Unified Architectures for Remote PHY Backhaul and 5G Wireless Fronthaul

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1. Introduction

Remote PHY (RPHY) deployment started in 2017 in some MSO networks. RPHY works well in deep fiber architecture; it puts RF modulation devices deep in the field, attached to the N+0 coax outside plant, while keeping MAC and higher layer devices in the center of the network, e.g.., in the Headend or data center. One of the main advantages of RPHY architecture is the efficiency. By moving RF modulators closer to the customers, higher order modulations such as 2K and 4K QAM can be used, therefore increasing the network efficiency. However, there are challenges for RPHY architecture. Besides the technical challenge of synchronizing RPHY and MAC, it also poses challenges on the backhaul network for RPHY. The communication protocol between RPHY and MAC is Ethernet at a rate of multiple Gigabit/s. To backhaul large amounts of high-speed Ethernet traffic in MSO's access networks is a challenge.

Another deployment in the communication industry is coming 5G wireless network services. Although most of the MSOs do not directly provide wireless services (not including Wi-Fi) to the end-customers today, many of them are contracted by wireless carriers to provide wireless backhaul and/or fronthaul services in their networks. The amount of data to backhaul 5G wireless is expected to increase greatly and pose a challenge to MSO's metro and access networks.

RPHY and 5G backhauls are new to MSO; it poses big challenges to MSO's access network. To design a unified and converged access network to backhaul RPHY and 5G traffic and at the same time align with the MSO long term migration direction to passive all fiber access networks is an even bigger challenge.

In this paper, we first analyze MSO's current access network architectures for DOCSIS and PON services, then discuss the options for RPHY and 5G wireless backhauls. We then propose two unified fiber access network architectures. One is based on DWDM and the other is based on PON, to backhaul RHPY and 5G wireless traffic.

2. MSO's Access Networks Today

Generally speaking, MSO's access networks today consist of HFC (hybrid fiber coax), active optical Ethernet Network (AON) and PON (passive optical networks) as shown in Figure 1.

Legacy HFC, although under constant upgrade, is mainly providing DOCSIS protocol (D3.0, D3.1 etc.) based cable data, voice and video services. Point-to-Point (P2P) active optical Ethernet is occasionally used for business customers. PON, either GPON (2.5G), XGS-PON (10G) or 10G EPON are used in recent years to provide high-speed services, for example Gigabit to both residential and business customers. Among the above-mentioned access networks, HFC is mostly deployed. The deployment of PON, which is considered as the migration direction, is increasing. AON, active optical Ethernet, has limited deployment in MSO networks.

From OSP (outside plant) point of view, HFC has P2P fiber from a cable headend to an optical node in the field; and P2MP (point-to-multiple-point) coax cables from a node to the end-users as shown in Figure 1.

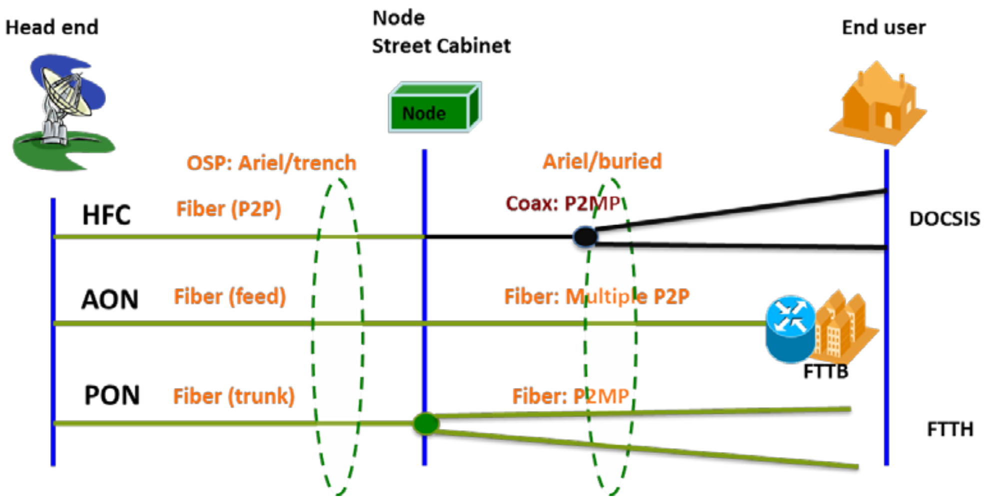

Figure 1 - MSO access architectures today

AON has P2P fiber from a headend to an end-user. A PON ODN (optical distribution network) has a P2MP fiber topology from a headend to the end-users.

3. Remote PHY and RPHY backhaul

3.1. Remote PHY in a nutshell

RPHY technology brings RF modulation deep in the field closer to the coax OSP. As a result, higher order modulations are possible for RPHY to increase efficiency, for example 4K and 8K QAM (quadrature amplitude modulation) are possible. DOCSIS MAC is physically located at the Headend or in data center servers. Gigabit to 10G Ethernet interfaces are assumed between RPHY and DOCSIS MAC. The RPHY and MAC are synchronized via SyncE, IEEE1588, etc.

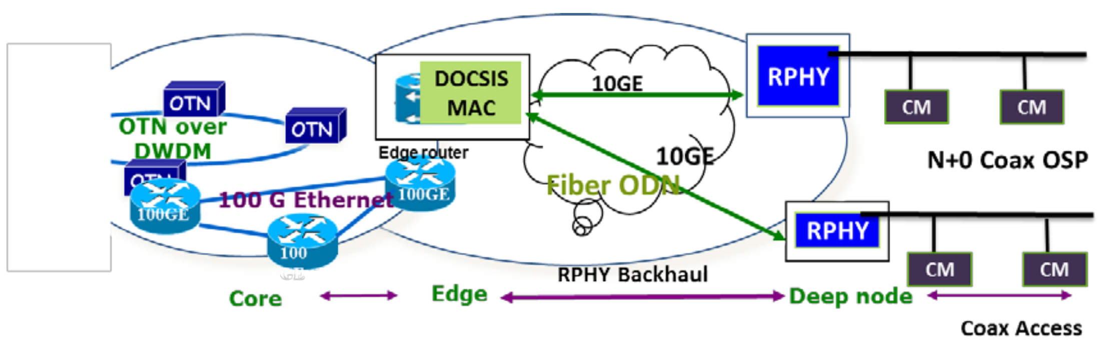

Figure 2 - Remote PHY

3.2. The network segment of RPHY

A RPHY node could be deployed deep in the access network segment, as shown in Figure 3. A HFC optical node normally feeds an "N+x" P2MP point-to-multi-point) coaxial cable plant, where the "x" in donates the number of RF amplifiers in the coaxial cable plant and "N" represents the HFC optical node.

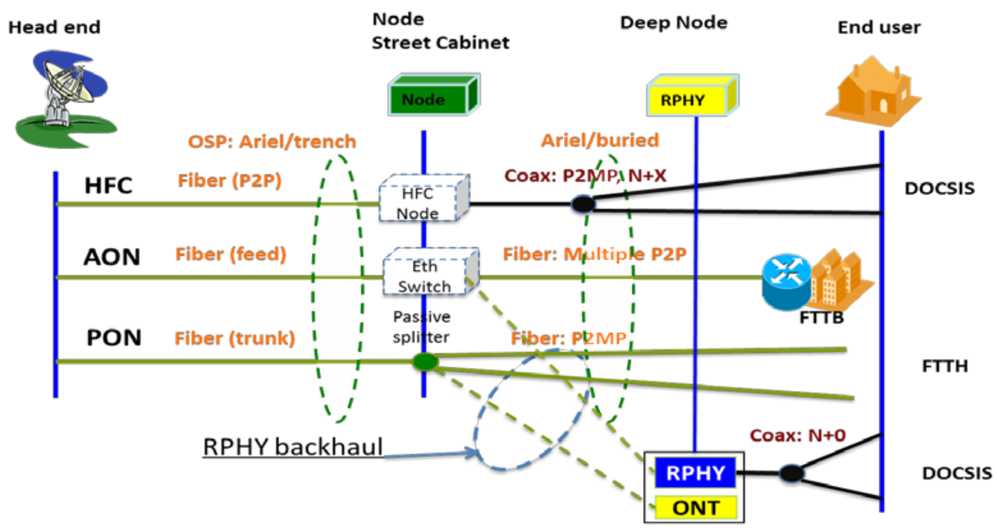

Figure 3 RPHY in MSO network

A RPHY often feeds a passive P2MP coaxial cable plant, which also is referred to as "N+0". Therefore, a RPHY node is located between a HFC optical node and the cable end-users. In this scenario, a RPHY node is a type of deep optical node.

3.3. RPHY backhaul

Under MSO's access network today, in reference to Figure 3, AON and PON can be used to backhaul RPHY traffic. In AON backhaul for RPHY, an Ethernet switch in the deep node location is used to aggregate RPHY traffic and uplink to the headend or data center via a P2P optical fiber. The advantage of AON backhaul is that it supports aggregation. The drawback is that there are active devices in the field. Since there are few AON in MSO's access network today, AON backhaul is not considered in the paper.

PON, such as XGS-PON, 10G EPON or NG-PON2, for RPHY backhaul is feasible. Since PON has been deployed in MSO access networks for many years and it is considered as the migration direction, PON RPHY backhaul provides a converged solution. We'll discuss PON for RPHY backhaul in section 6.

Another solution for RPHY backhaul is using passive DWDM which requires to the construction of a new DWDM OSP in the access network. It will also be discussed in section 5.

4. C-RAN 5G wireless fronthaul

4.1. 5G wireless fronthaul and backhaul in a nutshell

Several MSOs have been contracted to provide fiber connectivity for 3G and 4G fronthaul for wireless carriers for years. CPRI (Common Public Radio Interface), also called RoF (Radio over Fiber) has been used for 2G, 3G and 4G wireless fronthauls for wireless carriers for many years. The network for wireless backhaul and fronthaul architecture is called C-RAN (Centralized Radio Access Network), as shown in Figure 4.

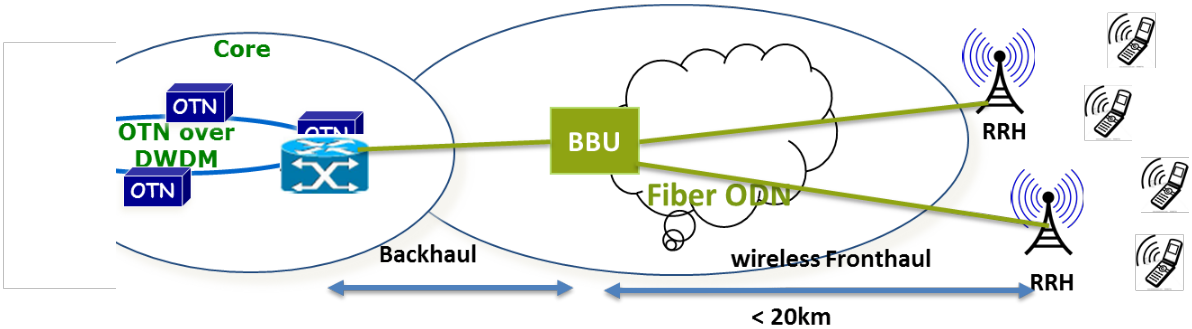

Figure 4 - C-RAN for wireless backhaul and fronthaul

Fronthaul fiber segments start from wireless BBU (Baseband Unit) to RRH (Remote Radio Head) running CPRI protocol. The fiber distance of a fronthaul segment is normally < 20km. The backhaul fiber segment is from BBU to the packet core network. The backhaul network is the packet data network, the fiber distance varies. The BBU is normally located at the wireless data center.

With the roll out of 5G services in the near future, there will be a huge increase in demand of fiber or DWDM wavelengths for fronthaul CPRI traffic.

4.2. Similarities of RPHY backhaul and 5G wireless fronthaul

There are astonishing similarities in network topologies for RPHY backhaul and 5G wireless C-RAN fronhaul. Figure 5 shows the network topologies of RPHY backhaul and 5G wireless fronthaul fiber networks.

- The fronthaul distance from wireless BBU to RRH is < 20 km. Statistics data shows that about 80% of RPHY are within 20 km distance from a cable headend.
- DOCSIS RPHY nodes and 5G small cell RRH are more closed to the end-users than their corresponding previous generations.
- Both RPHY backhaul and 5G wireless fronthaul networks can be built with P2P fiber, passive DWDM, active DWDM and high-speed PON.
- Both RPHY backhaul and wireless fronthaul need high-speed data transport networks, for example 10Gbps or 25Gbps rates.

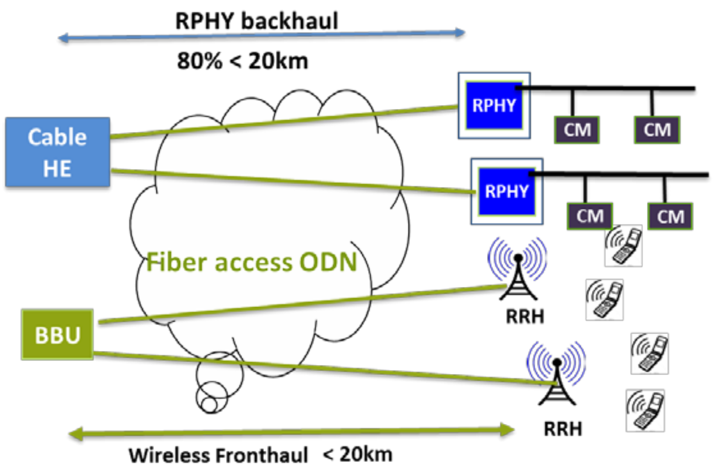

Figure 5 - Fiber networks for RPHY backhaul and 5G wireless fronthaul

Therefore, it is possible to design a unified fiber access network, whether built on DWDM or PON, to support both RPHY backhaul and 5G wireless fronthaul. For MSO, a common passive DWDM architecture for both RPHY and 5G wireless fronthaul benefits from the large volumes in wireless backhaul market.

5. A novel passive DWDM architecture for RPHY backhaul and 5G wireless fronthaul

5.1. High level requirement for common DWDM architecture

Firstly, the unified DWDM system should have low cost as well as flexibility in channel plan. This requires a passive DWDM architecture with no optical amplifications. The use of an optical amplifier, such as SOA (Semiconductor Optical Amplifier) or EDFA (Erbium-doped Fiver Amplifier), will not only increase the cost dramatically but will also impose an inflexible channel plan."Red-blue" filters are needed for bidirectional EDFA which excludes some channel plans such as interleave. It should support at least 20 km reach without optical amplification to meet the 5G wireless fronthaul reach and 80% of the RPHY reach.

Secondly, it should provide 1:1 fiber protection on DWDM trunk fiber. For a 32 channel system, the DWDM trunk supports 32 RPHY with 4096 end-users assuming one RPHY has 128 end-users. Therefore, 1:1 fiber protection is important for RPHY backhaul and it is required for 5G wireless fronthaul. Loss in the DWDM trunk will result in loss of many adjacent 5G cells which is not acceptable in wireless communications.

Thirdly, it should align with the migration direction to PON. The common ODN (optical distribution network) for DWDM supports overlay with all PONs. This means the common ODN should enable coexistence with GPON, or XGS-PON, or NG-PON2, or 10G EPON or 25Gbps/100Gbps EPON without any modifications.

Finally, the solution should be standard based.

5.2. Architectural challenges

There are a number of architecture challenges to design a common DWDM system optimized for RPHY backhaul and 5G mobile front-haul. For example, one challenge is the coexistence with all PONs, e.g. GPON, XGS-PON, NG-PON2, 10G EPON, 100G EPON on a common ODN. This requirement stems from the uncertainty of the future technologies, and the fact that no one really has a crystal ball. Another challenge is to keep DWDM system passive with at least 20km fiber reach and compensate the losses from DWDM filters, optical protection switch, coexist filters, etc.

Therefore, innovative architectures and new component technologies are needed.

5.3. A novel DWDM with PON overlay architecture

Figure 6 shows a system diagram the unified DWDM architecture for RPHY backhaul and 5G wireless fronthaul. This system has following characteristics:

1. The DWDM system coexists with all PONs that are standardized today, including GPON, XGS-PON, 10G EPON, and NG-PON2. This is achieved by two new coexistence schemes.

   a). The coexistence of all PONs with the DWDM system is achieved by using a C band bandpass filter instead of conventional PON coexistence filter at the OLT side, see the left side of Figure 6. The C band bandpass filter passes the C band wavelengths from the common port to one output port that connects to a DWDM MUX and reflects all other wavelengths to another output port that connects to an OLT. All the PONs that expect NG-PON2 use wavelengths out of C band, for example GPON uses 1310nm/1490nm, XGS-PON uses 1270nm/1578nm and 10G EPON uses 1270nm/1577nm for upstream and downstream. Therefore, all PON wavelengths will be separated from the C band wavelengths. As the result, if any one of the above mentioned PON connects to the OLT port in Figure 6, it will coexist with the DWDM system.

   NG-PON2 uses part of C band wavelengths for upstream. The 4 TWDM channels in NG-PON2 are located at the lower C band from 1524nm to 1534nm with 200GHz channel spacing. If the DWDM wavelength plan avoids this portion of C band, then the DWDM system can coexist with NG-PON2 as well.

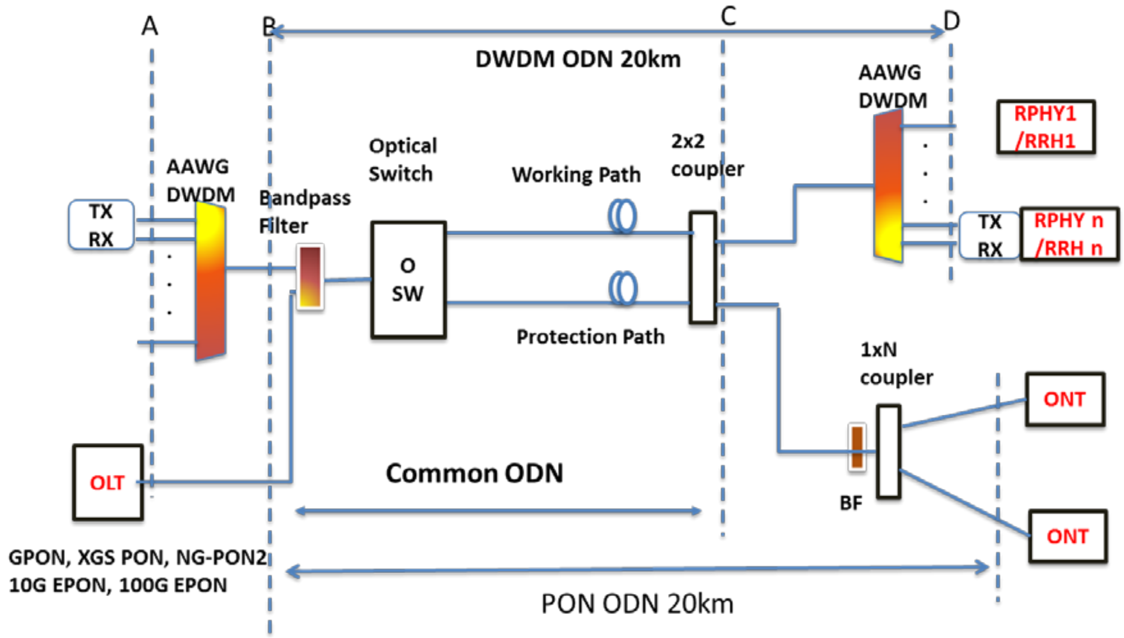

Figure 6 - A novel DWDM with PON overlay architecture

b). In the field, the coexistence of the DWDM system with all PON is realized by using 2x2 passive optical couplers with a C band blocking filter before the PON splitter, see the right side of Figure 6. The blocking filter could be the C bandwidth filter with the C band passing output not used.

2. The system supports 1:1 trunk fiber protection for DWDM and PON. The 2x2 passive optical coupler has two functions. One is to provide trunk fiber protection, and the other is to enable coexistence of DWDM with PON.

3. Gaussian AWG (Arrayed Wavelength Grating) is used for DWDM MUX and DMUX to lower the insertion loss caused by DWDM filters. Take a 40 channel DWDM system, compared with a thin film filter, Gaussian AWG can save at least 6 dB in link budget for a pair of MUX/DMUX.

4. The DWDM system can support 50 channels in C band with 100GHz channel spacing. Since there is no EDFA, no guard band is needed for "red-blue" filter. As the result full C band can be used.

5. Using 10G SFP+ EML transceivers, the passive DWDM system support at least 20km reach with the possibility to extend to 40 km reach with reasonable margins.

As being mentioned in 5.2, one of the challenges to keep the DWDM system passive (no EDFA) with at least 20 km fiber reach is lower passive loss. By using an innovative coexistence architecture, the link budget saving is about 3 dB. Combine the insertion saving from using Gaussian AWG, the total link budget saving is about 9 dB. This is critical to keep the DWDM system passive, otherwise EDFA would be required.

5.4. New component technologies

To keep the system passive while supporting at least 20 km reach, the low loss Gaussian AWG is assumed in the system architecture shown in figure 7. There are two issues with AWG, one is temperature stability; and the other is that the Gaussian AWG has a narrower passing band. However, these two problems can be solved with a recent development in optical component technologies.

AWG has many advantages over thin film filters, such as

- Constant insertion loss independent of channel counts, therefore has lower loss for large channel counts.
- More uniform loss between channels.
- Cyclic prosperity.

However, there is one main drawback for AWG – temperature instabilities. The wavelength variation for AWG is ~ 11ppm/degree C. In comparison, the wavelength variation for thin film filters is ~1 to 2 ppm/degree C. As the result, an AWG normally requires, or as an option, temperature control by thermoelectric (TE) devices, or by environment control. This limits the applications of AWG in outdoor and/or in extreme environments.

During the first decade of year 2000, research on temperature insensitive Athermal AWG (AAWG) made progress in labs. Like AWG, AAWG is also based on silica technology. It uses a material that has a different thermos expansion coefficient than that of silica to compensate for the reflection index change of silica caused temperature variations. Figure 7 shows an AAWG design [1].

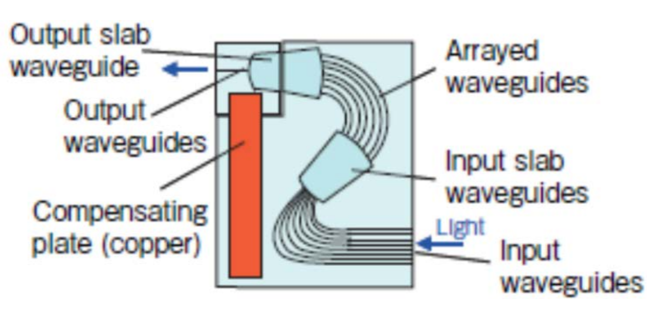

Figure 7 - Athermal AWG

In this design, a copper plate was used to compensate the thermal expansion of silica, the operating temperature range tested was -30 to +70/degrees C. Athermal AWG products are available today.

The second issue of Gaussian AWG/AAWG is the narrower pass band. Figure 8 shows a comparison of Gaussian AAWG with a flat top AAWG and thin film filter. The 1 dB pass band of Gaussian AAWG is ≥ 0.2 dB. In comparison, the 1 dB pass band of a flat top AAWG is ≥ 0.38

dB and the 0.5 dB pass band for the thin film filter is ≥ 0.22 dB. In order to use low loss Gaussian type AAWG, the laser transmitter needs to narrow wavelength variations. General speaking, an EML (electro-absorption modulator laser) has to be used. The EML is one type of external modulated laser, it has more wavelength stability than a direct modulated laser (DML). Take 10G EML SFP+ for example, the wavelength accuracy is

- EOL: ± 0.1 nm;
- BOL: ± 0.0 4nm.

BOL and EOL represent the "beginning of life" and "end of life" respectively. The EOL of wavelength drift of the 10G SFP+ is within the 1dB pass band of the AAWG.

Moreover, to mitigate the dispersion penalty, EML is also preferred for ≥ 20 Km reach 10G systems.

Table 1 - Comparison of AAWG and thin film filter

Parameter	Unit	AAWG Type		Thin Film
		Gaussain	Flat top	
Channel Spacing	GHz	100 GHz		100 GHz
Channel Count		40	40	32
Wavelength Accuracy	nm	± 0.05	± 0.05	± 0.05
1 dB pass band	nm	≥ 0.2	≥ 0.38	
3 dB pass band	nm	≥ 0.4	≥ 0.58	≥ 0.22 (0.5 dB)
Insersion loss	dB	≤ 3.5	≤ 6.0	≤ 5.4 (~6 for 40ch)
Uniformity	dB	≤ 1.5	≤ 1.5	≤ 2

Together, the Gaussian AAWG and EML transmitter enable the low insertion loss DWDM system dispatched in Figure 6. The passive DWDM system supports 20 km to 40 km of reach with up to 50 channels in C band. Comparing with optically amplified solution (using EDFA), the passive DWDM RPHY backhaul and wireless fronthaul; system has lower deployment and operational cost.

6. PON backhaul/fronthaul architecture

The advantage of the DWDM system discussed previously is that it is built on mature technologies and most of the optical component needed can be found off-shelf. On the other hand, if RPHY is considered as a transitional solution – deep fiber nodes with final migration path to PON, then using PON for network backhaul and fronthaul may provide a converge solution.

In the past few years, there has been increasing deployment of PON in MSO access networks, from GPON to 10G EPON. Since PON ODN is already deployed or start to deploy in MSO OSP, it would be beneficial to use PON ODN for RPHY backhaul from evolution to all fiber access networks point of view. However, migrate all coax OSP to PON ODN may take time, and need innovated coexistence solutions [2][3].

6.1. NG-PON2 for RPHY backhaul

TDM PON, such as GPON (2.5G) has been used by telecom carriers for 2G, 3G and 4G wireless backhaul and fronthaul for years. In recent years 10G PON (10G EPON, XGS-PON) and NG-PON2 (40G) are on the market. They are the candidates for 5G wireless backhaul and fronthaul. IEEE is developing 25G/100G EPON. These high-speed PONs are suitable for RPHY backhaul applications. Since the NG-PON2 is the higher rate PON on the market today, it is used to illustrate PON RPHY backhaul.

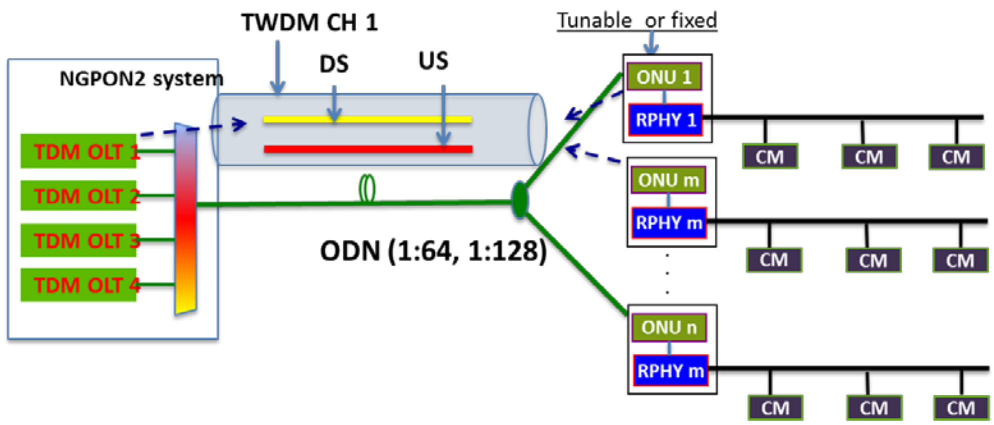

Figure 8 - NG-PON2 PON for RPHY Backhaul

NG-PON2 for RPHY backhaul architecture is in Figure 9. NG-PON2 is a hybrid TDM PON (10Gb/s/ch) and WDM (TWDM). The WDM PON architecture is based on tunable optics. It supports 4 10Gbps TDM PON channels (expandable to 8 TDM channels) and a number of P2P WDM PON channels. The downstream channels of NG-PON2 are in the L band from 1596 nm -1603 nm, and the upstream channels are in the C band from 1524 nm to 1544 nm. In current implementations, the TDM PON in NG-PON2 has 4 channels with 200 GHz channel spacing.

The cost of the NG-PON2 is a concern today due to the high cost of tunable lasers and tunable filters. However, it is feasible to implement NG-PON2 with fixed optical if bond 4 channels are used to form a 40Gbps PON with 4 pairs of 200 GHz or 100 GHz DWDM channels. This low cost solution is practical and could be standardized.

100G EPON (802.3ca), which has currently been developing at IEEE, is also a 4 channel WDM-TDM PON. The discussion of NG-PON2 for RPHY backhaul also applies to 100G EPON to some degree.

Figure 9 shows a NG-PON2 system for RPHY backhaul. In the field location, a RPHY is co-located with an NG-PON2 ONU. The RPHY and NG-PON2 ONU could be integrated on a circuit board, or connected vis external Ethernet interface. The Ethernet traffic from a RPHY is encapsulated into NG-PON2 frames to transport to the OLT. In this architecture, a NG-PON2 system also serves as an aggregation device. Compared with P2P DWDM solution, PON for RPHY backhaul is more efficient, it takes advantage of the statistical gain of bandwidth without using active Ethernet switches.

Another benefit of multi-channel PON such as NG-PON2 for RPHY back haul is traffic balance between the OLTs. In the tunable NG-PON2 case, an ONU can send traffic to multiple OLTs with fast tuning laser transmitter in principle. In the case of fixed optics with channel bonding, it is naturally a statistically traffic balanced solution.

6.2. NG-PON2 with 1:1 protection for RPHY backhaul

As discussed in in section 5.1, a DWDM RPHY backhaul and wireless fronthaul system prefers 1:1 fiber protection.   This requirement also applies to PON for RPHY backhaul and wireless fronthaul. Figure 10 shows a NG-PON2 RPHY backhaul system with 1:1 protection on trunk fiber and 4:1 protection on OLT.

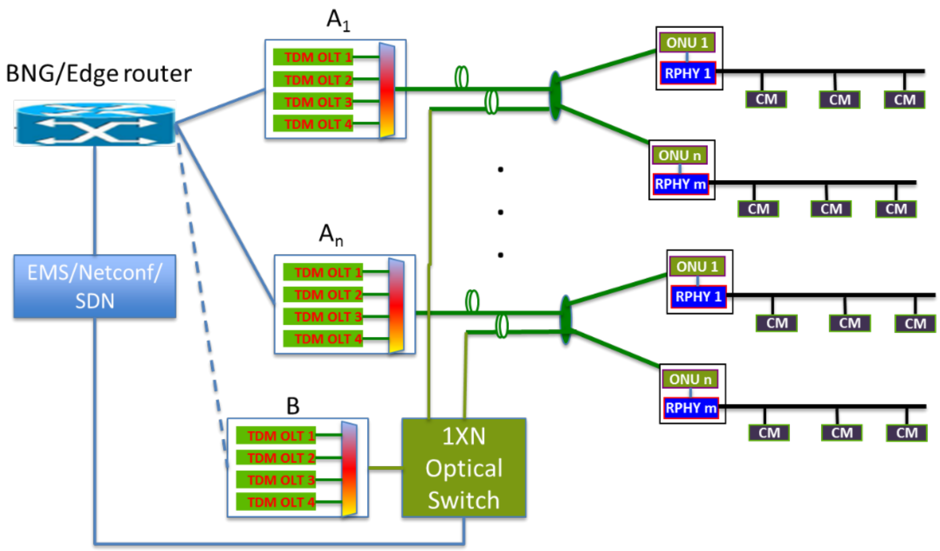

Figure 9 - PON for RPHY Backhaul with Protections

7. Conclusions

RPHY backhaul and 5G wireless fronthaul networks have similar network topologies, it is feasible to build unified architectures for both network applications. Two unified architectures are proposed. One is a unified passive DWDM architecture that coexists with all types of PON. The other architecture is based on high-speed PON. The DWDM is a mature technology for mobile fronthaul and RPHY backhaul today and the evolving high-speed PON may provide a lower cost solution for tomorrow.

8. Abbreviations

8.1. Abbreviations

AAWG	Athermal AWG
AON	Active Optical Ethernet Network
AWG	Arrayed Wavelength Grating
BBU	Baseband Unit
CPRI	Common Public Radio Interface
C-RAN	Centralized Radio Access Network
DOCSIS	Data over Cable System Interface Specifications

DS	downstream
EDFA	Erbium-doped Fiver Amplifier
EML	Electro-absorption modulator laser
GPON	Gigabit Passive Optical Networks
HFC	Hybrid Fiber Coax
ODN	Optical Distribution Network
OLT	Optical line terminal
ONU	Optical Network Unit
OSP	Outside Plant
PON	Passive Optical Networks
QAM	quadrature amplitude modulation
RPHY	Remote Physical Layer Device
RoF	Radio over Fiber
RRH	Remote Radio Head
SOA	Semiconductor Optical Amplifier
US	upstream

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