Mobile WDM Backhaul Network Designs for LTE-Advanced and Beyond Systems

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Abstract— This invited paper describes about mobile wavelength division multiplexing (WDM) backhaul network designs for future radio access networks. First, it introduces mobile backhaul requirements to support LTE-Advanced and Beyond with emphasis on coordinated multipoints (CoMP) techniques. It primarily considers WDM passive optical networks (WDM-PON) as promising optical access technologies for mobile backhaul access networks. It also presents two proposals that enhance backhaul capability for CoMP. One is to realize physical X2 links in WDM-PON, which are capable of establishing a dedicated high capacity and low latency optical links between base stations (BSs). The other is to enable multicasting in WDM-PON and it potentially reduces time to exchange control/data among BSs for CoMP. Simulation results verify that the proposed physical X2 links and multicasting enable more BSs to join cooperation by enhancing backhaul capability, resulting in improved user throughput by CoMP.

Keywords— Mobile backhaul networks, wavelength division multiplexing passive optical networks (WDM-PON), Coordinated multipoints (CoMP)

I. Introduction

As Long Term Evolution (LTE) service has recently launched, future radio access systems including LTE-Advanced are getting more attention in academies and industries. It also stimulates consideration to build new mobile networks or to upgrade it in order to be able to support future radio access systems. Followings are general requirements for mobile networks in comparison to fixed networks.

- More flexibility is required for mobility management, such as handover.
- Lower delay is required because delay budget is shared with wireless transport and wireless data processing.
- Higher operability including higher resilience and reliability is key factor especially for access networks providing base stations (BSs) with connectivity. Every-saving operation is getting more important for future networks.

Needless to say, higher capacity is required for access part (BS backhauling) in mobile networks than in fixed networks because one BS supports hundreds of users whereas one end point supports only few users in fixed network. As specified in LTE-Advanced, each BS, precisely speaking each sector needs to support maximum 1 Gbps capacity. One site typically consists of 3 sectors in cellular networks, therefore mobile backhaul access networks provide each site with more than 3 Gbps capacity. Additional backhaul capacity is required to support future radio access techniques, representatively, coordinated multipoints (CoMP) transmission/reception. CoMP has been considered as a promising technique for future radio access systems due to its

Figure 1: Next mobile network based on optical technologies
potential to improve cell-edge user throughput by allowing interference BSs to jointly serve users. However, it does not come for free but 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 mobile networks. This exchange needs to be done while CSI is valid, therefore it imposes not only higher traffic requirements but also more stringent latency requirements on mobile networks.

We believe that optical networking technologies are key enablers for future mobile networks due to huge bandwidth. Fig. 1 shows our conceptual image on next mobile networks based on optical technologies [1]. All mobile traffic should go through Serving gateway (S-GW) and PDG gateway (P-GW), therefore mobile network architecture looks like somehow centralized network. Ring networks can be used for metro/access networks where high resilience is favorable. For mobile backhauling to BSs, a wavelength-division multiplexing passive optical network (WDM-PON) has been considered. It has gained much interest in next-generation PON groups, for example, NG-PON2, thus it is expected to be a cost-effective solution capable of offering more than Gbps capacity to each optical line terminal (OLT) where a cell site with 3 sectors is located. However, it is not straightforward to simply use conventional WDM-PON architectures in FTTH networks for mobile backhaul networks. The following sections highlight these issues and suggest solutions for them.

II. Physical X2 links in WDM-PON

To realize CoMP, it is indispensable for cooperating BSs to share user data and/or cell information through mobile backhaul networks. Such exchange is usually carried out among neighboring BSs that give substantial influence on received radio signal power of users. The X2 interface, which defines logical interface between two BSs, is supposed to be used for such exchange to support CoMP.

The X2 interface is just logical interface, not physical links, therefore its performance strongly depends on implementation. Typically, it is realized through central node corresponding to OLT in PON, not direct connection between BSs due to cost reasons. This would bring about too much latency to support CoMP. Several works have reported that CoMP techniques generally require less than a few milliseconds latency with several Gbps capacity. Typical way of X2 implementation through central node has been no issue so far because X2 latency requirement of average 10 ms was specified for data forwarding in handover and control plane support in radio resource management. This requirement is not enough to support CoMP and X2 latency is likely to get even larger in future since NG-PON2 goes into the direction to have long range PON providing more than 100 km transmission distance. This brings us back into the point to build physical X2 links, meaning a direct communication link between BSs. However, it is not practical to deploy additional fiber between BSs only for this purpose due to high cost.

We proposed a cost-effective solution to realize physical X2 links in WDM-PON as shown in Fig. 2 [2]. All components used in this design are fully compliant with the conventional WDM-PON systems utilizing tunable laser as colorless optical source in ONU. The main idea is to adjust a tunable laser source to transmit different wavelength allocated to a target ONU. It is enabled by an additional optical coupler attached to N-by-N arrayed waveguide grating (AWG). For physical X2 point-to-point transmission, a source ONU generates the allocated wavelength of a target ONU by utilizing tunable laser, modulate X2 signals and transmits it through the same optical fiber. Because the uplink outputs of AWG are combined and applied to the main downlink port with passive optical coupler, generated X2 signals are automatically re-routed to a target ONU. This re-routing is done in passive devices including optical power combiner and AWG, therefore no active component is necessary in remote node. The transmission can be done by all optical processing, which offers no IP processing delay. Optical X2 signals do not need to travel long distance in fiber, therefore extremely low latency can be achieved in the proposed X2 links. Shorter transmission distance than conventional links also promises low transmission loss, resulting in high data rate transmission. It also makes it possible to use another wavelength band whose wavelength separation to the used wavelength band (C-band or L-band) corresponds to free spectral range of AWG. Unavailability of low noise optical amplifier in this band is not an issue since optical X2 links do not suffer from high transmission loss. It is possible to utilize just one tunable laser and photodetector for both use of down/uplinks and X2 links if wavelength tuning time in a tunable laser is short enough. For point-to-multipoint X2 transmission, broadspectrum light source can be used for an optical transmitter.

III. Multicasting in WDM-PON

As described earlier, WDM-PON offers virtually...
point-to-point links to each ONU. This would make it difficult to use WDM-PON system for mobile backhaul network applications that need broadcasting and multicasting capability. For example, multiple BSs need to have same user data for CoMP joint processing. This is where we need multicasting that enables to transmit one data to multiple ONUs.

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 help multi-copy multicasting which needs to duplicate one multicasting packet into several packets. It cannot avoid causing larger network overhead, which results in inefficient network operation. L1 layer multicasting is the most promising from the viewpoint of network operation.

This architecture can be summarized as two main parts: the use of N-by-N AWG instead of N-by-1 in OLT in order to separate out different wavelength from broadband optical source. With the help of AWG, the broadband optical signals are spatially separated in AWG and automatically routed to each port according to wavelength. It should be mentioned that the AWG used for this purpose is also used for multiplexing and de-multiplexing of down/uplink optical signals, so no additional AWG is required for multicasting. At each output of AWG, optical modulator or switch is connected and outputs are combined into main downlink port by using passive optical coupler. The use of optical modulators enables to apply different multicasting data into different wavelength allocated to different ONUs. Simpler approach is also feasible with applying optical switch instead of modulator, to block transmission to ONUs not getting multicasting data.

IV. System evaluation for CoMP applications

In order to investigate influence of the proposed X2 links and multicasting on CoMP applications, we performed system-level simulation. We consider distributed implementation of CoMP, where each BS is equipped with CoMP signal processing unit [3]. We proposed CoMP system architecture with multiple clustering steps, wireless clustering and backhaul network clustering [4]. When requested for CoMP, a serving BS decides a set of cooperating BSs according to the reference signal received qualities (RSRQs). In this step of wireless clustering, a neighboring BS giving higher RSRQ to a user has higher priority to join a cluster. The more BS in a cluster, the higher UE throughput can be expected, therefore we set the number of BSs in this wireless cluster as a main input parameter called cluster size. Based on network information feedback, a serving BS checks all BSs in a cluster if each BS fulfills backhaul network properties required for CoMP signal and/or data exchanges between itself and a serving BS. This procedure that we call backhaul network clustering [4] starts from the strongest neighboring BS in terms of RSRQ, and excludes BSs which have no enough backhaul network capability in order to avoid unnecessary signaling overhead in the following CSI collection step. This brings us a new metric, cluster feasibility, that is the proportion of BSs which turns out to have enough network capability for CoMP to a cluster size (BSs in a cluster decided by wireless clustering).

For simulations, we generated more than 2000 hexagonal cells and distributed in square with the inter BS distance of 500-m [4]. Then, neighboring BSs are grouped according to proximity and each group consists of 40 BSs. The RN is connected to an OLT via optical fiber and we assume all OLTs are optical fiber and we assume all OLTs are

![Figure 3: Proposed WDM-PON with L1 multicasting](image)
fiber. IP processing delay depends on how many IP processing is done for fiber link, and we assume 0.1 ms for one IP processing node which corresponds to OLT here. $R_{PON}$ is normalized link capacity factor indicating the ratio of fiber link capacity to the average data rate required for CoMP.

![Figure 5](image1.png)

Figure 5: CoMP cluster feasibility for conventional WDM-PON and WDM-PON with physical X2 links

Fig. 5 compares CoMP cluster feasibilities between conventional WDM-PON and the WDM-PON with the proposed X2 links for $L_{PON} = 50$ km. We clearly see that the proposed X2 links significantly improves CoMP cluster feasibility, which would mostly result in increased UE throughput by CoMP. It mainly comes from the feature that the proposed X2 links enable optical X2 signals to bypass in RN as long as two ONUs are in the same PON. For multipoint-to-point transmission, we assume TDMA is used to avoid collision with guard time of 1 μsec.

Fig. 6 compares CoMP cluster feasibilities between conventional WDM-PON and the WDM-PON with the multicasting capability for $L_{PON} = 40$ km and 50 km. It confirms that multicasting capability improve CoMP cluster feasibility, resulting from the reduced time to transmit user data to multiple target ONUs. It can be also seen that multicasting starts losing its advantage as transmission distance increases ($L_{PON} = 50$ km). As obviously seen in Fig. 5, physical X2 can be a good solution to solve this problem.

![Figure 6](image2.png)

Figure 6: CoMP cluster feasibility for conventional WDM-PON and WDM-PON with multicasting

V. CONCLUSION

We presented mobile backhaul network design based on WDM-PON technologies. WDM-PON has been considered for future mobile backhaul access networks, however it needs modification to be able to support future radio access techniques such as CoMP. We proposed two key enablers making WDM-PON more promising in mobile backhaul access networks, physical X2 links and multicasting OLT.

References