

# Mobile Backhaul Optical Access Networks for Coordinated Multipoint Transmission/Reception (CoMP) Techniques in Future Cellular Systems

Changsoon CHOI<sup>†a)</sup>, Thorsten BIERMANN<sup>†</sup>, Qing WEI<sup>†</sup>, Kazuyuki KOZU<sup>†</sup>, Nonmembers,  
and Masami YABUSAKI<sup>†</sup>, Member

**SUMMARY** This paper describes mobile backhaul optical access network designs for future cellular systems, in particular, for those systems that exploit coordinated multipoints (CoMP) transmission/reception techniques. Wavelength-division-multiplexing passive optical networks (WDM-PON) are primarily considered and two proposals to enhance mobile backhaul capability of WDM-PONs for CoMP are presented. One is physical X2 links that support dedicated low latency and high capacity data exchange between base stations (BSs). The other is multicasting in WDM-PONs. It effectively reduces data/control transmission time from central node to multiple BSs joining CoMP. Evaluation results verify that the proposed X2 links and the multicasting enable more BSs to join CoMP by enhancing the mobile backhaul capability, which results in improved service quality for users.

**key words:** mobile backhaul access networks, wavelength-division multiplexing passive optical networks (WDM-PON), coordinated multi-points (CoMP), X2 interface, multicasting

## 1. Introduction

Recent years have seen exploding growth in mobile data traffic with the rapid evolution of smart phones. This accelerates commercial LTE services in cellular networks, and the LTE-Advanced has gained all gravity of research and development activities in both network and radio design. According to the 3GPP discussion, the LTE-Advanced is supposed to provide 1 Gbps for downlink and 500 Mbps for uplink transmissions per cell. Considering that future cellular systems will continuously increase maximum capacity to cope with mobile data traffic increase, it is necessary to design a mobile network architecture that is able to scale with future demands. Given that the average revenue per user (APRU) is likely to increase at much lower rate than traffic demand increases, or even decreases with increasing traffic demands, it is critical to develop cost-effective mobile network architectures. This implies to strive for ease of network operation and management, as well as energy efficiency to reduce OPEX. There is no doubt that reducing CAPEX is far more important than any other factor when designing mobile networks.

We believe that optical network technologies play an important role to meet such requirements as well as to deal

with increasing traffic in next mobile network (NMN) [1]. Figure 1 illustrates the concept of NMN based on optical technologies. All mobile traffics typically go through a Serving gateway (S-GW) and a PDN gateway (P-GW), therefore the entire mobile network architecture is rather centralized. Ring networks can be used for metro/access areas where high resilience is critical. For access networks, passive optical networks (PONs) are a viable and cost-effective alternative to provide the large numbers of base stations (BSs) with backhaul connectivity. However, it is not straightforward to use conventional PONs for mobile backhaul access networks. Higher operability including higher resilience and reliability is required in mobile backhaul access networks than in fixed access networks. This is because a single BS provides connectivity to many users whereas an optical network unit (ONU) only connects to single or few end-users. Among all requirements, the most important one for mobile backhaul access networks is to fully support future radio access techniques.

Coordinated multipoint (CoMP) transmission/reception is a promising future radio access technique that requires higher mobile backhaul capability than current cellular networks would need. It has been extensively discussed in 3GPP as a promising technique to improve cell throughput (particularly for cell-edge users) by allowing different BSs to cooperatively manage interference and/or to participate in joint transmission/reception [2], [3]. However, it comes with increased backhaul traffic because neighboring BSs joining CoMP need to exchange user data and/or cell information such as channel state information (CSI) through the backhaul networks that connects cooperating BSs. This exchange needs to be done while CSI is valid (typically a few milliseconds). Therefore, not only higher bandwidth requirements but also more stringent latency requirements for the exchange via the backhaul networks have to be fulfilled.

This paper presents mobile backhaul access network designs for CoMP techniques in LTE-Advanced and future cellular networks. We primarily consider PON technologies to build mobile backhaul access networks in NMN. In current fiber-to-the-home (FTTH) markets, time-division-multiplexing passive optical networks (TDM-PONs) have been widely used due to its cost effectiveness and now evolved to 10GPON where the maximum link capacity from optical line terminal (OLT) to optical network units (ONUs)

Manuscript received June 19, 2012.

Manuscript revised October 3, 2012.

<sup>†</sup>The authors are with DOCOMO Communications Laboratories Europe GmbH, Munich, 80335, Germany.

a) E-mail: changsoon.choi@gmail.com

DOI: 10.1587/transele.E96.C.147

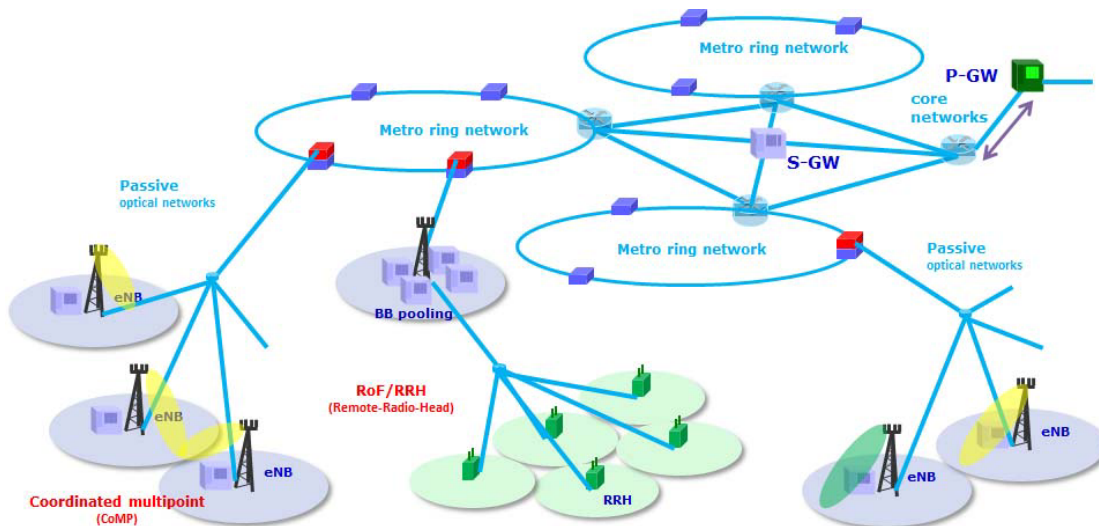


Fig. 1 Next mobile network based on optical technologies.

is 10 Gbps. However, since this link capacity is shared among all ONUs, a 10GPON has not enough capacity for mobile backhaul access networks. This becomes visible when looking at LTE-Advanced where each cell supports up to 1 Gbps and a site corresponding to an ONU in a PON is typically equipped with 3 sectors (cells). Therefore, we believe wavelength-division-multiplexing passive optical networks (WDM-PONs) capable of providing several Gbps to each ONU is better suitable for future mobile backhaul access networks. Nevertheless, it is not straightforward to simply use conventional WDM-PONs for mobile backhaul access networks supporting CoMP due to its stringent latency requirements. Section 2 describes a modified WDM-PON architecture with physical X2 links that promises much shorter delay for CoMP compared to conventional WDM-PON. Performance evaluations for different mobile backhaul access network designs are also presented. In Sect. 3, physical layer multicast is proposed for WDM-PONs and its influence on CoMP is presented. Finally, the paper ends with summary and conclusion in Sect. 4.

2. WDM-PON with Physical X2 Links

2.1 Proposed Architecture

To enable CoMP, it is indispensable for cooperating BSs to share user data and/or cell information via mobile backhaul access networks. Such exchanges are usually carried out among neighboring BSs that gives substantial influence on received radio signal power of user elements (UEs). The X2 interface, which is a logical interface between two BSs in the 3GPP standard is supposed to be used for such data exchange.

The X2 interface is not a physical link but a logical interface whose performance strongly depends on physical link implementation. In conventional mobile backhaul access networks, as shown in Fig. 2, the X2 interface is real-

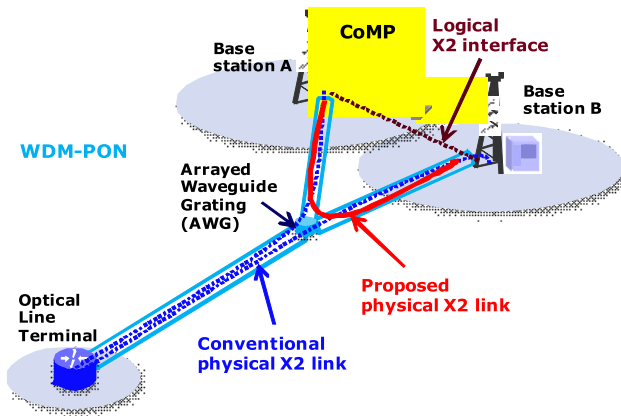


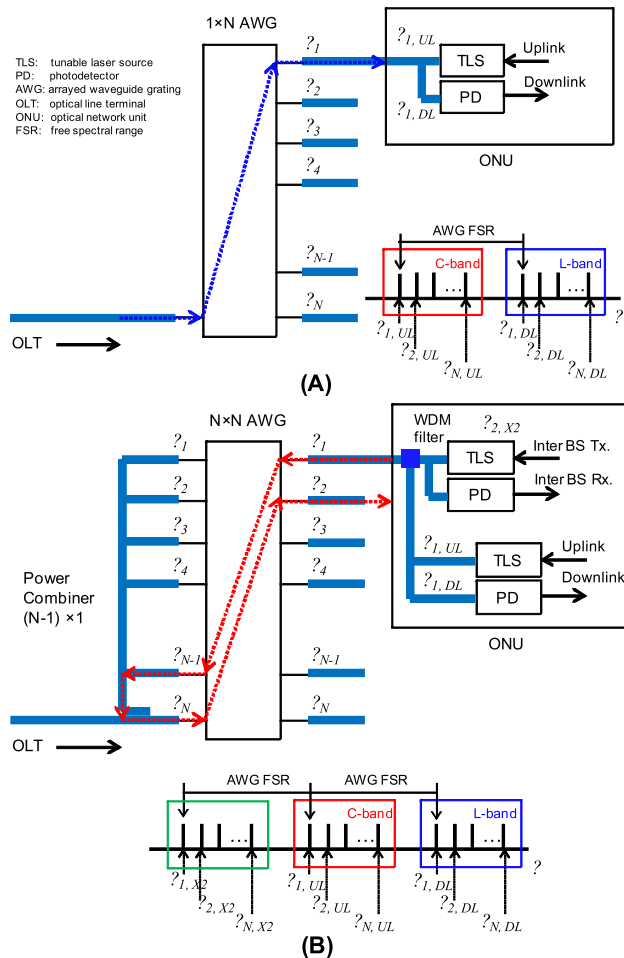
Fig. 2 Illustration of logical X2 interface, the conventional way of physical X2 implementation and the proposed physical X2 implementation.

ized through a central switching node (an OLT in a PON), not direct connection between BSs in order to reduce hardware costs. This way of X2 link implementation has been no issue so far because the conventional uses of the X2 interface, such as data forwarding for handover and control plane support in radio resource management, require a maximum latency of 10~20 ms, which can be easily achieved by this way of implementation. However, this delay is not enough to support CoMP. Several works have reported that CoMP generally requires less than a few millisecond latency with several Gbps capacity where detailed numbers depend on the used CoMP technique and UE mobility [2]. In addition, it is likely that this conventional X2 implementation ends up with much longer delays in the future since next-generation passive optical networks (NG-PON2) target much longer transmission distances of longer than 100 km. This leads to the idea of physical X2 links, meaning a direct communication link between BSs.

One of physical X2 link solutions commercially available is a microwave point-to-point (p-to-p) link for con-

necting two BSs. This approach, however, significantly increases BS construction costs since it requires a lot of additional hardware for microwave p-to-p links to cover all BSs in a cellular network. Furthermore, additional frequency licenses for microwave bands are needed. The limited bandwidth in these microwave bands makes it even more challenging to provide more than 1 Gbps. The use of higher frequency bands, such as millimeter-wave, could be an alternative solution. However, its components are much more expensive than for microwave. No matter what technique is used for p-to-p wireless links, it cannot provide link quality comparable to fiber links due to the susceptibility to environments. From the performance point of view, it would be ideal to build dedicated fiber links for the X2 interface between neighboring BSs. However, it is not practical to deploy another optical fiber only for the purpose of having a physical X2 link. In addition, cooperating BSs can be dynamically changed as UEs move, therefore X2 links should not be static to support UE mobility. In this paper, we proposed a cost-effective solution to realize physical X2 links in WDM-PONs as follows.

Figure 3 shows the comparison between the conventional WDM-PON and the proposed WDM-PON with physical X2 links. All components used in this design are fully compliant with a conventional WDM-PON utilizing a tunable laser as a colorless optical source in ONU [4]. The main idea is to use another tunable laser source for transmitting optical X2 signals and to attach passive optical coupler into an N-by-N arrayed waveguide grating (AWG) for re-routing optical X2 signals. For physical X2 point-to-point communication, a source ONU generates the allocated wavelength of a target ONU by utilizing a tunable laser, modulates X2 signals and transmits it through the same optical fiber. Because the uplink outputs of the AWG at the remote node (RN) are combined and applied to the main downlink port using the passive optical coupler, optical X2 signals are automatically re-routed to the target ONU according to its wavelength. This routing is fully done in passive devices including the optical combiner and the AWG. Hence, no active component is necessary in RN. (A Fiber Bragg Grating could be used to reflect optical X2 signals going into the main input of the AWG) Besides additional capacity, this approach also promises extremely low latency for X2 interface, coming from both no IP processing and shorter fiber transmission distance than in conventional link as shown in Fig. 3. In addition, lower loss in fiber transmission can be achieved, resulting in higher data rate. This low loss feature also makes it possible to use another wavelength band whose wavelength separation to the already used wavelength bands (C-band or L-Band) corresponds to free spectral range (FSR) of the AWG as shown in Fig. 3(B). The unavailability of a low noise figure optical amplifier in this new band is not an issue since optical X2 links do not suffer high transmission loss due to short traveling distance. It is also possible to use just one tunable laser and one photodetector for both uses of down/uplinks and X2 links if the wavelength tuning time of the tunable laser is short enough.



**Fig. 3** (A) conventional WDM-PON (B) proposed WDM-PON with physical X2 links.

From these features, the proposed physical X2 links are expected to provide high capacity and low latency point-to-point links between ONUs. For point-to-multipoints transmission, the wavelength tuning time of the tunable laser has to be minimized because it needs to be changed every time the destination ONU is changed. Detailed analysis and a proposal to mitigate such dependence will be given later. Alternatively, optical X2 broadcasting to all ONUs in one PON is also feasible if a broadspectrum optical source like superluminescent light emitting diode (SLED) is used instead of a tunable laser. A broadspectrum optical source contains all wavelengths in one band, therefore optical X2 signals are distributed to all ONUs through the AWG. In general, an SLED is much cheaper than a tunable laser. Hence, collocated two optical transmitters in an ONU is economically feasible. There will be cases where multiple ONUs need to simultaneously transmit optical X2 signals to one target ONU via only one wavelength. To avoid such optical X2 signal collision, a multiple access scheme can be used, for example, time domain multiple access (TDMA) or subcarrier multiple access (SCMA).

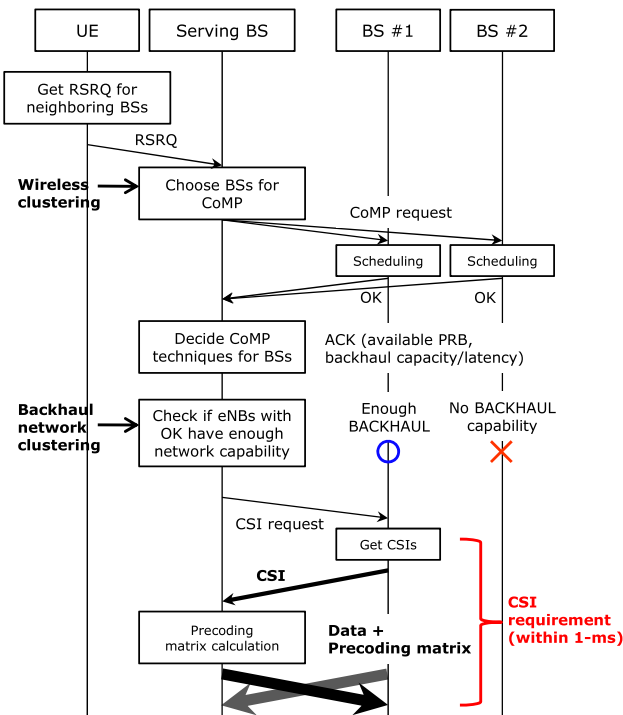


Fig. 4 CoMP system architecture used for simulation analysis. It consists of two main clustering steps: wireless clustering and backhaul network clustering.

## 2.2 Evaluation of Mobile Backhaul Access Network Design with Physical X2 Links for CoMP Applications

In order to optimize WDM-PON architecture and proposed physical X2 links, we developed system-level simulators for CoMP applications. We consider a distributed implementation of CoMP, where each BS is equipped with a CoMP signal processing unit [3]. In previous work [5], we proposed a CoMP system architecture with multiple clustering steps, wireless clustering and backhaul network clustering, shown in Fig. 4. When requested for CoMP, a serving BS decides a set of cooperating BSs according to reference signal received Quality (RSRQ) feedbacks from UEs. In this step of *wireless clustering*, a neighboring BS giving higher RSRP to a UE has higher priority to join a cluster. The more BSs in a cluster, the higher UE throughput can be expected. Therefore we set the number of BSs in this desired wireless cluster as a main input parameter called *cluster size*. Exploiting backhaul network information, a serving BS checks all BSs in a desired cluster if each BS fulfills backhaul network properties required for CoMP signal and/or data exchanges between itself and a serving BS. This procedure we call *backhaul network clustering* [6] starts from the strongest neighboring BS in terms of RSRP, and excludes BSs which have no enough backhaul network capability. This avoids unnecessary signaling overhead in the following CSI collection step. We observed a new metric, *cluster feasibility*, which is the ratio of BSs that fulfill the backhaul network

requirements of CoMP to the desired wireless cluster size (BSs chosen in the wireless clustering step).

For simulation, we generated more than 2000 hexagonal cells and distributed them in a square with the inter-BS distance of 500 m. Then, neighboring BSs are grouped according to proximity and each group consists of 40 BSs which are connected via the same PON tree. The RN is connected to an OLT via optical fiber and we assume all OLTs are co-located in one point that we call *OLT hotel*. The location of the OLT hotel is determined such that the maximum transmission distance,  $L_{PON}$  is fully exploited. We calculate the fiber propagation delay by  $L_{PON}/(c \cdot 2/3)$  where  $c$  is the speed of light and  $2/3$  comes from the inverse of the refraction index (1.5) of typical single-mode optical fiber. The total IP processing delay depends on how many IP processing steps are done for fiber link, and we assume 0.1 ms for one IP processing node which corresponds to OLT here. If they are in different PON group, it takes two times larger, 0.2 ms. Based on the assumption that OLTs are co-located in OLT hotel and their connections are mesh-like with very fast L2 switch, we consider link latency between OLT are negligible. Unlike TDM-PONs, WDM-PONs use a dedicated wavelength to each ONU, therefore link capacities of ONUs are fully independent each other.  $R_{PON}$  is the normalized link capacity factor indicating the ratio of fiber link capacity to the average data rate required for CoMP. For simplification, we used 1 Gbps UE data rate and additional 100 Mbps CSI exchange required for multiuser MIMO. Practically, it is possible to deploy 1 Gbps, 2.5 Gbps and 5 Gbps link capacity in WDM-PONs, therefore we have  $R_{PON}$  of 1, 2.5 and 5. We also assume that downlink and uplink are symmetric. Over entire networks, UEs are uniformly randomly distributed and only one single UE is associated to each BS. The simulation has been repeated for 1000 different UE locations and all results have been averaged to get the final results. For each simulation run, only one wireless cluster initiated by a UE in center cell is considered. In order to take into account practical large-scale fading channels for wireless clustering, we generated the shadow fading map of 61 cells where a UE mainly interested is located in the center cell [7]. A lognormal shadow fading model with the standard deviation of 8 dB is used. The shadowing correlations for inter-BS and intra-BS are 0.5 and 1, respectively. The path loss model used in the simulation is  $PL [dB] = 128.1 + 37.6 \cdot \log(L)$  where  $L$  is distance in kilometers.

Figure 5 shows the simulated CoMP cluster feasibilities in conventional WDM-PONs shown in Fig. 3(A) for different maximum transmission distance as a function of different number of clusters.  $R_{PON}$  is 2.5, meaning that WDM-PON link capacity is 2.5 times larger than data rate required for data exchange in CoMP. As cluster size increases, cluster feasibility decreases due to the increased traffic supporting more BSs for CoMP. It also indicates that cluster feasibility degrades if PON coverage increases, which mainly arises from the increased propagation time for fiber transmission. As stated earlier, NG-PON2 are likely to be deployed with increased PON coverage, however the result

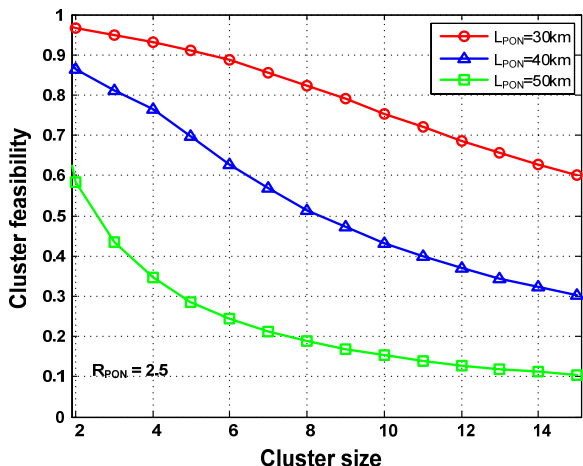


Fig. 5 CoMP cluster feasibilities for WDM-PONs with different maximum transmission distance.

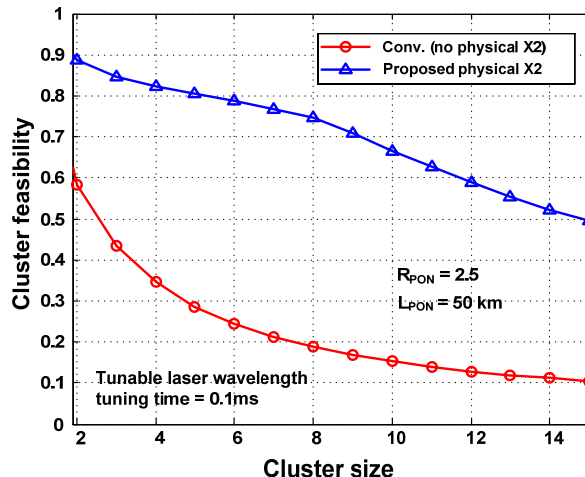


Fig. 7 CoMP cluster feasibilities for conventional WDM-PON and the proposed WDM-PON with physical X2 links.

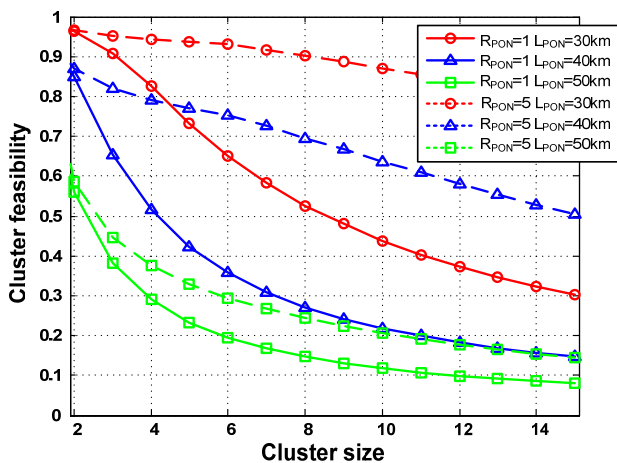


Fig. 6 CoMP cluster feasibilities for WDM-PONs with different link capacities and maximum transmission distance.

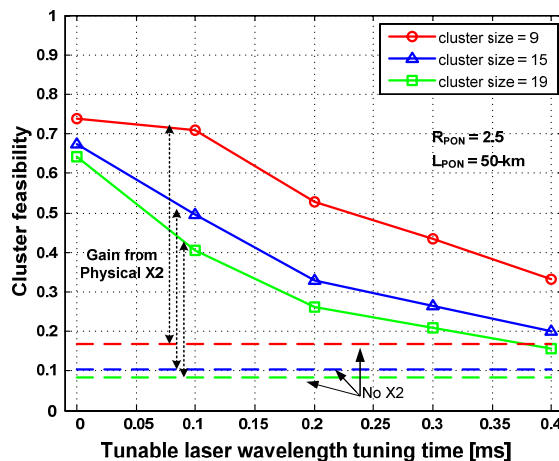


Fig. 8 CoMP cluster feasibilities as a function of wavelength tuning time in a tunable laser in the proposed physical X2 links.

implies that this approach may introduce a critical problem to use WDM-PONs for mobile backhaul access networks supporting CoMP.

Increasing the link capacity in WDM-PONs would be a solution to increase CoMP cluster feasibility with a minimum of hardware upgrades. Figure 6 shows the CoMP cluster feasibility for different link capacities,  $R_{PON} = 1$  and  $R_{PON} = 5$ . It is effective to increase link capacity for higher cluster feasibility in case of  $L_{PON} = 30$  km and  $L_{PON} = 40$  km. However, the improvement for  $L_{PON} = 50$  km is only marginal where the limitation is dominated by long propagation time in fiber transmission. This implies that we need to come up with physical X2 links, particularly for long-range WDM-PONs to support CoMP.

Figure 7 compares CoMP cluster feasibility of the proposed WDM-PON with physical X2 links with the conventional WDM-PON for  $L_{PON} = 50$  km. We clearly see that the proposed X2 link significantly improve CoMP cluster feasibility, which would result in increased UE throughput or service quality by CoMP. It mainly comes from the fea-

ture that the proposed X2 link enables optical X2 signals to bypass via RN, resulting in shorter transmission distance and shorter latency. For multipoints-to-point transmission that is required to collect CSIs from cooperative BSs in a cluster, we assume TDMA is used with guard time of  $1 \mu\text{sec}$  to avoid collision.

In case that point-to-multipoints transmissions are required for UE data distribution from a serving BS to several cooperating BSs, the proposed physical X2 link requires wavelength tuning whenever a destination ONU is changed. Tuning or switching optical wavelength in a tunable laser usually takes considerable time, therefore we investigate its influence on CoMP cluster feasibility of the proposed physical X2 links. Figure 8 shows different CoMP cluster feasibilities of the proposed X2 links with different tuning times for a tunable laser. It significantly degrades as wavelength tuning time increases, which means that it is crucial to minimize wavelength tuning time to support more BSs for CoMP. Even though several works have reported tun-

able lasers with  $\sim \mu\text{sec}$  or even nsec wavelength tuning time, most of tunable laser used in a colorless ONU in WDM-PONs have the tuning time in order of  $\sim \text{msec}$  due to cost reasons. These insights suggest finding a solution that mitigate the influence of tuning time in a tunable laser on cluster feasibility. For this problem, we propose a new point-to-multipoint transmission scheme that will be described in detail in the following section.

### 2.3 Point-to-Multipoint Transmission Scheme with the Reduced Latency in the Physical X2 Links

The main idea of the proposed transmission scheme is to use receiving BSs as transmitting BSs to forward UE data to other BSs in next transmission time slot. In the conventional approach for point-to-multipoints transmission in the physical X2 link, only a serving BS transmits UE data to other cooperating BSs. The proposed transmission scheme enables BSs that have received UE data in the first time slot to forward the data in the second time slot to other cooperating BSs that have not received UE data. Figure 9 shows the comparison between the proposed scheme and the conventional scheme used for analysis.

The left one is a serving BS which first chooses cooperating BSs based on UE feedback information. In the first time slot, the serving BS sends UE data to cooperating BS with the highest priority. Transmissions for the proposed and the conventional schemes become different in the second time slot. In the conventional one, the serving BS tunes its wavelength allocated to the second highest priority BS, and sends the UE data to that BS. The proposed scheme enables the BS that previously received UE data to forward it to the third priority BS. In the meantime, the serving BS sends UE data to the fourth priority BS. It allows to exponentially increase the number of BS that have received UE data from a serving BS. In the third transmission scheme, the proposed scheme has completed transmission to 8 BSs while the conventional one has only reached 3 BSs. The required transmission time for the proposed scheme can be expressed as

$$T_{total} = (T_{TL} + T_D) \cdot \text{ceil}(\log_2 N)$$

where  $T_{TL}$  is tunable laser tuning time,  $T_D$  is data transmission time,  $N$  is the cluster size and  $\text{ceil}(\cdot)$  is a function that maps a real number to the largest previous integer. On the other hand, the time for the conventional scheme is

$$T_{total} = (T_{TL} + T_D) \cdot N$$

These equations indicate that the difference gets larger as cluster size increases, meaning that the proposed scheme is more advantageous to support a CoMP with larger cluster.

We also simulated CoMP cluster feasibilities for the proposed and the conventional transmission schemes as shown in Fig. 10. It shows that the proposed scheme provides higher cluster feasibility, particularly for larger cluster size. For this evaluation, a tunable laser tuning time of

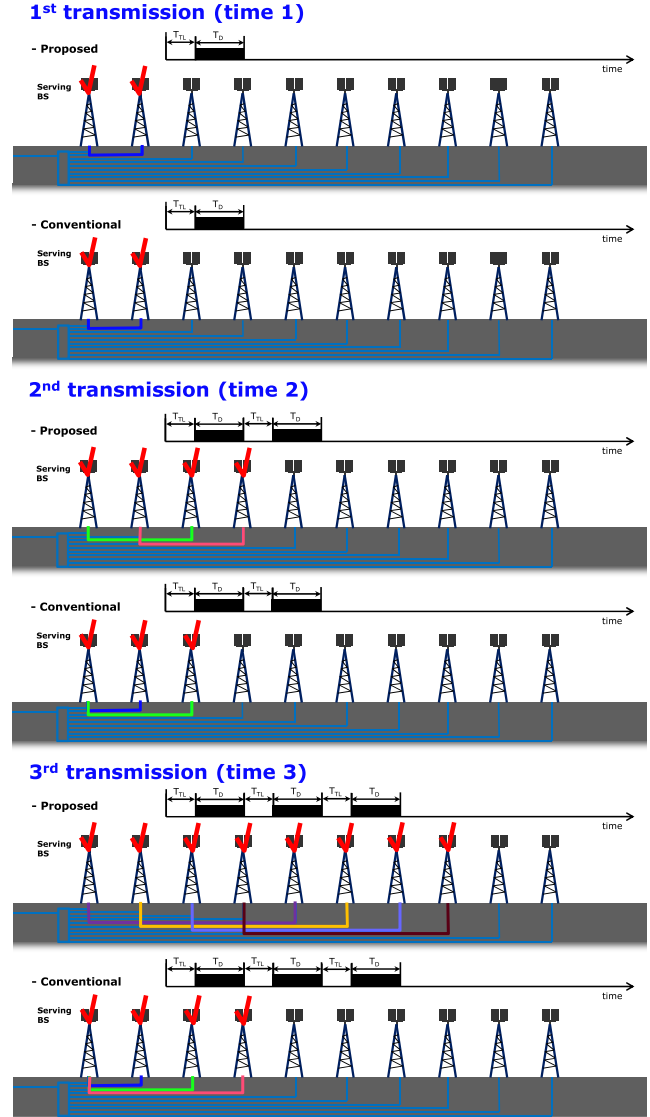


Fig. 9 Comparison of the proposed and the conventional schemes for point-to-multipoint transmission in physical X2 links.  $T_{TL}$  is tunable laser tuning time and  $T_D$  is data transmission time.

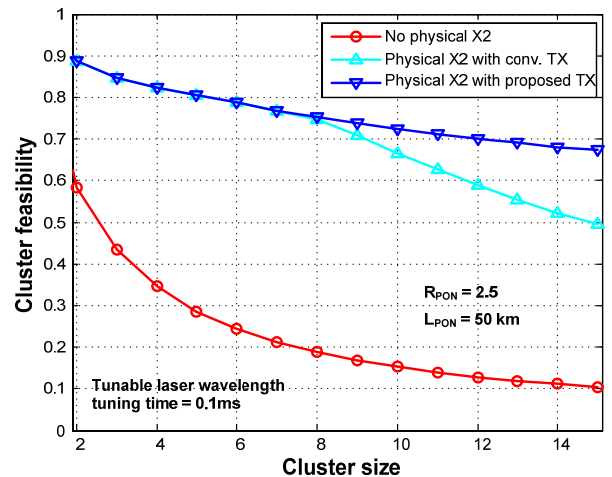


Fig. 10 CoMP cluster feasibilities for the proposed and the conventional transmission schemes in the physical X2 links.

0.1 ms was assumed. We expect the proposed scheme to improve cluster feasibility more significantly for larger tuning time in a tunable laser because reducing number of tuning becomes more effective to keep time requirement when using larger tuning time.

### 3. WDM-PON with Multicasting

#### 3.1 Proposed Architecture

WDM-PONs offer virtual point-to-point links to each ONU. This makes it difficult to use WDM-PONs for mobile backhaul access networks which need broadcasting and multicasting capabilities. For downlink CoMP joint processing techniques, multiple BSs need to have the same UE data. This is where we need multicasting that allows one central unit to transmit a single UE data to multiple BSs. Besides, there are several mobile applications that require multicasting capability, for example, paging and multimedia broadcast multicast service (MBMS). IP layer multicasting could provide the same functionality as physical layer (L1) multicasting does, however it cannot avoid the duplication of one multicast packet into several packets. This causes large network overhead, which results in inefficient network operation. L1 multicasting is most efficient than IP layer multicasting from the viewpoint of network operations.

There have been several approaches for the implementation of L1 broadcasting in WDM-PONs. One technique is to use a broadspectrum optical source at OLT [8]. It covers the entire wavelength spectrum in a band, thus it can deliver one broadcasting signal to all ONUs that belong to an OLT. To avoid signal collision between the broadcasting wavelength and downlink wavelengths, one could utilize another wavelength band with FSR separation to the downlink/uplink wavelength band. This way of implementation is very useful to provide cable TV or broadcasting services to FTTH subscribers. For mobile backhaul access networks, however, multicasting capability is missing. For CoMP applications, not every BS joins CoMP, meaning that the number of cooperating BS is usually limited where the detailed number depends on several radio and network parameters. Moreover, it is likely to have different cooperating groups of BSs serving different UEs simultaneously in a PON system. To provide different multicasting data to different groups of BSs, a mobile backhaul access network needs multicasting capability, not broadcasting capability.

Figure 11 schematically illustrates the proposed WDM-PON with L1 multicasting. It uses an N-by-N AWG instead of N-by-1 at the OLT with a broadspectrum optical source. With the help of the AWG, different optical wavelengths are spatially separated in the AWG and routed to each port according to the wavelength. An AWG used for this purpose can also be used for multiplexing and demultiplexing of down-/uplink optical signals, so no additional AWG is required for multicasting. At each output port of the AWG, an optical modulator or a switch is connected and outputs are combined into the main downlink port by a

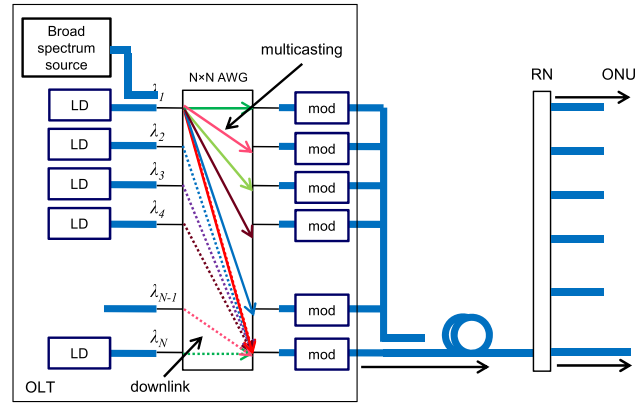


Fig. 11 Proposed WDM-PON with L1 (physical layer) multicasting. LD is laser diode and MOD is optical modulator.

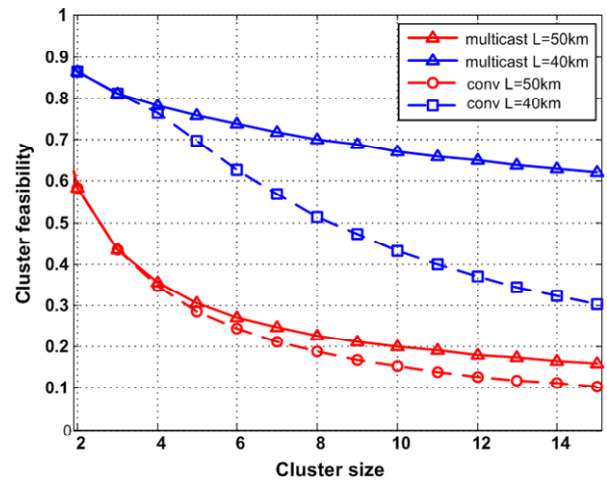


Fig. 12 CoMP cluster feasibilities for conventional WDM-PON and proposed WDM-PON with multicasting.

passive optical coupler. Using optical modulators enables to apply different multicasting data into different wavelengths allocated to different ONUs. A simpler approach is also feasible with applying optical switches instead of optical modulators, to block transmission to ONUs not involved in multicasting.

#### 3.2 Evaluation of Mobile Backhaul Access Network Design with Multicasting for CoMP Applications

We performed simulations of CoMP cluster feasibilities again to verify the advantage of multicasting for CoMP. Figure 12 compares CoMP cluster feasibilities between a conventional WDM-PON and the proposed WDM-PON with the multicasting capability for  $L_{PON} = 40$  km and  $L_{PON} = 50$  km. It verifies that multicasting capability improves CoMP cluster feasibility, due to the reduced time to sequentially transmit single user data to multiple ONUs. It also shows that multicasting starts losing its advantage as transmission distance increases ( $L_{PON} = 50$  km). As obviously seen in Fig. 7, physical X2 links are good solutions to this

problem.

#### 4. Conclusion

We presented mobile backhaul access network designs to better support CoMP in future cellular systems. WDM-PONs have been mainly considered and the two key enablers, a physical X2 link and a multicasting enabled OLT architecture, are proposed to make WDM-PONs a promising technologies for mobile backhaul access networks supporting CoMP. We verified their structural advantages of both approaches for CoMP applications by the developed CoMP system-level simulators. The results show that, using WDM-PONs with the proposed designs as mobile backhaul access networks, future radio technologies like CoMP can easily supported throughout the upcoming cellular network generations.

#### References

- [1] M. Yabusaki, J. Widmer, and L. Scalia, "Next mobile network based on optical switching," COIN 2010, Jeju, Korea, 2010.
- [2] M. Sawahashi, Y. Kishiyama, A. Morimoto, D. Nishikawa, and M. Tanno, "Coordinated multipoint transmission/reception techniques for LTE-Advanced," *IEEE Wireless Commun.*, vol.19, no.3, pp.26–34, June 2010.
- [3] V. Jungnickel, L. Thiele, T. Wirth, T. Haustein, S. Schiffermuller, A. Fork, S. Wahls, S. Jaeckel, S. Schubert, H. Gabler, C. Juchems, F. Luhn, R. Zavrtak, H. Droste, G. Kadel, W. Kreher, J. Mueller, W. Stoermer, and G. Wannemacher, "Coordinated multipoint trials in the downlink," *IEEE Globecom*, Nov. 2009.
- [4] C. Choi, Q. Wei, T. Biermann, and L. Scalia, "Mobile WDM backhaul access networks with inter-base-station links for coordinated multipoint transmission and reception systems," *IEEE Globecom*, Nov. 2011.
- [5] C. Choi, L. Scalia, T. Biermann, and S. Mizuta, "Coordinated multipoint multiuser MIMO transmissions over backhaul-constrained mobile access networks," *IEEE PIMRC*, Sept. 2009.
- [6] T. Biermann, L. Scalia, C. Choi, H. Karl, and W. Kellere, "Backhaul network pre-clustering in cooperative mobile access networks," *IEEE WoWMoM*, Sept. 2009.
- [7] A. Benjeboour, M. Shirakabe, Y. Ohwatari, J. Hagiwara, and T. Ohya, "Evaluation of user throughput for MU-MIMO coordinated wireless networks," *IEEE PIMRC*, Sept. 2009.
- [8] J.-H. Moon, K.-M. Choi, and C.-H. Lee, "Overlay of broadcasting signal in a WDM-PON," *Optical Fiber Communication (OFC) Conference*, 2009.



**Changsoon Choi** received B.S., M.S. and Ph.D. degree in electrical and electronic engineering from Yonsei University, Seoul, Korea, in 1999, 2001, 2005. He is now with DOCOMO Communications Laboratory Europe GmbH, Munich, Germany, where he is working on cooperative MIMO systems, energy efficient cellular networks and mobile backhaul networks for LTE-Advanced and future radio access systems. His industrial affiliation includes NICT, Japan, and IHP microelectronics, Germany, where he worked on next-generation wireless LAN systems and wireless backhaul links for LTE-Advanced.



**Thorsten Biermann** received his B.S. and M.S. degree in computer science from the University of Paderborn, Germany, in 2006 and 2008. Currently, he is pursuing Ph.D. studies on backhaul networks for Coordinated Multi-Point (CoMP) cellular systems at DOCOMO Communications Laboratory Europe GmbH, Munich, Germany.



**Qing Wei** received B.S. of Electrical Engineering, B.S. of Accounting from Shanghai Jiao Tong Univ., Shanghai, P.R.China in 1997. From 1997~1999 she worked in Philips Lighting Electronics (Shanghai) Co. Ltd as a research engineer. In 2001, she received a M.Sc. degree in Communications Engineering from the Technical University of Munich, Germany with academic award. In 2002, she joined DoCoMo Euro-Labs and has been worked on QoS, active network technology, cross layer design, sensor networks, IEEE802.11 MAC and mobility management. Her current working focus is next generation optical mobile network.



**Kazuyuki Koza** is a research manager at DOCOMO Communications Laboratories Europe GmbH. He received his B.E. and M.E. degree from Yokohama National University in 1995 and 1997, respectively. He joined NTT DOCOMO in 1997. He has worked for NTT DOCOMO in the area of mobile core networks. His research and development activities covered designing mobile network architecture and 3GPP standardization. Since 2010, he is a member of DOCOMO Euro-labs and is involved in research on next mobile networks.





**Masami Yabusaki** is a president and CEO in DOCOMO Communications Laboratories Europe GmbH. He received the B.S. M.S., Ph.D. degrees in electrical engineering from Waseda University in 1982, 1984, and 1993 respectively. He joined NTT (Nippon Telegraph and Telephone Corporation) in 1984. He was engaged in research of on-board baseband switch for an SS-TDMA system during 1984–1987, development of switch hardware and software for PDC (Personal Digital Cellular) system during 1988–

1991, and development and standardization of third generation mobile network, IMT-2000 during 1992–1999. He was the CEO of DoCoMo Europe S.A. in Paris during 1998–2000. He has led All-IP network research, development and SAE (System Architecture Evolution) standardization during 2000–2008. He is currently leading the research on next mobile core network, network value-added services, and 5G cellular wireless. He has been promoting the RCS (Rich Communication Services) nationally and internationally. In academic activity, he has served as a chairman of the mobile multimedia communication study committee in the IEICE and chairman of several special issues in the IEICE communication transaction. He has served also as a co-editor of special issues in IEEE Wireless Communication Magazine and a chairman of technical and panel session in the major conferences such as ICC and Globecom. In global standardization activity, he has served as a rapporteur of ITU-T SG11 on IMT-2000 radio access signaling and as a vice-chairman of 3GPP TSG-CN on GSM evolved IMT-2000 CN. He is now a convener of 3GPP improvement adhoc. He was awarded several prizes including the Young Engineers Award from IEICE in 1989, the Global Activity Promotion Award and the Achievement Award from ITU-AJ in 1998 and 2004, etc.