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Mobile Backhaul Architecture for Low-Latency Point-To-Multipoint System

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Abstract – In this paper, passive optical network (PON) based mobile backhaul architecture enabling the ultra-low communication latency among adjacent BSs is introduced, which can be used to support fast handover for end users with high mobility.

Keywords: Multipoint, CO, PON, OLT, etc.

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1. INTRODUCTION

PON is a point-to-multipoint system, which typically consists of an optical line terminal (OLT) at the central office (CO), optical distribution network (ODN) with passive power or wavelength splitters, and optical network units (ONUs) at subscribers' side. PON is widely used for access networks due to its simplicity, high capacity and energy efficiency [1]. It can be categorized into several subclasses according to the used multiple access techniques and the end-to-end transmission, i.e., time division multiple PON (TDM-PON), wavelength division multiple PON (WDM-PON), time and wavelength division multiple PON (TWDM-PON) [2, 3].

TDM-PON utilizes TDM access techniques. In the upstream direction (from the ONU to the OLT), each ONU burst is transmitted in an assigned time-slot and the signals sent from all ONUs are multiplexed in the time domain. In the downstream (from the OLT to the ONU), packets are broadcasted to all ONUs using one or more power splitters at remote node. Here, the remote node can be passive wavelength splitters or wavelength multiplexer/demultiplexer (e.g., array waveguide grating).

WDM-PON utilizes WDM access techniques, in which the wavelength selectivity can be done by remote node. In WDM-PON, each ONU is assigned a specific wavelength, thus this architecture can provide higher bandwidth per user and ONUs can work at the individual data rate rather than the aggregated one.

TWDM-PON is stacked by multiple PONs and has combined TDM and WDM capabilities. In such TWDM-PON, multiple wavelengths are multiplexed together to share a single feeder fiber, and each wavelength can be shared by multiple users through TDM. TWDM-PON has been regarded as the most potential candidate for next generation passive optical network stage 2 (NG-PON 2) [3].

2. PON BASED MOBILE BACKHAUL NETWORK

PON is a promising solution for mobile backhaul. The conventional PON based mobile backhaul architecture is depicted as Figure 1. Each ONU is associated with one BS and connected to the OLT. The OLT distributes/aggregates the traffic from/to the mobile core network.

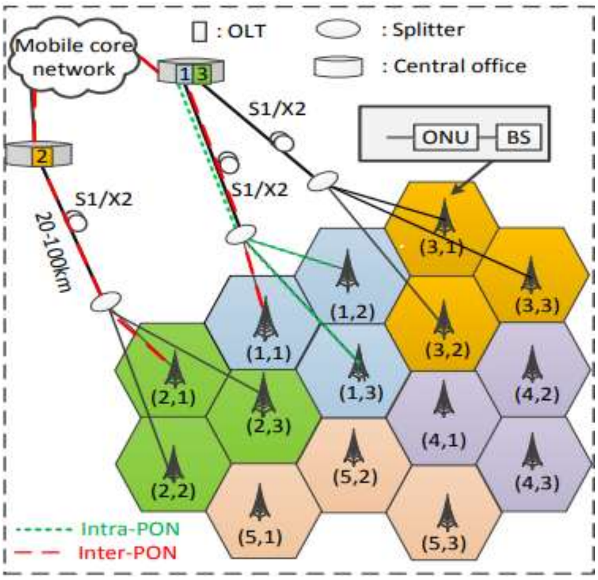


Figure 1: High level view of the conventional PON based mobile backhaul architecture

Two interfaces S1 and X2 are defined at BS in mobile backhaul networks. S1 is used for the communications between the BS and the central aggregation switch in core networks. X2 is a logical interface for direct inter-BS information exchanges, which supports functions such as Co MP and handover [4]. In PON based mobile backhaul networks, both S1 and X2 traffic are transmitted from the ONUs to the OLT. If the BSs are associated with ONUs within the same PON, the X2 traffic can be handled at the CO where the OLT is located (see green dotted line in Fig.1) with one-hop forwarding. In such a case, the latency may remain low. However, the fiber section between the splitter and the OLT can be up to 100 km in a long-reach PON, thus the latency can be significantly increased. As a result, the stringent end-to-end latency requirement may not be satisfied. In addition, when the BSs are associated with ONUs that belong to different PONs, the X2 traffic has to pass several active nodes and segments, especially in the case the OLT are located in different Cos.

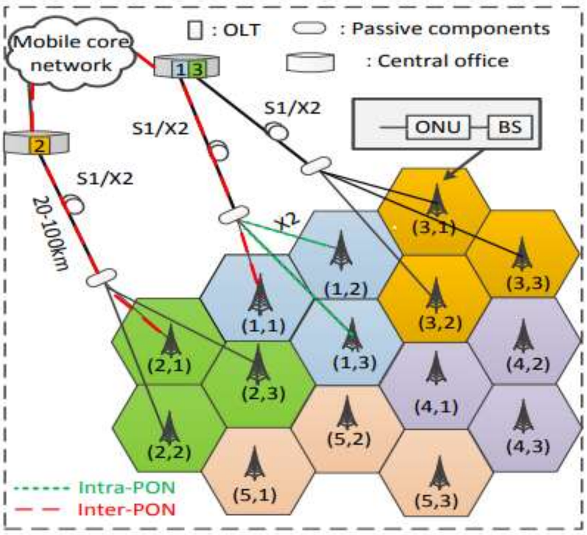


Figure 2: High-level view of PON based backhaul architecture with modified remote nodes

In order to solve the above issue on latency, PON based mobile backhaul networks have been studied. The key idea is to enhance the connectivity between neighboring BSs for supporting inter-BS communications. As shown in Figure 2, for BSs that are associated to ONUs within the same PON, the X2 traffic can be directly transmitted to the OLT through the passive components (see green dotted line) without being handled by the OLT or the active nodes located farther. Here, the passive components can be a splitter-box containing several passive combiners and diplexers or a multi-port in and multi-port out arrayed.

Waveguide grating (AWG) [5-8]. However, if the BSs are associated to ONUs that belong to different PONs, the X2 traffic will have to be first sent to the OLT and even farther to the mobile core networks for processing. Therefore, the existing solutions cannot support the low-latency inter-BS communication, especially for the case where the OLT are located in different COs. On the other hand, enhancing the connectivity in PON may lead to increased risk of signal conflicts, which brings challenges for the control plane design. Nevertheless, the existing media access control (MAC) protocols for PON (e.g., multipoint control protocol (MPCP) [7, 8]), are far from sufficient to support such a control-plane problem, on which there are very few studies focusing.

In this paper, propose a novel PON based mobile backhaul architecture that realizes the enhanced interconnections among neighboring remote nodes, as an extension of the existing PON based backhaul architectures. Figure 3 shows the high-level view of the proposed architecture, in which the connectivity among BSs associated to the same PON (named intra-PON) and also the ones associated to the neighboring PONs (named inter PON) can be enhanced.

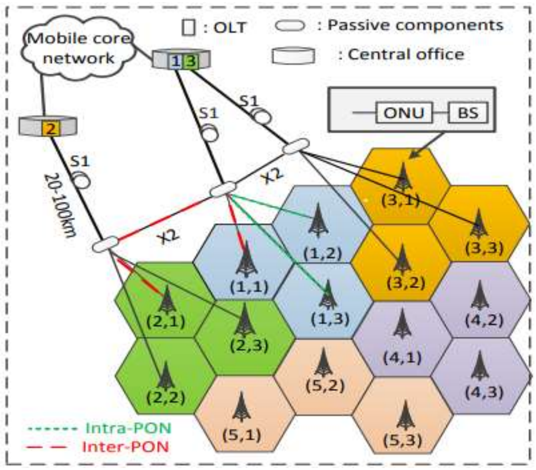


Figure 3:High-level view of the proposed PON based architecture with interconnections among neighbouring remote nodes.

3. PHYSICAL LAYER ARCHITECTURE DESIGN

Figure 4 presents the detailed physical-layer design of the proposed PON based mobile backhaul architecture. As shown in the figure, PON1 is connected with other (M-1) PONs. Here, PON1 is referred to as the serving PON, and its connected PONs are target PONs. A serving PON and its target PONs form a virtual communication group (VCG). Note, any PON can become a serving PON and form its own VCG. In a VCG, each PON is connected with the OLT and N ONUs through a (M+2)×N splitter. At the side towards the OLT, (M-1) ports of each splitter are reserved to connect its adjacent splitters for inter-PON communications, while another two ports are connected to each other by an isolator, enabling the upstream data to be broadcasted to ONUs within the PON, thereby inter-PON and intra-PON communication can be directly achieved without through any active nodes (see green dotted line and red dashed line in Fig. 3.4). When the number of the supported ONUs in one PON is large, the power attenuation induced by the multiport splitters may become unendurable. In this regard, optical amplifiers can be used to increase the link power budget by deploying between the splitter and the isolator or between the neighboring splitters.

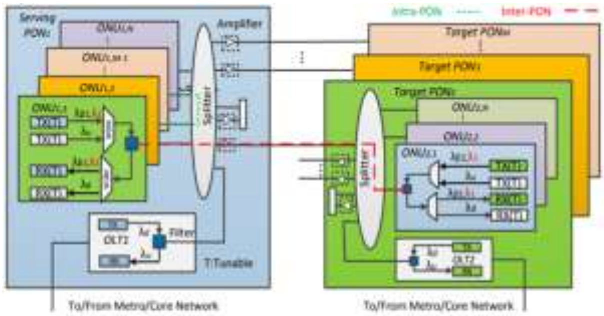


Figure 4: PON based mobile backhaul network architecture for interconnection among adjacent remote node

As shown in Figure 4, each ONU is equipped with two tunable transceivers (TRx). One is used for the transmission of S1 traffic between the ONU and the associated OLT, while the other one is responsible for the inter-BS communications in both intra-PON and interPON cases (i.e., X2 traffic).

In addition, in order to avoid signal conflicts and to realize fast communications for inter-BSs, we designed a wavelength assignment scheme tailored for the proposed architecture. A pair of {λ_u, λ_d} is used to for the upstream and downstream communication between the OLT and ONUs in one PON, respectively. In a VCG, each PON is assigned with one unique wavelength ($\lambda_{\beta i}$) to achieve inter-BS communication within PON_i (i=1, 2…M). While M-1 ONUs in PON_i (i.e., $ONU_{i,h}$, h=1,2,3…M-1) are specified as relay ONU, each of which is assigned with another wavelength belonging to the wavelength subset Pi for the inter-BS communications with its neighboring ONUs associated to PON_k (k=1, 2…M, k≠i) in the same VCG.

4. COMMUNICATION PROTOCOL

Consider a VCG consisting of three PONs, each of which has two ONUs for simplicity, as shown in Figure 5. In such VCG, PON1 is the serving PON, and PON2 and PON3 are the target PONs. The data for inter-BS communications are transmitted periodically within a fixed cycle time (Tc), which can be divided into two periods (Tc1 and Tc2). Tc1 is used for the intra-PON communications, while Tc2 is used for the inter-PON communications. At the beginning of Tc , each ONU in one PON is assigned with a specified time slot to report the size of data to be sent by broadcasting a request message (see the squares in the beginning of Tc1 in Figure 5). Specifically, the ONUs needs to notify other ONUs of their absence, even if they have no data to be transmitted. After the request messages are received, the polling tables related to all ONUs will be updated, which contains the information, such as the time stamp, the source and destination addresses.

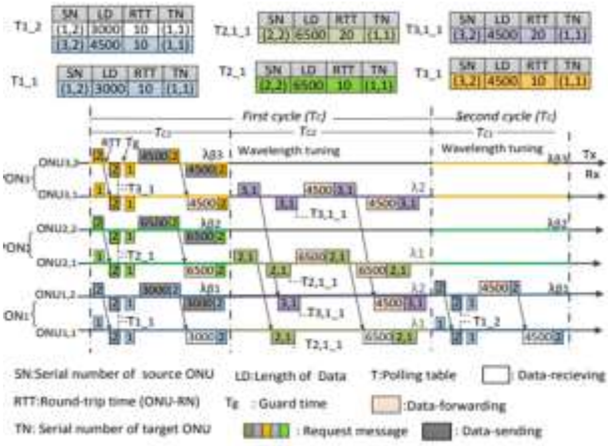


Figure 5: Medium access control protocol

With the information contained in the polling table, each ONU can schedule the bandwidth according to specific bandwidth allocation algorithm and calculate the starting time of each time slot for data transmission. At the end of the data transmission, a new request containing the information about the needed bandwidth in the next round of T_{c1} is sent. Once the current period T_{c1} is finished, all relay ONUs tune the wavelength for intra PON communication to the wavelengths for inter-PON communications. Similarly, the relay ONUs need to report their data sizes and update the polling tables in T_{c2}. If the destination is the relay ONU in the other PON, the data are received in T_{c2}. Otherwise; the data need to be forwarded in Tc1 of the next cycle to its final destination, as shown in Figure 5.

5. BANDWIDTH ALLOCATION ALGORITHM

In the proposed DBA algorithm, each ONU can request a transmission time slots (R_e) as much as it needs while not exceeding the maximum available transmission time lots (G_{max}), which means the granted transmission time slot is

$$G_e = Min\ (G_{max}, R_e) \quad (1)$$

In order to avoid that the channel is monopolized by one ONU, Gmax should satisfy the following constraint

$$G_{max} <= (T_{cl} - T_{req})/N - T_g \quad (2)$$

where, T_{req} is the time for transmitting request messages by N ONUs in one PON, T_g represents the guard time between two consecutive time slots for different ONUs. To avoid collision at splitters, the starting time of the (i+1)th time slot is carefully calculated as

$$T_s^{i+1} = T_s^i + RTT^i/2 - RTT^{i+1}/2 + T_e^i + T_g \quad (3)$$

where, T_s^i, T_e^i, are the starting time and duration of i[th] time slot, and RTT^i is the round-trip time (RTT) for propagation between the source ONU and the splitter in the i^{th} time slot.

6. PERFORMANCE EVALUATION

The performance of the proposed scheme in terms of average end-to-end (E2E) packet latency and jitter is investigated by numerical simulation. E2E packet latency consists of propagation delay, processing delay for switching implemented at the OLT, and queuing delay. The average E2E latency is the average value of the E2E latencies for both interPON and intra-PON communications. Table 1 show the parameters used in the simulation.

Table 1: Simulation parameters

Parameter	Value
Number of PONs in one VCG(M)	6
Number of ONUs in one PON(N)	5
Distance between two adjacent splitters	2km
Propagation delay within the optical links	5μs/km
Guard time	1μs
Wavelength tuning time	1μs
Link rate in both upstream and downstream	10Gbps
Buffer size for each ONU	50M bytes
Processing time at active nodes	0.2ms
Distance between ONU and splitter	1km
Size of the VCG(considering that one BS may need the connectivity to around 20-30 neighbouring cells	20-30
Confidence level	95%

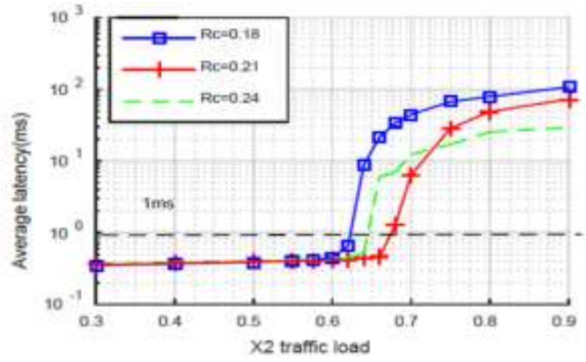
Each polling cycle can be divided into two cycles (T_{c1} and T_{c2}) for intra PON and inter-PON communications, respectively. We define the ratio of T_{c1} over T_{c2} as Rc. In one VCG, all UEs are assumed to have the same probability to communicate with each other. Therefore, the ratio of the size of the data for inter-PON communications over that for intra-PON communications (R_d) can be calculated by

$$R_d = \big(N \times (M-1)\big)/(N \times M - N - 1) \qquad (4)$$

Here, the number of wavelengths used for intra-PON communication in each PON is 1, while that for inter-PON communication is M-1. To maximize the bandwidth utilization, the amount of data that is to be sent during T_{c2} and T_{c1} have better to be proportional to the average amount of actual data generated for the inter-PON and intra-PON communications. According to this principle, the value of Rc can be calculated by

$$R_C = \frac{R_d}{(M-1)/1} = N/(N \times M - N - 1) \qquad (5)$$

In the simulation, when N = 5 and M = 6, R_c is 0.21. As shown in Figure 6, the average E2E latency can be less than 1 ms when the X2 traffic load is lower than 0.6. For the latency requirement of less than 1 ms, the performance reaches the best when Rc = 0.21, which further verifies our conclusion.



Figue 6: Average latency versus X2 traffic load for *Tc* = 0.5 ms.

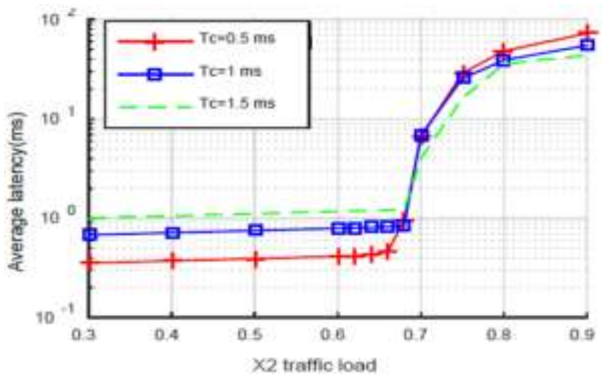


Figure 3.7: Average latency versus X2 traffic load with *Rc* = 0.21.

Further compare the performance of the proposed scheme with two benchmarks, which are based on the conventional PON based mobile backhaul networks (Figure 1). In Benchmark 1, the same transmission channel is used for X2 traffic and S1 traffic, while in Benchmark 2, X2 traffic and S1 traffic are respectively transmitted in specific transmission channels. It can be seen in Figure 8 that, compared to the two benchmarks, the proposed scheme performs the best in terms of average E2E latency. The average E2E latency for most packets is less than 0.5 ms even when considering the fluctuation of the latency, which is the lowest among three schemes.

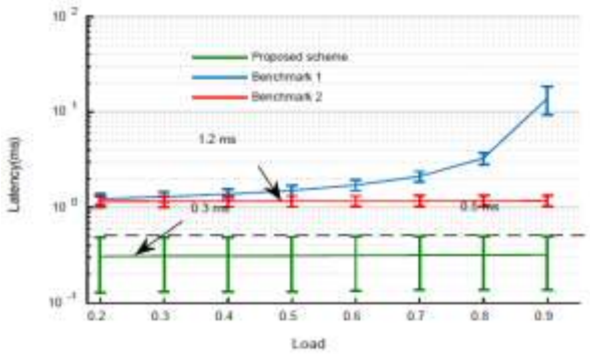


Figure 8: Latency vs. total traffic (where X2 traffic is 10% S1 traffic). *Rc*= 0.21, *Tc* =0.5 ms, *L*=20 km.

An effects of the S1 traffic load and the distance between OLT and splitters (L) on the performance of the proposed scheme are further studied. The simulation results show that the average E2E latency can maintain less than 1 ms no matter what S1 traffic load and L are.

In addition, the impact of user mobility in terms of UE speed and density on the performance of the proposed scheme is studied. UE in a given cell is assumed to move to its neighboring cell with an equal probability. And the handover requests arrival follows the Poisson process. Once a handover occurs, both control-plane traffic and user-plane traffic are exchanged through X2 interface. Here, the control-plane traffic includes Handover Request message, Handover Request Acknowledge message, Status Transfer message and Release Resource message, while user-plane traffic is referred to as the forwarded user data. The Handover frequency in one cell is related to, the density of active UEs (U), the average speed (S, km/h) of the UE and the diameter of a cell (D, km). In each handover procedure, four control messages are exchanged, the size of which can be expressed as

$$C_{x2}=4*m*U*S*D/3600(bits/s) \quad (6)$$

In the simulation, the average length of the control message (mm), is set to 120 bytes. U = ρ·p with ρ denoting the number of UE per km^2 (referred to as UE density) and p representing the probability of the UE in an active session. Similarly, user traffic that is transmitted between the source and the target ONU can be expressed as

$$U_{x2}=U*S*D*T*F/3600(bits/s) \quad (7)$$

Where T is typically 0.05s, which denotes the duration time of the handover. F represents the traffic flow per UE (bit/s), which includes multiple services (e.g., voice, web browsing, file and video download), following uniform distribution in range of [0,100] Mbit/s .

Figure 9 shows that with the latency requirement constraint of 1 ms for mobile backhaul networks, the maximum U can be up to 67000 per km^2 , when S = 40 km/h. The maximum U decreases to about 5000 per km^2 as S increases to 500 km/h. It can be seen that the proposed scheme can well support large group and high-speed mobility, with some of the typical requirement in 5G scenarios satisfied (i.e., 2000 per km2 for S500 km/h)

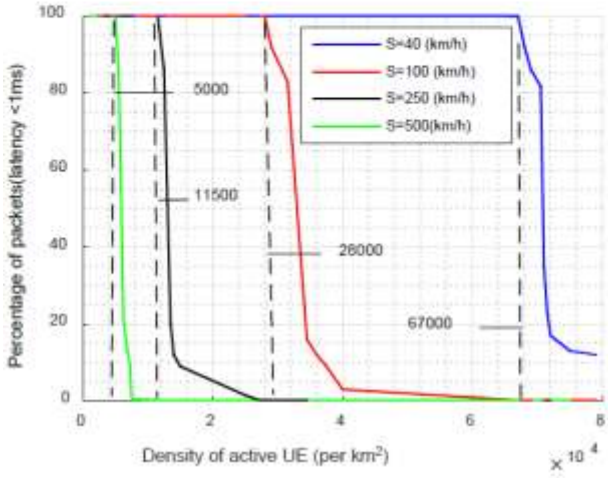


Figure 9: Percentage of packets (latency<1 ms) as a function of the density of active UE.

7. CONCLUSION

PON based mobile backhaul architecture, in which the connectivity among adjacent BSs can be enhanced by adding fibers between splitters. In addition, a tailored communication protocol and dynamic bandwidth allocation algorithm are proposed. Simulation results show that less than 1ms communication latency can be achieved in the proposed scheme. Such architecture is also compatible with the legacy TDM-PONs and can be regarded as the primary option for next generation PON state 2 (NG-PON2) technologies, i.e., TWDM-PON

On the other hand, deploying new fibers between splitters belonging to different PONs may bring a new issue of cost. Thus, how to minimize the cost induced by such fiber connections needs to be further investigated.

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