IOWN GLOBAL FORUM

Ultra Wideband Optical Transmission White Paper

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1. Introduction

The All-Photonics Network (APN) incorporates photonic (optical) technology not only within the network but also between directly connected endpoints. This enables significantly lower power consumption, enhanced quality, increased capacity, and reduced latency, all of which are challenges that are difficult to overcome with current electronics-based technologies. Optical networks and end-to-end use of optical technologies play an important role in achieving the target of IOWN GF. The rapid growth in data traffic and the emerging need to support advanced applications such as high-definition streaming, cloud services, and generative AI make it imperative to achieve larger capacity transmission in APN. In addition, as the bitrate of optical signals increases, the bandwidth per wavelength will expand, reducing the number of available wavelengths within a limited optical band. It is necessary to improve the transmission capacity in APN while addressing the increase in available wavelengths and the enhancement of optical signal bitrate. To cope with the above-mentioned situations, it is important and efficient to introduce a new technology, which we refer here to as Ultra-Wide Band Optical Transmission (UWOT) technology. The Open All-photonics network Architecture (OAA) Task Force has introduced UWOT technologies in Functional Reference Architecture Releases 1 and 2. We consider this technology to be very important as the next technology after APN, and we have thought that open discussion is necessary.

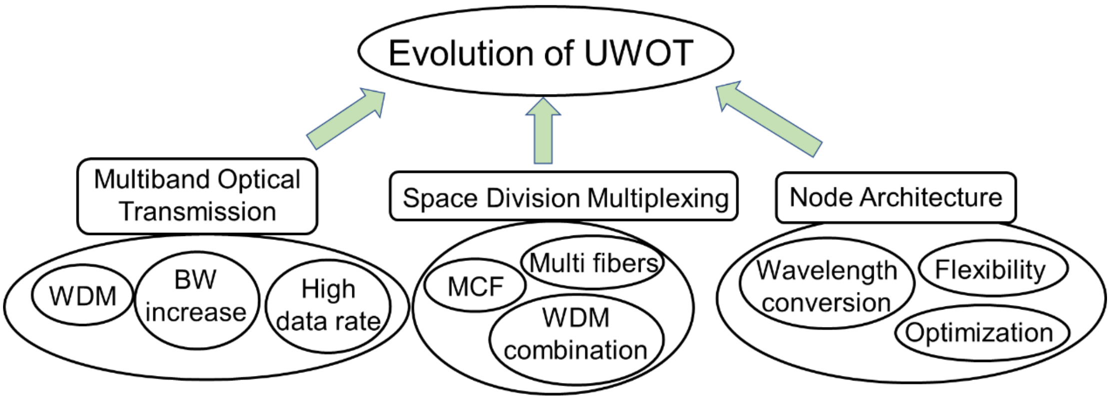

Figure 1-1-1 Evolution of UWOT technologies

Figure 1-1-1 illustrates the evolution of UWOT technologies, concentrating on three primary areas: multiband optical transmission, Space Division Multiplexing (SDM) technology, and node architecture. It highlights the key components and benefits of each technology, showing their role in advancing optical communication systems through improved bandwidth, capacity, flexibility, and interoperability.

Since UWOT comprises innovative technologies to realize the challenging objectives of IOWN, these technologies have not been proven in current networks yet. Therefore, this white paper introduces these technologies, shows technical issues that need to be addressed and provides information to potential users / operators on how to implement the UWOT technologies into APN.

1.1. Examples of early adoption use cases

There are several potential use cases to utilize UWOT technology.

Potential use case #1 : Campus network

As bandwidth demand increases due to advances in AI, and cloud services become more diverse and sophisticated, campus networks are required to increase the number of fibers and the number of cross-connections. In campus networks, fiber installation is too costly for daily operation from the following standpoint. First, unlike the data centers, campuses rarely conduct fiber installation. So the labor cost cannot be shared by many orders. This makes fiber costs very high. Second connectors can be used at a few points because the insertion loss of connector-based extension is higher than that of splicing and moreover connectors occupy large space. So they cannot fits small branching points. Third, high-density optical distribution frame is too large for campuses. In other words, an optional distribution frame (ODF) for a thousand ports is full-rack system. It is worth the space for data centers because it raises their values. However, it would be too large and costly for campuses.

Because of the above reasons many campus networks today are built with packet switches and pre-cabling. This often results in technology debt; in other words, it leaves campus networks behind in the evolution of transceivers. Some campuses may frequently upgrade transceivers to keep up with the transceiver product lifecycle. But that would be very costly.

New Solution: Campus APN with UWOT

So, the industry has started developing wavelength division multiplexing (WDM)-based solutions. We expect Open APN to be adopted as an architecture for open and disaggregated solutions. However, there is an issue. With today's C-band DWDM systems and 400 Gbps coherent transceivers, we can create as many as 64 channels on one fiber. However, transceivers of future generations will use wider wavelength channels, reducing the number of channels on one fiber. This will eventually force campus networks to install additional fibers and larger ODFs.

Therefore, this is where UWOT comes in. It will enable campus networks to keep up with the evolution of transceivers without installing additional fibers and larger ODFs.

Having said that, we should develop UWOT technologies to achieve the following the cost of APN node upgrades to support UWOT is much less than the cost of additional fiber installation and ODF upgrades.

Potential use case #2 : Submarine cable

The highest transmission capacity achieved in submarine cable systems currently is 500 Tbps per cable, with expectations of reaching 1 Pbps by 2028, driven by a projected compound annual growth rate (CAGR) of 32%. In submarine cable systems, the deployable cable diameter is constrained, and strict power limitations exist. Furthermore, cost optimization makes an increase in the number of fibers within a submarine cable increasingly difficult. In the C-band, fibers have the lowest attenuation, and amplifiers installed in cables operate with the highest power efficiency. The SDM technology offers a solution by enhancing the core count, which boosts the overall capacity of submarine cables while maintaining cable diameter and weight. This approach takes full advantage of the C-band, paving the way for the adoption of high-density cables employing thin coating fibers and multicore fibers in future submarine cable systems.

Potential use case #3 : Data center interconnect

The demand for data capacity, driven by AI-based applications, is increasing at an unprecedented pace. Hyperscalers are planning to address this surge by leasing dark fiber and laying new optical fibers. However, the current number of optical fibers may become insufficient in the future, and completing new optical fiber installations requires significant time and investment over several years.

Moreover, new data centers are often constructed near power plants to meet higher power availability demands. These locations may not align with existing optical fiber routes, further complicating connectivity. In regions and cities where fiber availability is limited, multi-band multiband transmission technology offers a promising solution. This technology maximizes the use of available optical fibers by utilizing multiple wavelength bands, thereby enhancing capacity without the need for extensive new optical fiber installations.

This approach may prove to be cost-effective while also providing the necessary flexibility and scalability to adapt to future technological advancements and capacity demands.

To meet the growing demand for increased capacity, various approaches are being explored. Data center interconnects are often constrained by limited duct space (e.g., 1.25-inch ducts). High-density cables offer an efficient solution, enabling high-capacity data transmission without the need for costly duct replacements. For further increase of the capacity, multicore fibers can be used. Two- or four-core multicore fibers can achieve a two- or four-times capacity increase while maintaining the cable diameter. By utilizing fan-in and fan-out devices, it is possible to directly leverage existing single-mode fiber technology. This SDM solution employing high-density cables or multicore fibers contributes to the development of low-energy consumption data center systems.

2. Application scenarios

In this chapter we discuss a petabit-class transmission system as an Open APN target for 2030 aiming for a capacity that is 125 times greater than current networks.. In order to achieve such a system, multiple scenarios are considered depending on the use case and applicable area in the current APN system. The UWOT team could address several fundamental technologies such as multiband, multifiber/multicore technologies, narrow channel grid, and bi-directional transmission. Therefore, It is beneficial to explore various scenarios for realizing a petabit-class APN system by implementing different technologies over time while considering the diverse requirements of APN across various application domains.

2.1. Description of the scenarios

We examine three scenarios as depicted in Fig. 2-1-1 and explore which of UWOT technologies should be used to realize petabit-class transmission considering both economic and practical perspectives in each case. As summarized in Table 2-2-1, the three scenarios are: (1) Long haul (LH) network systems and submarine systems, (2) Terrestrial and metro network systems, and (3) Data center interconnect (DCI) network systems. First, in scenario 1, the LH core and submarine cable system have limited space for cable laying and require high power efficiency without repeater system. In this scenario, the number of fiber counts should be increased, and subsequently the number of bands should be increased. Next when it comes to the terrestrial system and metro network region in scenario 2, it is difficult to deploy new fibers and enable high interconnectivity between HWs should be required. In this case, it is possible to increase the capacity per wavelength, expand the bandwidth that efficiently utilizes the existing system, and combination use of multifiber or multicore is important while considering the limited direction and WSS port counts in both APN-I and APN-G. In the DCI network region of scenario 3, space saving and power saving are highly required, and it is difficult to introduce new hardware (HW) equipment additionally in the existing brownfield network. Here, it is necessary to increase the fiber utilization efficiency by adding the new wavelength band. The below is an example of the scenario descriptions.

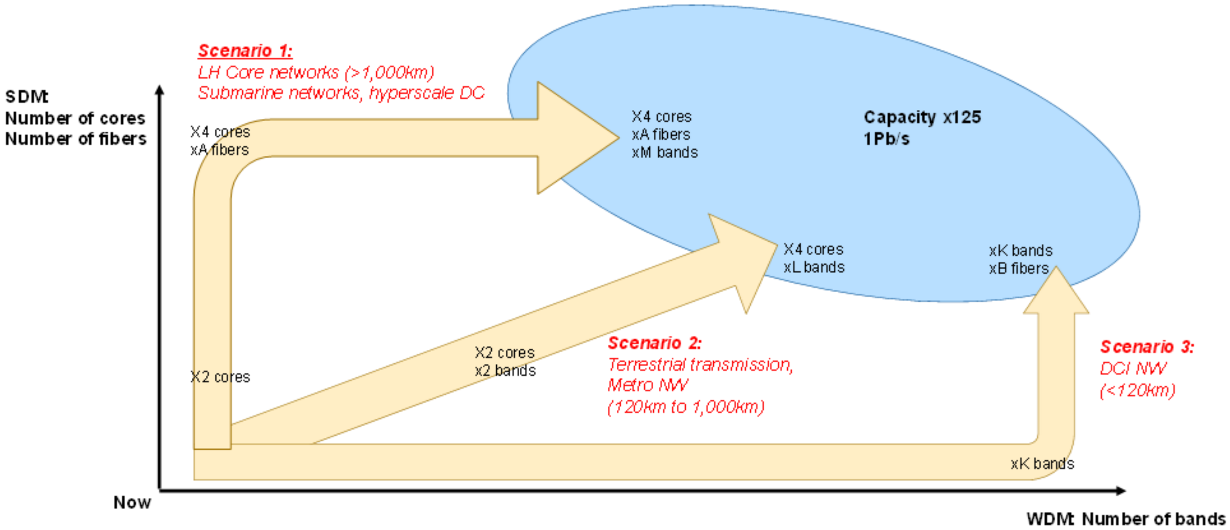

Figure 2-1-1: Three scenarios reaching to 1 Pb/s APN system

Table 2-2-1: Example of the scenario descriptions.

	Submarine NW LH Core NW	Terrestrial NW Metro NW	DCI (Datacenter Interconnect)
Distance	> 1000 km	120~1000km	~120 km
Descriptions/Features	Space & Power constraint	Mixture of PtoP and ROADM New fiber deployment difficulty, Interoperability	Amp/ROADM often not needed Space & Power limitation Difficulty in onboarding new HW to a brownfield NW
Current capacity/fiber,band	8~20Tb/s@100~200Gb/s	8~20Tb/s@100~200Gbs	8~20Tb/s@100~200Gb/s
Approaches	multi fiber, MCF, C+L	Beyond 1.6 Tb/s, S+C+L, multi fibers, MCF	Beyond 1.6 Tbps, S+C+L+U(O), multi fibers, MCF
~2030	One Peta-bit class APN system		

3. Multiband transmission

3.1. Overview of the multiband transmission

The current APN system is generally applied in the C band. As shown in Fig. 3-1-1, by expanding the wavelength band used for optical fiber transmission from the C band to a new wavelength band such as the L band, S band, E band, U band, and O band, the fiber utilization efficiency can be increased up to 2 times and 4 times compared with the conventional C band use while utilizing the fiber already installed. And, if the wavelength band from the O band to the U band can be utilized, the effective utilization of the wavelength resource could be increased by up to 10 times more in the future APN system.

In order to realize such bandwidth-expansion technology, studies on expansion from C and L bands to new wavelength bands such as S, E, U, and O bands have started in academic field and research and development of amplification technology which can be used in parallel and wide band, and wavelength conversion technology which converts WDM signals into different wavelength bands at one time, etc. have also become popular [3-1][3-2].

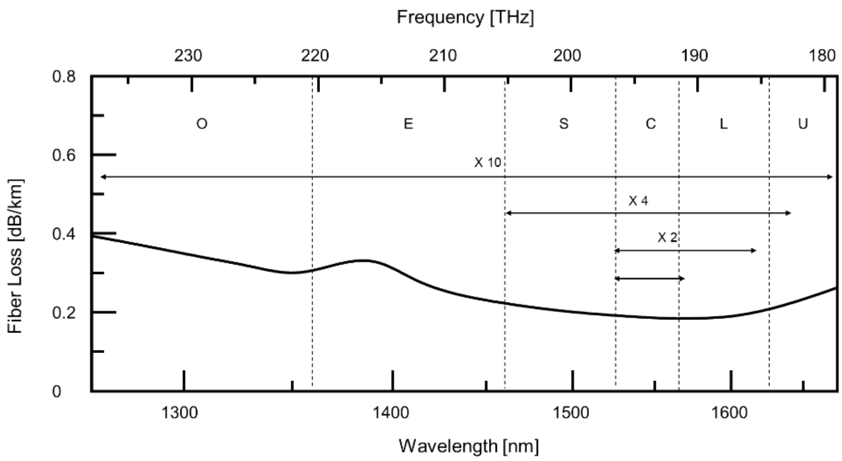

Figure 3-1-1: Fiber loss characteristics in Ultra-wideband wavelength range

3.2. Fiber characteristics from O to U bands

In the evolving landscape of optical communications, the division of the optical spectrum into specific bands - C-band, L-band, S-band, U-band, and O-band - plays a pivotal role in addressing the diverse needs of UWOT systems. This section delves into the characteristics, general uses, and potential integration of these bands into UWOT, highlighting their advantages, constraints, and impact on UWOT's performance.

The C-band, covering wavelengths from approximately 1530 nm to 1565 nm, is well known for its low attenuation and moderate dispersion, making it ideal for long-haul optical communications. It is the most widely used band in current fiber-optic networks due to its efficient amplification by erbium-doped fiber amplifiers (EDFAs).

Adjacent to the C-band, the L-band covers wavelengths from about 1565 nm to 1625 nm. It provides an extended spectrum for communication which is particularly valuable when the C-band is exhausted.

The S-band ranges from approximately 1460 nm to 1530 nm and, while not as commonly utilized, offers potential for applications where broader spectrum availability is desired. Covering wavelengths beyond 1625 nm, the U-band is considered for its potential to further expand the usable optical spectrum for communication systems.

The O-band spans from 1260 nm to 1360 nm and is known for its low dispersion, making it particularly suitable for short-reach and metro applications where maintaining signal integrity is critical. Incorporating these diverse bands into UWOT systems could significantly enhance bandwidth and system capacity, addressing the ever-increasing demand for data transmission. While the C-band and L-band offer broad and established platforms for long-haul communications, the S-band, U-band, and O-band present opportunities for system expansion and optimization in specific scenarios. However, the successful integration of these bands into UWOT necessitates overcoming their inherent limitations through technological advancements and system design innovations.

The strategic utilization of the C-band, L-band, S-band, U-band, and O-band in UWOT systems has the potential to revolutionize ultra-high-speed data transmission. As the field of optical communications continues to evolve, understanding and leveraging the unique advantages of these bands will be crucial in meeting the future demands of optical networks.

3.3. Amplification technologies from O to U bands

The amplification of optical signals across various bands from O to U, including O-band, S-band, C-band, L-band, and U-band is a cornerstone of modern optical communication systems (Fig. 3-3-1). This section delves into the amplification techniques applicable to these bands, highlighting their characteristics, general uses, and potential integration into UWOT systems. This subsection will explore the benefits and limitations of these amplifiers and assess their impact on the performance of UWOT systems. C-band amplification, spanning from 1530 nm to 1565 nm, is the most prevalent in optical networks, primarily utilizing EDFAs. These amplifiers are renowned for their high efficiency and broad gain spectrum, making them ideal for long-haul transmissions.

L-band amplification extends the spectrum from 1565 nm to 1625 nm, using specialized EDFAs and Raman amplifiers to accommodate the higher wavelengths. It is often employed to expand network capacity alongside the C-band.

S-band amplification, ranging from 1460 nm to 1530 nm, is less common and typically relies on thulium-doped fiber amplifiers (TDFAs) and Raman amplification. Its use is exploratory, focusing on untapped spectrum opportunities.

U-band amplification, for wavelengths beyond 1625 nm, is an emerging area, necessitating the development of new amplification techniques, such as advanced EDFAs, Raman amplifiers, and potentially parametric amplifiers, to effectively utilize this spectrum.

O-band amplification, covering wavelengths from 1260 nm to 1360 nm, is crucial for short-reach and metro applications. The primary technique involves the use of semiconductor optical amplifiers (SOAs), praseodymium-doped fiber amplifiers (PDFAs) and bismuth-doped fiber amplifiers (BDFAs) and tailored for lower wavelengths.

The integration of amplifiers across the O to U bands into UWOT systems offers the potential to dramatically enhance bandwidth, flexibility, and capacity. Each band's amplification technique brings unique advantages to the table, from short-reach signal integrity in the O-band to capacity expansion in the L-band and U-band. However, the successful deployment of these amplifiers in UWOT necessitates overcoming inherent limitations, such as attenuation and nonlinear effects, through technological innovation and system optimization. Amplification techniques from O to U bands are integral to the advancement of optical communication systems, including UWOT. As the demand for ultra-high-speed data transmission continues to grow, the strategic utilization of these amplifiers will be crucial in meeting the future needs of optical networks.

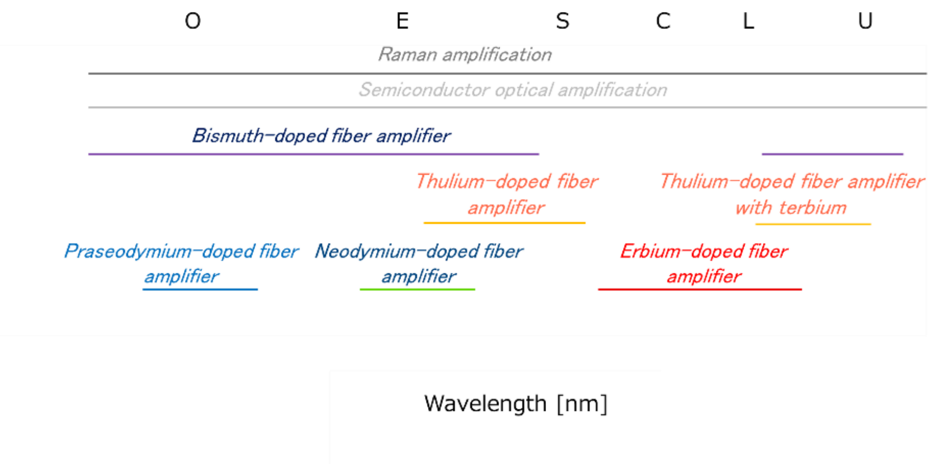

Figure 3-3-1: Amplification technologies over wide-band spectrum

3.4. Technical gap analysis between current technologies and wideband technologies

As the demand for higher bandwidth and more efficient optical communication systems continues to escalate, the transition from current technologies to wideband technologies, spanning from O to U bands, becomes increasingly critical. This section conducts a gap analysis, highlighting the disparities between the existing fiber characteristics and amplification techniques and the requirements for implementing UWOT systems. This subsection will explore the challenges and opportunities presented by expanding the operational spectrum and how they might influence the evolution of optical networks.

Table 3-4-1: Gap analysis

	Current APN	UWOT	Challenges	Opportunities
Fiber characteristics	Designed for C-band operations	Utilization of a broader spectrum, from O to U bands, each with distinct characteristics.	Dispersion Attenuation Material limitations for fibers	Innovative fiber designs
Amplification technologies	EDFA for C, L bands	Wideband amplification technologies	Current amplification technologies are band-specific Nonlinear effects	Advanced amplification technologies: TDFA for S band, BDFA for O band and U band. Raman amplification covers wide range of transmission spectrum.

The transition to UWOT systems presents both significant challenges and opportunities. The technical gaps in fiber characteristics and amplification techniques necessitate a concerted effort in research and development to realize the full potential of wideband technologies. These two approaches are important to fill the gap between the current technologies and UWOT.

Material Science Advances: Developing fibers with optimized characteristics for wideband operation is crucial. Advances in material science could lead to fibers that exhibit lower attenuation and dispersion across a broader spectrum.

System Design Optimization: Overcoming the amplification challenges requires not only the development of new amplifiers but also the optimization of system design to mitigate nonlinear effects and ensure signal integrity.

Bridging the technical gaps between current technologies and UWOT technologies is essential for the advancement of optical communication systems. By addressing the challenges in fiber characteristics and amplification techniques, the industry can unlock the potential of UWOT, paving the way for ultra-high-speed data transmission and more efficient optical networks.

References

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[3-2] Tomoyuki Kato, Shohei Beppu, Daiki Soma, Hidenobu Muranaka, Shun Okada, Hiroyuki Irie, Yuta Wakayama, Noboru Yoshikane, Takehiro Tsuritani, Yu Tanaka, Takeshi Hoshida, "U-Band WDM Transmission Over 90-km Deployed Fiber-Optic Cable Leveraged by S+C+L-Band WDM Channels," W4D.3, OFC2024.

4. Space division multiplexing

4.1. Overview of SDM

In contrast to WDM, where individual communication signals are transmitted on different optical carrier frequencies (or wavelengths), SDM refers to the multiplexing in the spatial domain in the form of parallel fibers as well as parallel fiber cores or copropagating spatial modes in a single strand of fiber. As traditional WDM transmission systems are already operating very close to their nonlinear Shannon limit estimates and multiband systems are limited in terms of capacity scaling, the migration to spatially parallel systems is the only long-term path forward in dealing effectively with the unabated growth in network traffic. The most straightforward spatially parallel system architecture are high-density cables containing large bundles of fibers. To reduce cable diameter and weight, dedicated SDM fibers such as weakly coupled multicore fibers (WC-MCFs), randomly coupled multicore fibers (RC-MCFs) and multimode fibers (MMFs), as illustrated in Fig. 4-1-1, have been developed over recent years. Fiber bundles are inherently free of coupling (or crosstalk) between individual spatial paths, and WC-MCFs are usually designed to keep crosstalk between cores at a level that does not significantly affect transmission performance. On the other hand, the spatial paths in RC-MCFs and MMFs are strongly coupled and therefore require advanced multiple-input multiple-output digital signal processing (MIMO DSP) at the receiver (RX) to separate the signals of each spatial path. Since the development of advanced MIMO DSP is expensive, WC-MCFs alongside high-density cables are likely the SDM fiber technologies to be deployed in commercial networks in the near future. In the following, we briefly discuss each of these two technologies in more detail.

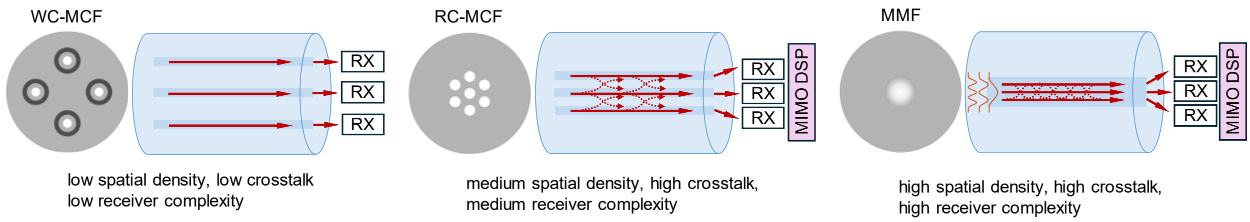


Figure. 4-1-1 Three types of SDM fibers (WC-MCF, RC-MCF, MMF)

4.2. High-density cables

Recently global data traffic has been increasing drastically due to the popularity of various internet services and cloud applications, and the demand for higher transmission capacities in optical fiber networks is expected to grow even further in the future. High-density cables are one of the SDM technologies that will be able to meet this requirement by increasing the number of optical fibers per cross-sectional area of a cable and thus contribute towards an optimized use of limited installation space.

Conventional optical fibers with a standard 250 µm coating diameter were mainly used in high-density cables in their beginning phase, and the number of optical fibers per cable cross section was simply increased in response to demand in transmission capacity. After numerous developments and deployments, those high-density cables with 250 µm coating diameter fibers started to face difficulties in cases where the existing installation environment does not allow an enlargement of the cable's outer diameter due to the high density to be installed.

To overcome these difficulties and to utilize installation space more efficiently, optical fibers with a reduced coating diameter of 190 µm have been adopted in high-density cables to achieve a higher spatial density than previous cables based on 250 µm optical fibers. In general, a thinner coating layer provides less protection against mechanical stress and leads to degradation in transmission loss and other propagation properties, however countermeasures such as improved raw material properties, cable designs and manufacturing methods have been devised to maintain the cable performance that is required for actual use.

To support the continuous increase in transmission capacity, more recently, reduced coating diameters of less than 190 µm (e.g., 160 µm) have been introduced to further increase the density of optical fibers in cables. These thin coating layers, however, pose significant challenges to achieve the necessary cable performances and further studies are needed on both cabling technologies and optical fiber performance evaluation to overcome those.

On the other hand, MCFs have also been considered and studied for its application in high-density cables. Depending on the number of cores in an MCF, a further increase in density would be possible and some additional effects would be expected such as multiple cable installation into one duct, longer installation distances or lighter cable weight etc.

4.3. Multicore fibers

A WC-MCF with a 125 µm standard cladding diameter is expected to be the first SDM optical fiber to be deployed commercially. The two major reasons why keeping the standard cladding diameter is currently important are:

(i) Mass-productivity: although an SDM optical fiber with a larger cladding diameter can accommodate much more spatial channels in one fiber, an optical fiber with two times larger cladding diameter requires a preform with four times larger volume. Thus, it would require significant modifications to the existing fabrication process of an optical fiber.

(ii) Smooth technical migration: existing cabling and connection technologies can be used by maintaining the geometrical dimensions, and single-mode and separated core operation enable the use of the existing system interface by ensuring backward compatibility with existing single-core single-mode fibers (SMFs).

Two or four cores can be accommodated in a 125 µm cladding diameter while maintaining the backward compatibility with existing single-core SMF.

Three parameters are mandatory for ensuring the inter-operability of WC-MCF. These are cladding diameter D, number of cores N, and core pitch L. D is fixed at 125 µm, and N can be set to 2 or 4 by considering the backward compatibility to existing SMFs. L directly affects the crosstalk XT between the neighboring cores. L also has a tradeoff relationship with the cladding thickness t when D is constant. t affects the confinement loss αc in a WC-MCF. Thus, a suitable L can be designed by considering the maximum and minimum L values which are respectively restricted by an allowable αc and XT limits. These guidelines, specifications and test method should be standardized in the international standardization development organizations for ensuring the inter-operability.

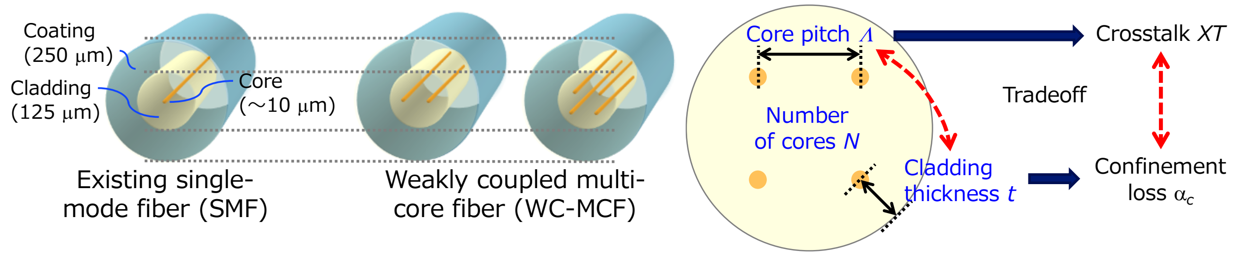


Figure 4-3-1 Schematic image of WC-MCF with a standard 125 µm cladding diameter (left) and key geometrical parameters of WC-MCF for ensuring the inter-operability (right)

4.4. Multicore fiber connectivity

This subsection examines the state of the art and future outlook of key technologies that will enable the implementation and integration of MCFs in optical communication systems.

Connectors are crucial in fiber optic networks, enabling the joining and detachment of fiber segments. In MCF technology, the development of specialized connectors is critical for maintaining signal integrity across multiple cores. Currently, the industry has achieved significant progress in creating connectors that can precisely align multiple cores. These connectors are engineered to efficiently couple light between MCFs and either single-core fibers or other MCFs.

Looking ahead, the evolution of MCF connector technology aims to reduce insertion loss and back reflection, enhance durability, and streamline the connection process. Innovative design approaches—including automated alignment systems and the use of advanced materials—are anticipated to enhance performance and promote the widespread adoption of MCF connectivity.

Fusion Splice for MCF is one of the key technologies for installation of MCF. Since an MCF comprises multiple cores in the cladding, rotational alignment for mated fibers is necessary. For fusion splicing in the field, an automated alignment technique is crucial. So far, two alignment methods have been proposed. One is the end face viewing method and the other is the lateral viewing method.

Fan-In Fan-Out (FIFO) technology is essential for interfacing MCFs with other components of optical networks. It facilitates the transition between MCFs and arrays of SMFs, acting as a bridge for signal distribution and aggregation. Current FIFO solutions are effective, yet they often require complex fabrication processes. The next generation of FIFO technology seeks to enhance integration density and reduce losses. Current research is concentrating on streamlining the manufacturing process and shrinking the footprint of FIFO devices. Advances in micro-optics and photonic integration are expected to significantly influence the evolution of FIFO, yielding more compact and efficient interfaces.

4.5. Multicore fiber amplifier

In the field of optical communications, the relentless pursuit of higher bandwidth and data transmission rates has spurred the development of MCF amplifier technology. The WC-MCF amplifier represents a significant breakthrough, enabling the simultaneous amplification of multiple independent channels and thereby greatly increasing effective transmission capacity.

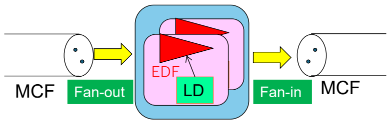
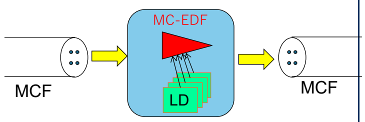
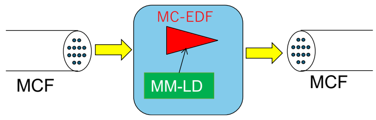
The state of the art of WC-MCF amplifier technology is characterized by distinct amplification mechanisms within each core. This approach effectively decouples the channels, preventing interference and preserving signal integrity. A range of excitation methods has been explored to optimize the amplification process, notably cladding and core pumping techniques.

Cladding pumping, which introduces pump light into the cladding of the MCF, is preferred for its ability to uniformly excite all cores with a single multimode pump source. However, this method faces challenges in efficiently coupling pump light into each core, potentially leading to unequal gain among the cores. In contrast, core pumping involves directly injecting single-mode pump light into each core, often employing a FIFO device. Although this technique provides greater precision in controlling the gain for each channel, it requires multiple pump sources and intricate coupling systems, potentially elevating the system's complexity and cost.

Looking ahead, the prospects for weakly coupled MCF amplifier technology encompass the development of innovative pumping schemes that aim to provide uniform gain across all channels while minimizing noise. Furthermore, integrating cutting-edge materials and waveguide designs is expected to enhance the power conversion efficiency and scalability of these amplifiers.

Progress in photonic integration and fiber design is expected to lead to more compact and effective MCF amplifier modules, which will be pivotal for the forthcoming generation of high-capacity, long-haul optical communication systems. FIFO-less MCF amplifier technology is an example of photonic integration technology. This FIFO-less approach aims to eliminate the need for separate transition devices between MCFs and single-core fibers. Consequently, the FIFO-less MCF amplifier technology can eliminate the need for intermediary devices between MCF-based EDF and pump light sources. The pursuit of FIFO-less amplification is currently directed toward simplifying optical network design, eradicating potential sources of signal loss, and enhancing system performance. With continuous research and innovation, the WC-MCF amplifier is set to play a central role in fulfilling the escalating demands for data transmission capacity within the optical networking domain.

Table 4-5-1 Amplifier types for MCFs

MC-EDFAs by Individual amps	Core pumping	Cladding pumping
		
Multiple EDFAs are embedded.	Each core of MC-EDFA is excited.	All cores are excited simultaneously.

4.6. Technical gap analysis between current technologies and multicore fiber technologies

High-density cables with reduced coating fibers can be used with the existing technologies. This section describes a gap analysis, especially between MCF technologies and current SMF technologies.

Table 4-6-1: Gap analysis

	Current APN	UWOT	Challenges	Opportunities
Fiber	Single-mode fibers	Multicore fibers	Large-scale and low-cost fabrication	Improvement of fabrication process and standardization
Connectivity	Splicers with core alignment	Splicers with rotational alignment	Mass-splicing of MCFs	Low-cost and small-size splicers
Amplifier	Single-core EDFA	FIFO+Single-core EDF Core pump EDFA Cladding pump EDFA	High power conversion efficiency and gain uniformity	Low-loss integrated multicore devices

The transition to UWOT systems employing multicore fibers presents both significant challenges and opportunities. The technical gaps, especially in fiber, connectivity, and amplification techniques necessitate a concerted effort in research and development to realize the full potential of the UWOT.

- **Fiber**
  One of main issues regarding to multicore fibers is crosstalk, and many methods for crosstalk reduction and crosstalk treatment have been proposed, So far, low production volumes and requiring additional manufacturing processes lead to higher fiber cost. Accelerating the standardization and development of mass production technology are necessary.

- **Connectivity**
  FIFOs are new to current transmission systems and necessary unless the transmission system is MCF native. As mentioned above, losses and size reductions are underway. Low cost is also necessary for widespread usage.
  Low-loss single-MCF splicing technology employing rotational alignment with the lateral viewing method has been developed. However, plural-MCF splicing technology, which will be useful where there are many MCFs, has not been realized. Innovative solutions will be required.
- **Amplifier**
  Core pumping and cladding pumping schemes can be attractive from the perspective of compactness, low energy consumption and low cost. This will be achieved by development of high efficient multicore EDFs and low-loss integrated devices.

4.7. Near-term application of SDM

SDM technologies which can be used in the APN have been described. High-density cables employing thinner coating diameter fibers and WC-MCFs with standard cladding diameter are promising candidates for capacity expansion of APN. How SDM technology will be implemented in APNs will vary depending on the use cases.

In submarine cables or ultra long-haul transmission lines, high-efficient amplifiers and a reduction of the number of amplifiers are required due to the severe power limitation in the cables. Fibers have the lowest attenuation and EDFAs are most power efficient in the C-band, respectively. Cable size is also limited. This will lead to the early adoption of energy efficient WC-MCF transmission systems with SDM amplifiers utilizing the C-band.

In metro transmission lines or terrestrial lines, SDM can be combined with the multiband technologies for further capacity expansion. In network design the allocation of data channels to fibers or cores and wavelengths is one of the critical issues that need to be solved to use the network more efficiently.

In short reach transmission lines such as data-center interconnects, duct size and space for deployment of fibers are limited. Reduction of deployment and running cost is important. While the multiband is attractive as a technology to enhance the capacity without new fiber deployment, a WC-MCF system is also attractive as it can expand capacity while having good compatibility with current single mode fiber transmission systems.

5. Node Architecture

5.1. Overview of optical node

Optical nodes are important elements for implementing optical networks in the form of ring and/or mesh topology. Specifically, optical nodes based on reconfigurable optical add/drop multiplexer (ROADM) or optical cross-connect (OXC) technologies are playing a key role in today's transport networks. The essential function of an optical network is to provide guaranteed connectivity to client nodes or systems (e.g., Internet Protocol (IP) routers or Ethernet switches) by provisioning optical paths. Each optical node on the path route enables each incoming optical signal to be output to the desired direction without the need for O/E/O conversion. The primary motivation for introducing optical nodes is to minimize costly, power- and space-hungry O/E/O conversion. Moreover, such nodes enable remote path setup and tear-down operations without human intervention, which is also beneficial to network operators.

In general, current optical networks rely on the multidegree ROADM, of which typical configuration is shown in Fig. 5-1-1. Please note that Fig. 5-1-1 illustrates a route and select type colorless, directionless, and contention-less (CDC) ROADM. It mainly consists of wavelength-selective switches (WSSs) and multicast switches (MCSs). Current optical nodes are required to be capable of handling each optical signal between any combination of ingress and egress ports with the desired bandwidth granularity. For achieving this, bandwidth-variable WSSs are located at all the ports and perform wavelength de-/multiplexing and switching. In addition, MCSs enables flexible add/drop operations [5-1].

Toward UWOT deployment, optical nodes must handle huge spectrum resources in the context of multi-band and SDM parallelism. It is quite natural that advancements in WSS and MCS technologies are useful at least as short-term solutions. Such advancements include improving optical specifications such as bandwidth, port count, and granularity. Device integration and architectural change are also becoming important, which will be discussed in the following subsections.

5.2. Technical gap analysis

Multi-band transmission and SDM technologies have a huge potential for increasing network capacity. To get a better grasp of UWOT-specific requirements and differences from the current technologies, this subsection describes a gap analysis from the viewpoint of optical node.

As described in previous chapters, multi-band transmission technologies increase the number of wavelengths (or channels) in the spectrum dimension, while SDM increases those in the spatial dimension. Accordingly, optical nodes must handle huge numbers of wavelengths in a cost-, energy-, and space-efficient manner. Specifically, node throughput must be scaled in a hardware-efficient manner considering limitations of optical switch devices (e.g., port count and bandwidth).

When deploying UWOT technologies nationwide, we must consider the impacts of deployment status in terms of the differences in physical attributes between node degrees, as illustrated in Fig. 5-2-1. For instance, the differences in band operation and fiber type can be performance limiting factors.

5.3. Typical evolution scenarios

This subsection presents typical evolution scenarios of optical networks/nodes, where UWOT technologies are progressively deployed. Since multiband transmission and SDM can be complementary approaches, possible evolution paths can vary as depicted in Fig. 5-3-1.

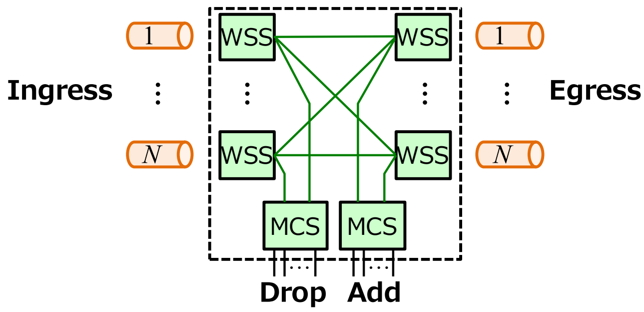


Figure 5-1-1: CDC-ROADM

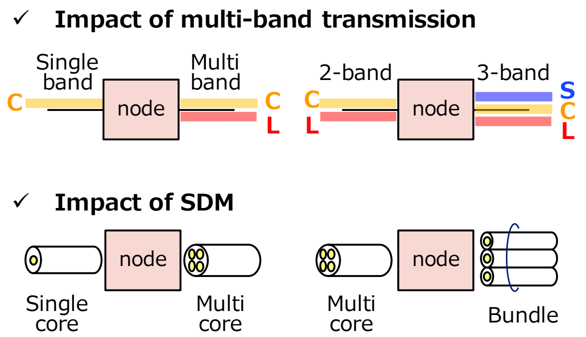


Figure 5-2-1: Impact of UWOT deployment

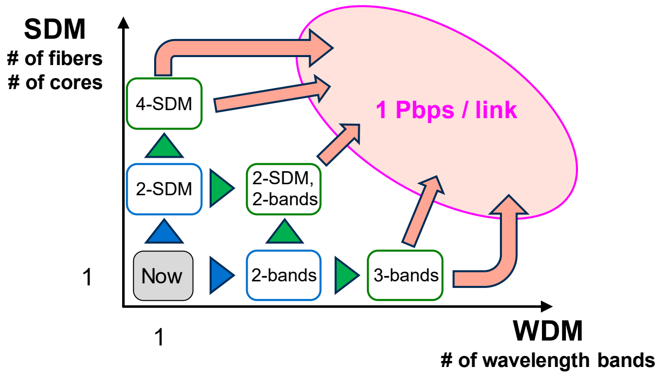


Figure 5-3-1: UWOT evolution scenarios

Typically, current optical networks rely on single-band (e.g., C-band) ROADM nodes with single-mode fibers. As the next step, C+L-band transmission technologies are attracting much interest from both academia and industry and being deployed for a viable short-term solution. This naturally requires 2-band optical nodes. Another path is an SDM solution, which corresponds to the vertical axis in Fig. 5-3-1. Considering mid-term solutions, there can be multiple paths from the C+L-band one, for example. They include a 3-band (e.g., S+C+L-band) and a 2-SDM C+L-band solutions.

For resolving issues described in the previous subsection, band-switchable cross-connect (using wavelength conversion (WC)) and inter-core cross-connect can be useful, as mentioned in [5-2]. Note that WC technologies enable the translation of optical signals from one wavelength to another, facilitating seamless communication even across diverse network segments that operate on different wavelength plans. This becomes increasingly important in multivendor and multidomain environments. Also note that benefits provided by WC include increased network agility and improved wavelength utilization.

5.4. Configuration options

This subsection provides possible candidates for optical node configurations in particular steps of UWOT deployment. Note that configurations that are actually applied depend on various factors including network operator preferences and device technology trends.

Fig. 5-4-1 shows examples of 2-band (C+L-band) optical nodes, in which a separate type (Fig. 5-4-1(a)) and an integrated type (Fig. 5-4-1(b)) are depicted. Specifically, the former utilizes components for each single band, which enables a pay-as-you-grow upgrade. On the other hand, the latter utilizes integrated optics (e.g., WSSs that can cover both C and L bands [5-3], which enables hardware-scale reduction. Similarly, examples of 3-band (S+C+L-band) optical nodes are shown in Fig. 5-4-2.

In addition, potential 2-SDM and 2-band nodes are illustrated in Fig. 5-4-3, which includes a flat type (Fig. 5-4-3(a)) and a hybrid type (Fig. 5-4-3(b)). The former relies on a large-scale wavelength cross-connect (WXC) for exceptional switching flexibility. Integrated devices (e.g., twin WSSs) can be useful for compactly implementing this type. On the other hand, the latter utilizes SXC (spatial cross-connect that can handle optical signals at space granularity (e.g., fiber and/or core)) in combination with WXC. As discussed in [5-4], such a hybrid type has a potential for hardware-scale reduction.

Moreover, Fig. 5-4-4 introduces a WC-capable 2-band optical node, which can greatly enhance the switching flexibility. By utilizing WC, performance limitation caused by the difference in band operation between node degrees (pointed out in Sect. 5.2) can be efficiently avoided.

These options provide an opportunity to discuss how to evolve optical node/network toward the forthcoming era where UWOT technologies are extensively applied.

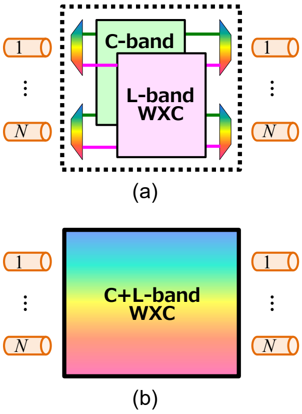


Figure 5-4-1: 2-band node

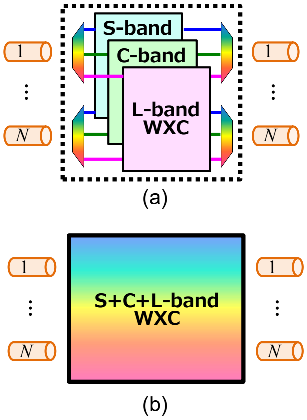


Figure 5-4-2: 3-band node

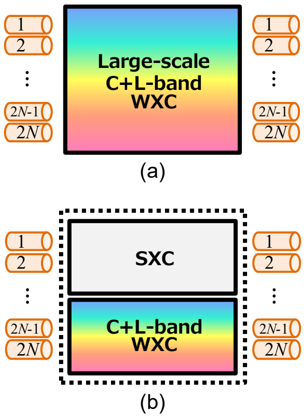


Figure.5-4-3: 2-SDM 2-band node

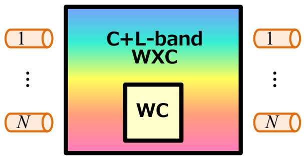


Figure.5-4-4: WC-capable node

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6. Trends in standardization

6.1. The Influence of standardization bodies on UWOT Development

This chapter outlines the trends among key standardization bodies that could influence the evolution and adoption of UWOT. It provides insights into how these trends may shape the future direction of UWOT within the IOWN GF.

Standardization bodies play a crucial role in defining optical communication technologies. They set industry standards that guarantee interoperability between devices and the reliability of systems. These established standards not only guide technological development but also encourage innovation within a unified framework. They facilitate economies of scale, lower barriers to market entry, and bolster consumer confidence. By establishing benchmarks for performance and safety, standardization bodies expedite the adoption of new technologies, simplify regulatory compliance, and contribute to the worldwide expansion of the industry.

6.2. Trends in Standardization Bodies (OpenROADM MSA, OIF, ITU-T, IEEE, TIP, IEC)

This subsection examines the role of standardization bodies in the development of UWOT and their potential impact on its future advancement. Here, we will discuss the standardization bodies such as OpenROADM MSA, OIF, ITU-T SG15, IEEE802.3, TIP, and IEC. Table 6-2-1 summarizes the activities of standardization bodies related to UWOT technologies.

Table 6-2-1 Standardization bodies related to UWOT technologies

Standardization bodies	Relationship with UWOT technologies in IOWN GF
OpenROADM MSA	The open definition and standardization of ROADM technology by OpenROADM MSA enables seamless interoperability between products from different vendors, thereby enhancing the flexibility and scalability of UWOT systems.
OIF	By standardizing optical interfaces, the OIF strengthens the foundation for high-speed data transmission in UWOT systems. The OIF specifications provide essential guidelines for improving the interoperability and performance of UWOT technology.
ITU-T SG15	ITU-T SG15 develops international standards for optical transport networks. ITU-T standards set benchmarks for the reliability, performance, and interoperability of UWOT systems.
IEEE 802.3	IEEE 802.3 standards specify the technical requirements for the data link layer and physical layer in UWOT systems, facilitating rapid and efficient data communication.
TIP	The TIP promotes an open approach to increase flexibility, efficiency, and scalability in UWOT systems.

Standardization bodies	Relationship with UWOT technologies in IOWN GF
IEC	IEC standards establish criteria for the quality and performance of optical fibers, optical connectors, and other optical components in UWOT systems, ensuring technical consistency and reliability.

OpenROADM MSA [6-1]

OpenROADM MSA is an initiative aimed at fostering open standards and interoperability within optical networking. The project's main goal is to define the functions and interfaces of ROADM technology in an open manner, enabling products from different vendors to operate seamlessly together.

Under this initiative, open standard specifications and APIs are being developed and made publicly available, allowing network equipment vendors and service providers to access and utilize them freely. Standardization through OpenROADM MSA is expected to broaden market choices and promote competition. Ultimately, OpenROADM MSA envisions promoting an open network architecture that is crucial for the future, aiming to facilitate innovation across the entire ecosystem.

OIF [6-2]

OIF is an industry consortium that plays a pivotal role in developing and promoting standards for the optical networking industry. One of OIF's primary activities is centered on the advancement of optical interfaces, which are critical components in facilitating high-speed data transmission over optical fiber networks. OIF's work on optical interfaces focuses on creating specifications that ensure compatibility and interoperability between various optical networking products. These specifications cover a range of parameters, including form factors, wavelengths, modulation formats, and transmission rates. By standardizing these elements, the OIF helps to streamline the deployment of optical networking equipment and systems, making it easier for network operators to integrate products from different vendors.

ITU-T SG15 [6-3]

ITU-T Study Group 15 (SG15) is the leading group responsible for networks, technologies, and infrastructures for transport, access, and home. It plays a critical role in developing global standards for optical and other transport networks, which are fundamental to the functioning of the internet and telecommunications services.

The contributions of ITU-T SG15, particularly the work of optical interfaces and SDM, are instrumental in shaping the future of UWOT. As the demand for higher bandwidth and more efficient networks continues to grow, the standards developed by this group will underpin the next generation of communication systems, enabling new services and applications for users around the world.

IEEE 802.3 [6-4]

The IEEE 802.3 working group is a task force within the IEEE responsible for developing standards related to Ethernet, a technology foundational to the modern data communications network. This group's activities encompass a broad spectrum of Ethernet-related technologies, with a particular focus on the evolution and enhancement of Ethernet standards to meet the growing demands for higher-speed data transmission and greater efficiency.

IEEE 802.3 has been instrumental in standardizing high-speed Ethernet technologies such as 100G Ethernet and 400G Ethernet. These efforts have led to the creation of various standards, including IEEE 802.3ba, IEEE 802.3bj, and IEEE 802.3bs, which define the physical layer specifications and management parameters for implementing high-speed Ethernet over optical fiber. The group continues to explore new technologies and methodologies that can push the boundaries of Ethernet speeds even further, such as 800G Ethernet and 1.6T Ethernet. As technology progresses, IEEE 802.3's work will continue to underpin the growth and evolution of Ethernet as the backbone of global data communication.

TIP [6-5]

The Telecom Infra Project (TIP) is an engineering-focused initiative driven by operators, suppliers, developers, integrators, and startups to disaggregate the traditional network deployment approach. The project's mission is to collaborate across the telecom industry to build new technologies and adopt innovative solutions that drastically improve the flexibility, efficiency, and scalability of telecommunications networks. One of the significant activities within TIP is the Open Optical & Packet Transport (OOPT) project group. OOPT's mission is to create open and disaggregated solutions that can be implemented across dense metro and backbone networks as well as for broadband access. This involves developing a set of open standards, designs, and technologies that enable a more vibrant supplier ecosystem, fostering a competitive and dynamic market for network deployments. As the industry continues to evolve, the work of TIP and OOPT will likely play an influential role in shaping the next generation of telecom infrastructure.

IEC TC86 [6-6]

The International Electrotechnical Commission (IEC) is instrumental in the standardization of optical technologies, and its Technical Committee 86 (TC86) on Fiber Optics has been actively developing standards for multicore fiber components. Noteworthy achievements include the 2022 issuance of IEC TR 61292-12, which addresses fiber amplifiers for SDM systems, and IEC PAS 63503-3-30:2023, establishing interface dimensions for 4-core fiber optic connectors. The latest update to IEC 61300-3-4 extends to include methods for measuring MCF attenuation, thus promoting the technology's commercial viability. Furthermore, the integration of very small form factor (VSFF) optical connectors is critical to expanding the capacity of data centers. Currently, IEC SC86B Working Group 6 is focused on the standardization of the mechanical interface for the Type SAC connector, as detailed in IEC 61754- Part 36.

In summary, the current standardization trends are pivotal for the advancement of UWOT. They provide the necessary guidelines and frameworks that ensure compatibility, drive down costs, and promote consumer trust. As these trends continue to evolve, they will undoubtedly shape the trajectory of UWOT, making it a cornerstone of future optical communication systems.

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7. Introduction of new technologies

7.1. Early introduction of UWOT technologies

In a first step to introduce UWOT technologies, they are likely to be introduced in limited parts of existing APN infrastructure, either replacing obsolete equipment or as new and limited deployments, where APN infrastructure face a bottleneck in capacity. This introduction may be limited to small areas. Therefore, the compatibility and interface of deployed UWOT technologies with legacy APN will be necessary. This can be considered as a hybrid deployment, comprising both UWOT technologies and legacy technologies and taking care of the compatibility between them.

In this respect, each technology family in the UWOT scope must be considered separately.

7.1.1. Hybrid deployment of additional bands

Generation of signals over new bands can be generated directly in the new band or converted to and from the new band from a legacy band, like the C band, for which APN-T are already available and mass-produced. Therefore, the latter solution is likely to be more a widely adopted solution for the first step of deployment of additional band related technologies.

In the same manner, components and subsystems, including optical amplifiers or nodes, may not be compatible with new bands in the early-stage deployment of UWOT technologies. Again, wavelength conversion between compatible and non-compatible parts is a likely solution to enable early deployments. Notably, when both legacy bands and new bands are to be used at the same time, conversion of new bands to legacy bands must be operated in a parallel manner.

Finally, the compatibility of optical fiber with new bands must be managed and signals over new bands. Again, routing over parallel and non-compatible fibers is possible with wavelength conversion. An example of hybrid deployment of additional bands is given on Fig. 7-1-1.

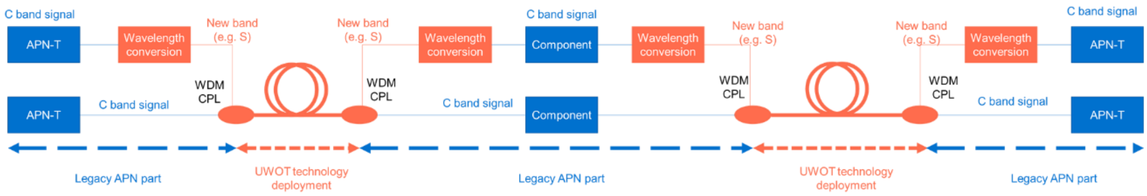

Figure 7-1-1: Hybrid deployment of new bands

7.1.2. Hybrid deployment of multicore components and fibers

In the early stage of SDM technology deployment, SDM parts of APN must be connected to legacy APN parts; furthermore, some components, including APN-T or amplifier may not be implemented using multicore fibers, or may be available in more volume or lower cost in legacy single core fibers. Therefore, these different parts must be connected using SDM conversion or interfacing, which is realized with FIFO devices. This connection is possible provided that the degree of parallelization of legacy single core fiber is equal to the number of used cores of SDM parts.

In a first step, SDM based UWOT technologies could be deployed only as multicore fiber, connected to APN-T and devices through FIFO. Then, optical amplifiers can be deployed as SDM too, which would limit the use of FIFO to around nodes and APN-T. Such a hybrid deployment for SDM is illustrated on Fig. 7-1-2

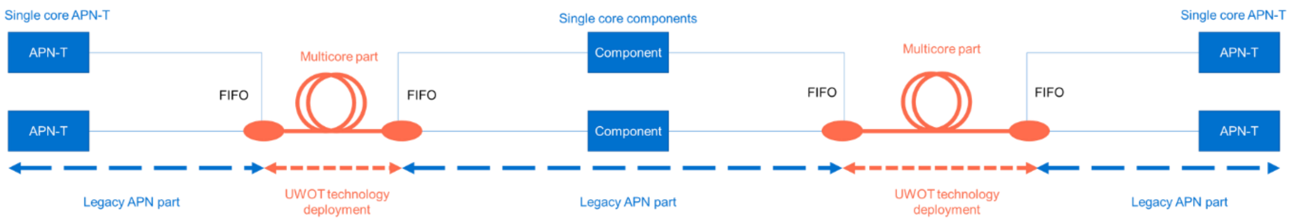

Figure 7-1-2: Hybrid deployment of multicore technology

7.2. Later deployments of UWOT technologies.

As early deployments in hybrid manner start and development time enables the use of UWOT technologies, more parts and components of APN will be available as UWOT native. This means that APN-T, amplifiers and components will be able to accommodate new bands, without using wavelength conversion, or will be able to be interfaced directly with multicore fibers without FIFO, or will be a combination of these technologies.

When all components of APN become available as UWOT native (as shown in Fig. 7-2-1), the deployment of fully UWOT links and parts of APN become possible only through electrical interfacing with the legacy part of APN. Nonetheless, in such a stage the deployment of UWOT native components is not mandatory and may still be economically efficient in parts of APN, which do not require higher capacity.

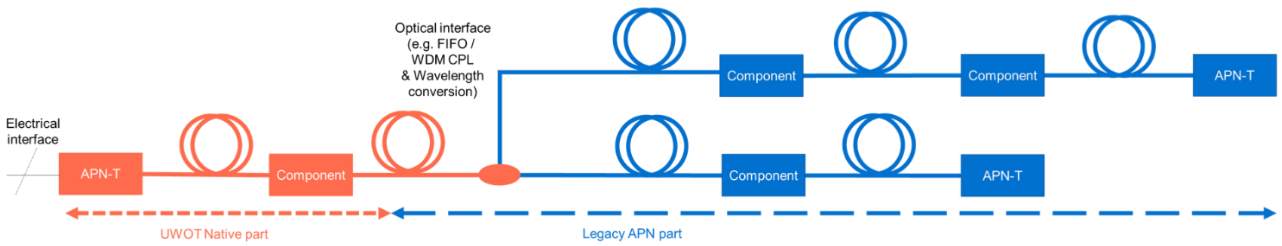

Figure 7-2-1: Later deployment of UWOT technologies

7.3. Timing of introduction

As recent reports show the demonstration of band conversion devices and wavelength conversion devices for single channels too, the hybrid deployment of UWOT technologies for additional bands becomes possible in 2027 for the scenario based on DCI links [7-1]. As far as

SDM technologies are concerned, the first deployment is announced for 2025 in submarine cables [7-1]. It is plausible that such deployments will start in hybrid manner too.

With the development of more components for multiband system, amplifier deployments for mutiband can be foreseen in ~2026, transponders in ~2027 and nodes in ~2027. A UWOT native deployment for multiband, starting with the S band can be foreseen in ~2027, first in DCI links, then in core networks and finally in longer distance links like submarine links.

As far as SDM technology is concerned, high-density cables have been deployed in DCI and can be deployed in submarine cable systems after 2025. On the other hand multicore amplifiers could be deployed in ~2028 and with SDM APN-T in ~2030, an SDM native solutions could be first deployed in submarine networks. Then they could used in DCI links first and adapted to core networks next.

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8. Conclusions

We have discussed UWOT technologies, including the use of additional spectral bands and MCFs. The combination of these technologies is essential for enabling a potential 125-fold increase in transmission capacity. We have described key technical considerations, including transmission links and node architectures, and identified trends in standardization necessary for wide-scale deployment.

These technologies, will gradually be deployed within APN, initially through hybrid deployments featuring UWOT technologies interfacing with legacy APN infrastructure. Such interfacing can be realized with wavelength conversion for additional bands and with FIFOs for multicore fibers, allowing compatibility and a smooth transition from legacy systems. As these technologies mature and become widely available, UWOT native deployments will become feasible in APN segments demanding the highest capacity, while in less demanding segments legacy technologies can remain in use interfacing both electrically and optically. The deployment of UWOT technologies will initially involve additional spectral bands for short-distance applications such as DCI, sand SDM in long-distance applications such as submarine links. With growing capacity demands, the combination of SDM and spectral bands is expected across a wider range of applications, enhancing network capacity further.

As UWOT technologies will become available in APN, they will also enable additional functionalities, including fiber-optic sensing and quantum key distribution. The use of UWOT technologies with these features remains an area to be explored in future publications.

Moreover, with APN likely expanding into novel application areas, UWOT technologies may eventually be deployed over new transmission media, including terrestrial and space-based free-space optical links. Specific scenarios and timelines for such deployments require further investigation, but significant progress is anticipated around 2030, following widespread adoption of fiber-based UWOT technologies.

Emerging technologies are also likely to significantly impact UWOT around 2030. Notably, hollow-core fiber (HCF) technology promises several advantages for APN, including substantial reductions in latency due to light propagating primarily through air rather than silica. HCF also offers significantly lower nonlinearity and the potential for ultra-low-loss transmission over extended wavelength bands. The latter attribute is particularly beneficial for high-capacity network segments. The use of HCF combined with SDM remains an open research question. However, HCF-based links could represent a subsequent evolutionary stage for UWOT within the APN.

Furthermore, the deployment of SDM technologies is not limited to WC-MCFs. Although WC-MCFs are currently considered to be the earliest candidates for deployment, future implementations utilizing MMFs or RC-MCFs could emerge once MIMO signal processing [8-1] becomes available for signal demodulation and implemented in application-specific integrated circuit (ASIC) for transceivers. Such a technology could become available after 2030 and be used in conjunction with additional bands.

In summary, the evolution of UWOT technologies and its implementation in various applications will enable the realization of ultra-high-capacity APN by 2030. Beyond 2030, technologies such as HCFs and advanced MIMO signal processing hold the promise of even greater capacity enhancements, although significant research efforts are still required in these fields.

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Abbreviations and acronyms

For the purposes of this Reference Document, the following abbreviations and acronyms apply:

ABBREVIATION	FULL DESCRIPTION
AI	Artificial Intelligence
API	Application Programming Interface
APN	All-Photonic Network
APN-G	Open APN Gateway
APN-I	Open APN Interchange
APN-T	Open APN Transceiver
ASIC	Application-Specific Integrated Circuit
BDFA	Bismuth-Doped Fiber Amplifier
CAGR	Compound Annual Growth Rate
CDC	Colorless, Directionless, and Contention-less
DCI	Data-Center Interconnect
DSP	Digital Signal Processor
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
FIFO	Fan-In Fan-Out
GF	Global Forum
GOIP	Group of Optically Interconnectable Port
GSNR	Generalized Signal to Noise Ratio
HCF	Hollow-Core Fiber
HW	Hardware
IP	Internet Protocol
LH	Long Haul
MC-EDFA	Multicore Erbium Doped Fiber Amplifier
MCF	Multicore Fiber
MCS	Multicast Switch
MIMO	Multiple-Input Multiple-Output
MMF	Multimode Fiber
MSA	Multi Source Agreement

ABBREVIATION	FULL DESCRIPTION
OAA	Open All-photonic network Architecture
ODF	Optional Distribution Frame
OXC	Optical Cross-Connect
PoC	Proof of Concept
PtoP	Point-to-Point
RC-MCF	Randomly-Coupled Multicore Fiber
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RX	Receiver
SDM	Space Division Multiplexing
SMF	Single-Mode Fiber
SOA	Semiconductor Optical Amplifier
SXC	Spatial Cross Connect
PDFA	Praseodymium-Doped Fiber Amplifier
TDFA	Thulium-Doped Fiber Amplifier
UWOT	Ultra-Wide Band Optical Transmission
VSFF	Very Small Form Factor
WC	Wavelength Conversion
WC-MCF	Weakly-Coupled Multicore Fiber
WDM	Wavelength Division Multiplexing
WSS	Wavelength-Selective Switch
WXC	Wavelength Cross Connect
XT	Crosstalk

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[7-1]	Announcement by Google Cloud, Delivering Multi-Core Fiber Technology in Subsea Cables | Google Cloud Blog	7.3
[8-1]	W. Yi, et al, "Recent Advances in DSP Techniques for Mode Division Multiplexing Optical Networks with MIMO Equalization: A Review" *Applied Sciences* 9, no. 6: 1178 (2019)	8

History

Revision	Release Date	Summary of Changes
1.0	September 11, 2025	Initial Release