Performance Analysis of Optical Mobile Fronthaul for Cloud Radio Access Networks

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Abstract. Cloud radio access networks (C-RAN) separates baseband units (BBU) of conventional base station to a centralized pool which connects remote radio heads (RRH) through mobile fronthaul. Mobile fronthaul is a new network segment of C-RAN, it is designed to transport digital sampling data between BBU and RRH. Optical transport networks that provide large bandwidth and low latency is a promising fronthaul solution. In this paper, we discuss several optical transport networks which are candidates for mobile fronthaul, analyze their performances including the number of used wavelength, round-trip latency and wavelength utilization.

1. Introduction

The amount of mobile traffic will exceed 500 exabytes by 2020, driven by the proliferation of smart mobile devices and high-definition video application [1]. Small cell and distributed antenna are promising technologies to increase access rate of radio access networks (RANs), but required to be “light” and low power consumption. To satisfy this requirement, RANs architecture is evolving from “distribution” to “cloudification”, which means to separate the digital baseband unit (BBU) of conventional cell sites (see Figure. 1(a)) from remote radio heads (RRHs), and pool BBUs to a cloud-centric site (see Figure. 1(b)). With the benefit of the cloud RAN (C-RAN), conventional complicated and power-hungry cell sites can be simplified to RRH only, which reduces the related power consumption and site maintenance.

As the baseband processing moving to the “cloud”, a large amount of digitalized in-phase and quadrature-phase (IQ) samples generated by RRHs need to be transported to a BBU pool. The transport network between RRH and BBU pool is so called mobile fronthaul (MFH). Different from the backhaul that connects the BBU pools and mobile evolved packet core (EPC), MFH is a new network segment that appears in the C-RAN. It bridges the RRH and BBU pool through some specific interfaces. Typical MFH interfaces include common public radio interface (CPRI), open base station architecture initiative (OBSAI), and open radio interface (ORI), which cover the areas of digitalized IQ samples transportation, frame control and management issues [2]. With the rapid growth of small cell and distributed antenna, MFH network is attracting much attention. Wavelength division multiplexing (WDM) networks that come naturally with large bandwidth, low latency and green, show great potential as fronthaul solution.

In this paper, we study several possible optical transport solutions for MFH, including passive and active WDM networks. Network performances such as the number of used wavelength, round-trip latency and wavelength utilization ratio are compared and analyzed among different solutions.
2. Mobile Fronthaul Requirements for C-RAN

Firstly, C-RAN architecture brings a huge overhead to fronthaul link. The bit rate has reached the gigabits per second level and presents a multi-rate property according to different cell site technologies and data compression method.

In addition, wireless traffic is time-dependent that require different bandwidth during different time periods. Therefore, MFH should be designed to not only support high-bandwidth capacity, but also support flexible bandwidth allocation. Secondly, since the digitalized IQ data over CPRI link is at the level of physical radio signal, the MFH needs to support strict time delay for immediate signal processing. In addition, advanced C-RAN applications such as coordinated multipoint (CoMP) and virtual BBU migration are time-sensitive, low latency should be guaranteed for these services. The acceptable level of delay for a round-trip is under ~500μs, including the fiber propagation delay and equipment delay [2, 3]. Thirdly, MFH should be able to multiplex CPRI links in either electrical or optical domain, and send them to an available BBU pool. How to coordinate fronthaul resource with radio and BBU resources in an efficient way is a big challenge to mobile operator. In our previous work [4], we proposed a converged optical and wireless network architecture by using software-defined networking (SDN) technology to orchestrate heterogeneous resources in the C-RAN for a resource optimization goal.

Figure 1 Distributed radio access networks (D-RAN); (b) Cloud based radio access networks (C-RAN)

3. Optical Transport Solutions for Fronthaul Network

WDM networks that come naturally with large bandwidth, low latency and green, show great potential to build MFH networks, and they can be classified in active and passive WDM solutions. As active one, the CPRI signal is encapsulated for example by means of OTN frame or Ethernet frame, and then multiplexed to a WDM wavelength. In this case, optical/electrical/optical (O/E/O) conversions and power supply are required at intermediate nodes. Passive solution is based on the passive multiplexing and de-multiplexing, such as optical splitter (OS) and optical multiplexer (OMUX). No O/E/O conversions and power supply are needed at intermediate nodes in a passive case. For the MFH network topology, point-to-point, tree, and ring are main candidates while taking into account RAN implementation cost. Five possible optical fronthaul solutions are discussed and compared as follows.

Table 1 Optical transport solutions for comparison.

|                | Fiber required | Latency | Wavelength utilization | Reliability |
|----------------|----------------|---------|------------------------|-------------|
| Dark fiber     | ***            | *       | *                      | *           |
| WDM-PON        | **             | *       | *                      | **          |
| WDM-Ring       | *              | *       | *                      | ***         |
| TWDM-PON       | **             | ***     | **                     | *           |
| TWDM-Ring      | *              | ***     | ***                    | ***         |

Dark fiber is a direct connected fiber-pair between BBU and RRH (see Figure. 2(a)). A RRH has its exclusive fiber link to a BBU pool. Optical transponder at both sides performs E/O or O/E conversion to modulate/de-modulate a CPRI signal onto an optical carrier. Deployment over dark fiber is a straightforward option, and the latency is related to light-propagation delay only. However, it requires more fiber links, and the network reliability and flexibility are rather weak. WDM-PON is a passive
A tunable filter (TF) will decouple the WDM signals at the ONU site. With the benefit of wavelength multiplexing, WDM-PON saves more fiber links than dark fiber. The latency of WDM-PON depends on propagation. WDM-Ring is similar to WDM-PON (see Figure. 2(c)), but the wavelength selecting function is moved to the intermediate nodes through an optical add-and-drop module (OADM). Compared to WDM-PON, WDM-Ring improves network flexibility and reliability, and further reduces the number of required fibers. However, both WDM-PON and WDM-Ring have low wavelength utilization ratio when mobile traffic rate is far below a wavelength’s capacity. To cope with this problem, TWDM technology combines WDM and TDM to not only support high-bandwidth provision but also fine-bandwidth allocation. TWDM-PON solution is shown in Figure. 2(d). CPRI signals are multiplexed in a TDM manner by an electrical multiplexer (EMUX) first, and then multiplexed to a wavelength channel. Therefore, a wavelength contains different RRHs’ information, and a TWDM slot which belongs to a given RRH can be extracted at the local ONU site.

It improves wavelength efficiency, but the cost and energy consumption increase because of electrical processing. Besides, dynamic bandwidth reservation for upstream will cause a delay in the TWDM-PON solution. TWDM-Ring is an active WDM solution (see Figure. 2(e)), electrical add-and-drop modules (EADMs) and OADMs are placed at intermediate nodes. Wavelength efficiency is the best among the all, but a large number of O/E/O conversions will increase the cost and energy consumption as well as latency. A qualitative comparison of different MFH solutions are shown in Table I. In the following section, we will introduce some quantitative comparisons from the simulation results.

4. Simulation Results and Analysis

Figure 3 shows the simulation scenario, the vertexes of the regular hexadecagon represent a BBU pool and 15 RRHs. The edge length of the regular hexadecagon is 2.5 kilometers. The blue lines represent the links of ring topology, while the red lines are for PON topology. Table II shows the network parameters in the simulation. The capacity of a wavelength is 10 Gbps. A CPRI basic frame contains 128 bits, and 256 basic frames are to form a CPRI hyper frame. We consider several factors that cause the fronthaul latency. TDM switch latency is to switch TDM signals in a fabric, which is considered in TWDM solutions [3]. Transmission latency is the time duration to transmit a CPRI hyper frame [3]. O-
E-O conversion and FEC coding/decoding occurs at each termination of optical signals [4]. For the upstream of TWDM-PON, dynamic bandwidth allocation (DBA) will cause additional latency [5]. Passive WDM filter and optical splitter introduce no additional delay or a relative small value (~ns), which are ignored in the simulation. We consider two mobile traffic distributions, Nominal and Zipf with the average rate is 2Gbps and ratio is 0.5. Simulation results are shown in Figure 4-6, each data point in the figures is average over 105 experiments.

Figure 3 Simulation topology

Figure 4 Number of used wavelength vs. total traffic rate.

Figure 4(a) and Figure 4(b) show the number of used wavelength for different MFH solutions. TWDM-PON uses the lowest number of wavelength among the all, because of TDM manner. TWDM-Ring can also multiplex CPRI signals in the time domain, but the wavelengths are added and dropped at intermediate nodes, which causes the wavelength fragment. Wavelength fragment can lead some wavelengths to be not available for some links. TWDM-PON has no wavelength fragment, because all the wavelengths are duplicated and sent to every single ONU.

Figure 5(a) and Figure 5(b) show the round-trip latency. Dark fiber achieves the lowest latency performance, because the fiber is directly connected between BBU and RRH. The latencies of dark fiber as well as WDM-PON and WDM-Ring are caused by light-propagation delay only, and the values are related to the distance between BBU and RRH. TWDM-PON performs higher latency than WDM-PON, because the upstream bandwidth reservation which causes approximate 40μs delay [5]. TWDM-Ring shows the highest latency at low traffic rate because a large number of O/E/O conversions (main
latency contributor) occur at intermediate nodes. As traffic rate increases, the curve goes down close to WDM-Ring, because each RRH is assigned to a wavelength to carry CPRI signals.

![Average round-trip latency vs. total traffic rate](image)

![Wavelength utilization vs. total traffic rate](image)

**Figure 5** Average round-trip latency vs. total traffic rate

**Figure 6** Wavelength utilization vs. total traffic rate

**Table 2** Network Parameters in Numerical Simulation

| Parameters                                      | Values     |
|------------------------------------------------|------------|
| Bandwidth of Wavelength                        | 10 Gbps    |
| CPRI basic frame                               | 128 bits   |
| TDM switch fabric                              | ~5.2 µs    |
| Transmission time                              | ~4 µs      |
| Propagation time                               | 5 µs/km    |
| Optical-Electrical-Optical conversion          | ~15 µs     |
| Latency [2, 3, 5]                               |            |
| FEC coding/decoding                            | ~5 µs      |
| DBA for PON                                     | ~40 µs     |

Figure 6(a) and Figure 6(b) reflect the wavelength utilization efficiency. TWDM-Ring outperforms TWDM-PON. This is because a TWDM slot is duplicated and sent to every single ONU, which leads to the waste of wavelength resource in some links. For example, link (3, 2) of the PON topology contains all the wavelength and time information, but only one TWDM slot is for RRH2.

5. Summary

We discussed various promising optical MFH solutions, and evaluated their performances standing on the network point of view. Network performances, such as the number of used wavelength, round-trip latency and wavelength utilization ratio, were compared and analysis through simulation. From
simulation results, we find that TWDM technology can improve the resource efficiency, but introduce higher round-trip latency.

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7. References
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