RFoG: OVERCOMING THE FORWARD AND REVERSE CAPACITY CONSTRAINTS

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Abstract

The paper will present technical analysis and performance modeling for forward transmitters to show that in the absence of RF loss in the access distribution networks, bandwidth in excess of 1.6 GHz and capacity in excess of 10 Gbps can be supported at nominal incremental cost. Hence, in this case, RFoG has the potential of exceeding 10G PON/EPON forward capacity without the need to add overlay systems.

For the reverse path, the paper will show how FDD can take advantage of forward and reverse wavelength separation (WDD) to support full duplex communication in RFoG systems with very high upstream path capacity. Ultimately, WDD enables the capacity of an entire single wavelength to be dedicated to the forward or the reverse path. This increased capacity in the upstream can exceed 1 Gbps and be provisioned in a manner that provides full compatibility with the deployed network edge equipment; equipment in the headend and even more importantly consumer electronics and the operator's terminal equipment on the customer premises.

INTRODUCTION

The industry has agreed – there will always be the need for more bandwidth driven by higher data speeds, over-the-top services, 3D-TV, more HDTV – the list goes on. There is no such concept as 'too much bandwidth.' However, the industry's newest architecture, RFoG, has until very recently suffered from quite the opposite – it was unable to match the capacity of proven HFC networks. Initially RFoG deployments were motivated mostly by the desire to provide FTTH networks based on business considerations unrelated to the cost or capability of the technology. Given the investment required, it was important for RFoG to match the capabilities of HFC networks. The technology has successfully accomplished this objective within the first four years of deployment.

The technology today allows for all of the below:

1) Reach of 20 km in a passive configuration with 32-way field split;
2) Support for full forward capacity of the HFC network;
3) Support for reverse capacity of 27-30 MHz load with up to four 6.4 MHz 64-QAM signals with adequate operational margins;
4) All of the above with a combining group of 500 customers (1,000 HP) for highly interactive services;
5) And with analog modulated reverse laser technology to provide the widest possible interoperability.

Extended reach for customers located further than 20 km from headends and hubs was also added to this list of accomplishments.

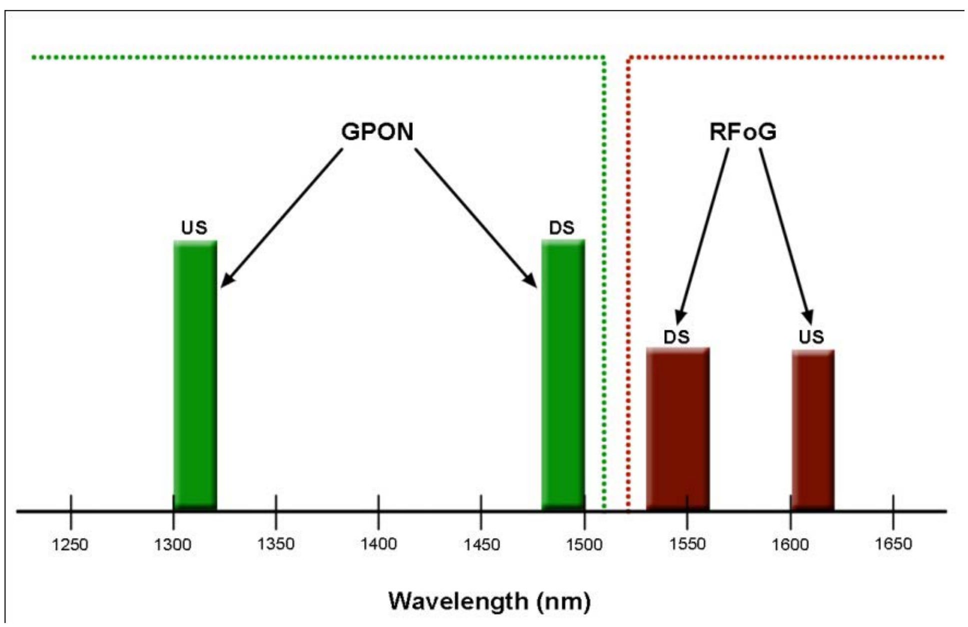
To complete the list, the RFoG technology was enhanced with the capability to prevent OBI when non-TDMA reverse access protocols are used (e.g., S-CDMA) or several (multiple MAC domains), non-synchronized multiple TDMA services are activated or ingress is high enough to break the reverse transmitter squelch[1, 2].

What happens next, when even more bandwidth is required? This is the question that all broadband telecommunications network operators are pondering.

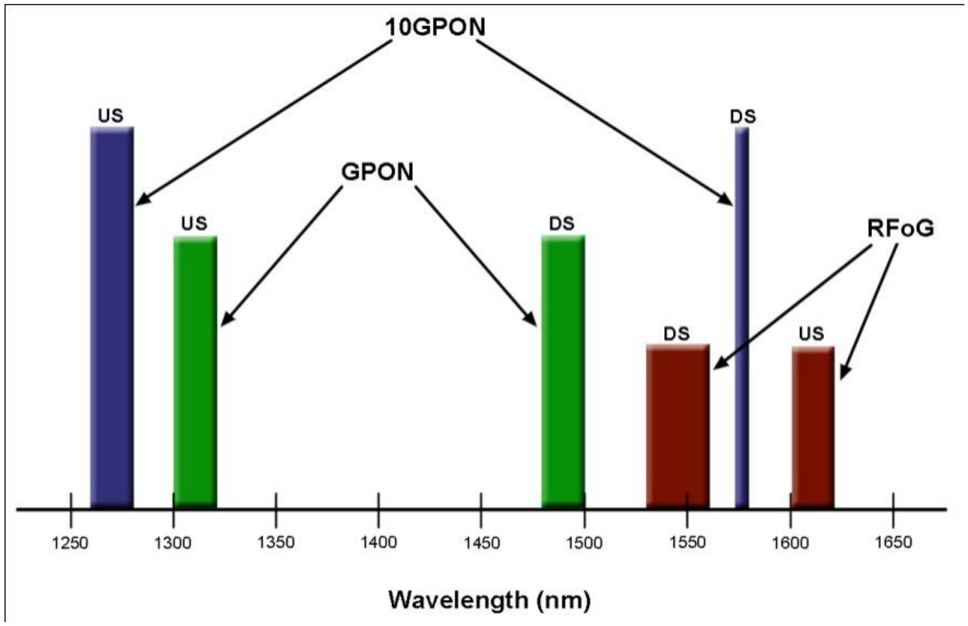
RFoG networks offer some comfort to the operators who installed them based on other considerations. These networks offer options for expanding both forward and reverse capacity in an easy to implement manner. In a world of changing and growing demand for capacity and continuously changing traffic parameters (with asymmetrical capacity demand in the forward and reverse directions continuously changing based on the traffic characteristics of an application "du jour"), the ease of capacity expansion for installed RFoG networks is a critical factor adding to their benefits.

RFoG FTTH AND PON OVERLAY

An RFoG network is a specific case of an FTTH system. The downstream and upstream wavelength selection can enable compatibility of the RFoG network with other FTTH technologies such as GEPON or GPON. The selection of wavelengths for achieving such compatibility with GPON and 1G EPON (a.k.a. GEPON) has been defined by the industry and documented in the SCTE RFoG standardization effort[3]. This wavelength allocation as currently defined by the industry is presented in Figure 1 and enables compatibility with GPON and GEPON systems by addition of a relatively simple optical diplex filter. However, to also achieve compatibility with 10G PON and 10G EPON systems, a more complex, and expensive optical filter would have to be deployed. This translates into higher cost of the R-ONUs (RFoG ONUs).



a) Wavelength Compatibility with GPON/GEPON Overlay (with Optical Filter Overlay)



b) Wavelength Allocation for RFoG Compatible with GPON, GEPON and 10G PON/EPON

Figure 1: Existing Recommended Wavelength Allocation for RFoG System Compatible with GPON/GEPON Systems

Modified wavelength allocation remedies this situation. Figure 2 depicts a wavelength allocation for compatibility with GPON/GEPON and 10G PON/EPON systems by allowing a simple optical filter to separate RFoG and PON wavelengths. An RFoG system with wavelengths presented below is simple to build with a low incremental cost for an optical filter. The simplicity of the internally integrated RFoG filter for separating forward and reverse signals at the R-ONU is also maintained.

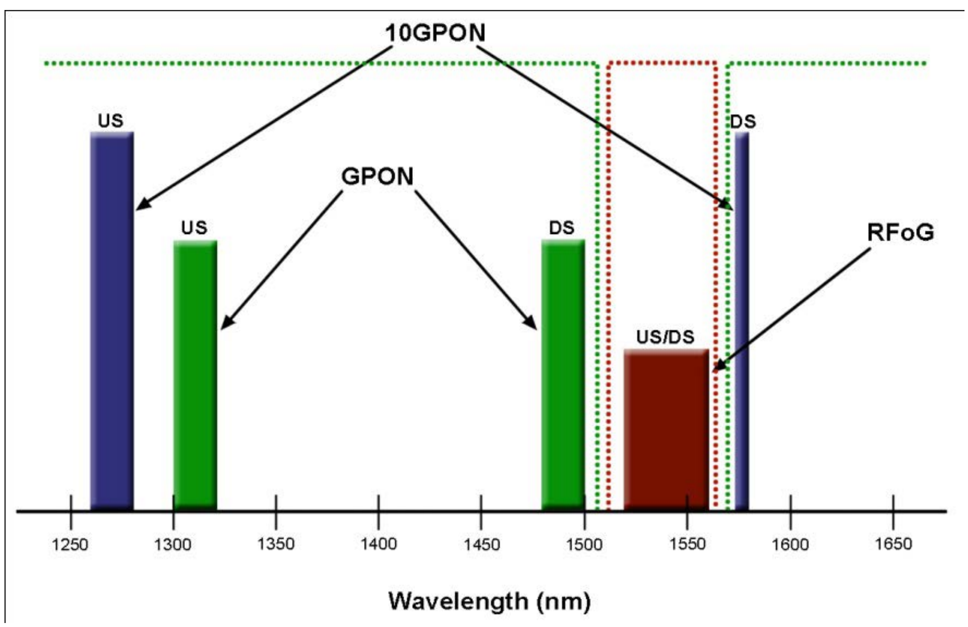


Figure 2: Proposed RFoG Wavelength Allocation for Compatibility with GPON/GEPON and 10G PON/EPON Systems

PON overlay over RFoG network permits fast expansion of the network capacity in both the forward and reverse paths beyond that readily achievable in HFC systems. Forward capacity can be enhanced by 10 Gbps in the forward direction and by 1, 2.5 or 10 Gbps in the reverse direction.

Although forward capacity expansion can be accomplished in HFC networks, this comes at a significant upgrade cost. Traditional HFC network of 1 GHz can support approximately 6 Gbps capacity with conversion to digital-only load. Further expansion of forward capacity would require both an upgrade of the network performance and, related to it, increased maintenance cost (to support 1024-QAM signals) or bandwidth expansion of the optical transmitters, nodes, RF amplifiers and passives (with the associated labor cost). The expansion of the reverse capacity in HFC networks is even more difficult and costly.

Although both forward and reverse capacity expansion is less burdensome and costly to address in Fiber Deep HFC N+0 networks, a PON overlay for RFoG network provides an easier path. However, easier might not necessarily mean less costly. This expansion of capacity with PON overlay requires the addition of a new set of edge devices with duplication of optoelectronics. The cost, including additional headend components, optical filters, R-ONUs compatible with PON overlay and PON ONUs can range between $200 and $500/customer today even with just a moderate increase in capacity by deploying GPON or GEPON components.

Our industry elected to use FTTH RFoG systems for residential services instead of converting to FTTH PON systems to preserve the deployed base of and sizeable investment in headend and hub equipment and consumer electronics and consumer terminal equipment through the preservation of the FDM structure of the transported signals. The RFoG network delivers the same FDM signals as the traditional HFC network. But the most important fact is that with the technological advances of the last five years, RFoG systems can be built to provide capacity expansion paralleling (if not exceeding) the capacity the expansion offered by PON overlay at a cost projected to be lower (possibly significantly lower) than the cost of additional PON overlay equipment and overlay filters and without the need for any other RFoG upstream wavelength than 1310 nm.

RFoG WITH EXPANDED CAPACITY

The RFoG network, as already explained above, is an FTTH system. It supports FDM signals while *x*PON systems today deliver services by transporting digital baseband (TDM) signals. This difference stems from historical differences in the transport media used by operators favoring RFoG systems and operators favoring *x*PON systems. RFoG is favored by operators that historically used coaxial cable with RF amplifiers for reach extension to deliver telecommunication services to their customers while *x*PON systems are favored by operators that historically used passive copper pairs. These two systems differ in the way they support bidirectional communication: active coaxial systems achieve it through FDD (efficient for long distances supported by active coaxial networks) while passive copper system support it with TDD suitable for shorter distances and lower speeds. Passive coaxial network in HFC N+0 systems can also support bidirectional communication using TDD.

Fiber can easily transport either FDM RF signals (and has been deployed in these applications since the late 1980s) or baseband digital signals. Fiber based FTTH systems, whether RFoG or PON, can support FDM RF signals and baseband digital signals as well. Despite being passive in nature for the last several miles, both RFoG and *x*PON systems support bidirectional communication based on perfect FDD technology: WDD. In the case of *x*PON networks, forward and reverse signals occupy overlapping frequency bandwidths and full duplex service is enabled by WDM technology. In the case of traditional RFoG systems that mimic HFC networks, the FDD used in the active coaxial network has been preserved to support bidirectional communication. This arrangement allows compatibility with the existing consumer equipment and terminals and headend/hub equipment.

However, FDD is not technically required to support full duplex communication in RFoG PON because forward and reverse signals are carried on separate, not conflicting and well isolated wavelengths. Figure 3 depicts the simple fact that as long as the FDM RF signals are kept from overlapping each other before EO and after OE conversions, they can occupy overlapping RF bandwidths in the fiber where they are carried on separate wavelengths.

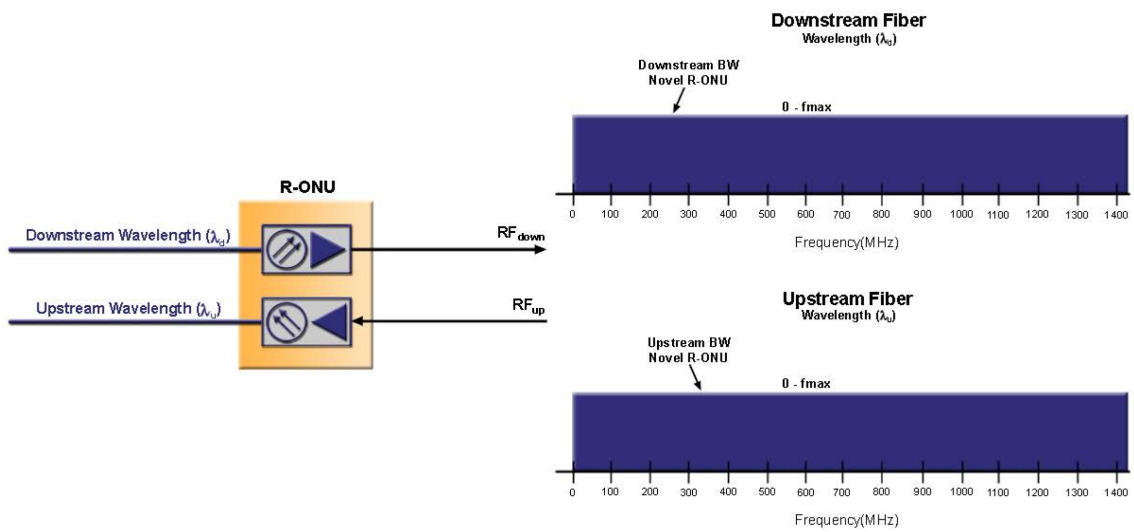


Figure 3: WDM as Replacement for FDD

<u>Forward Capacity</u>

WDM technology enables dedication of the entire single wavelength capacity either to forward or reverse signals. How much wavelength capacity can be used in a particular system will depend on edge equipment quality and many other non-trivial factors. In the forward direction, several solutions for increasing forward capacity are available. One of the most straightforward is increasing capacity of the forward transmitter.

The analysis below is based on the assumption that before additional capacity is added to an RFoG network, the transition to digital-only load has been completed. The following performance of the RFoG network forward components and parameters of the carried signals are also assumed:

1) Link loss budget of 19.5 dB at 1550 nm:
   a. Fiber length of 6 km (1.5 dB loss)
   b. Passive loss of 18 dB (splitters for 32 and filters)
2) Transmitter:
   a. Directly modulated
   b. 10 dBm optical output power
   c. Transmitter load of 149 channels with 256-QAM signals
3) R-ONU receiver:
   a. Thermal noise performance of 5 pA/√Hz (after the filter separating forward and reverse wavelengths)

Under these assumptions with predistortion circuitry implemented to compensate for dispersion/chirp related second order CIN, CNR for the RFoG optical link will equal approximately 40 dB. The test results for this fiber length and received input level confirm the modeling numbers.

The same transmitter can be used to carry signals above 1,002 MHz for additional capacity. Let us make assumptions about these signals:

1) Additional load of 600 MHz
2) Modulation of 64-QAM
3) Level relative to the load below 1,002 MHz at −6 dBc.

For this transmitter type, two factors will affect the link CNR after the additional load is implemented:

1) Lower OMI/channel at the same composite OMI,
2) Higher CIN caused by additional second order intermodulation products due to interaction between the laser chirp and fiber dispersion.

The OMI correction for CNR is simple to calculate and for the assumptions listed above will approximate to 0.7 dB CNR degradation for 256-QAM channels based on the following equation:

$$10 \times \log \left({}^{N_1}\!/_{N_2} \right)$$

where:

N_1 – channel count for the original load (149 channels)

N_2 – equivalent (in level to 256-QAM channels) channel count for the new load equivalent (149 + 100/4)

The CNR correction for second order CIN is more difficult as it depends on predistortion circuitry efficiency. Assuming no predistortion, the following equation can be used to calculate noise floor relative to additional 64-QAM channel levels.

$$N(f)_{64-QAM} = 10 \log \left[N_{CSO} \left(2\pi f\, m \frac{\lambda^2}{c} D\, L\, \upsilon \right)^2 \right]$$

where:

N_{CSO} – number of CSO beat products at RF frequency f

m – OMI (per channel) of the added 64-QAM channels

D – fiber dispersion

L – fiber length

λ – optical wavelength of the transmitter

ν – laser chirp at 100% peak OMI.

Figure 4 presents the beat count plot for beats generated by the additional load between 1,002 and 1,602 MHz and the level of CIN relative to frequency of the beats. Figure 5 presents the noise (as defined by the equation above) generated by the beats for lasers of different chirp at the frequency of the worst performance (~400 MHz). The noise floor is referenced to the level of 256-QAM channels (6 dB higher than the channels within 1,002 and 1,602 MHz frequency range).Although each beat power is spread over double the channel width, they overlap except for the extreme frequencies of beats hence the correction for the peak value of noise floor can be neglected (noting that a small downside correction could be applied due to the fact that the QAM channels is only 5.3 MHz wide).

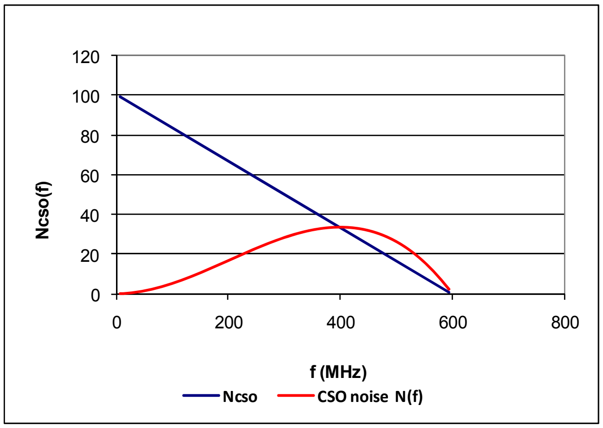


Figure 4: CSO_ beat count distribution and their relative level as a function of frequency

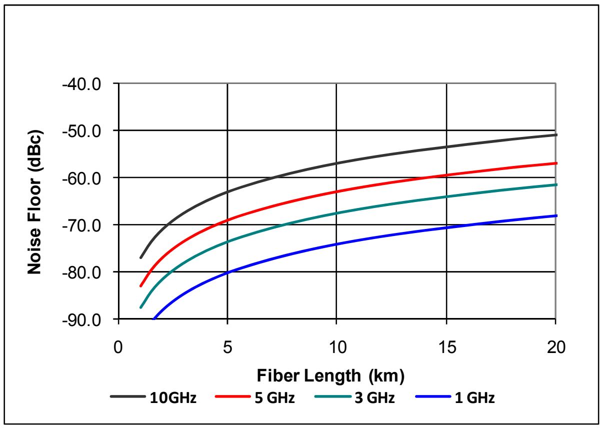


Figure 5: CIN noise caused by the load between 1,002 and 1,602 MHz at the worst frequency relative to the level of 256-QAM signals for lasers with different chirp

The noise levels depicted in Figure 5 are negligible for the distances used in the model (6 km) even without predistortion. It is therefore safe to assume that the CNR degradation caused by additional load of the forward transmitter for the link described and under the assumptions presented above will be limited to 1 dB across the 108 to 1,002 MHz bandwidth.

The assumptions above define only one of many possible sets of conditions but there are many tools at the disposal of optical link engineers to extend the reach and to allow different channel loading. The performance modeling is indispensable during the selection of these tools and the topology of the network.

In the example described above, forward capacity was expanded by approximately 2.8 Gbps without significant additional cost (except for the cost of NRE to be recovered by the vendors). Many other technologies and approaches are available to expand capacity even further. Tools for expanding RFoG network bandwidth up to 2 GHz with 256-QAM load across all frequencies are readily available. These tools can more than double the forward bandwidth from approximately 6 Gbps to 12.5 Gbps. This bandwidth can scale from supporting 1,000 HP to being shared among 32 HP (and even fewer customers). It provides unbeatable and scalable offer in terms of cost and capacity in all RFoG systems where there is no RF loss heavily dependent on frequency as is the case in coaxial networks.

Reverse Capacity

The forward capacity expansion in RFoG systems is quite dramatic and achieved at relatively low incremental cost. But even more dramatic is the capability for expansion of the reverse capacity way beyond the capacity of today's 5-42, 5-65 and even 5-85 MHz HFC networks. The capacity of these systems can at best reach 120, 240 or 360 Mbps respectively. RFoG capacity is not limited by bandwidth. The bandwidth limitation is the legacy having its origin in HFC RF active networks that required FDD to support bidirectional traffic over relatively long distances with the help of amplification of both forward and reverse signals. The asymmetry of the FDD arrangement was created due to limited demand for reverse capacity and due to the fact that most of the spectrum above 50 MHz was allocated to off-air broadcast services, with consumer electronics designed to receive those signals.

In RFoG systems where the entire wavelength is dedicated to carry reverse signals between electrical interfaces, the bandwidth limitation disappears. How much bandwidth can be used and how much capacity can be provided depends on the system architecture and performance of its components.

The tradeoffs[4] among several network parameters can significantly increase RFoG network potential for expanded capacity. In this paper, two of them will be explained in detail.

One of the two factors is the level of aggregation. The HFC networks show high level of flexibility in aggregation levels. Fortunately, thanks to the technological advances in RFoG reverse receivers, this aggregation flexibility has been maintained. Figure 6 depicts a design of a high aggregation receiver that avoids the penalty of RF combining of typical HFC receiver outputs. A careful compromise between thermal noise performance of the front end of this receiver and parasitic parameters of the photodiodes used in this example enable expansion of the available bandwidth to between 300 and 400 MHz at reasonable thermal noise performance (see Figure 7) and aggregation levels of 128 HP. When the capacity available in this design becomes insufficient, de-aggregation (see Figures 8 and 9) can lead to higher bandwidth and hence increased aggregate (burst) capacity and capacity-per-user in the reverse path (see Figure 10). This last de-aggregation step provides RFoG customers with the ultimate bandwidth that photodiodes analyzed in this example can support.

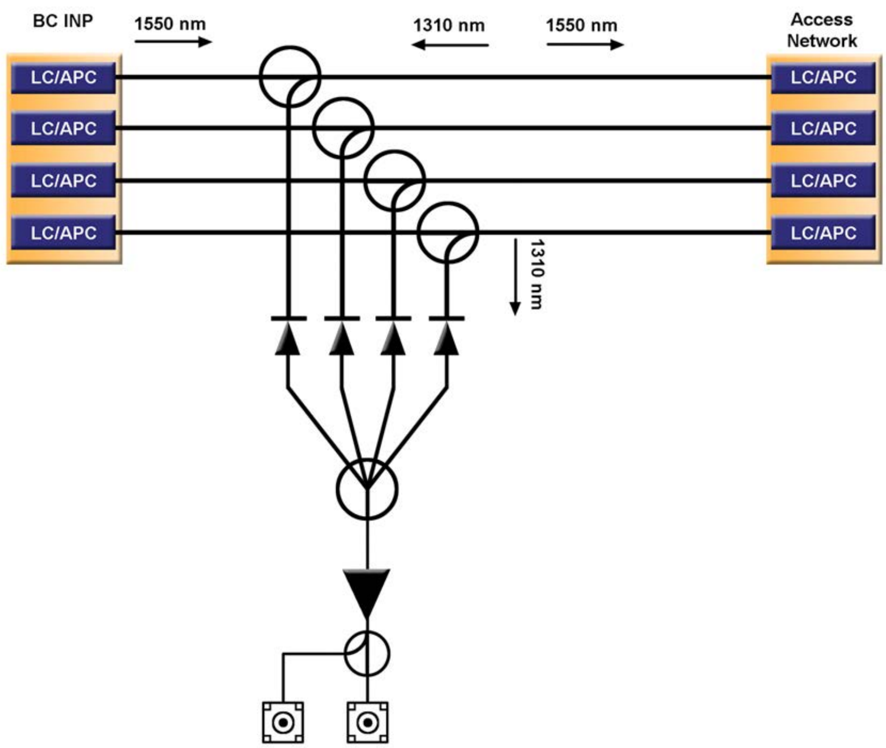


Figure 6: Design of High Aggregation Receiver without Noise Aggregation Penalty

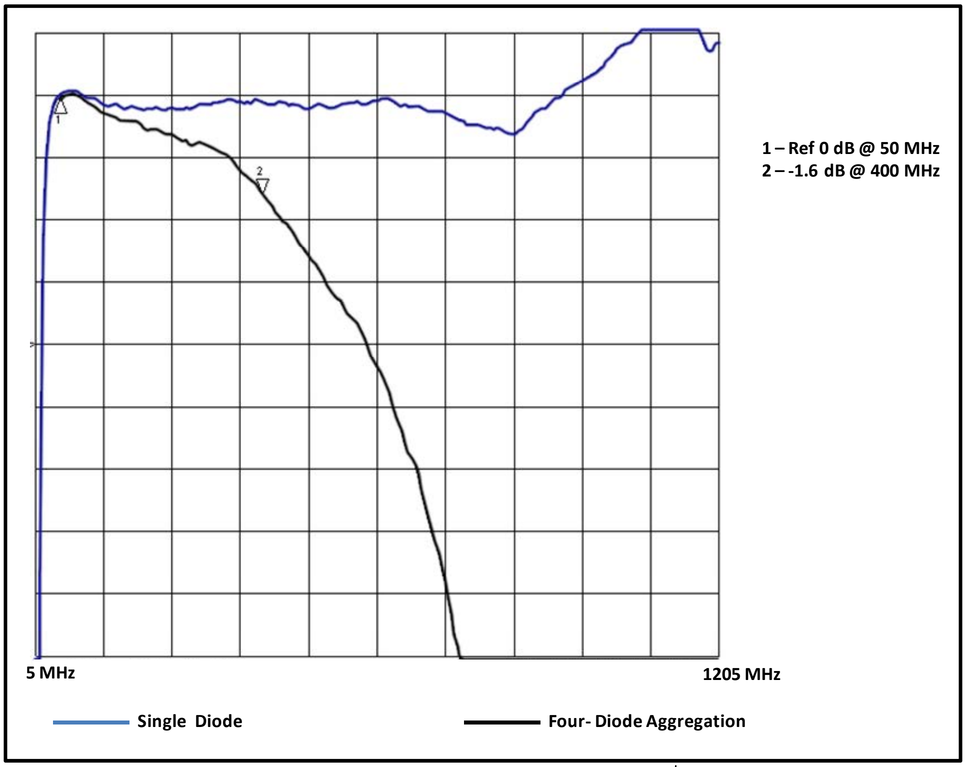


Figure 7: Bandwidth Capacity for 128 HP Aggregation Level and 4 pA/√Hz Equalized Thermal Performance

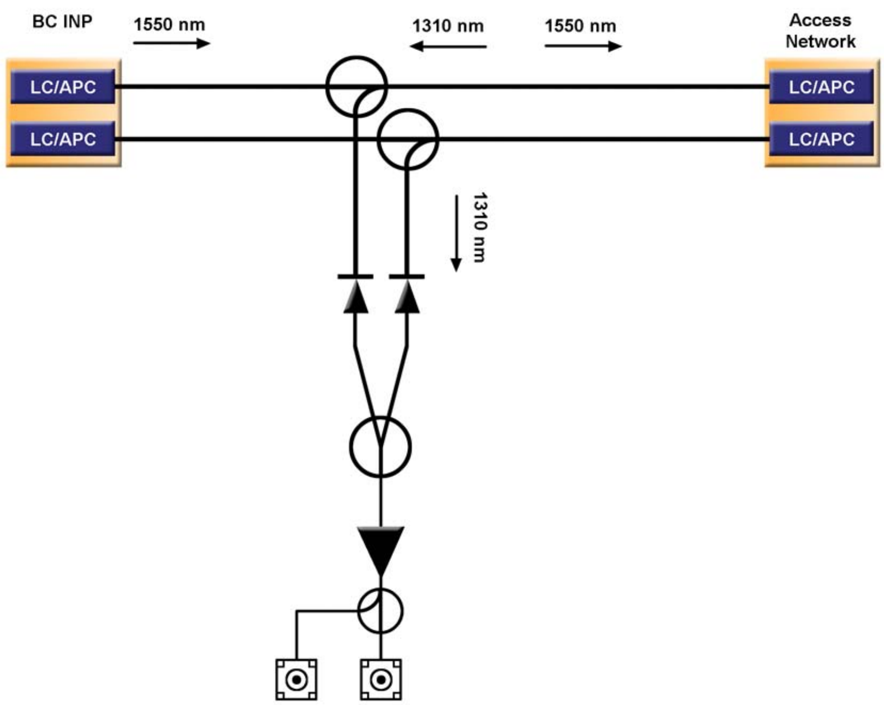


Figure 8: Reverse Receiver Design with 64 HP Aggregation Level

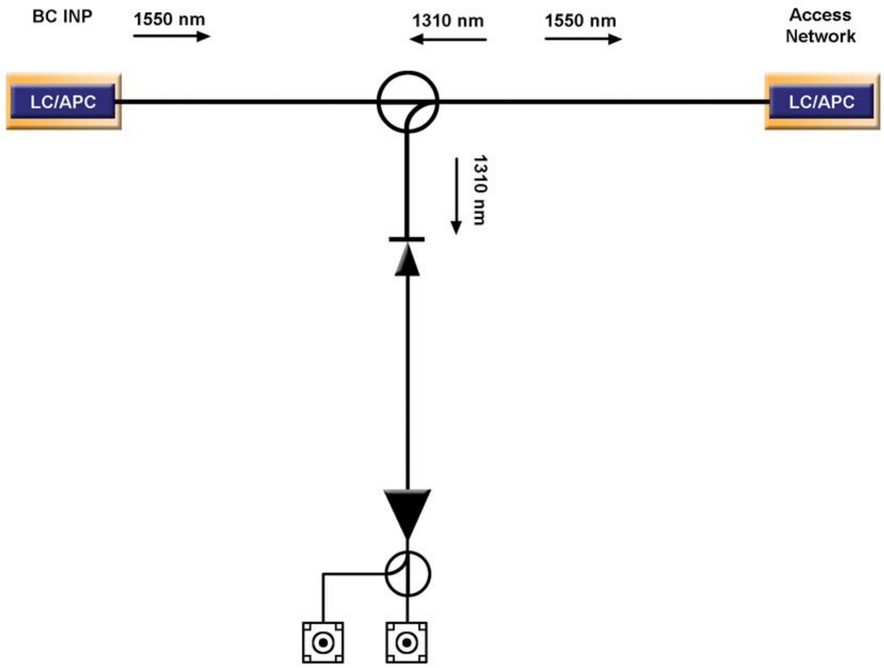


Figure 9: Receiver for 32 HP without Aggregation

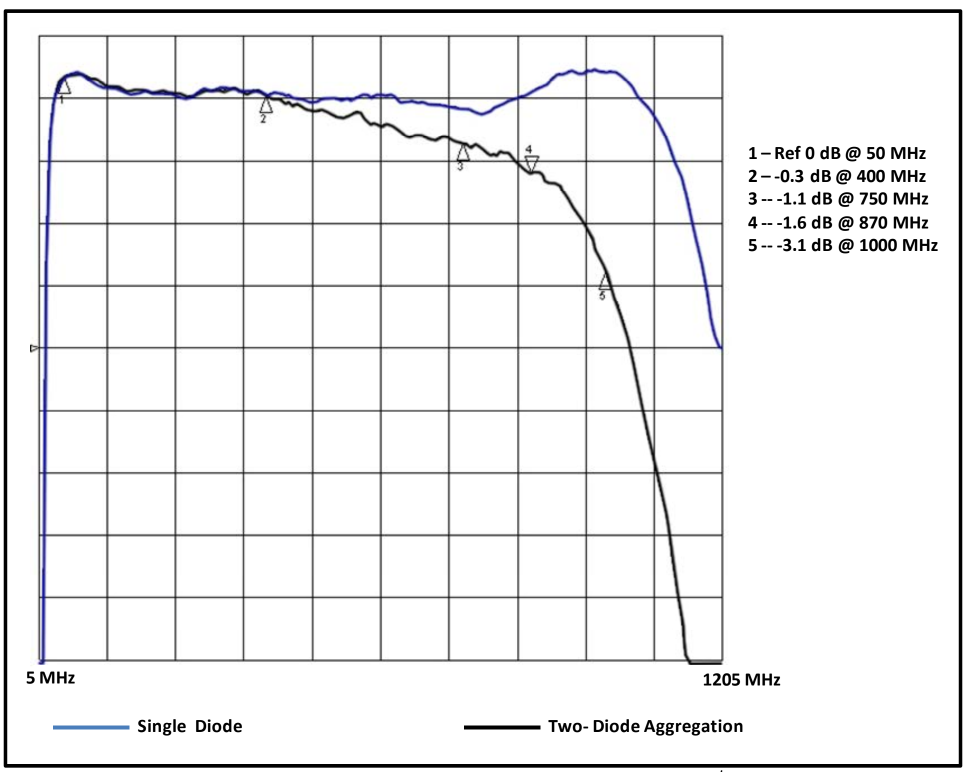


Figure 10: Bandwidth Capacity for 64 and 32 HP Aggregation Levels and 4 pA/√Hz Equalized Thermal Performance

Thermal noise performance plots in Figures 7 and 10 indicate that at 4 pA/√Hz equalized thermal noise performance, the available bandwidth for:

- 128 HP aggregation level is 320 MHz
- 64 HP aggregation level is 640 MHz
- 32 HP aggregation level is 960 MHz.

Based on the available bandwidth and digital signal requirements, several capacity configurations were modeled under the following assumptions:

1) Link loss budget of 19.0 dB at 1310 nm:
    a. Fiber length of 6 km (2.0 dB loss)
    b. Passive loss of 17 dB (splitters for 32 and one filter)
2) R-ONU transmitter:
    a. Directly modulated
    b. 2 dBm optical output power
    c. Transmitter load as in analyzed load capacity models
3) Headend receiver:
    a. Thermal noise performance of 4 pA/√Hz (after the filter separating forward and reverse wavelengths)
    b. Bandwidth as in analyzed aggregation examples
4) The channels are assumed to be similar to DOCSIS® channels (channel bandwidth, modulation and symbol rates).

Example 1:

At an aggregation level of 128 HP, the network is bandwidth limited and the capacity is optimized with 50x6.4 MHz channels of 64-QAM modulation. The modeled performance (see Figure 11) indicates just sufficient operational dynamic range for 10E-6 uncoded BER performance. The total reverse capacity is 1.5 Gbps. With these channels bonded, the burst capacity would exceed the burst capacity of GEPON networks or traditional RFoG capacity with GEPON overlay.

Example 2:

At an aggregation level of 64 HP, the network is performance limited and the capacity is optimized with a mix of 64-QAM and 16-QAM channels. Maintaining the same dynamic range for 64-QAM channels as in example 1, the optimal capacity would be supported with approximately 38x6.4 MHz channels of 64-QAM modulation and 62x6.4 MHz channels of 16-QAM modulation for a total reverse capacity of 2.4 Gbps. However, for operational simplicity at this level of aggregation, loading with 100x16-QAM would be preferred. It would provide wider operational dynamic range and uniform loading across the entire bandwidth.

Example 3:

At an aggregation level of 32 HP (single RFoG group), the network is performance limited and the capacity is optimized with 150x6.4 MHz channels of 16-QAM modulation. The modeled performance (see Figure 12) indicates comfortable operational dynamic range for 10E-6 uncoded BER performance. The total reverse capacity is 3 Gbps. Up to 12x6.4 MHz channels of 64-QAM modulation to support legacy modems at the highest possible capacity can be added at lower frequencies with the remaining load of 16-QAM channels. Although the capacity gain in this case is minimal, it could be beneficial to support legacy modems at higher rates. Alternatively, wider operational dynamic range can be traded for longer reach (extended to 10 km).

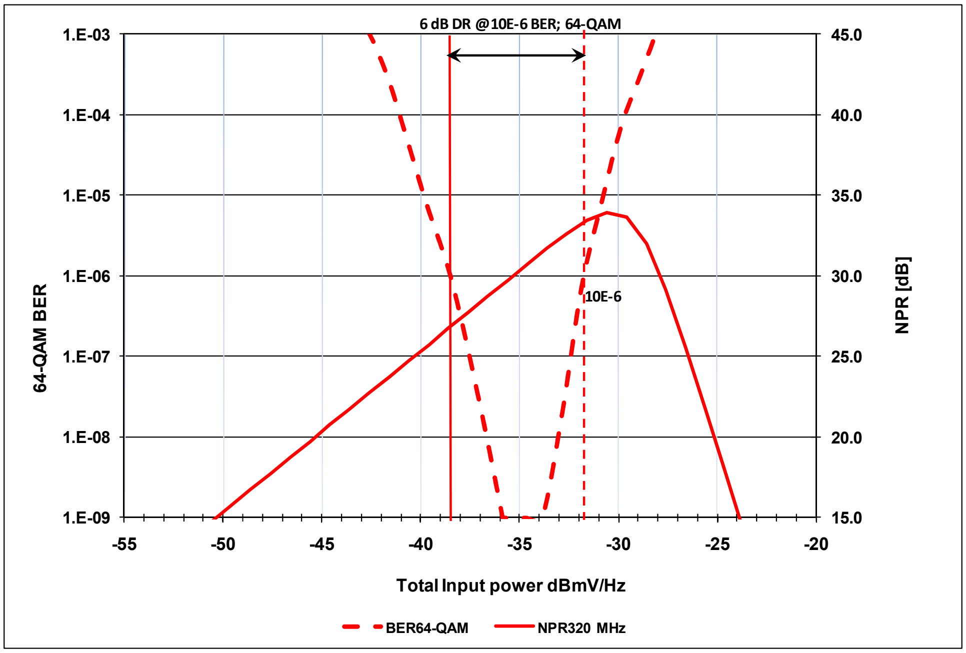


Figure 11: Reverse RFoG System Performance at 128 HP Aggregation Level with 320 MHz Load of 64-QAM Signal

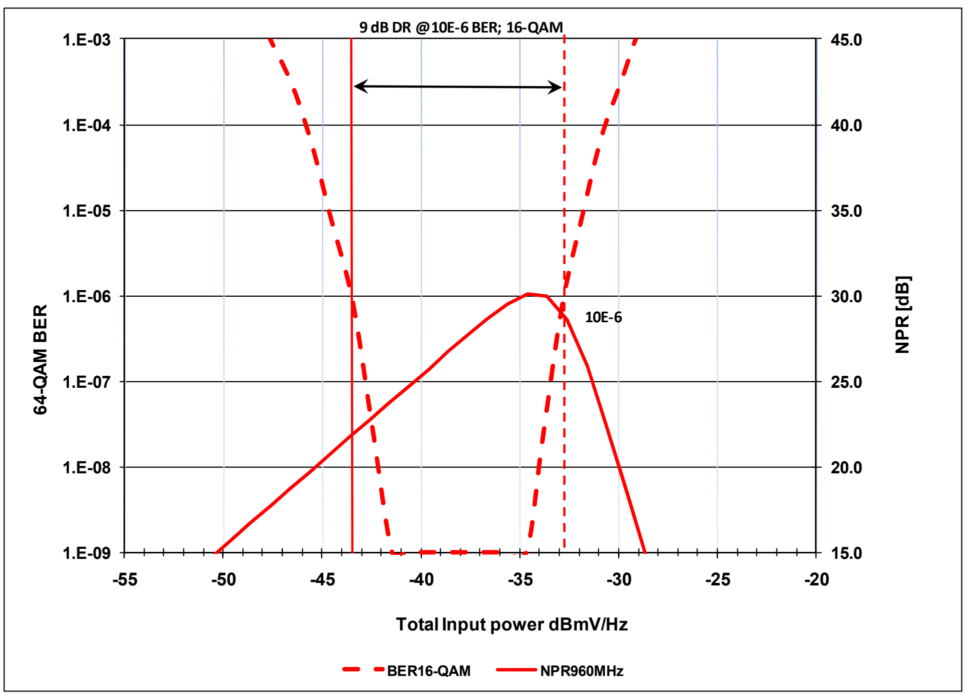


Figure 12: Reverse RFoG System Performance at 32 HP Aggregation Level with 960 MHz Load of 16-QAM Signal

The examples described above document that even with quite standard components, RFoG FTTH networks can significantly expand reverse capacity available to operators. Free of the FDD bandwidth constraints of coaxial active networks, RFoG FTTH networks can match and exceed capacity of the PON networks while preserving operators' investment in headend/hub equipment and consumer electronics whether owned by the operator or by customers. This is due to the fact that the RFoG networks preserve the FDM nature of signals.

The capacity expansion implementation of must take this desire to preserve investment into account to enable the legacy equipment to operate without interference while providing the extended capacity in the forward and reverse directions.

RFoG Capacity Potential: Recapitulation

RFoG FTTH systems are capable of supporting full-duplex (bidirectional) communication without maintaining reverse and forward signals in different frequency ranges. The FDD required in coaxial active networks to separate these signals is replaced with WDM where different wavelengths can carry overlapping RF bandwidths, especially in a counter-propagating mode. This fact enables RFoG networks to provide capacity matching capacity of GPON/GEPON and 10G PON/EPON systems as explained in the paper. Moreover, given that there is no RF distribution network to speak of, the levels in the forward and the reverse bandwidth do not have to be excessively high to secure adequate performance. Finally, the required isolation between the legacy equipment and extended bandwidth signals can be accomplished within the R-ONU.

Figure 13 presents an example of an R-ONU implementation that separates legacy signals in a manner compatible with all consumer electronics and consumer terminal equipment using built-in isolation between the legacy HFC signals and the signals supporting enhanced capacity. It also provides a separate port for the FDD RF signals with enhanced (symmetrical or asymmetrical) capacity service. This R-ONU is transparent to signals appearing on the second port as long as they observe the frequency allocation of that FDD system. The frequency allocation, channel scheme, modulation type and level, coding and protocols of these signals are at the discretion of the system operator assuming that the link (downstream and upstream) performance is adequate to transport these signals unimpaired.

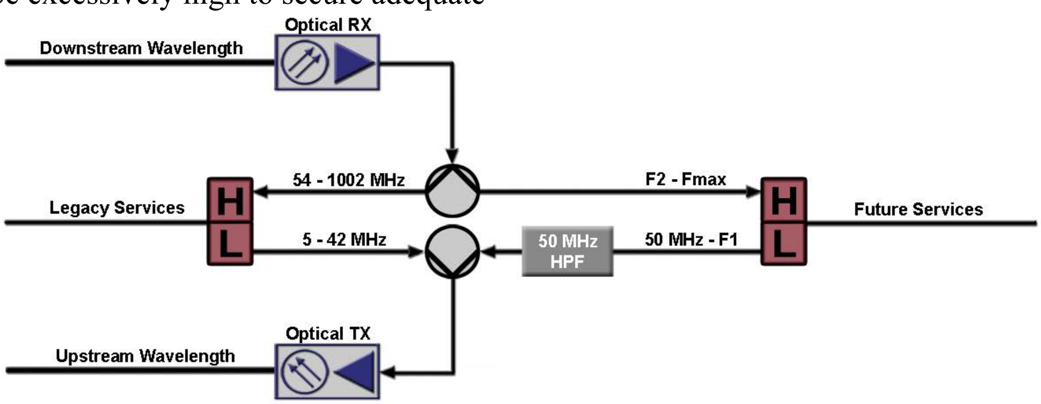


Figure 13: Example of High Capacity R-ONU with Legacy and Enhanced Capacity FDD Bi-Directional Communication (F1<F2)

Many other implementations[4] are feasible, including implementations with integrated cable modems, advanced cable modems for expanded capacity, home networking circuitry, EMTA for voice services and other service terminals.

CONCLUSIONS

RFoG systems are the networks of choice in green field scenarios for operators who prefer the FDM signal delivery method for communication services, especially in places where the construction cost of such a network is lower than the construction cost of an equivalent HFC network. As reported by the industry, this is usually the case where population density falls below approximately 50 HHP/mile. Other business considerations may also influence RFoG technology selection for deployment in a particular project. RFoG systems match HFC network capacity and flexibility but more importantly, they can exceed it. Indeed, operators who deploy these systems can be assured that the system can readily be provisioned or upgraded at any time in the future for capacity well in excess of any HFC network deployed today. They can match and exceed the capacity of GPON/GEPON and 10G PON/EPON networks at minimal incremental cost while preserving all the benefits of HFC networks. The capacity expansion can be accomplished with PON overlay. However, significant cost reduction can be accomplished by deploying enhanced capacity RFoG systems at minimal incremental cost if any. The choice of options will be dictated by the operators' preferences and cost considerations. Modern RFoG systems are basically future-proofed.

ACKNOWLEDGEMENTS

Krzysztof Pradzynski and Sudhesh Mysore contributed critical material and analysis to this paper to enhance its value. The author wishes to thank them for their contributions.

ABBREVIATIONS AND ACRONYMS

10G PON	ITU-T's next-generation broadband transmission standard with 10 Gbps throughput, a.k.a. 10G-PON or 10GPON
10G EPON	IEEE 802.3 Ethernet PON standard with 10 Gbps throughput, a.k.a. 10G-EPON or 10GEPON
BER	Bit Error Rate
CIN	Composite Intermodulation Noise
CNR	Carrier-to-Noise Ratio
DOCSIS®	Data over Cable Service Interface Specification
DR	Dynamic Range
EMTA	Embedded Multimedia Terminal Adapter
EO	Electro-Optical
FDD	Frequency Division Duplex
FDM	Frequency Division Multiplexing
FTTH	Fiber to the Home
GEPON	IEEE 802.3 Ethernet PON standard with 1 Gbps throughput, a.k.a. 1G-EPON, G-EPON or 10GEPON
G PON	ITU-T G.984 Gigabit PON standard with 2.488 Gbps throughput, a.k.a. 1G-PON or G-PON
HDTV	High Definition Television
HFC	Hybrid Fiber Coaxial
HHP	Households Passed
HP	Households Passed
MAC	Media Access Control
Mbps	Mega Bits per Second
NRE	Non-recurring Expense
OBI	Optical Beat Interference
OE	Optical-Electrical
OMI	Optical Modulation Index
ONU	Optical Network Unit
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
RFoG	Radio Frequency over Glass
R-ONU	RFoG Optical Network Unit

S-CDMA	Synchronous Code Division Multiple Access
SCTE	Society of Cable Telecommunications Engineers
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
WDD	Wavelength Division Duplex
WDM	Wavelength Division Multiplexing
*x*PON	Any of a family of passive optical network standards (e.g., GPON, GEPON, 10G PON)

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