, as OFDMA technology is designed for even more efficient usage of the upstream spectrum by having multiple CMs transmit at the same time.

In DOCSIS 3.1, the OFDMA upstream is comprised of a continuous progression of OFDMA frames and each OFDMA frame contains a number of simultaneous minislots that is based on the amount of spectrum allocated to the OFDMA carrier.

As an example, in DOCSIS 3.1 when using a 2048 fast Fourier transform (FFT) size and the minimum of 10 MHz of spectrum, there will be 25 simultaneous minislots. This can be derived by understanding that the 2048 FFT size uses a subcarrier spacing of 50 kHz, meaning there are 10 MHz ÷ 50 kHz per subcarrier = 200 subcarriers. Per the DOCSIS 3.1 MULPI specification [7], there are 8 subcarriers per minislot, yielding 25 simultaneous minislots. In DOCSIS, a minislot is the smallest unit of upstream bandwidth allocation. The CMTS assigns minislots for CMs to transmit in.

The capacity of a minislot, how many Bytes of information it can carry, is based on both how many OFDMA symbols are in an OFDMA frame and the modulation of that symbol.

A typical OFDMA configuration used in the lab analysis is shown in Figure 10 and uses 24 MHz of OFDMA upstream, which at a 2048 FFT size (50 kHz subcarrier spacing), results in 480 subcarriers available. At 8 subcarriers per minislot, this configuration supports 60 simultaneous minislots.

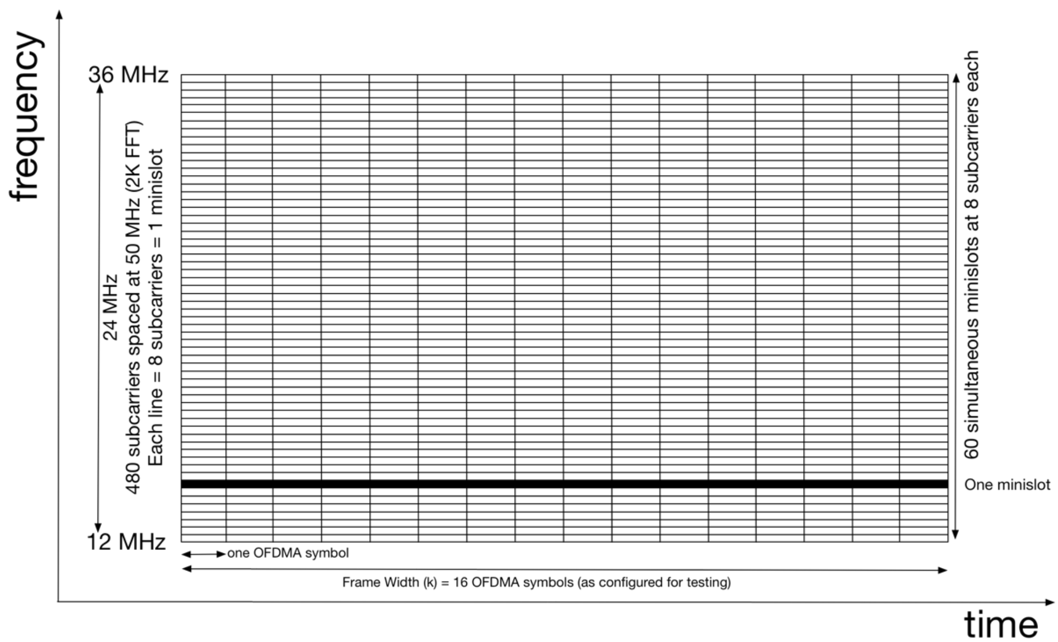

Figure 10 – DOCSIS 3.1 Upstream OFDMA Frame Structure

Based on an OFDMA frame width of 16 OFDMA symbols per frame and each subcarrier operating at 64 QAM, each minislot was capable of carrying approximately 77 Bytes of data. When testing with upstream 64 Byte packets and including DOCSIS overhead, then one TCP ACK would easily fit within two minislots. Thus, depending on CMTS scheduling and OFDMA overhead, up to 30 CMs (and their associated R-ONUs) could be transmitting at the same time.

In summary DOCSIS 3.0 upstream channel bonding allowed several CMs to simultaneously transmit on the upstream, up to one modem per carrier. On a typical North American cable network with four upstream carriers, there can be up to four CMs simultaneously transmitting. Depending on configuration, DOCSIS 3.1 allows even more CMs to simultaneously transmit on the upstream, depending on traffic loading. The bottom line is that when a DOCSIS 3.1 upstream is operated on an RFoG network there is a higher probability of OBI.

8. Managing OBI

If OBI is present, it will cause data transmission errors on the return path for as long as the two (or more) offending R-ONUs are transmitting simultaneously. All it takes is two R-ONUs transmitting at the same time to cause OBI that will wipe out the signals from any other R-ONUs which happen to be transmitting at that same time.

OBI only happens when two conditions are met; those being at least two R-ONUs at substantially the same wavelength and transmitting at the same time. The ONUs used for this testing were all specified to transmit at 1610 nm, however, there was still enough variation between most of those R-ONU upstream laser wavelengths that they would not cause OBI. It was only when certain pairs of R-ONUs were transmitting that OBI was observed.

An observation then is that OBI may not occur on an RFoG network if the natural variation of R-ONU upstream laser wavelengths are spaced appropriately. However, the next group of R-ONUs may have one or more pairs of R-ONUs that do transmit at a substantially similar wavelength and OBI can occur. This can make OBI a difficult issue to track down. OBI may not happen on all RFoG networks and when it does occur OBI is transient in nature, occurring only when the right two R-ONUs are transmitting at the same time.

Assuming the RFoG network is designed for thirty-two R-ONUs (due to optical loss on the fiber network), having fewer R-ONUs on that network can also lower the chance that there will be two R-ONUs using the same frequency. There are just fewer R-ONUs on that network so less of a chance that two are at the same wavelength. However, running the network below capacity could increase the overall cost of that installation.

Likewise, there are cable architectures that include multiple CMs in the home. In this case there is a higher chance that the R-ONU would be transmitting because of more return path transmitters (CMs) in the home. And in the case of DOCSIS 3.0 or DOCSIS 3.1 technology, there can be multiple simultaneous transmission opportunities which if two R-ONUs are on the same frequency could lead to a higher likelihood of OBI on that network.

If OBI is present, mitigation techniques typically fall into two categories; solutions in the optical domain and solutions in the DOCSIS domain.

Solutions in the optical domain rely on techniques to manipulate the wavelengths of the R-ONUs that hit the optical receiver. If overlapping wavelengths can be minimized or eliminated, then the possibility of OBI can be reduced.

Solutions in the DOCSIS domain typically focus on reducing either the number of CMs that can transmit simultaneously, or on recognizing groups of CMs (i.e., R-ONUs) that cause upstream errors when they transmit at the same time, and not scheduling these modems to simultaneously transmit.

These two different types of solutions have associated pluses and minuses. This paper does not attempt to an in-depth analysis of the various solutions on the market. An operator planning to operate a DOCSIS 3.1 upstream over an RFoG network should consider looking into solutions in the case that OBI is observed on that network.

Conclusion

DOCSIS 3.1 upstream technology can increase the probability that OBI will occur on an RFoG network. OBI will not occur on all networks. However, the current direction of the industry of considering RFoG networks for new build opportunities, deploying more upstream transmitters (e.g., DOCSIS CMs) in a home, and migrating to the DOCSIS 3.1 upstream can all increase the probability of OBI. Understanding how OBI occurs is a first step in considering alternatives to mitigate the effects of OBI, and researching appropriate mitigation techniques.

Abbreviations

ATDMA	advanced time division multiple access
CM	cable modem
CMTS	cable modem termination system
CW	continuous wave
dB	decibel
dBm	decibel milliwatt
dBmV	decibel millivolt
DOCSIS	data over cable service interface specifications
EIA	electronic industries alliance
FEC	forward error correction
FFT	fast Fourier transform
FTTH	fiber to the home
HFC	hybrid fiber/coax
Hz	hertz
IPS	interface practices subcommittee
ISBE	International Society of Broadband Experts
ITU	International Telecommunications Union
LO	local oscillator
MAP	DOCSIS upstream bandwidth allocation map
MHz	megahertz
nm	nanometer
OBI	optical beat interference
OFDMA	orthogonal frequency division multiple access
PAR	project authorization request
QAM	quadrature amplitude modulation

RF	radio frequency
RFoG	radio frequency over glass
R-ONU	RFoG optical networking unit
SCDMA	synchronous code division multiple access
SCTE	Society of Cable Telecommunications Engineers
THz	terahertz
TV	television

Bibliography & References

[1] Radio Frequency over Glass Fiber-to-the-Home Specification, ANSI/SCTE 174 2010

[2] Digital Broadband Delivery System: Out of Band Transport Part 1: Mode A, ANSI/SCTE 55-1 2009

[3] Digital Broadband Delivery System: Out of Band Transport Part 2: Mode B, ANSI/SCTE 55-2 2008

[4] *Comparison Of Demodulator-Modulator Versus Heterodyne Signal Processing For CATV Head Ends*, G. Rogeness, Proceedings of the NCTA, 1967

[5] Data-Over-Cable Service Interface Specifications; DOCSIS 3.0 MAC and Upper Layer Protocols Interface Specification, CM-SP-MULPIv3.0-I30-170111

[6] Data-Over-Cable Service Interface Specifications; DOCSIS 3.1 Physical Layer Specification, CM-SP-PHYv3.1-I10-170111

[7] Data-Over-Cable Service Interface Specifications; DOCSIS 3.1 MAC and Upper Layer Protocols Interface Specification, CM-SP-MULPIv3.1-I10-170111