NMN | OPS | WDM-PON

Technology Reports

Optical Mobile Network

Recent years have seen exploding growth in mobile data traffic with the rapid spread of smart phones and the commercialization of LTE services. In the future, services will become more sophisticated and radio access technologies will be introduced with higher speed and wider bandwidth, increasing the load on mobile networks even further. DOCOMO Communication Laboratories Europe GmbH has been conducting research on optical mobile networks, the next generation of mobile networks, which offer much higher speed and bandwidth with very low energy consumption. In this article we provide an explanation of this new type of mobile network.

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1. Introduction

Recent years have seen explosive growth in mobile data traffic with the rapid spread of smart phones and the commercialization of LTE services. New Network Value-Added Services (NVAS) and other advanced services [1] continue to emerge, created using a large variety of enablers[*1], and these will accelerate the introduction of even faster radio access technologies such as LTE-Advanced[*2]. LTE-Advanced, is a radio access technology that will be developed in the future and is expected to complete development around 2015. It will have downlink speed of up to 1 Gbps, and uplink speed of up to 500 Mbps [2]. Further in the future, there is also extensive research on Beyond LTE-A, targeting downlink speeds of up to 10 Gbps.

If the volume of mobile data traffic continues to increase beyond expectations in this way, the Next Mobile Network (NMN) [3] [4] will need to be scaled up to meet the demands of future traffic. In order for the network to support these radio access technologies, it will be necessary to upgrade not only mobile network equipment such as gateways, base stations and the transport network interconnecting them, but also the mobile network transport devices themselves.

Given that Average Revenue Per User (ARPU) is likely to increase at much lower rate than traffic demands, or even decrease with increasing traffic demands, it will be important to develop the next mobile network to be more cost-effective. This implies that future mobile networks must be easier to operate, easier to manage, energy efficient and environmentally friendly to reduce OPeration EXpenditure (OPEX). Needless to say, minimizing CAPital EXpenditure (CAPEX) will also definitely be an important aspect of building the NMN.

Considering these factors, we

*1 **Enabler**: A function or a component of a service configuration that can be used by multiple service scenario controllers.

*2 **LTE-Advanced**: A radio interface enhancing LTE to be standardized as 3GPP Release 10.

believe that rapidly-growing optical networking technologies will play an important role for the evolution of future mobile networks, making them faster, more efficient and more environmentally friendly. Mobile networks must support a higher level of flexibility and network control than fixed networks in order to support user mobility and radio access technologies. To achieve this, current limitations of optical networking technologies must be overcome, and they must be adapted to mobile networks. In this article, we describe an Optical Mobile Network (OMN) architecture and solutions, implemented with optical networking technology and supporting user mobility and radio access technologies.

2. Optical Transport Technology

2.1 Core Network

With optical transport, the medium has the distinct feature of providing huge bandwidth with low transmission losses. Hundreds of wavelengths can be multiplexed onto a single optical fibre using Wavelength Division Multiplexing (WDM)*3. Currently, a single wavelength can carry 10, 40 or 100 Gbps, so a single fibre pair can easily transport several tens of Tbps [5]. There are currently three types of optical switching technologies, namely Optical Circuit Switching (OCS), Optical Packet Switching (OPS) and Optical Burst Switching (OBS). OBS is actually a hybrid of the previous two. OCS technology is able to switch data streams with granularities from the sub-wavelength, wavelength and waveband levels to the fibre level. OPS uses the same principles as IP packet switching and thus achieves the highest multiplexing flexibility. It requires buffering and packet processing in the optical domain, which is quite expensive for optical networks, but there is active research to overcome these issues. OBS, a hybrid of OCS and OPS, it exchanges and transmits data bursts of multiple packets rather than single packets, and performs switching in burst-packet units. An issue with OBS is that before data is transmitted, a transmission path from the source to the destination must be secured and reserved, so methods for avoiding collisions on intermediate network nodes when securing a transmission path can be complex. For this reason OBS is not yet used on large scale networks.

Optical switching technology is still in the research stages, so although user data is transmitted over high-speed optical links in current networks, routing and switching is done electronically. In other words, received optical signals are converted to electrical signals for routing and switching, and then converted back to optical signals for transmission by optical fiber. This Optical-to-Electrical/electrical-to-Optical (OEO) conversion and electronic processing places major constraints on requirements for network capacity and delay in end-to-end data transmission on networks. Current LTE/Evolved Packet Core (EPC)*4 mobile network architectures are built on transmission networks connecting electronic routers and optical fiber in this way, so they do not fully utilize the benefits of optical networking. As such, applying optical transmission features in current mobile network architectures and improving on current optical transmission equipment are important issues in designing an OMN.

2.2 Access Network

A Passive Optical Network (PON)*5 is widely used for the optical access network, which is the last mile of an optical transport network. Time-Division-Multiplexing-PON (TDM-PON)*6 is the main technology used for Fiber To The Home (FTTH) services due to its high cost efficiency. The IEEE and ITU-T are also promoting the advancement of TDM-PON to support increases in fixed-network traffic.

1) 10G EPON

10G Ethernet PON (EPON) was formally standardized and published as the IEEE 802.3av standard in September 2009. 10G EPON expands the uplink and downlink bandwidths of the 802.3ah standard to 10 Gbps and has good compatibility, allowing 10G

*3 **WDM**: A technique for multiplexing multiple optical signals of different wavelength on a single optical fiber cable. Allows multiple signals to be transmitted on a single cable at the same time, so it is used for high speed and high capacity.

*4 **EPC**: An IP-based core network standardized by 3GPP for LTE and other access technologies.

*5 **PON**: A bidirectional point-to-multi-point link from an Optical Line Terminator (OLT) to multiple ONUs (see *7), using a passive routing unit.

*6 **TDM-PON**: A PON system that avoids signal collisions by allocating a different time slot to each ONU (see *7). Commercial FTTH services using TDM-PON support 1 Gbps on the downlink and 622 Mbps on the uplink.

EPON Optical Network Units (ONU)[*7] and 1G EPON ONUs to coexist on the same PON.

2) NG-PON

In parallel, ITU-T has defined a Next-Generation PON (NG-PON) in the ITU-T G.987 standard, to support the increasing bandwidth requirements of emerging services.

The approach of NG-PON can be divided into two phases:

- Phase 1: NG-PON1

  NG-PON1 is an intermediate upgrade for Gigabit-PON (GPON) systems, supporting 10 Gbps on the downlink and 1 Gbps on the uplink.

- Phase 2: NG-PON2

  NG-PON2 is a long-term solution using an entirely new type of optical network, such as WDM-PON[*8]. NG-PON2 supports 10 Gbps on both the uplink and the downlink.

As already mentioned, 10G EPON and NG-PON1 use TDM technology and link capacity[*9] is shared among all ONUs, so even 10G PON would present capacity limitations in supporting future mobile backhaul[*10] traffic. LTE-Advanced supports up to 1 Gbps on the downlink, so that the backhaul access traffic on a LTE-Advanced base station can be greater than 1 Gbps. Normally, one base station accommodates multiple sectors, further increasing the backhaul network capacity required by a single base station, so a single 10G PON link may only be able to support a single base station. For this reason, 10G EPON and NG-PON1 technologies are not practical for future mobile backhaul access networks.

For this reason, DOCOMO Communications Labratories Europe GmbH (hereinafter referred to as "DOCOMO Euro-Labs") has been researching WDM-PON as a promising optical access technology for future mobile backhaul access networks. Each ONU in a WDM-PON is assigned a dedicated wavelength for higher capacity (40 Gbps downlink and 10 Gbps uplink, compared to 10 Gbps/1 Gbps for TDM-PON), longer range (50 to 100 km, compared to 30 km for TDM-PON), strong security between ONUs and easy upgrading.

3. OMN Architecture

DOCOMO Euro-Labs' vision for a future OMN architecture based on the latest optical networking technologies is shown in **Figure 1**. Lambda switching[*11], which is a type of OCS, is used for the core network[*12] where ultra-high-speed switching and tunneling are indispensable. OPS is also used to aggregate traffic. In this way, some of the conventional mobile network nodes, including the Mobility Management Entity (MME)[*13], the Packet data network Gateway (PGW)[*14] and Serving Gateway (SGW)[*15], are integrated with the optical transport, indicated by MME_O, PGW_O and SWG_O, respectively. This preserves compatibility while increasing network capacity and reducing energy consumption. Practically, the optical transport layer provides data transport and switching functionality, as well as user data flow management. User data flow management is handled by the MME_O linked to PGW_O and SGW_O.

Access networks need more cost-effective optical solution than core networks, so use of PON technology together with metro-ring[*16] networks is promising. Access network designs must also consider functionality to support future radio access technologies. One such technology that should be supported is Coordinated MultiPoint (CoMP)[*17] technology.

4. OMN Solution Proposal

4.1 Optical Mobility Management

In addition to the general requirements of fixed networks, such as Operation Administration and Maintenance (OAM)[*18], network resilience and QoS guarantees, mobile networks must also support user equipment mobility. This requirement is implemented in mobile network mobility management functions of location registration, handover and paging[*19]. In conventional networks, these functions are performed in the electrical domain, but this may not be efficient in future optical mobile networks. For handover in particular, the

*7 **ONU**: The component in a PON system placed at the end-user location.

*8 **WDM-PON**: A PON system that allocates one or more dedicated wavelengths to each ONU.

*9 **Link capacity**: The bandwidth of a single link.

*10 **Backhaul**: Indicates the route connecting a wireless base station to the core network (see *12).

*11 **Lambda switching**: A technology for routing information in an optical network by switching individual wavelengths onto different routes. Also called photonic switching or wavelength switching.

*12 **Core network**: A network consisting of switches, subscriber information management systems and other equipment. Mobile terminals communicate with the core network through the radio access network.

*13 **MME**: A logical node accommodating a base station (eNodeB) and providing mobility management and other functions.

*14 **PGW**: A gateway acting as a point of connection to a PDN, allocating IP addresses and transporting packets to the SGW.

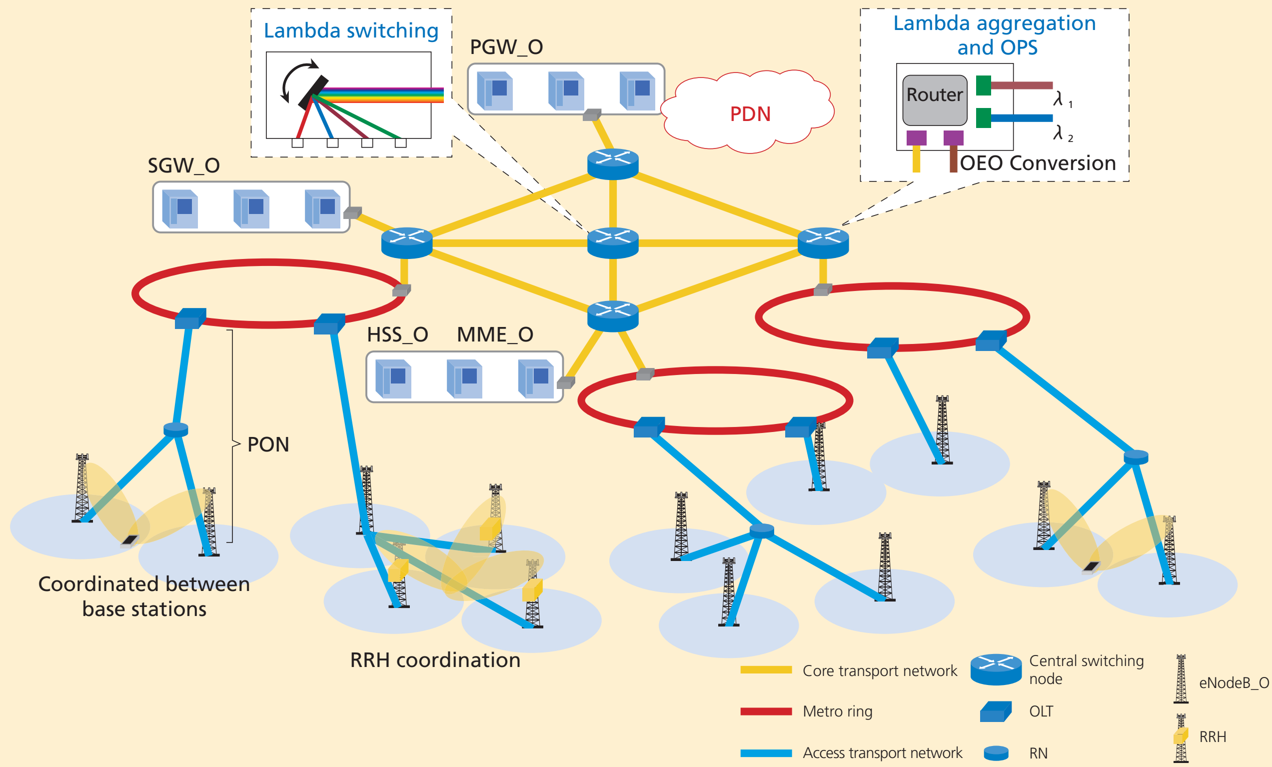

Figure 1 Optical mobile network architecture

many OEO conversions and electrical-domain processing required for tunnel management and data transport consume energy and introduce delay. As mentioned earlier, reducing the number of OEO conversions and electronic processing in the OMN is an important research topic for DOCOMO Euro-Labs.

DOCOMO Euro-Labs' design for managing user data flows in an OMN is shown in **Figure 2**. In the OMN architecture, tunnels are implemented in the protocols of lower layers such as the L1 and L2 layers, so tunnel design using optical switching technology needs to be studied.

1) Tunneling Protocol

In the LTE/EPC standard, tunnels transporting user data are identified using the General Packet Radio Service (GPRS)[*20] Tunneling Protocol (GTP)[*21]. External data packets, such as from the Internet, are sent through their respective GTP tunnels by the PGW, and then transferred to the radio base station (eNodeB[*22]) at the user's location by the GTP tunnel. When the user moves from the area of one eNodeB to another, the applicable GTP tunnel is reconfigured by the SGW and PGW (Fig. 2 (1) and (2)) in the network to switch the user data flow. As shown in the LTE/EPC model in Fig. 2, the GTP protocol is on top of the User Datagram Protocol (UDP)[*23] and Internet Protocol (IP). The SGW processes the GTP, UDP and IP protocols for each packet passing through it, and these must be routed correctly. In the OMN architecture, tunnels transporting user data are identified in lower layer protocols, so transfer processing done on user data by SGW_O is done with lower layer protocols only. This reduces the OEO conversion and electrical domain processing required

*15 **SGW**: The area packet gateway accommodating the 3GPP access system.

*16 **Metro-ring**: Indicates a network with a ring network topology, used in metropolitan areas where traffic from access networks is concentrated.

*17 **CoMP**: Technology which sends and receives signals from multiple sectors or cells to a given UE. By coordinating transmission among multiple cells, interference from other cells can be reduced and the power of the desired signal can be increased.

*18 **OAM**: Operations, Administration and Management functions on a network.

*19 **Paging**: Calling all mobile terminals at once when there is an incoming call.

*20 **GPRS**: The packet communications system used by GSM and UMTS.

*21 **GTP**: A communication protocol for user data transmission which provides functions such as establishing communication path and data transfer in core network.

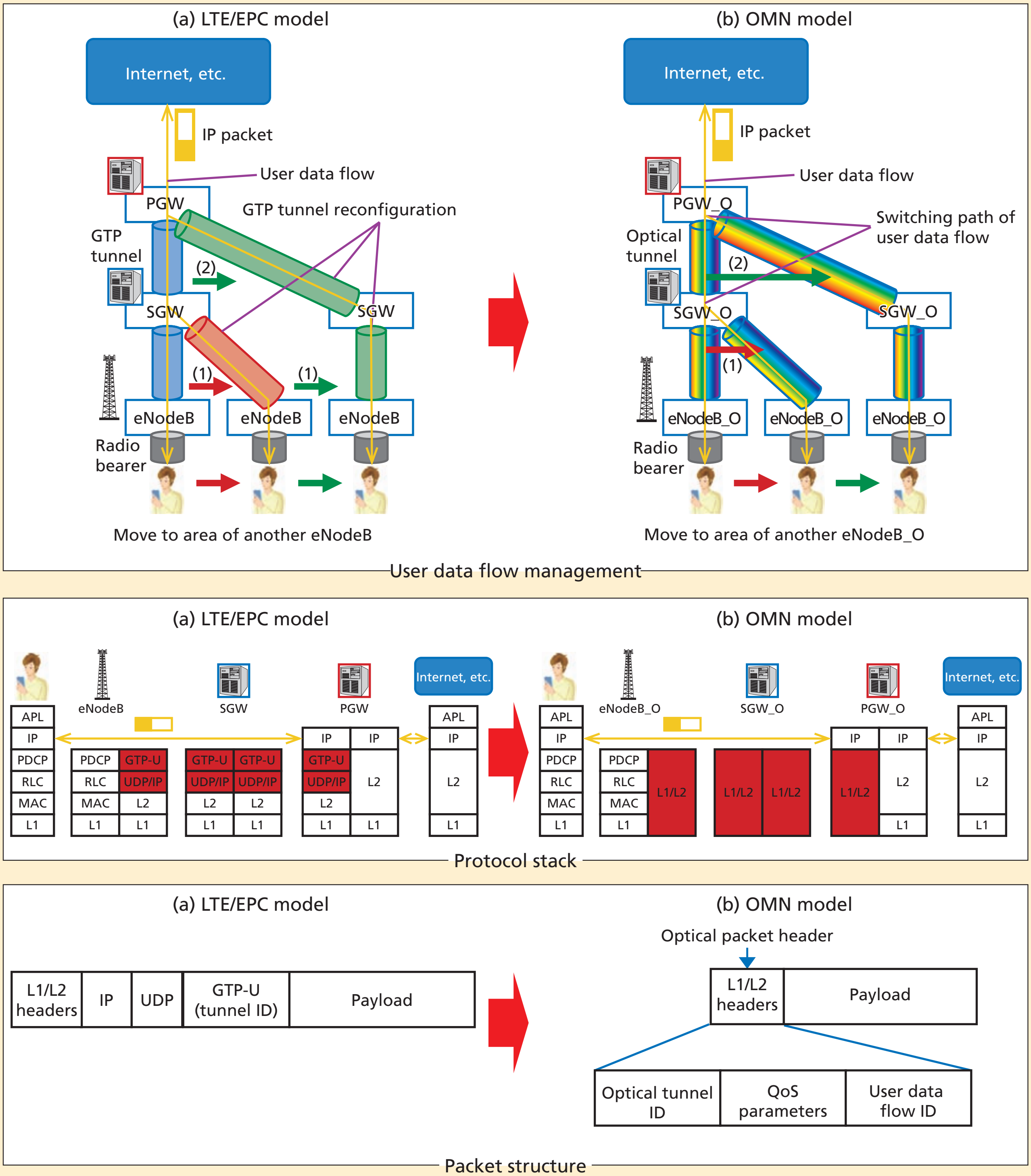

Figure 2 User data flow control design for OMN

*22 **eNodeB**: Base station equipment for LTE and later. Increases integration, combining functionality of the radio control (RN) and base station (BTS) equipment.

*23 **UDP**: A higher-level protocol than IP, the standard protocol used on the Internet. Unlike TCP, it does not have functions to confirm communication between server and terminal or retransmit data that was not delivered to its destination.

by SGW_O at the IP, UDP and GTP layers and reduces the overhead on user packets, compared to GTP tunnel processing.

2) Optical Switching Technology and User Data Flow Control

To realize tracking of a mobile user in the optical layer, optical network routers and switches need to identify data flows for different users and be able to switch individual user data flows separately in the optical layer. OCS technologies such as Optical Cross Connectors (OXC)[*24], Optical Add/Drop Multiplexers (OADM)[*25], and Reconfigurable Optical Add/Drop Multiplexers (ROADM)[*26] can switch at the wavelength or sub-wavelength level, with optical channels from 1.25 to 100 Gbps. Using these, optical packets can be multiplexed and demultiplexed from different optical channels on an Optical Transport Network (OTN)[*27]. However, the minimum bandwidth of individual channels on the OTN is 1.25 Gbps, or Optical-channel Data Unit (ODU)[*28] 0. Thus, the switching granularity possible using OCS technology is too large to switch individual user data flows such as a voice call, for example, which would range from 21 to 320 kbps [6].

In contrast, an OPS network [6] [7] can switch data flows with the granularity of user packets, giving very flexible switching granularity that is very suitable for the dynamic characteristics of mobile traffic.

Based on the above analysis, DOCOMO Euro-Labs is designing a user-data flow control mechanism to implement user-data flow control in the optical layer. The following information is included to the optical packet control header shown in Fig. 2.

- Optical tunnel ID
- QoS parameters
- User data flow ID

The optical tunnel ID and QoS parameters are used in the optical routers and optical switches when transporting optical packets. The user data flow ID is used in the SGW_O to map to the optical tunnel, which leads to the next transmission destination (eNodeB_O or PGW_O). When the user moves, only the SGW_O mapping tables for user data-flow ID and optical tunnel ID need to be modified. These main parameters are included in the optical packet header, so the payload[*29] is switched by the optical switchers and routers without electronic processing or OEO conversion.

The design of this mechanism included design in the U-Plane[*30] as well as the C-Plane[*31] in the optical network nodes, SGW_O, PGW_O and eNodeB_O. Issues in the C-Plane, as shown in **Figure 3**, include the interfaces between the mobility control node (MME_O) and the optical network nodes (SGW_O, PGW_O and eNodeB_O), and the internal interfaces in the optical network nodes between OPS optical transport devices and control functions. We plan to work on these designs together with the U-plane design.

4.2 Supporting Future Wireless Access Technologies with Optical Technology

1) Issues with the Mobile Backhaul Network

For LTE-Advanced and future radio access technologies, CoMP transmission and reception systems have been studied as a key enabling technology to improve User Equipment (UE) throughput. With CoMP, multiple Base Stations (BS) are coordinated to serve

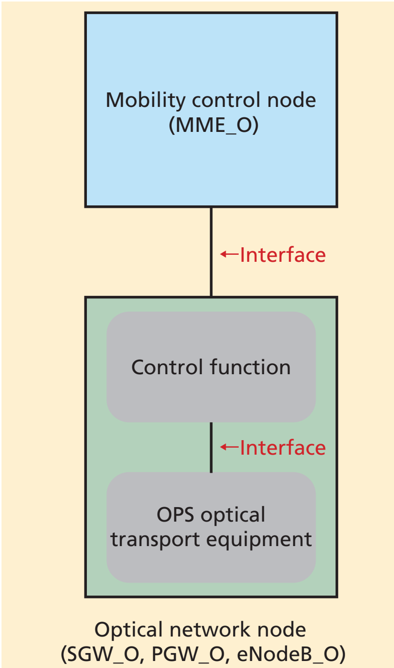

Figure 3 Interface design for the user data flow control mechanism

*24 **OXC**: Equipment used by telecommunications operators to switch high-speed optical signals in optical-mesh and other fiber-optic networks.

*25 **OADM**: A system able to take arbitrary light wavelengths from among multiple wavelengths in a WDM signal and drop them or add them at any other point.

*26 **ROADM**: An optical branching and insertion system that performs remote switching of traffic in wavelength layers in a WDM system.

*27 **OTN**: A system able to transport data as-is, including payload data as well as control signals and other overhead.

*28 **ODU**: Optical transport Data Unit, defined in OTN, standardized by ITU-T. The ODU bit rate is 1.25 Gbps.

*29 **Payload**: The part of the transmitted data that needs to be sent, excluding headers and other overhead.

*30 **U-Plane**: A path for the transmission of user data to the C-Plane (see*31), which is a control signal transmission.

one out of many UEs, managing co-channel interference more efficiently and achieving higher Multiple-Input-Multiple-Output (MIMO)*32 multiplexing gain by increasing the number of virtual antennas[9]. For cellular networks that reuse a single frequency, this technology can help increase UE throughput, particularly at cell boundaries where interference from neighboring cells can severely limit performance. However, BSs using CoMP must share cell information, such as Channel State Information (CSI), and user data with each other through the backhaul network, which greatly increases the amount of traffic on the mobile backhaul network. As such, the information and amount of data passing through the mobile backhaul network depends on the CoMP technology being used and the number of BS participating in CoMP [10].

Also, when providing UE with data communications services, all information exchange on the backhaul network must be completed within a fixed amount of time, introducing a new delay constraint. This delay constraint depends on the mobility of the user equipment, but ranges from 1 to 5 ms.

A feasibility study is already being conducted at 3GPP on coordinating within BS and with Remote Radio Heads (RRH)*33, where the mobile backhaul network issues are relatively minor, as shown in **Figure 4**(a). In these cases, all of the signal information (CSI, etc.) and user data exchange can be done easily within a single BS, avoiding any issues with capacity or delay in the mobile backhaul network.

On the other hand, DOCOMO Euro-Labs has been examining these mobile backhaul issues in order to enable CoMP to be applied in a wider range of scenarios. Specifically, as shown in Fig. 4(b), our goal is to implement CoMP between multiple BSs by sharing information and data through the mobile backhaul network, serving UE that are located in sectors belonging to different BSs.

When coordinating between BSs participating in CoMP, the BSs exchange large amounts of user data and signals (CSI, etc.) over the mobile backhaul network, so CoMP performance depends heavily on the performance (capacity and delay) of the backhaul network. Thus, to support CoMP, the performance of the mobile backhaul network needs to be improved.

2) Implementing the Physical X2 Link with WDM-PON

One of the most effective ways to

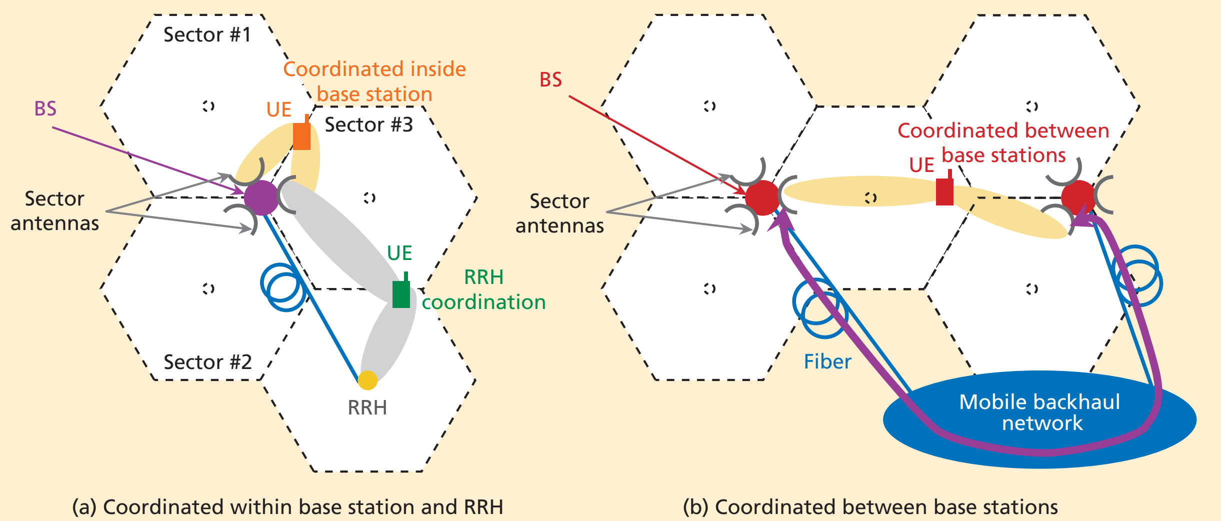

Figure 4 CoMP technology overview

*31 **C-Plane**: Transmission path for control signals such as establishing and disconnecting communications.

*32 **MIMO**: A signal transmission technology that uses multiple antennas at both the transmitter and receiver to perform spatial multiplexing and improve communication quality and spectral efficiency.

*33 **RRH**: Base-station antenna equipment installed at a distance from the base station using optical fiber or other means.

improve the performance of the mobile backhaul network is to implement a physical connection configuration (hereinafter refferred to as “a physical X2[*34] link”) between BSs effectively. The most important factor affecting the signal strength and interference level received by the user equipment is interference from a neighboring BS, so in most cases, user data and signals exchanged for CoMP are with a neighboring BS. In most cases, as shown in **Figure 5**, BSs are accommodated by a switching node and the X2 interface is shared with the connection to the core network to minimize hardware costs. According to 3GPP specifications, X2 interface delay must be an average of 10 ms and be a maximum of 20 ms [11] for LTE systems that do not support CoMP, so the conventional implementation of the X2 interface, as shown in Fig. 5, is not an issue. This is because the use cases for the X2 interface in LTE systems are limited, such as exchanging control signals and data transport for handover, and do not require such short delay times.

Attempting to implement CoMP between base stations using this conventional X2 interface implementation, the delay and capacity of the X2 interface will clearly become a restriction and not support the delay requirements for CoMP. For this reason, it was necessary to revert to direct links between BSs and physical X2 links had to be built in designing the mobile backhaul network. Also, for future mobile networks using smaller cell sizes, more information must be exchanged at higher speeds due to more frequent handovers. This is also a significant factor in the need to build physical X2 links for future mobile backhaul networks.

One possible physical X2 link solution that is currently available commercially would be to link two BSs using a point-to-point microwave link. As is easy to imagine, this would require additional hardware for many microwave links as well as licenses for using microwave frequencies in order to connect all BSs within the network and would greatly increase the cost of building BSs. It is also difficult to achieve greater than 1 Gbps, as required for LTE-Advanced and faster networks, with limited bandwidths in the microwave band.

As an alternative solution, higher frequencies, such as millimeter wave could be considered, but this would be much more expensive than microwave. Currently, no matter what radio technology is used for point-to-point wireless links, all are susceptible to external environmental factors and cannot guarantee quality comparable to optical fiber links. From the performance perspective, it would be desirable to provide the X2 interface with optical fiber links, but it would not be practical in terms of cost to install new, dedicated-fiber X2 links.

Using TDM-PON for physical links between BSs has also been proposed recently [12]. With this approach, an optical coupler[*35] is used at the Remote Node (RN)[*36] to distribute the X2 interface signal in the optical domain. In this

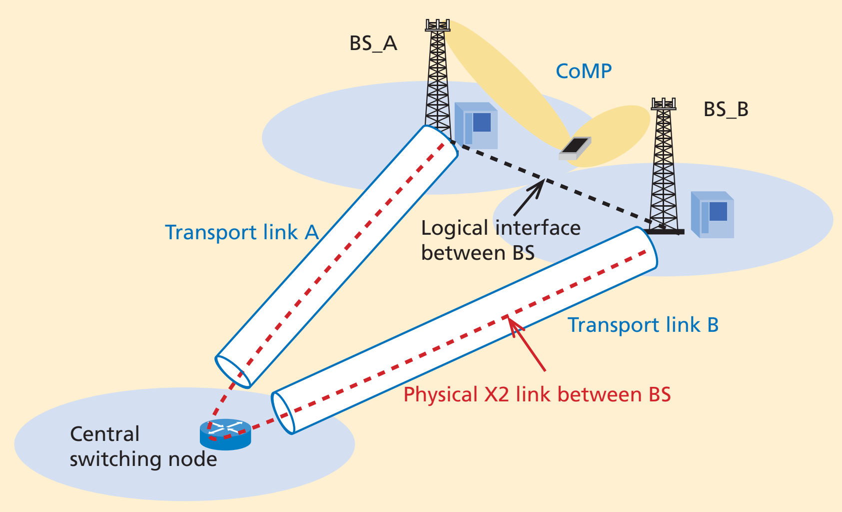

Figure 5 Physical and logical X2 interfaces on the mobile backhaul access network

*34 **X2**: A reference point between eNodeB, defined by 3GPP.

*35 **Optical coupler**: A passive optical device that combines optical signals from several fibers into a single fiber.

*36 **RN**: A node in a PON system where the optical signal is physically separated.

case, the X2 interface delay can be reduced because the signal directly bypasses the RN internally and does not go through the central switching component or Optical Line Terminal (OLT). However, with this approach, signals are broadcast to a predefined BS group of the neighboring four or six BSs, so the inter-BS signals are sent to BSs that do not need the signal. This causes loss of Signal-to-Noise Ratio (SNR)*37 due to distribution and restrictions on the X2 link data rate.

At DOCOMO Euro-Labs, we have studied the design and optimization of a WDM-based mobile backhaul network to implement X2 links satisfying the requirements to support CoMP. **Figure 6** shows a conventional WDM-PON, and **Figure 7** shows the proposed WDM-based mobile backhaul access network using a physical X2 link [13]. All of the components used in this design are compatible with conventional WDM-PON, and a variable wavelength laser is used as a colorless light source*38 in the ONU. The significant aspects of this proposal are:

- Use a separate variable wavelength laser light source to transmit the X2 signal
- Route the X2 signal in the optical domain using a passive optical coupler attached to an N × N Arrayed Waveguide Grating (AWG)*39

Physical X2 point-to-point communication is accomplished by having the source ONU generate the wavelength allocated to the destination ONU using its variable wavelength laser, modulating it with the X2 signal and transmitting it over a common optical fiber. The AWG uplink output is combined and injected into the main downlink port, which is equipped with a passive optical coupler. Thus, the X2 signal is automatically routed according to wavelength to the destination ONU, as-is in the optical domain. This routing is accomplished using passive devices such as the optical combiner and AWG, so no active components are needed in the RN. Also, no IP processing is done, and the fiber transmission distance is shorter than conventional links, as shown in Fig. 7, so extremely short delays are achieved on the X2 interface. The short fiber transmission distance also reduced fiber transmission losses,

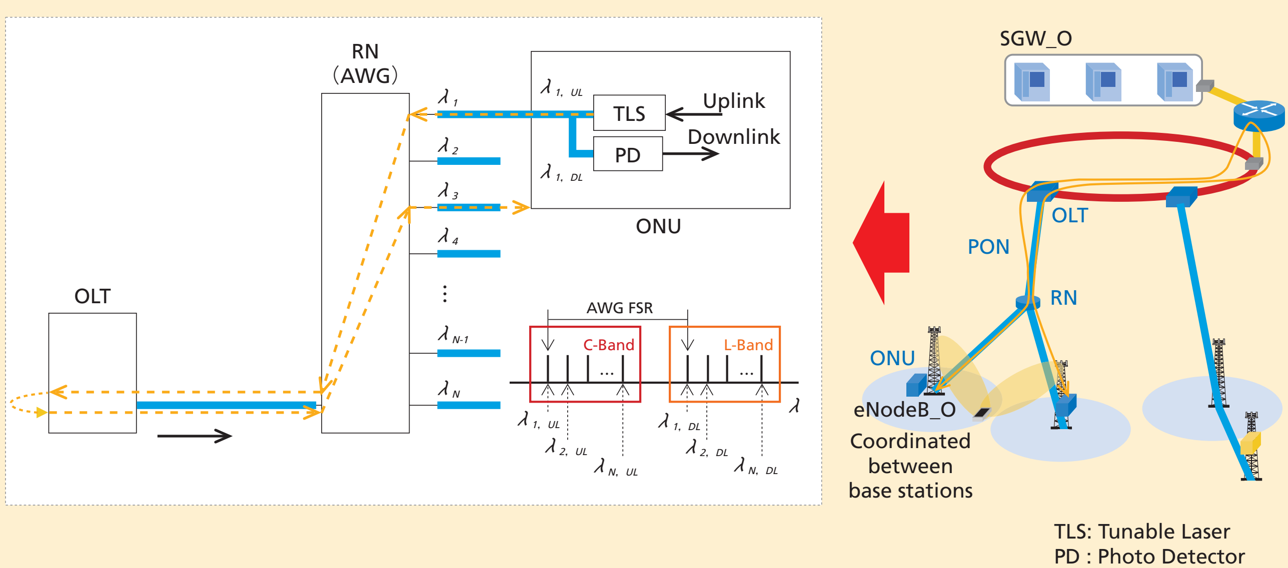

Figure 6 Conventional WDM-PON

*37 **SNR**: The ratio of the electromagnetic power of the desired signal to electromagnetic power of noise in wireless communication.

*38 **Colorless light source**: A light source used within a PON system and able to generate light of any wavelength needed.

*39 **AWG**: A device for multiplexing and demultiplexing multiple wavelengths of light using planar optical circuits.

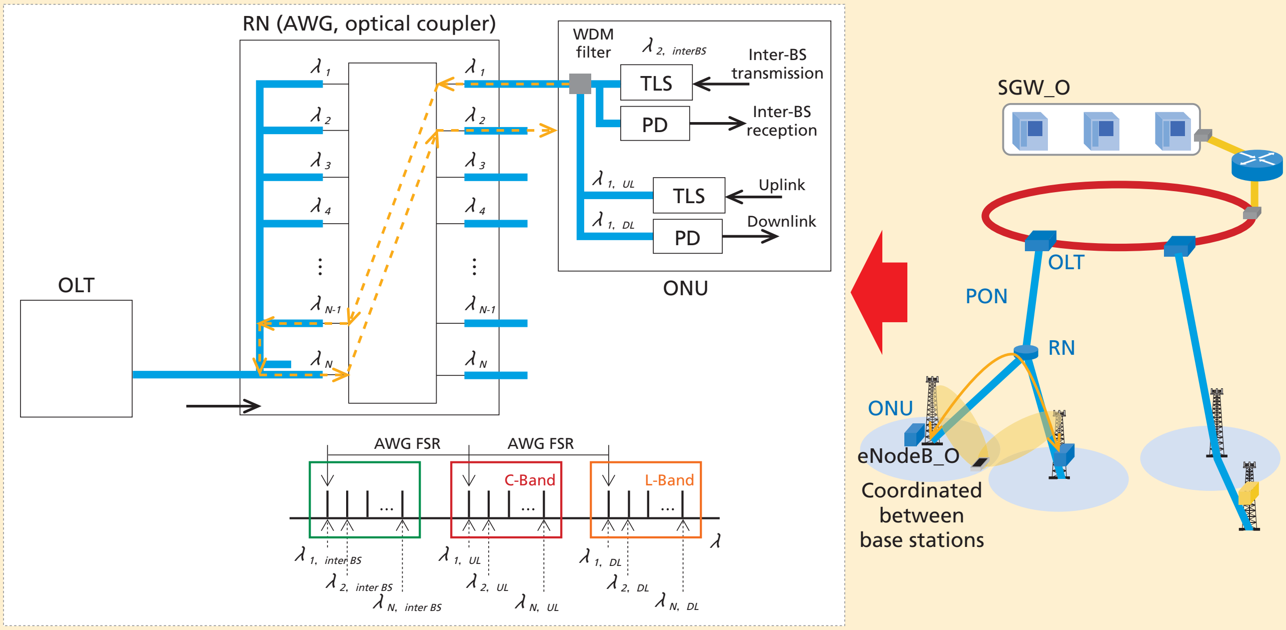

Figure 7 Overview of WDM-based mobile backhaul access network using physical X2 links

allowing high transmission data rates. With these advantages, wavelength bands other than the C-Band[*40] and the L-Band[*41] can be used for the X2 interfaces, as shown in Fig. 6 and 7. Low-noise optical amplifiers cannot be used in these bands, but this is not an issue because the X2 link transmission losses in the fiber are low. With these features, the proposed physical X2 link should provide high-capacity, low-delay point-to-point links. If some other wide-band light source such as a Super-luminescent Light Emitting Diode (SLED) is used in the design for point-to-point transmission, instead of the variable wavelength laser, broadcast of all of the X2 interface signals to all of the ONU in a single PON could be done in the optical domain. Wideband optical sources include all wavelengths in a single band, so the X2 signals are distributed to all ONU through an AWG equipped with optical splitter, as shown in Fig. 7. Normally, SLEDs are much less expensive than variable wavelength lasers, so it would be economically feasible to deploy two optical transmitters at the same time.

5. Conclusion

In this article, we have presented a vision for a future optical mobile network architecture. This solution applies optical mobility management and enhanced optical access technology, enabling the NMN to provide broadband access to users with low energy consumption. In the future, DOCOMO Euro-Labs will continue its research efforts advancing optical technologies for mobile networks, with a goal of commercializing the proposed optical mobile network architecture by the year 2020.

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*40 **C-Band**: Optical spectrum with wavelengths from 1,530 to 1,565 nm.

*41 **L-Band**: Optical spectrum with wavelengths from 1,565 to 1,625 nm.

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