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Chapter

Enabling Optical Wired and Wireless Technologies for 5G and Beyond Networks

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Abstract

The emerging fifth-generation mobile communications are envisaged to support massive number of deployment scenarios based on the respective use case requirements. The requirements can be efficiently attended with ultradense small-cell cloud radio access network (C-RAN) approach. However, the C-RAN architecture imposes stringent requirements on the transport networks. This book chapter presents high-capacity and low-latency optical wired and wireless networking solutions that are capable of attending to the network demands. Meanwhile, with optical communication evolutions, there has been advent of enhanced photonic integrated circuits (PICs). The PICs are capable of offering advantages such as low-power consumption, high-mechanical stability, low footprint, small dimension, enhanced functionalities, and ease of complex system architectures. Consequently, we exploit the PICs capabilities in designing and developing the physical layer architecture of the second standard of the next-generation passive optical network (NG-PON2) system. Apart from being capable of alleviating the associated losses of the transceiver, the proposed architectures aid in increasing the system power budget. Moreover, its implementation can significantly help in reducing the optical-electrical-optical conversions issue and the required number of optical connections, which are part of the main problems being faced in the miniaturization of network elements. Additionally, we present simulation results for the model validation.

Keywords: 5G, backhaul, centralized unit (CU), common public radio interface (CPRI), distributed unit (DU), fiber to the X (FTTX), fronthaul, functional split, optical wireless communication (OWC), passive optical network (PON), photonic integrated circuits (PICs), radio access network (RAN), radio over fiber (RoF)

1. Introduction

There have been growing concerns regarding the increasing number of unprecedented bandwidth-intensive mobile applications and services being experienced by the Internet. A notable cause of the increase in the traffic and the subsequent pressure on the network is the Internet of things (IoT) technologies. For instance, massive IoT (mIoT) schemes have caused remarkable revolutions in the amount of

mobile devices and applications in the networks. This is in an effort to enhance the user experience in delivering enhanced mobile broadband (eMBB) services and providing ultra-reliable low-latency communication (uRLLC) for critical communication and control services. In theory, IoT comprises universal existence of a collection of things like mobile PCs, tablets, smartphones, actuators, sensors, wireless routers, as well as radio-frequency identification (RFID) tags. It is remarkable that these devices are capable of cooperating not only with each other but also with their neighbors. By this approach, they are able to achieve common network goals by means of unique addressing scheme [1, 2]. Furthermore, it has been predicted that massive number of mobile devices on which various bandwidth-intensive applications and services will be operating and will be Internet connected [3]. In actual fact, there is a tremendous demand for effective systems that are capable of delivering various services in a cost-effective manner while meeting the essential network demands. Consequently, in an effort to accomplish the next-generation mobile network technical demands, there have been intensive researches on viable solutions that can satisfy the network requirements.

Additionally, to support the anticipated massive devices, there has been general consensus that the fifth-generation (5G) wireless communication system is the viable and promising solution. Meanwhile, massive multiple-input multiple-output (M-MIMO) antenna and millimeter-wave (mm-wave) technologies are anticipated to be integrated into the 5G networks, so as to enhance the wireless system bandwidth. This is due to the fact that radio-frequency (RF)-based wireless system transmission speeds are highly constrained by the regulated RF spectrum. This limitation can be attributed to numerous advanced wireless systems and standards such as UWB (IEEE 802.15), iBurst (IEEE 802.20), WiMAX (IEEE 802.16), Wi-Fi (IEEE 802.11), as well as the cellular-based 3G and 4G. On the other hand, there is a vast amount of unexploited and underutilized frequency at high bands [2, 4] as expatiated in Section 2. Nevertheless, the radio propagation at higher frequency bands is comparatively demanding. Consequently, advanced scheme like beamforming (BF) technique is essential for radio operation at the bands. The technique will help in compensating mm-wave band inherent path loss in the radio access network (RAN) [5–7].

In addition, owing to several innovative technologies that have been implemented in the optical communications, significant improvements have been noted in the network performance [8]. Among the remarkable improvements are the increase in the network reach, optical system capacity, and the number of users that can be effectively supported. This is as a result of cutting-edge optical fiber-based technologies. The optical schemes have been increasingly advancing deeper into different access networks, in order to provide various services such as mobile backhaul/fronthaul and multitenant fiber to the X (FTTX) with some variants of fiber-based broadband network architectures as discussed in Section 3. For instance, the optical broadband network architectures, such as fiber to the curb or cabinet (FTTC), fiber to the node (FTTN), fiber to the building (FTTB), fiber to the premise (FTTP), and fiber to the home (FTTH), proffer commercial solutions to the communication network performance bottleneck, by progressively delivering services in close proximity to the numerous subscribers [2].

It is noteworthy that various 5G use cases like uRLLC and eMBB can be effectively achieved by radio elements and BSs that are not far-off the end users or wireless devices. This is due to the fact that close proximity helps in facilitating better signal quality, with lower latency and higher data rates in the system [9]. This can be effectively realized by means of passive optical network (PON) technologies such as gigabit PON (GPON), 10Gbps PON (XG-PON), as well as Ethernet PON (EPON). It is noteworthy that one of the key issues is the process of supporting

different service demands with the intention of realizing ubiquitous and elastic connections. As a result, optical and wireless networks convergence is very indispensable. This is not only a cost-effective approach but also enables high-network penetration, in order to achieve the envisaged ubiquitous feature of the next-generation network (NGN) [2]. Based on this, there is a growing consensus of opinion that high-capacity optical fronthaul scheme is one of potential solutions for addressing the network demands. For instance, if the CPRI standard is to be directly employed for the transportation of a considerable number of long-term evolution-advanced (LTE-A) and/or 5G radio signals, an enormous aggregate bandwidth will be required on the backhaul/fronthaul networks [10].

Furthermore, it has been observed that the reference system architectures for the 5G standardizations are based on the notion of heterogeneous networks where mm-wave small cells are overlaid on the larger macrocells [9]. This will enable the RAN to handle the growing traffic demands. In addition, to contain the massive deployment of small-cell BSs, cloud RAN (C-RAN) has been adopted as a promising architecture to ensure effective scalability regarding deployment cost as well as energy consumption [11–14]. The C-RAN offers an innovative architecture that is really different from the traditional distributed RAN (DRAN). In the C-RAN architecture, the baseband unit (BBU) is shifted away from the cell sites where it is normally located in the DRAN. Consequently, BBU collections that are usually referred to as BBU pools are centralized at the central office (CO). With this configuration, the remote radio heads (RRHs) are left at the cell sites.

As a result, C-RAN implementation offers significant benefits such as improved system spectral efficiency and better flexibility for further RRH deployments than the DRAN. Likewise, with the centralized BBUs, C-RAN supports greener infrastructure, enhanced interference mitigation/coordination, better resource pooling, improved BS virtualization, as well as simplified management and operation. Besides, multiple technologies can be supported with smooth and scalable evolution. Furthermore, in the C-RAN architecture, the BBU pools are connected via the fronthaul network to the RRHs. It is remarkable that the de facto air interface standard that is usually employed for connecting the BBU pools to the RRHs is the common public radio interface (CPRI) protocol. This is an interface that helps in the digital baseband sample distribution on the C-RAN fronthaul. However, stringent requirements concerning jitter, latency, and the bandwidth are imposed on the fronthaul network for seamless connectivity. This makes the CPRI-based fronthaul links to be prone to flexibility and bandwidth limitations, which may prevent them from being visible solutions for the next-generation networks [11, 12]. Meanwhile, it has been noted that the 5G systems will impose higher requirements on the transport network regarding latency, bandwidth, reliability, connectivity, and software-defined networking (SDN) capability openness [15]. A number of approaches such as cooperative radio resource allocation and data compression technologies have been adopted to address the challenges; however, the fronthaul capacity demand is still considerable high [11, 12].

The viable means of addressing the capacity requirement is through the implementation of passive optical network (PON) solutions such as wavelength division multiplexed PON (WDM-PON) and ultradense WDM-PON (UDWDM-PON). The PON architectures are compatible with the 5G networks and are capable of supporting both wired and wireless services. Based on the PON architecture, individual RRH has the chance to communicate with the BBU pools using a dedicated wavelength. Besides, in the upstream direction, the aggregate wavelengths can be further multiplexed into a single shared fiber infrastructure at the remote node (RN). They can eventually be de-multiplexed at the CO [11, 12]. As aforementioned and as depicted in **Figure 1**, optical and wireless network convergence is a
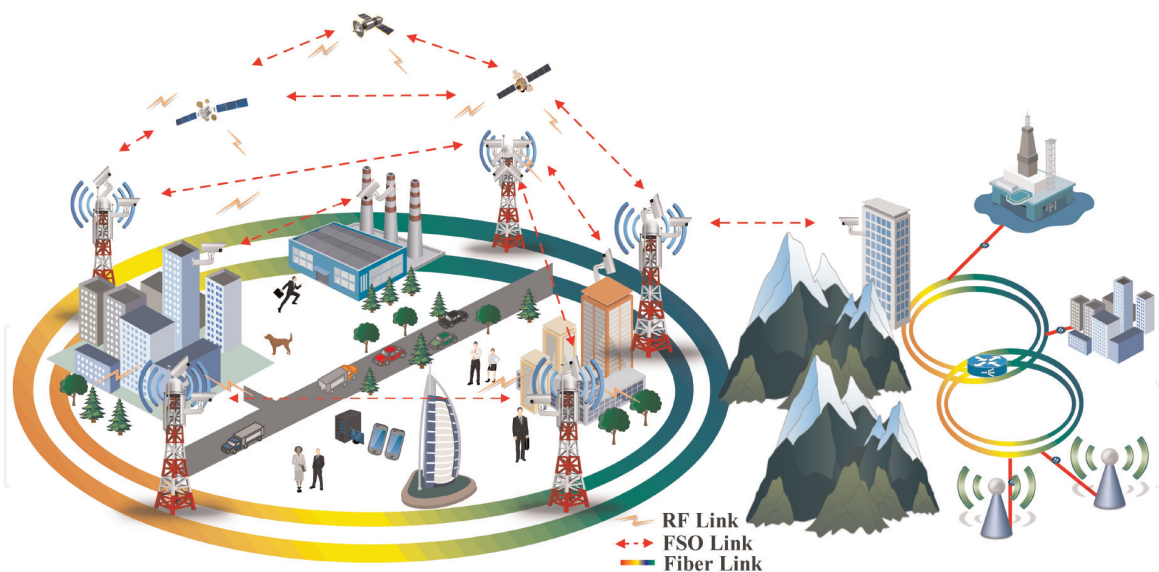
Figure 1.
A scenario for optical and wireless access networks convergence (adapted from Alimi et al. [2]).

promising scheme for exploiting the optical system inherent bandwidth and the mobility advantage of wireless connectivity, which can help in realizing the 5G network envisaged capacity and energy efficiency. In addition, optical wireless communication (OWC) is another feasible and attractive optical broadband access solution that is capable of supporting high-capacity, high-density, and low-latency networks. Therefore, it can effectively address the network requirements for different applications and services at a comparatively lower cost. So, it has been seen as an alternative and/or complementary solution for the existing wireless RF solutions [4, 16–18]. This chapter presents optical wired and wireless networking solutions for high-capacity, high-density, and low-latency networks. Furthermore, because of its potential for intense revolution and salient advantages, we focused on the second standard of the next-generation PON (NG-PON2) system. In addition, with the exploitation of notable features of photonic integration, we design and develop the physical (PHY) layer architecture of the NG-PON2 system. The proposed NG-PON2 architectures offer an enabling platform for active device integration into the chip to ensure a significantly low propagation loss. We also present simulation results for model validation. This helps in demonstrating the potential of photonic integration for optical architectures.

Furthermore, with concise information on the enabling optical wired and wireless technologies and the need for alleviating the stringent requirements in the network being introduced, we present comprehensive overview of the fronthaul transport solutions in Section 2. The salient needs for PON in the envisaged ultradense network deployments are considered in Section 3. In Section 4, a practical method for network investment optimization by the operators based on PON system coexistence is discussed. In Section 5, we present a number of viable schemes for alleviating the imposed stringent requirements in the system. The NG-PON2 PHY architecture design and development based on photonic integration are demonstrated in Section 6. In Section 7, the obtained simulation results with further discussion are presented. Section 8 concludes the chapter.

2. Fronthaul transport solutions

The fronthaul protocol can be transported by different viable means. Apart from the usually employed small form pluggable and serial constant bit rate CPRI

specification that is based on digital radio over fiber (D-RoF) implementation, there are other innovative and standard fronthaul interfaces such as Open Base Station Architecture Initiative (OBSAI), next-generation fronthaul interface (NGFI), open radio interface (ORI), and enhanced CPRI (eCPRI) that can be used [19–21]. In [11], we give an overview of various prospective and standard fronthaul interfaces. In this chapter, for reference purposes, we focus on the extensively employed CPRI protocol. However, it should be noted that the transport methods to be discussed in this section are applicable to other fronthaul interfaces. The transport methods discussed in this section are grouped into wired and wireless fronthaul solutions.

2.1 Wireless fronthaul solution

Wireless transport schemes are very viable fronthaul solutions that have resulted into tremendous evolutions in the communication systems. This is due partly to the inherent advantages such as operational simplicity, ease of deployment, scalability, roaming support, effective collaboration, and cost-effectiveness. Furthermore, it is an appropriate scheme for complementing fiber-based fronthaul solutions. However, their susceptibility to transmission channel conditions makes their implementation effective for short range. Besides, the current solution can only support few CPRI interface options. This brings about bandwidth limitation for this solution. Moreover, to alleviate this, promising wireless technologies like mm-wave and wireless fidelity (Wi-Fi) can be employed in the fronthaul [11, 22, 23].

As aforementioned in Section 1, there is a huge amount of unexploited and underutilized frequency at high bands. The fronthaul in which mm-wave is being employed is feasible due to the availability of various compact and high-dimensional antenna arrays for commercial use in the band. Besides, as a result of 60 GHz standards like 802.11ad, 802.15.3c, and WirelessHD that have been issued, considerable attention has been given to mm-wave communications. Nonetheless, the inherent high propagation losses of the mm-wave communications give rise to comparatively shorter transmission range [11, 22, 24, 25].

In addition, as stated in Section 1, RF-based system transmission speeds are substantially limited due to a number of advanced wireless systems being deployed in the network. Consequently, to meet the demands of the current and future wireless networks, many chipset suppliers and wireless operators have been paying significant attention to the unlicensed spectrum. The major focus is in the 2.4 GHz and 5 GHz frequency bands that are under implementation by the Wi-Fi. This is being used for the 5G LTE-Unlicensed communication systems [11, 26]. With this implementation, the unlicensed spectrum resources could be effectively allotted to the LTE system, in order to have more capacity for supporting the Wi-Fi users [27].

Furthermore, it is remarkable that the Wi-Fi unlicensed spectrum is a promising solution for the fronthaul network. A notable advantage of exploiting the unlicensed spectrum for the fronthaul network is due to the fact that separate frequency procurement for the fronthaul might not be necessary for the network providers. Besides, the same spectrum could be effectively reused in the access and fronthaul links. This can be accomplished by means of time-division multiplexing (TDM) and frequency-division multiplexing (FDM) schemes. Another way of achieving this is through opportunistic fronthauling, in which unlicensed spectrum can be sensed. For instance, the RRH can sense unlicensed spectrum that is available (unused unlicensed spectrum) and then employ it for fronthauling. Besides, in a situation where the active user signal is considerably lower than the predefined threshold, the RRH can also make use of the spectrum. In addition, the fronthaul link constraints could be effectively eased via the Wi-Fi. This is majorly due to the fact that it can be employed for offloading [26]. Although Wi-Fi networks are

capable of offering relatively high-data rates, they exhibit limited mobility and coverage. The drawbacks can be reduced by employing Wi-Fi mesh networks [11, 28].

2.2 Wired fronthaul solution

The wired network offers a number of advantages such as low interference, enhanced coverage, low latency, and high reliability and security. Due to these advantages, they have been able to stand the test of time and continue to be relevant despite the advent of wireless systems. Some of the fronthaul solutions that are based on wired links are dark fiber, passive WDM, WDM-PON, WDM/optical transport network (OTN), and Ethernet. In this subsection, we present potential wired-based fronthaul solutions that can support the network requirements.

2.2.1 Dark fiber solution

Dark fiber offers an attractive fronthaul solution. With this implementation, transmission equipment is not required between the BBU pools and the radio remote units (RRUs), consequently resulting in easiest deployment solution with least possible latency. Nevertheless, since dark fiber solution is based on point-to-point (P2P) direct connections, it lacks the required network protection, making it not a good candidate to support 5G use cases such as uRLLC services in which high reliability is required. Besides, its implementation demands huge amount of fiber resources. In the 5G systems in which ultradense networks are envisaged, the required amount of fiber is even more challenging. So, the fiber resources may be inadequate to support mIoT devices and other envisaged multimedia devices. Therefore, availability of fiber and the associated deployment cost may be the limiting factors for the dark fiber solution employment. This inefficiency can be addressed with the aids of different WDM and Ethernet solutions [11, 22, 23, 29].

2.2.2 Ethernet solution

In Ethernet-based fronthaul solution, packet technologies that encourage statistical multiplexing feature are employed. This helps in achieving traffic convergence and in enhancing the line bandwidth usage. Besides, considerable fiber resources can be saved due to its support for point-to-multipoint (P2M) transmission. Nevertheless, a number of issues such as identification as well as fast forwarding of low latency services deserve considerable research attention in this approach. Also, further efforts are required for backward compatibility with CPRI transmission and high-precision synchronization. Based on these, the Institute of Electrical and Electronics Engineers (IEEE) has established a task group known as time-sensitive networking (TSN) which is a part of the IEEE 802.1 working group, to study the latency-sensitive Ethernet forwarding technology. Reasoning along the same lines, the IEEE 1914 next-generation fronthaul interface (NGFI) working group has been established not only for the development of the NGFI transport architectures and the associated requirements but also for the definition of radio signal encapsulation specification into Ethernet packets [11, 29].

2.2.3 WDM-based solution

The requirement for low-latency transmission in the range of 10-Gb/s makes WDM-based network the usually adopted option for the fronthaul links. At large, WDM-based fronthaul methods can be grouped into two solutions which are active

and passive. In active solution, other protocols are used for the CPRI traffic encapsulation, before being multiplexed on the fronthaul network. Also, the solution offers robust network topologies with considerable flexibility. Moreover, with optical amplifiers, the network reach can be significantly extended. Another important distinguishing feature of an active solution is that the cell site demarcation point requires power supply for operation. On the other hand, a passive solution mainly depends on CPRI link passive multiplexing (MUX)/demultiplexing (DEMUX). Besides, this solution's demarcation point can function effectively without any battery backup and power supply. Nonetheless, active equipment can be employed for the system monitoring at the CO demarcation point [11, 22, 23, 29].

In general, the main dissimilarities between the passive and active solutions can be recognized in the nature of their routing table and switching granularity. For instance, unlike the active solution, routing table can be statically and dynamically configured as well as associated with the interface; that of passive solution is fixed and lacks configuration capability. Likewise, the passive solution switching granularity is based on spectrum or time slot as being implemented in the TWDM-PON, while an active solution presents finer switching granularity which can be based on packet or frame switching. Consequently, the active solution offers better configuration flexibility; however, it is power-consuming and relatively complicated [12]. In the following, we expatiate on different WDM-based fronthaul solutions.

2.2.3.1 Passive WDM

In this approach, a passive optical MUX/DEMUX is employed for multiplexing a number of wavelengths on a shared optical fiber infrastructure for onward transmission. Therefore, the implementation can save considerable fiber resources via the support for multiple channels per fiber. Also, the employed optical components introduce negligible latency, so, the stipulated jitter and latency requirements for CPRI transport can be effectively met. Moreover, due to the passive nature, power supply is not required for the associated equipment operation. This brings about high power efficiency in the network. Besides, this approach is not only a cost-effective solution but also offers simple maintenance. Nevertheless, the cost implication of the wireless equipment deserves significant attention. This is due to the required colored optical interfaces at the BBU and RRU. Also, factors that need consideration are the limited transmission range and inadequate optical power budget of a relatively complex topology such as chain or ring network. This can be attributed to the accumulated insertion loss owing to multiple passive WDM components. Besides, the approach offers no robust operations, administration, and maintenance (OAM) potentials, and usually, line protection is not provided. Passive WDM implementation can also be limited by the need for well-defined network demarcation points [11, 22, 23, 29].

2.1.3.2 WDM/OTN

When WDM/OTN scheme is employed, multiplexed and transparent signal transmissions can be achieved over the fronthaul link to multiple sites. Thus, the fiber capacity is increased by enabling multiple channels on a shared fiber infrastructure [11, 23, 29]. This can be realized by encapsulating the inphase and quadrature component (I/Q) data by means of OTN frame; this is subsequently multiplexed to the WDM wavelength. Consequently, any wavelength can be employed for routing the resulting frame to the destination port [12]. Apart from being able to save fiber resources, other notable advantages of this solution are provision for OAM capabilities, network protection, service reliability, as well as

service level agreement (SLA) management and network demarcation. Furthermore, this solution presents attractive features regarding low latency and high bandwidth. It is also a good approach for attending to the required colored optical interface at BBU and RRU by the passive WDM. Since colored optical interface is not demanded, wireless equipment deployment challenges are alleviated drastically by the WDM/OTN solution. Another significant advantage of the approach is the offered easy scalability. This is due to the fact that there is no need for replacing the wireless equipment optical interfaces while upgrading from non-C-RAN to the C-RAN architecture. Notwithstanding, the major drawback of the solution is the relatively higher cost of the equipment. Although power supply is not required for WDM transport in the approach, it is essential for wavelength translation and active management [11, 23, 29].

In addition, the WDM-based systems such as coarse WDM (CWDM) and dense WDM (DWDM) exhibit promising features for the fronthaul transport applications. For instance, apart from the offered high throughput and low latency, CWDM is very cost-effective regarding fiber resource usage and equipment expenses. Also, DWDM is widely known for the higher channel counts that can be efficiently supported. This can help further in increasing the number of small cells and the associated RRHs that can be deployed effectively. Furthermore, it helps in improving the fiber resource efficiency.
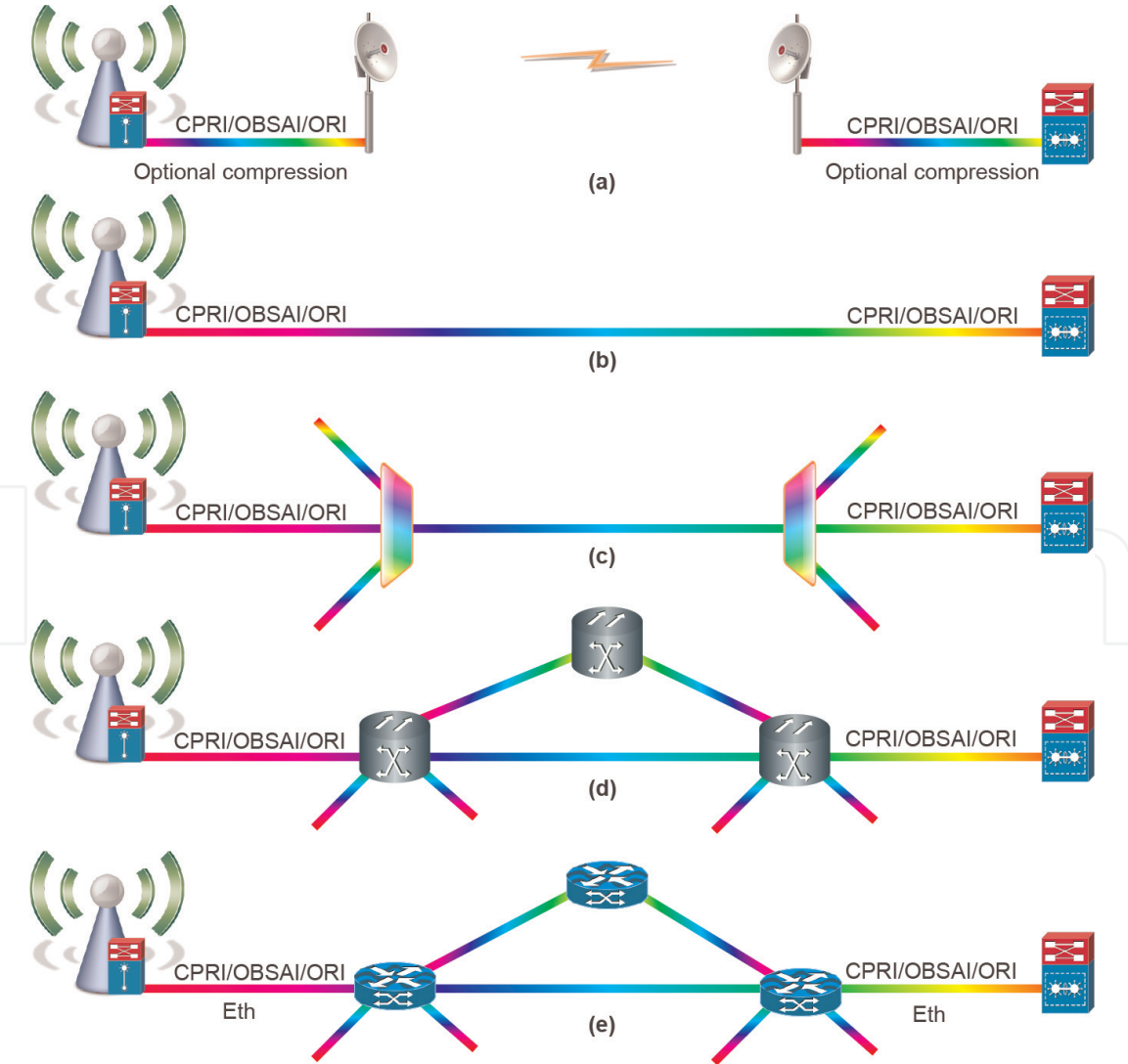
Figure 2.
Potential 5G fronthaul solutions: (a) microwave, (b) point-to-point, (c) WDM-PON, (d) OTN, and (e) Ethernet.

It is remarkable that WDM-based schemes can be used in conjunction with PON technology in order to further enhance the system performance. This scheme is highly appropriate for the anticipated massive RRHs and ultradense small cell deployment as explicated in Section 3. It should be noted that, for RAN to be well deployed, especially in the urban environments, the radio elements should be, as much as possible, in close proximity to the subscribers. So, the remote elements could be mounted on different places such as buildings and street lamp poles. Therefore, the arbitrary nature of the remote element placement can be efficiently supported with the implementation of WDM schemes.

Furthermore, as discussed, there are a number of ways by which the C-RAN fronthaul can be realized; nonetheless, the imposed stringent requirements make fiber-based method the widely adopted in the C-RAN. However, optical fiber implementation for ultradense networks, besides being time-consuming, may render the C-RAN schemes uneconomical and less flexible. It is remarkable that wireless fronthaul offers attractive and flexible solutions for information exchange between the centralized unit (CU) and distributed unit (DU). This is owing majorly to the offered advantages such as higher flexibility, lower cost, and undemanding deployment when than the fixed wired fronthaul counterparts. Therefore, innovative optical wireless solutions with good scalability and operational simplicity, coupled with easy of deployment, are really desirable [11].

In addition, apart from physical fiber-based methods being discussed, OWC system, also known as a free-space optical (FSO) communication system, is another attractive and feasible optical wireless fronthaul. The FSO provides a range of benefits such as low latency and high capacity that make it viable for addressing network requirements in a cost-effective manner [4, 16–18]. The potentials for the FSO implementation in the fronthaul network and different innovative concepts that are appropriate for improving the FSO system performance, while easing the stringent system requirements, are discussed in Section 5. Different potential 5G fronthaul solutions are depicted in **Figure 2**.

3. Passive optical network (PON)

The existing fiber-based methods as well as active P2P Ethernet might unable to meet the envisaged bandwidth-intensive traffic requirements by the 5G and beyond networks. For instance, ultradense network deployments with the associated huge network resources are envisaged in the 5G network. As illustrated in **Figure 3**, PON system can make better use of the current fiber infrastructures than the existing P2P system such as CPRI. This helps considerably in reducing the required number of interfaces in the network. As a result, it aids not only in reducing the site space, but also substantial amount of system power can be saved [30]. As explained in Section 2, PON technology has been deemed as an attractive access network solution owing to the presented advantages such as low-operation cost, high bandwidth, and low-maintenance cost [11, 31, 32].

It should be noted that the PON architectures have been experiencing continuous and gradual evolution, so as to considerably enhance the service availability and the related data rates. The offered technological options and the intrinsic benefits have been attracting the operators in deploying a number of PON systems. It has been observed that the most widely deployed one is the gigabit PON (GPON) system. Moreover, the first standard 10 Gbps PON technology, the next-generation PON (NG-PON) system, known as 10-gigabit PON (XG-PON1) has also been gaining considerable attention. With continuous demand for further capacity, there are innovative PON generations such as 10-gigabit symmetric PON (XGS-PON)
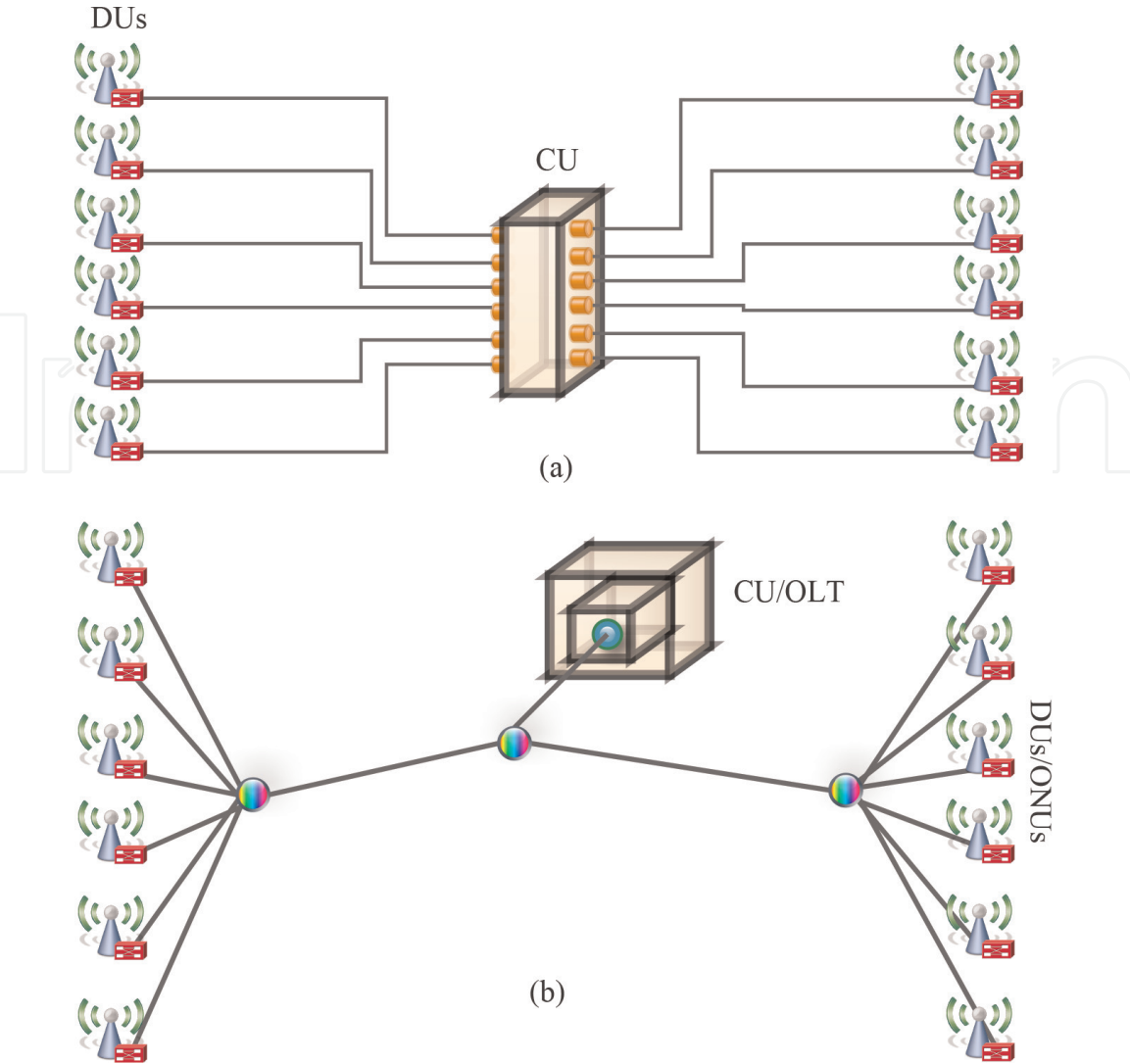
Figure 3.
Potential fronthaul solutions (a) CPRI-based and (b) PON-based schemes.

and the second standard of NG-PON (NG-PON2) that are now becoming the target of various providers [33]. In PON system, WDM and TDM techniques are normally employed to further enhance the capacity and fiber efficiency. Based on these techniques, the PON system can be broadly grouped into WDM-PON and TDM-PON.

Moreover, it is noteworthy that the TDM-PON is capable of giving considerable greater bandwidth for various data applications; however, availability of the resources that can be delivered to the end users is limited. In contrast, the issue can be effectively addressed with the WDM-PON scheme. This can be done by assigning a peculiar wavelength per subscriber. As a result of this, a distinct, high-data rate, as well as secure P2P channel, can be delivered over a high-capacity and longer optical reach, between each of the subscriber and the CU. Consequently, a WDM-PON scheme is suitable for partitioning the ONUs into a number of distinctive virtual P2P links over the shared physical optical infrastructure by multiple operators. This attribute facilitates fiber efficiency compared to P2P Ethernet. Similarly, in relation to TDM-based systems, it gives lower latency. These features make WDM-PON a disruptive solution that is very appropriate for FTTX as well as mobile backhaul and fronthaul applications. This will eventually aid the operators not only in developing converged networks but also in enhancing the current access networks. As a consequence of this, some redundant COs can be eliminated in an attempt to enhance the network performance in cost-effective ways [11, 31, 32].

Moreover, it is remarkable that advantages of both WDM-PON and TDM-PON can be effectively exploited though joint application of the schemes. This results in the TWDM-PON architecture. The potential PON architectures and their applications in telecommunication systems are presented in the subsequent subsections.

3.1 TDM-PON application

The TDM-PON can be grouped into broadband PON (BPON), asynchronous transfer mode (ATM) PON (APON), Ethernet PON (EPON), and GPON. In the existing telecommunication networks, GPON and EPON are the widely adopted schemes. Therefore, in the following, we focus on both schemes.

3.1.1 EPON application

The data traffic being encapsulated in the Ethernet frames as defined by the IEEE 802.3 standard is transported by the EPON solution. Different network elements such as optical network unit (ONU), optical line terminal (OLT), and optical distribution network (ODN) are the building blocks of a standard EPON system and other PON architectures. In the EPON solution, PON topology is exploited for getting the Ethernet access. Based on the joint schemes, EPON solution is capable of offering high bandwidth and good network scalability. Besides, due to the fact that it is highly compatible with Ethernet, network management can be supported in cost-effective manners. Likewise, as illustrated in **Figure 4**, FTTB, FTTC, and FTTH network architectures can be supported depending on the ONU deployments and demarcation point between the copper cable and optical fiber termination [32].

Typically, ONUs can be deployed beside the telegraph pole junction boxes, or else, at roadside when FTTC system is employed. Also, different types of twisted pair cables can be utilized for connecting the ONUs and the respective customer. It has been observed that FTTC technology offers a cost-effective and practical solution for delivering narrowband services. However, FTTC solution is not an ideal scheme, when broadband and narrowband services are to be incorporated [32].

Moreover, the ONU deployment can be made closer to the users in the FTTB solution. So, it can be located inside the buildings through further optical fiber penetration into customer homes. This can be achieved by means of cables, local
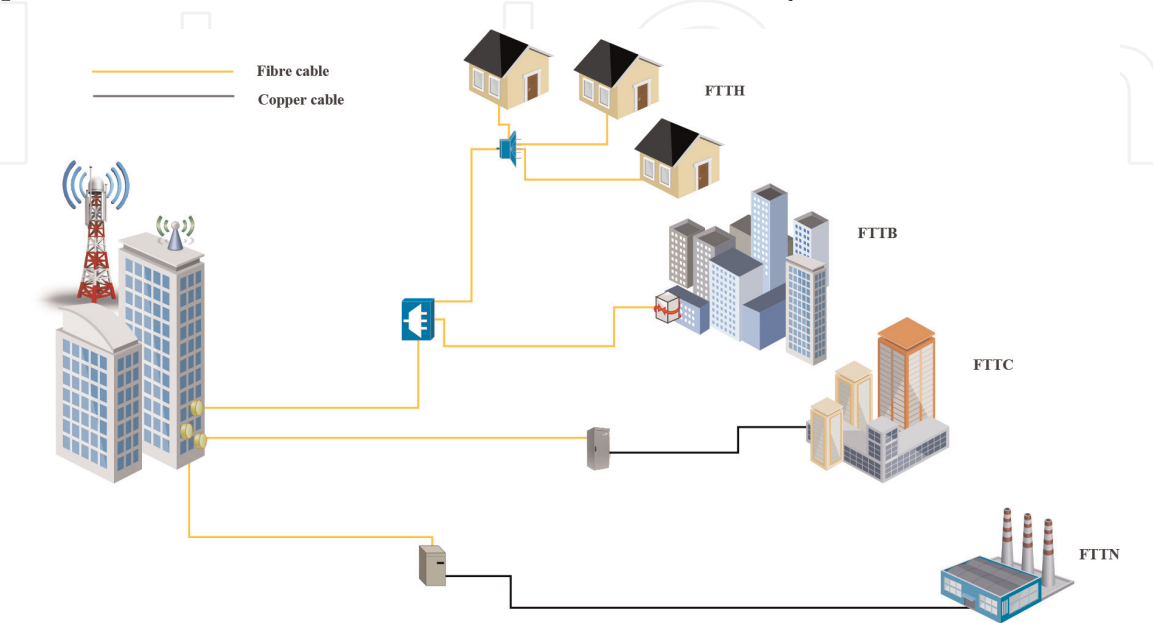
Figure 4.
FTTX architectures.

area networks (LANs), or asymmetric digital subscriber line (ADSL) broadband communication technologies. Relatively, FTTB employs more optical fiber in the connection than FTTC solution. This makes it more appropriate for broadband/narrowband service integration [32].

Furthermore, ONU deployment can take place right inside the subscribers' homes or offices in the FTTH solution. This facilitates a fully transparent network in which the ONUs are independent of the wavelength, bandwidth, as well as transmission mode and technology. These benefits enable FTTH scheme to be very ideal for access network implementations [32].

In addition, the discussed IEEE 802.3 Ethernet is a 1-Gbit/sec EPON standard. It is remarkable that there is a 10G EPON standard that is capable of supporting 10G/10G symmetric DS and US transmission. In another effort to attend to the system requirement, the IEEE 802.3ca task force has been working relentlessly on the development of 25G/50G/100G EPON standards. A notable feature of the entire EPON standards is that they are designed to be both backward and forward compatible. This is to ensure that legacy service, as well as innovative higher-speed service, can be effectively supported using the same ODN [34].

3.1.2 GPON application

Furthermore, to address the growing traffic demands, XG-PON1 has been presented. The XG-PON1 is capable of delivering higher data transmission than the legacy GPON system. Moreover, in an effort to keep the existing investments, it is backward compatible with the GPON. Also, the GPON ODN, as well as framing and management, is inherited by the XG-PON1. This encourages the reuse of the existing network elements [35].

3.2 WDM-PON application

The WDM-PON enables multiple-wavelength transmission through the multiple operators' shared optical fiber infrastructure rather than one wavelength in the PON system. This helps in ensuring that WDM-PON meets the huge subscribers' bandwidth demands. Furthermore, it presents various merits such as high wavelength efficiency and relatively simpler network management. This encourages support for various services than the TDM-PON. Besides, all anticipated services can be delivered over a shared communication network infrastructure.

In addition, it can effectively support different access networks such as FTTB, FTTH, and FTTC. Also, both small-scale and large-scale subscribers can be concurrently supported as well. Based on the inherent huge bandwidth, different types of BS bandwidth requirements can be appropriately met. Its implementation can also help in the network reach extension and in the current EPON network transition. This will help in keeping the current network investment while enhancing the network scalability [32]. In addition, UDWDM-PON offers a wavelength grid that is relatively denser for the WDM scheme. This helps not only in supporting a huge amount of aggregated wavelengths per fiber but also in accommodating higher number of RRHs per feeder fiber. Nonetheless, with the envisaged NGN stringent transport network requirements, UDWDM will be unable to maintain the high per-wavelength bit rates resourcefully. For instance, subcarriers' aggregation for high-speed services usually bring about considerable latency. Therefore, UDWDM implementation is preferred in situations where there are ultradense RRH deployments and inadequate feeder fiber accessibility. Besides, it also finds application in antenna sites which demand a low-peak but high sustainable rate [6]. As discussed in subsection 3.3, WDM-PON can be employed along with TDM-PON to achieve a

hybrid WDM-TDM-PON solution known as time and wavelength division multiplexed (TWDM-PON) scheme. Apart from being efficient for both small-scale and large-scale subscribers, the hybrid scheme offers a promising solution for applications in telecommunication environment.

3.3 TWDM-PON application

It is notable that TDM-PON implementation in the 4G networks offers a very cost-efficient solution for a wavelength channel sharing between the cell sites, by means of diverse time slot allocations for different cell sites. However, with the evolution of mobile networks, the major ITU-defined application scenarios such as eMBB, uRLLC, and massive machine-type communications (mMTC) could make TDM-PON solution unsuitable for the fronthaul transport network in the 5G and beyond networks. As aforementioned, a hybrid TWDM-PON scheme is a feasible solution with abundant bandwidth capable of supporting the fronthaul demands.

With the scheme, time slots, as well as wavelength resources, can be allocated dynamically between the RRHs. The offered centralized and virtualized PON BS can considerably help in the system energy savings. Likewise, the virtualized scheme presents a number of advantages such as low handover delay, excessive handover reduction, and better network reliability. This results in cost saving, cell-edge user throughput improvement, and enhanced mobility management [32, 36, 37]. The associated multiple wavelengths, as well as potential for wavelength tenability, give TWDM-PON unprecedented means of improving the network functionalities compared with the basic TDM-PONs [36, 37]. Likewise, orthogonal frequency-division multiplexed PON (OFDM-PON) is another promising PON solution. With OFDM, there is a comparable high potential for flexible bandwidth resource sharing as experienced in the TWDM. On the other hand, regarding the reach, the OFDM variants in which direct detection is employed usually present poor performance. Similarly, variants in which coherent detection is implemented are comparatively too expensive [6]. Furthermore, it is noteworthy that among its counterparts such as standard WDM-PON, optical code division multiplexed PON (OCDM-PON), and OFDM-PON that are capable of offering 40 Gb/s or higher (80 Gb/s) aggregated bandwidth, the full service access network (FSAN) community has chosen TWDM-PON as a major broadband solution. Apart from the inherent huge capacity with 1:64 splitting ratio, it has a long reach of 40 km. The salient features enable TWDM-PON system to meet the future broadband service requirements [37–39].

A typical TWDM-PON system architecture is depicted in **Figure 5**. In a conventional TWDM-PON solution, multiple wavelengths can effectively coexist in a shared ODN by means of WDM. Moreover, each of the wavelengths is capable of serving multiple ONUs through TDM access. With reference to the ITU-T recommendation, 4–8 wavelengths in L band (1590–1610 nm) and C band (1520–1540 nm) can be employed for the downstream (DS) and upstream (US) transmissions, respectively. Also, each of the DS wavelengths can operate at 10 Gb/s, while the US can function each at 2.5 or 10 Gb/s data rate [32, 37].

In addition, the TWDM-PON ONUs employ colorless tunable transceivers for selective transmission/reception of any US/DS wavelengths (data) via a pair of US/DS wavelengths. With this approach, the ONU inventory issue can be prevented. In essence, the transceiver features help in easing network deployment as well as inventory management. Furthermore, load balancing can be supported effectively in the TWDM-PON system. Besides, with dynamic wavelength and bandwidth allocation (DWBA) implementation, large bandwidth can be flexibly exploited. It is remarkable that TWDM-PON is a stack of four 10-gigabit PONs (XG-PONs) with
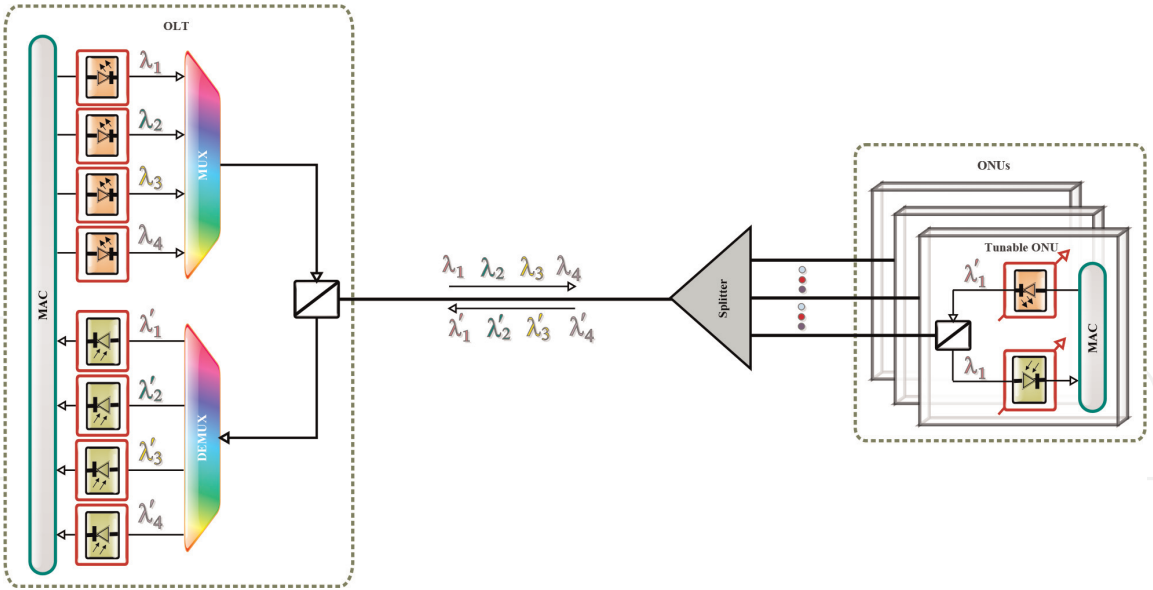
Figure 5.
Typical TWDM-PON architecture.

four pairs of wavelengths. In the stack, each XG-PON is operating on different wavelengths. Also, as stated earlier, the GPON and XG-PON GEM frames are compatible with and can be employed in the TWDM-PON solution. Based on this and the ability for coexistence with existing PON solutions, it is a viable scheme for optical access network swift evolution [11, 32, 37]. Consequently, TWDM-PON has been adopted for the NG-PON2. In NG-PON2, TWDM-PON can be employed with optional P2P WDM overlay extension. It is remarkable that DWDM scheme will enable NG-PON2 to deliver multiple unshared P2P connections, while TDM scheme simultaneously offers multiple P2M connections. This will enable the operators to efficiently support both fronthaul/backhaul and business services with the P2P WDM overlay technology, by using dedicated wavelengths [11, 40, 41].

In addition, based on the inherent colorless tunable transceivers of the TWDM-PON ONUs, three classes of wavelength channel tuning time have been specified for the NG-PON2 by the physical media dependent layer recommendation (ITU-T G.989.2). **Table 1** illustrates the specified tuning time classes by the G.989.2 recommendation. It should be noted that different innovative technologies can be exploited by the wavelength tunable devices in order to have the capability for supporting various classes. This will enable a number of potentials for the NG-PON2 system at relatively different costs. Out of the defined three classes, Class 3 is based on the slowest tunable devices. Consequently, it is applicable in scenarios with occasional tuning operations or in applications that can tolerate short service disruption. On the other hand, Class 1 wavelength tunable devices present the shortest tuning time. This feature makes them attractive for offering DWBA feature in the network. Besides, with this class implementation, the ONU transmission wavelengths can be dynamically controlled by the OLT for wavelength hopping between the transmission periods [42].

	Class		
	1	**2**	**3**
Tuning time	<10 μs	10 μs to 25 ms	25 ms to 1 s

Table 1.
Tuning time classes [42].

Although a TWDM-PON offers effective bandwidth resource allocation among multiple clients, meeting the low latency and jitter requirements of certain services may be challenging. Consequently, its implementation for the NGN RAN transport network depends mainly on the RAN use cases and deployment scenario requirements [6]. In Section 5, we present a number of viable means for alleviating the growing stringent requirements in the system. Furthermore, as aforementioned, the NG-PON2 system employs multiple wavelengths that demand for tunable transceivers at the ONUs. However, this requirement might hinder its implementation as the existing optical tunable transceivers are uneconomical. Based on this, a number of operators have been looking for ways around this by envisaging provisional scheme adoption before the full NG-PON2 migration. This will enable them to have a seamless transition with least possible or no disruption in the offered services. One of viable solution is the XGS-PON. It offers an improved commercial solution as a result of the less costly elements being employed.

3.4 XGS-PON application

The XGS-PON presents a novel technology that offers a generic solution for the NG-PON system. It can be viewed as an uncomplicated variant of TWDM-PON in which the wavelength tunability and mobility are eliminated for a more cost-effective reason. In addition, there can be an efficient coexistence between the XGS-PON and TWDM-PON using the same fiber infrastructure, since the employed wavelengths by each technology are different. Consequently, the operators can exploit the lower-cost XGS-PON for quick delivery of 10 Gbps services. This will also enable them to seize 10 Gbps services opportunities for immediate deployments. With XGS-PON, there can be cost-efficient, gradual upgrade, and well-controlled transition to a full TWDM-PON system, with minimum or no disruption to the offered services. It can also facilitate TWDM-PON system by enabling its deployment using the wavelength by wavelength approach. This will really help in pay-as-you-grow scheme for effective system upgrade and migration [33, 43].

Besides its capability for delivering 10 Gbps in both US and DS directions, XGS-PON has high potential for the dual rate transmission support as well [44]. Based on this, the 10/2.5G XG-PON ONUs and 10/10G XGS-PON ONUs can be coupled to the same OLT port via a native dual US rate TDMA scheme. It is remarkable that XGS-PON dual rate presents a comparable cost to XG-PON; nonetheless, it is capable of providing 4 times of the XG-PON US bandwidth. In addition, XGS-PON has been seen as a transitional scheme to NG-PON2 due to its ability for offering the associated NG-PON2 high-data rates in conjunction with the XG-PON1 CAPEX efficiency [33, 43]. Furthermore, it should be noted that the GPON employs 1490 and 1310 nm in the DS and UP, respectively. Likewise, XGS-PON utilizes 1578 and 1270 nm in the DS and UP, respectively. This implies that the XGS-PON service can be effectively overlaid on the same infrastructure as that of GPON. Similarly, the G.989 standard is employed in NG-PON2. The G.989 supports TWDM technologies and it is a multiwavelength access standard [44].

In addition, NG-PON2 is not only a state-of-the-art PON technology with the potential for intense revolution in the operational models of providers but also offers them flexible platform that is capable of enhancing their agility to the market demands as never before. Besides, it has the ability for cost-effective support for both the scale and capacity of the existing gigabit services while at the same time having more than enough room for the multi-gigabit bandwidth requirements of the future networks [38]. Consequently, based on the aforementioned advantages and its proficiency for multiple networks converging with outstanding

performance, in this work, we focus on the NG-PON2 system. Its PHY architecture and development are presented in Section 6.

4. PON system coexistence

Furthermore, in an effort to make considerable profit, different operators have been developing high-bandwidth demanding applications and services. Good examples of such notable ultra-broadband systems are high-definition television (TV) and mIoT. It has been envisaged that there will be a further increase in the bandwidth demand due to the innovative services such as online gaming, home video editing, interactive e-learning, next-generation 3D TV, and remote medical services. However, it should be noted that NG-PON system deployment entails huge initial investments. For instance, in the greenfield FTTH systems, out of the total network investments, the ODN deployment takes between 70 and 76%. Therefore, network investment optimization can be achieved by the operators with the existing ODN exploitation. Besides, compatibility between the NG-PON evolution and the present GPON system is highly essential [35, 44].

Moreover, efficient support for bandwidth-intensive applications and services depends on coexistence of different PON technologies. The coexistence will help in the network investment optimization when the existing ODNs are shared. For instance, a network in which service delivery is being offered by GPON and needs upgrade in order to support new FTTH access technologies can coexist with the PON technologies such as XGS-PON and NG-PON2. This can be realized with the aids of a coexistence element. Based on the desired scenario, various ONT and OLT

| | | Class | | | | | | | |
		A	B	B+	C	N1	N2	E1	E2
Loss	Min. (dB)	5	10	13	15	14	16	18	20
	Max. (dB)	20	25	28	30	29	31	33	35

Note: The degree of severity of specific class requirements could vary from one system category to another.

Table 2.
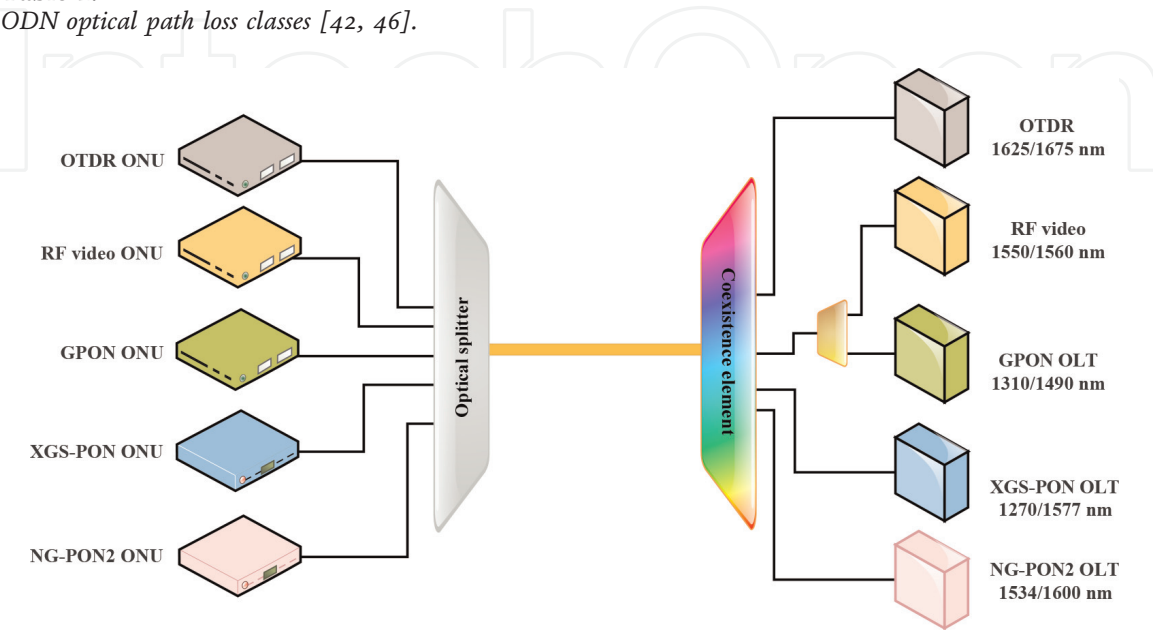*ODN optical path loss classes [42, 46].*

Figure 6.
PON system coexistence.

generations can effectively coexist over a shared ODN fiber infrastructure. Besides, optical time-domain reflectometer (OTDR) and RF signals can also coexist with the PON systems. This is mainly due to the fact that there is no wavelength overlap between each of the technologies. So, this permits in-band measurement without any service interruption [34, 45]. Different ODN optical path loss classes are presented in **Table 2**.

It is remarkable that, apart from the fact that the existing GPON subscribers can be kept together with higher-bandwidth services, the coexistence will also give the operators the profound chance to take advantage of different approaches such as asymmetrical and symmetrical data rates. They also have deployment flexibility by operating on fixed or tunable wavelengths in order to offer appropriate operations and services at suitable costs. It will also assist the operators in the NG-PON evolution path not only by allowing them to upgrade their networks accordingly but also for gradual migration to the evolving PON technologies that are capable of offering the full optical potential. Thus, they have the liberty of adopting the cost and deployment pace that best fit their precise business requirements [43]. More-over, this will enable the operators in making further revenue by exploiting flexible bandwidth and wavelength plans in order to support any service type as well as any business need. **Figure 6** depicts a PON system coexistence for a gradual and pay-as-you-grow expansion [33].

5. System requirement alleviation schemes

As explained in Section 1, C-RAN is envisioned to be a promising candidate for efficient management of the access network and the associated emergent complexity. This is due in part to its cost-effectiveness and remarkable flexibility for the network element deployments. Normally, the inphase and quadrature (I/Q) component stream transmission in this architecture is via the D-RoF-based CPRI. It is remarkable that CPRI-based fronthaul demands huge bandwidth which could be a limiting factor in the 5G and beyond networks in which mm-wave and massive MIMO are anticipated to be implemented. Consequently, an advanced optical transmission technology such as analog RoF (ARoF) has to be employed for an efficient fronthaul solution realization [11, 13, 14].

5.1 RoF schemes

The RoF schemes offer efficient and economical methods for modulated RF signal transmission. For instance, it can be used for transmission from the CO, to a number of distributed RRHs, through low-loss optical fiber networks, by employing an optical carrier. In addition, as aforementioned in Section 1, optical and wireless network convergence is highly imperative for scalable and cost-effective broadband wireless networks. The envisaged convergence for the next-generation mobile communication networks can be efficiently achieved with the implementation of RoF. This is due to its simplicity and efficiency in conveying wireless signal via an optical carrier. Furthermore, the inherent low attenuation and huge bandwidth of optical link can effectively support multiple wireless services on a shared optical fronthaul network. Moreover, with RoF implementation, the CUs and DUs can be well-supported. This offers effective centralized network control that subsequently presents advantages such as easy upgrade, simple maintenance, and efficient resource sharing [11, 47, 48].

It should be noted that there are various RoF options that can be employed in the network. Furthermore, each of the viable options presents related distinct merits

and demerits. Out of the variants, the highly spectrally efficient scheme is the ARoF. Besides, its implementation results in a most power-efficient and least complex RRH design. Nevertheless, it is susceptible to intermodulation distortion which is as a result of optical and microwave component nonlinearity. This results in relatively shorter operating distance. Moreover, the transmitter components such as oscillators, digital to analog converters (DACs), and mixers consume a considerable amount of power. On the other hand, with D-RoF implementation, the ARoF-associated nonlinearity issue can be effectively mitigated. However, in a scenario where high baud rates and high carrier frequencies are required, the DAC power consumption and expenditure are excessively high. Also, if upconversion is required or implemented at the RRHs, it turns out to be substantially high. Consequently, having a fixed phase relation among various RRHs is really challenging. Besides, digitized sample transmission, rather than the analog signal, brings about a significantly low spectral efficiency. The aforementioned drawbacks can be more challenging when densely distributed RRHs are to be supported [11, 47, 48]. Therefore, to address the challenges, a hybrid scheme that is capable of exploiting the ARoF and D-RoF schemes can be employed. One of notable techniques for a hybrid scheme is based on the implementation of sigma-delta-over-fiber (SDoF). This scheme helps in ensuring digital transmission that can support simple and power-efficient RRHs. Besides, there is no need for high-resolution and high-speed DACs with its implementation [47].

It is noteworthy that the RoF scheme employment is contingent on physical optical fiber availability. On the other hand, for the envisaged ultradense small-cell deployment, fiber deployment is not only time-consuming but also capital intensive. Likewise, there could be inappropriate system deployment due to the associated right-of-way acquisition. For these reasons, as well as limited number of the deployed fiber, the FSO system practicability has been considered [11, 13, 14].

5.2 FSO scheme

FSO communication presents an alternative technology for optical fiber systems. It is based on RF signal transmission between the CU and the DU apertures via the free space. Therefore, being an optical wireless technology, the fiber media are not required, and, consequently, trenches are unnecessary for its implementation. Moreover, like a well-developed, viable, and widely employed RoF technology, FSO scheme is capable of supporting multiple RF signal transmission. Apart from having inherent optical fiber features like RoF, FSO scheme offers additional merits regarding time-saving and cost-effectiveness, since there is no need for physical fiber deployment. This makes it to be very applicable in scenarios where physical network connectivity through optical fiber media is challenging and/or unrealistic. Besides, it is capable of delivering broadband services in rural area where there is an inadequate fiber infrastructure [11, 13, 14]. It is noteworthy that, when employed as a complementary solution for fronthauling, FSO can be a promising mobile traffic offloading scheme for alleviating the stringent requirements of bandwidth-intensive services transmission via the mobile networks.

In addition, the FSO scheme offers a number of benefits such as high bit rates, ease of deployment, full duplex transmission, license-free operation, improved protocol transparency, and high-transmission security. These salient merits enable the FSO scheme to be considered as a viable broadband access technology. It is capable of addressing various services and applications' bandwidth requirements at low cost for the NGNs. Based on these, the RF signals over FSO (RoFSO) idea have been presented. This is in an effort to exploit the inherent massive transport

capacity of optical systems and the related deployment simplicity of wireless networks [11, 13, 14].

Furthermore, a DWDM RoFSO scheme implementation has the capability of supporting concurrent multiple wireless signal transmission [49]. Nevertheless, the FSO systems have some drawbacks due to their susceptibility to the atmospheric turbulence and local weather conditions. The effects of these can cause beam wandering, as well as scintillation, which in due course results in the received optical intensity fluctuation. Consequently, the system reliability and availability can be determined by the extent of the effects. As a result, FSO technology is relatively unreliable like the normal optical fiber technology. Therefore, apart from the fact that these can limit the RoFSO system performance, its employment for uRLLC applications might also be limited as well. Consequently, the drawbacks hinder the FSO scheme as an effective standalone solution. Therefore, for the FSO scheme to be effective, the associated turbulence-induced fading has to be alleviated [2, 17, 18, 50]. Based on this, several PHY layer ideas like maximum likelihood sequence detection, diversity schemes, adaptive optics, and error control coding with interleaving have been presented to address the issue [11, 50, 51]. Besides, innovative schemes such as relay-assisted transmission and hybrid RF/FSO technologies can be implemented to enhance the system performance regarding capacity, reliability, and availability [11].

5.3 Hybrid RF/FSO scheme

A hybrid RF/FSO scheme exploits the inherent high-transmission bandwidth of the optical wireless system and the related deployment simplicity of wireless links [2]. In addition, the hybrid RF/FSO system idea does not only base on concurrent means of attending to the hybrid scheme related limitations, but it also entails ways of exploiting both approaches for a reliable heterogeneous wireless service delivery. The hybrid scheme is able to achieve this by incorporating the RF solutions' scalability and cost-effectiveness with the FSO solutions' high data rate and low latency. Consequently, the technology is able to address the high throughput, cost-effectiveness, and low-latency requirements of the system. Besides, it presents a heterogeneous platform for wireless service provisioning for the envisaged 5G and beyond networks [11, 13, 14, 52, 53].

5.4 Relay-assisted FSO scheme

One of feasible methods of turbulence-induced fading mitigation is the spatial diversity scheme. In this technique, there are multiple deployed apertures at the receiver and/or transmitter sides. This is in an effort to realize extra degrees of freedom in the spatial domain. It is remarkable that spatial diversity is an appealing fading mitigation scheme, owing to the presented redundancy feature. On the other hand, multiple-aperture deployment in the system causes a number of challenges like an increase in the cost and system complexity. Moreover, in order to prevent the spatial correlation detrimental effects, the aperture separation should be sufficiently large. Furthermore, a notable approach for simplified spatial diversity implementation is a dual-hop relaying scheme. It is noteworthy that there has been extensive implementation of the scheme in the RF and wireless communication systems. Application of the scheme in these fields not only aids in improving the receive signal quality but also helps considerably in the network range extension [2, 11, 13, 14].

Conceptually, multiple virtual aperture systems are generated in the relay-assisted transmission with the intention of realizing salient MIMO technique

features. The architecture takes advantage of the RF and FSO features for an efficient and reliable service delivery. In addition, a relay-assisted transmission system is an innovative communication technique known as a mixed RF/FSO dual-hop communication system. The dual-hop scheme meaning can be easily under-stood from its architecture. In the architecture, the transport networks from the source to the relay system are RF links; however, the transport networks between the relay system and the associated destination node(s) are FSO links. Hence, in a dual-hop system, RF is used for signal transmission at one hop, while FSO trans-mission is implemented at the other. The FSO link mainly functions to facilitate the RF users' communication with the backbone network. This is purposely for filling the connectivity gap between the backbone and the last-mile access networks. Accordingly, the offered architecture can efficiently address the system-related last-mile transmission bottleneck. This can be effectively achieved by supporting multiplexed users with RF capacities. The users can also be aggregated onto a shared high-capacity FSO link. This will help in harnessing the inherent huge bandwidth of an optical communication system. Another outstanding advantage of this scheme is that any kind of interference can be easily inhibited via its implementation. This is due mainly to the fact that the RF and FSO operating frequency bands are completely different. Consequently, it offers better performance than the traditional RF/RF transmission schemes [2, 11, 13, 14].

5.5 RAN functional split

The RAN functional split is another innovative and practical scheme for allevi-ating the imposed fronthaul requirements by the C-RAN architecture [11, 54]. For instance, to address the drawbacks of CPRI-based fronthaul solutions, an eCPRI specification presents additional physical layer functional split options and a packet-based solution. Consequently, unlike the conventional constant data rate CPRI in which the stream significantly depends on the carrier bandwidth, as well as the number of antennas, the eCPRI stream does not depend on either of the factors but on the actual traffic load. In essence, apart from being able to alleviate the stringent bandwidth demands, multiple eCPRI stream can also be multiplexed onto a wavelength for onward transmission over the fronthaul network [12].

In addition, with recent network architecture development, the traditional BBU and RRU have been reformed into different functional entities which are the CU, DU, and RRU/active antenna unit (AAU). With the configuration, the CU majorly focuses on non-real time and part of the traditional Evolved Packet Core function-alities. This involves high-level protocol processing like dual connectivity and radio resource management. In addition, the DU is responsible for the real-time media
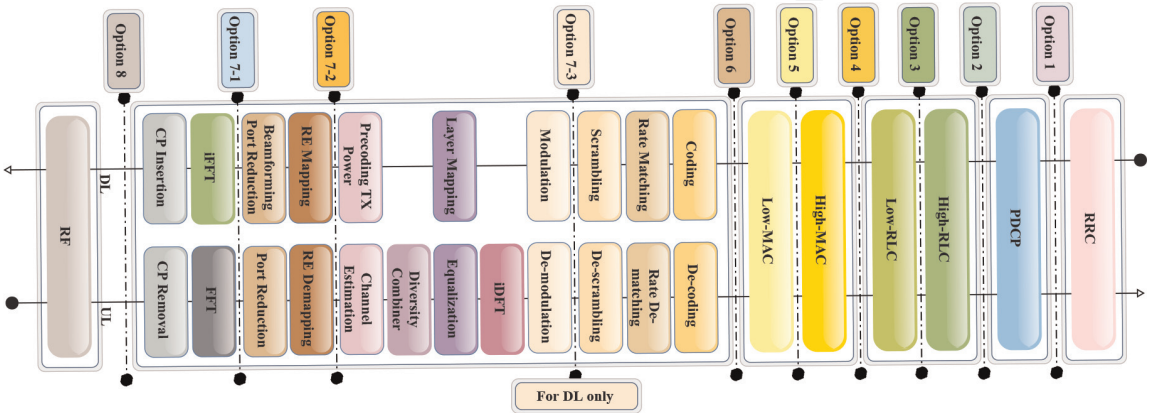

Figure 7.
Functional split options between CU and DU with emphasized PHY layer.

access control layer functions like HARQ flow and physical layer function processing. Also, when massive MIMO antennas are to be employed, certain parts of the physical layer functions can also be shifted to the RRU/AAU. The implementation will not only aid in lessening the associated transmission bandwidth between the RRU/AAU and DUs but will also help in reducing the transmission cost considerably. Therefore, a number of functional split options have been presented in order to reduce the processing and network resource cost considerably. As shown in **Figure 7**, each of the option is categorized according to the demarcation point between the CU and the DU. Therefore, depending on the deployment scenarios and use cases, each option offers different degrees of flexibility regarding resource allocation for different service requirements [12, 29].

6. NG-PON2 physical layer architecture design and development

The NG-PON2 physical layer requirements are very challenging. Besides, the requirements are even more strict than the legacy PON technologies. For instance, when compared with the GPON taken into consideration the related spectrum, GPON employs only one channel for the transmission and one for the reception, with a very wide wavelength allocation (up to 100 nm). On the other hand, in NG-PON2, there are <4 nm to accommodate four channels. Consequently, this means that the thermal control must be very precise in order to keep each channel inside the specified channel space (which is +/−20 GHz). As aforementioned, there are multiple channels in NG-PON2 transmission; therefore, the receiver must be tunable so as to work for any one of them at a particular time while others are rejected. This requirement implies that there is a need for a very tight band-pass filter too for efficient operation. Also, the tuning time classes, already presented in **Table 1** in Section 3, are likewise strict and difficult to achieve on the hardware side. Besides, one of the major related issues is the amount of the required optical-electrical-optical (OEO) conversions, which can bring about an unviable and unsustainable system [55].

6.1 Photonic integrated circuit

The optical communications evolution has initiated enhanced photonic integrated circuits (PICs) that present a cost-effective alternative to data transmission. With PIC technology implementation, a number of optical components such as modulators, lasers, amplifiers, detectors, etc. can be merged/integrated on a single chip. Consequently, it helps in optical system design simplification, system reliability enhancement, as well as significant power consumption and space reduction. In addition, there can be considerable reduction in the amount of OEO converters required for the system implementation. This subsequently results in the total network cost reduction [55]. Thus, it is anticipated to be an enabling and viable technology with immense flexibility and reconfigurability in a number of fields [56]. A PIC has numerous advantages over the traditional optical sub-assemblies (OSAs). For instance, considering the occupied volume, the PICs allow a very dense architecture in a small area, passing also by the optical losses; however, the losses in the OSAs are higher because of the internal free-space alignment between each optical component. Also, other notable advantages of the PICs compared with the OSAs are lower power consumption, lower footprint, and cost-effectiveness. Therefore, PICs have the capability of permitting flexible and high data rate solutions [39, 55].

In the following, for the system realization, we propose three different architectures: the ONU architecture, the OLT architecture, and the architecture that can perform both functions just by hardware selection. It should be noted that all of these architectures have the transmit and the receive parts.

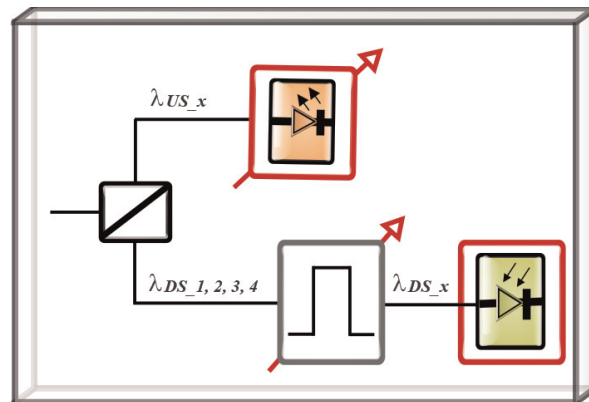### 6.1.1 NG-PON2 ONU transceiver architecture

The ONU transceiver architecture is represented in **Figure 8**. This is a very simple structure regarding the optical setup, but the electrical control is very tough, mostly because of the tunability (both on the transmitter and on the receiver). In this example, there is one tunable laser. The laser can be tuned by temperature and can be directly or externally modulated (the latter would also need a modulator after the laser). On the receiver part, there is an optical band-pass filter which has to be tunable to allow one of the downstream channels and cut the rest of the spectrum. The tunable band-pass filter is followed by an optical receiver.

6.1.2 NG-PON2 OLT transceiver architecture

As explained before, the OLT is not tunable; both transmitter and receiver should work on the same fixed wavelength pair, as depicted in **Figure 9**. Consequently, four pairs of optical devices will be needed. Since it is very difficult to encapsulate everything on the same transceiver, the solution that is being followed commercially is having four different transceivers, one for each wavelength pair, and the wavelength multiplexer (WM) device is external. This WM should, in each port, allow one wavelength pair, meaning that in each port, it should pass only one downstream and the respective upstream channel.

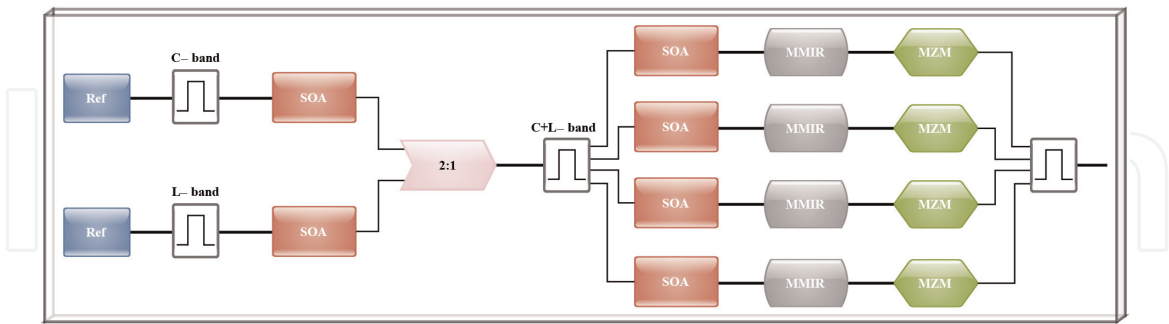### 6.1.3 NG-PON2 OLT/ONU transmission architecture

The architectures presented in **Figures 8** and **9** are the basic ones to have functional devices for NG-PON2. But taking advantage of photonic integration, it is possible to develop a much more complex circuit with more functionalities, which is being presented next. **Figure 10** illustrates the block diagram of an architecture that can be used both as ONU and OLT. This helps in exploiting the advantage of both functionalities on a single chip. The purpose (OLT or ONU) to be served can be achieved just by hardware selection. This proposed architecture fits inside a 4 4.6 mm indium phosphide (InP) PIC. In the following subsection, we present the final design and some obtained simulation results.

Figure 8.
ONU transceiver architecture.
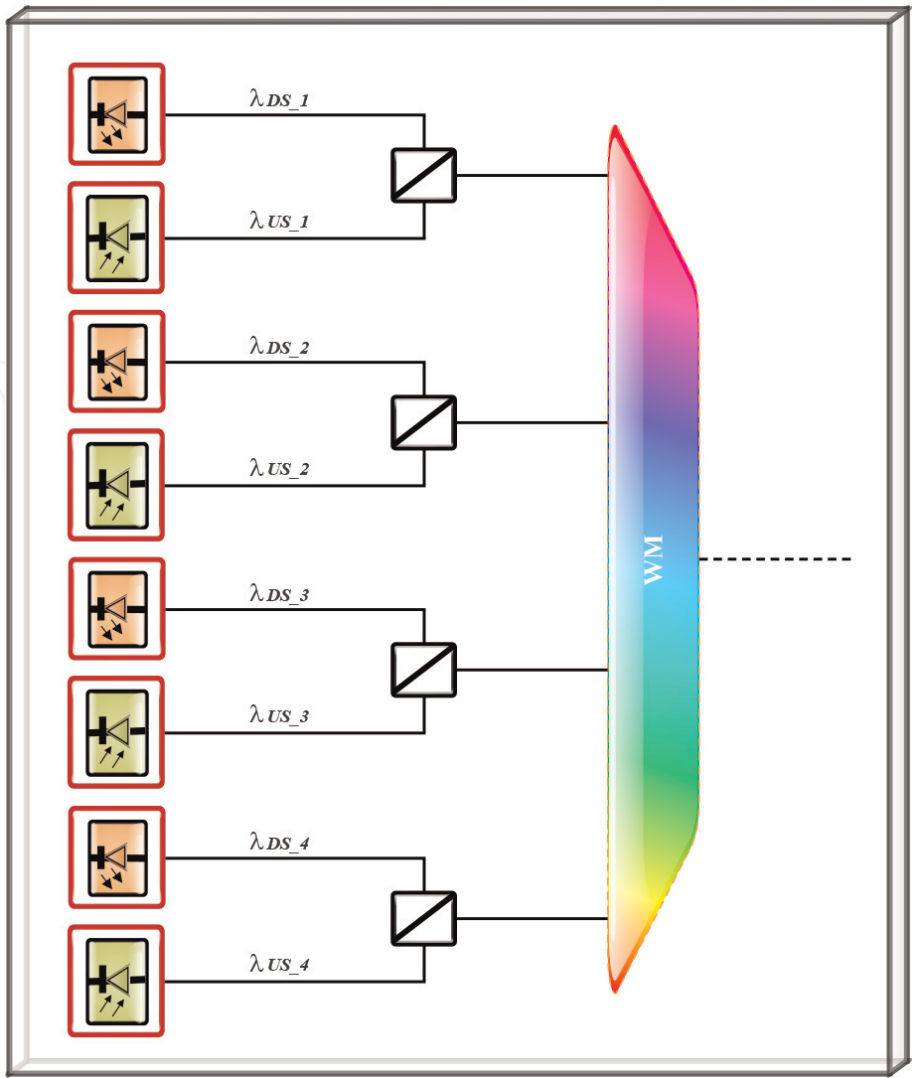
Figure 9.
OLT transceiver architecture.

Figure 10.
Block diagram of OLT/ONU transmission architecture.

6.2 PIC implementation of OLT/ONU and receiver circuits

The architecture comprises four lasers, four Mach-Zehnder modulators (MZM), and a number of filters. Two of the filters are for changing the operational frequency band (C band for upstream transmission and L band for downstream). Also, one filter is employed for tuning the four lasers to the correct wavelength. Besides, at the output, there is one filter working as a combiner of the four lasers. The band selection is made using the two semiconductor optical amplifiers (SOAs) that are placed after the band filters. It is noteworthy that the two SOAs are working as

switches and determine the chip's operating mode (i.e., OLT or ONU). Therefore, one of the SOAs is amplifying the light (active SOA), while the other is absorbing (passive SOA). Consequently, by this configuration, only one band filter is contributing to the setup. The employed lasers are built using laser cavities which contain SOAs that are being used for gain purposes, filters, and reflectors on both sides. The C + L band filter helps in the selection of the downstream or upstream channel [39].

Moreover, the architecture includes also a multimode interferometer reflector (MMIR) before the band selection and another one after each gain SOA. These reflectors define the laser cavity limits. The second MMIR, after the gain SOAs, only reflects 50% of the light, and the remaining 50% is the laser cavity output and is sent to the MZM for modulation. After the modulation on the MZMs, all four channels are combined in just one, and the resulting light signal is sent to the output
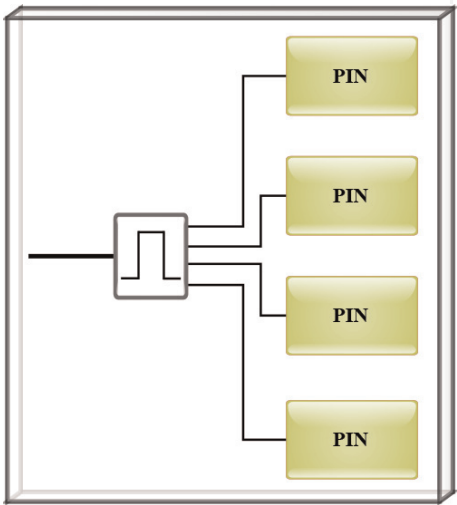
Figure 11.
Receiver block diagram.
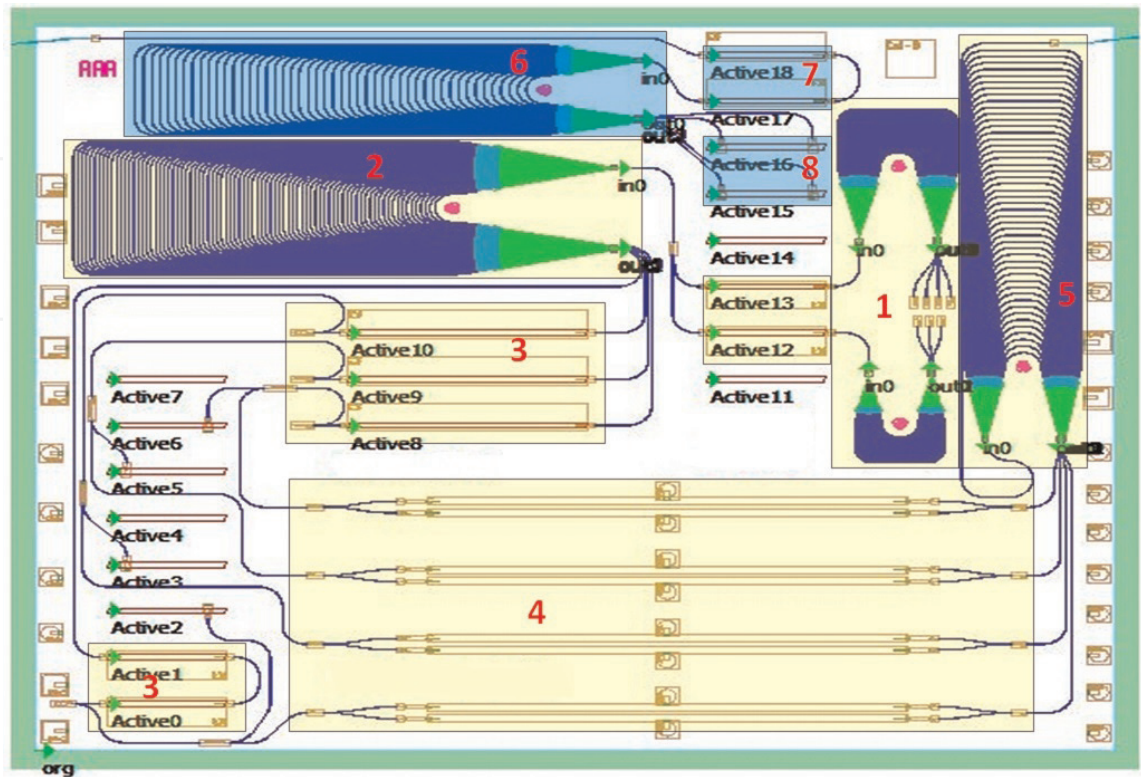
Figure 12.
OLT/ONU integrated transceiver design masks.

of the PIC, where a fiber will be aligned to collect the light, and subsequently, it will be sent to the network [39].

6.2.1 PIC implementation of receiver circuit

This PIC has also a receiver circuit, but it is a simple one, with just a wavelength division multiplexer (WDM) filter which receives the light from the network and routes each NG-PON2 channel for a different PIN. The receiver circuit schematic is depicted in **Figure 11**.

6.2.2 PIC implementation of OLT/ONU circuit

Using the photonic design kit (PDK) from the foundry Smart Photonics and a software for PIC design (Phoenix Software at the time, meantime bought by synopsis) for the implementation, the final circuit masks of the chip are shown in **Figure 12**.

7. Results and discussion

In this section, we present the obtained simulation results with further discussion on NG-PON2 physical layer architecture design and development based on PICs. **Figure 13** shows the spectral simulation results obtained using advanced simulator for photonic integrated circuits (Aspic) software from filarete. On the left figure, there is the downstream operation (L band selected), and on the right there is the upstream (C band selected). In the figure, the spectra in blue, pink, orange, and green are the four channels. In both cases, it is possible to conclude that there is about 30 dB of suppression of replicas. The suppression facilitates smooth operation of the system by preventing intra-channel interference.

The reason for using laser cavities is due to the limitations on the foundry. During the chip's design period, the Smart Photonics did not offer lasers on their process design kit (PDK). Consequently, improvements in the architecture can be undertaken to potentiate the results. For instance, the laser cavities could be replaced by distributed feedback (DFB) or distributed Bragg reflector (DBR) lasers that have narrow linewidth and a stable single mode operation. In this case, the cavity would disappear, and the filtering should be done after the lasing. In addition, the architectures can be simplified using only one modulator; nevertheless, it
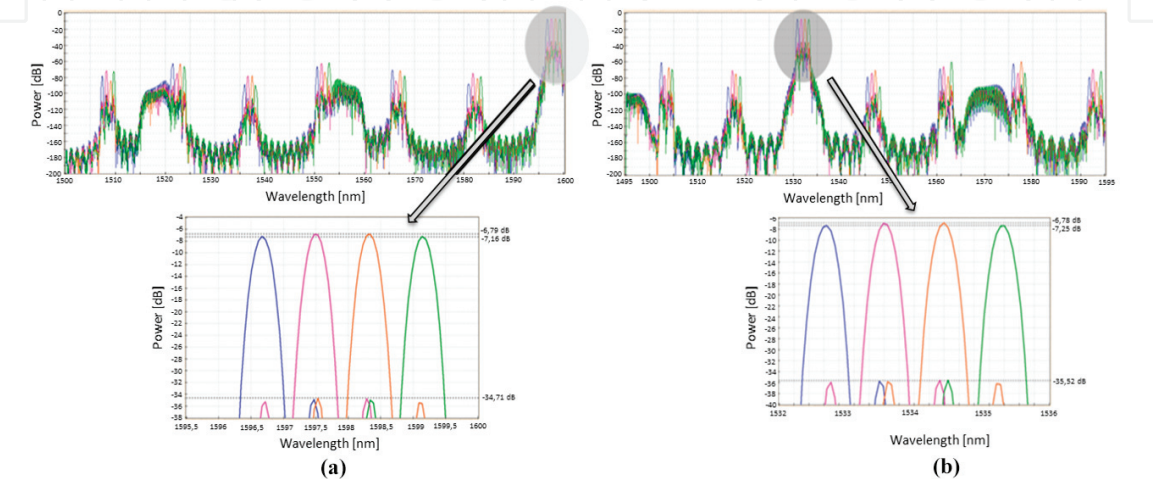
Figure 13.
Optical spectra at the transmitter output (a) downstream and (b) upstream.

would not be possible to transmit the four channels simultaneously; this implies that only one channel can be transmitted at a time. The proposed and developed architectures demonstrate the potential of photonic integration for optical architectures. Consequently, the architectures not only have the ability of supporting high data rates, high density, and flexible solutions but also offer advantages such as low power consumption, improved functionality, low footprint, and cost-effectiveness.

8. Conclusion

The 5G based system is a promising solution for attending to the growing concerns about the traffic pressure on the network. Also, the envisaged massive number of deployment scenarios and use cases to be supported brings about high-bandwidth and low-latency requirements for the 5G networks. The small-cell-based C-RAN approach can efficiently attend to the associated ultradense deployment. However, the C-RAN-based approach imposes stringent requirements regarding jitter, bandwidth, and latency for the mobile transport networks. In this book chapter, we have presented wired and wireless transport solutions that are capable of addressing the C-RAN-based stringent requirements and, consequently, the 5G mobile transport network demands. Furthermore, owing to its significant and inherent advantages for the 5G and beyond networks, we have focused on the NG-PON2 system. We have exploited the salient advantages and the low footprint platform offered by the PICs in the NG-PON2 system design and implementation. Based on these technologies, the proposed architectures are capable of alleviating the associated losses in the system while also helping in increasing the system power budget. In addition, employment of the proposed architectures can help the device makers, service/network providers, and infrastructure and chip vendors, in lowering the footprint of network elements.

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