Flexible Optical Network Enabled Proactive Cross-layer Restructuring for 5G/B5G Backhaul Network with Machine Learning Engine

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Abstract: It demonstrates a flexible optical network enabled "Network Restructuring as Traffic Changes" for 5G/B5G backhaul network, which realizes proactive cross-layer network generation and mitigation-based network recovery, powered by cognitive enhancement and decision deduction.
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1. Introduction

While 5G is being commercialized, Beyond 5G systems (B5G) attracted significant interest and several projects have recently started to explore B5G systems [1]. In B5G, massive connection and multi-service (eMBB, mMTC, uRLLC, etc.) communication require massive full-mesh logical connection in 5G/B5G backhaul network (BH), and the high traffic dynamics brings great challenges on the network utilization efficiency. High traffic dynamics require that the network could be adjusted timely; otherwise, it will result in low bandwidth utilization efficiency. Note that BH network usually needs Layer-3 functions to support flexible configuration of 5G/B5G building blocks [2]. Thus, BH is comprised of IP layer and optical layer in most cases. However, standing at the IP layer, optical networks is usually considered as a stationary one, which make it difficult for IP layer to react to the traffic changes.

In this demonstration, "Network Restructuring as Traffic Changes" is implemented for 5G/B5G BH network, aiming to fully use the optical network flexibility to make the IP network restructured promptly according to IP traffic distribution, also to provide timely fast BH network recovery when a failure occurs. To achieve this, a deep IP-optical integration architecture is needed; however, when IP layer and optical layer are considered in the network operation, it is obvious that much more variables are involved in the joint optimization process, which makes the feasible solution space is too large to be searched. When facing the massive connection requirements, this issue will be more serious.

Here, we proposed intelligence defined network architecture combining ML and SDN-enabled hierarchical centralized control to overcome the above challenges. Besides using SDN technology to rebuild the IP layer and the optical layer in 5G/B5G BH network, Machine learning (ML) approached are deployed as a solution to deal the challenge with the cognitive enhancement and decision deduction [3]: **1) Cognitive enhancement:** focusing on how to make the IP layer more flexible and reliable with fully using optical layer to restructure IP network with SDN and Reinforcement learning, based on the traffic pattern prediction and network telemetry data. **2) Decision deduction:** Q-learning is used to re-configure the optical layer and mitigate the IP forwarding and routing policy to recover the faulty IP node instead of rerouting the affected traffic flows individually, avoiding the IP layer state synchronize.

2. Innovation

In this demo, ML-assisted cross-layer network restructuring covers the "whole chain", including traffic prediction, network topology restructuring, mitigation-based fast failure recovery. Which achieves "5G/B5G Transport Changes as Traffic Changes", resulting in high utilization efficiency and high reliability.

- **Proactive cross-layer network restructuring on demand and seamless:** The conventional resource scheduling assumes that the optical network is stationary, resulting overbooking and low efficiency in BH. In this demo, we reconfigure the optical network to restructuring/adjusting IP network (topology and link capacity) dynamically with RL and short-term traffic predication on demand, which will improve the utilization of both optical network and IP network. Importantly, this online network upgradation will not interrupt the existing services in BH.

- **Hybrid network fault recovery with RL based on dual-layer configuration-migration:** A physical IP node failure may lead to lots of services interruption. Then, the recovery time of conventional flow-based recovery method will increase almost linearly with the failed service flows. This demo is to recover the faulty IP node instead of the affected services individually, to achieve a quick network recovery in seconds level. Through dual-migration in IP-Optical hybrid network and reinforcement learning recovery algorithm, the fault recovery time is almost independent of the number of fault services.
- **Deep IP-optical integration with hierarchical centralized control:** Super controller (SC) can access all physical resources and the whole topology information, IP controller (IP-C) schedules traffic and optical controller (O-C) provides physical links from RRU to CN. In this scheme, SC has flexible resource scheduling capabilities and configuration capabilities, IP-optical resource will be deeply integrated.

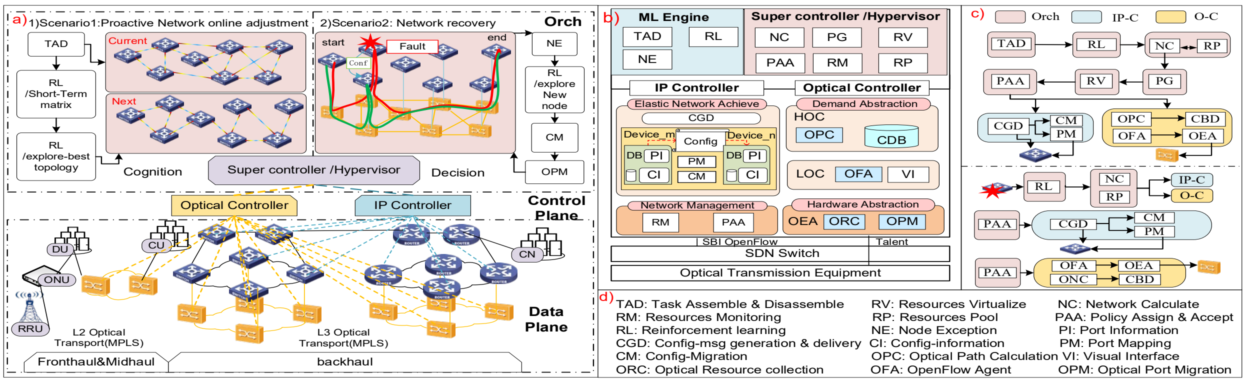

Fig.1 a) The networks architecture and two focused demonstration scenarios. b) The control plane architecture. c) The workflows for two demonstration scenarios. d) Abbreviation table

3. Demo Description and ML Procedure

Demo Description: The scheme architecture is shown in Fig. 1 a). The date plane layer is divided into fronthaul (FH) & midhaul (MH) and backhaul (BH). In BH, The IP layer scheduling network resources from CU to CN. The optical layer provides physical links from RRU to CN. Control plane is a centralized hierarchical control structure. The SC can access all physical resources, the whole topology information and manages IP-C and O-C. The elastic network module in IP-C achieve flexible cross-layer online adjustment in BH, and the management module is used for underlying resources control. The O-C is divided into three parts, the High-Optical Controller (HOC) schedules the optical resources, and the Low-Optical Controller (LOC) maps the HOC control instructions to the Optical Equipment Agent (OEA) control instructions to control the underlying OTN (OXC) for data transmission.

Two scenarios will be demonstrated as in Fig. 1. In Fig.1a), which demonstrated the procedure of network reconstructing based on cognitive enhancement and network recovery based on decision deduction after failure with RL in BH. The workflow of the two scenarios is shown in Fig. 1 c). (1) **Proactive network restructuring based on RL**. First, the ML engine TAD receives the service request, predicts the short-term traffic and calculate the optimal network topology of the lowest energy consumption with RL. Then NC, PG and RV generation strategy, the PAA sends the policy to the IP-C and O-C respectively, and the IP-C generates the configuration through the CGD to complete the reconstruction of the IP layer by port mapping and Configure-migration. The O-C completes the optical path establishment through the OFA. (2) **Network recovery based on RL**. First, the SC receives the node exception, calculates the best stand-by node through RL, and sends the instructions to the NC. The NC generate a migration policy. The IP-C uses the CGD to complete the node migration of the IP layer. The O-C completes the optical path migration through the OFA.

ML Procedure: (1) **In restructuring network,** we predict traffic using gated recurrent units (GRUs) in a neural network [4]. **a) data preparation:** the peak traffic with fixed interval is convert into time-serial data and standardizes and groups; **b) training and prediction:** After model training for a period time using sample data, import traffic to get predicted traffic; **c) Optimized network:** Given nodes location, training a neural network with the lowest energy consumption as the objective function based on short-term traffic, and getting the optimized network topology. (2) **In network recovering,** Q-learning is used to calculate the dual-migration recovery result because of the fast convergence in a dynamic network environment. **a) data preparation:** IP nodes are divided into service transmission nodes and stand-by nodes in the resource pool, each link weight is energy consumption and capacity. **b) Training and decision making:** The target function is to recover the network with the lowest energy consumption if the service traffic is lower than the capacity and the future short-term predicted topology resources are not used. When exception occurs, the optimal stand-by nodes will be found quickly.

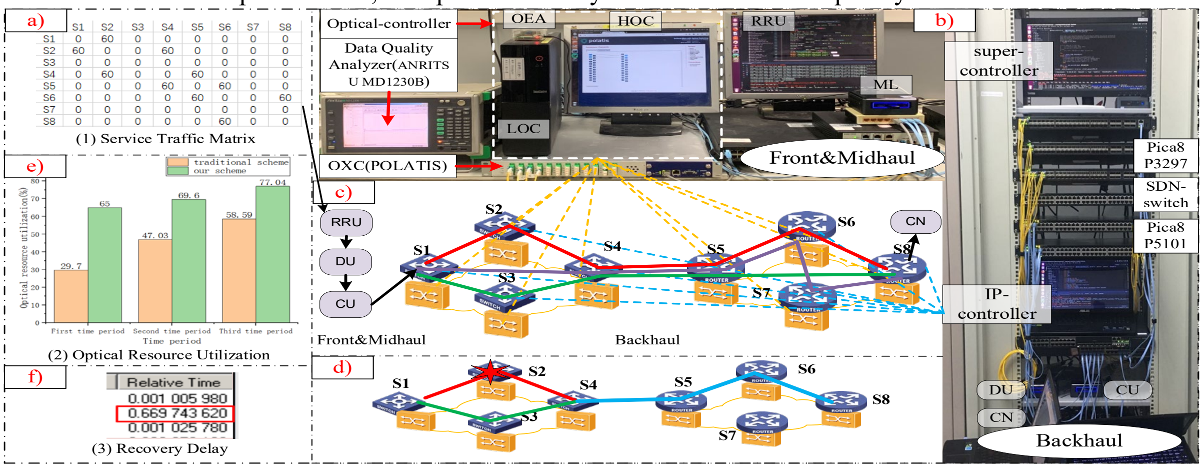

Fig.2 a) Service traffic matrix. b) The tested of proactive cross-layer restructure. c) The experimental topology of IP network restructuring. d) The experiment of network recovery. e) The comparison of the optical resource utilization between our scheme and traditional scheme. f) the delay of network failure.

4. Demo experiment result and conclusion

In order to verify the feasibility of our scheme, the experimental topology and experimental bed shown in Fig.2 b) c) d) were designed. Fig.2 a) shows service input traffic matrix from CU to CN, which is the topology generated by the initial traffic flow matrix through RL prediction and calculating. Fig.2 b) shows the proactive cross-layer restructuring testbed. We use SDN switch as the IP switching device in BH, the optical cross-connect (OXC) and All-optical SDN switch to simulate optical transport network (OTN) as the optical transmission device in FH & MH & BH. Meanwhile, controller is implemented by python script on Ryu. In addition, the delay caused by network recovery is measured using data quality analyzer. Fig.2 c) shows three networks for IP network reconstruction. The red line represents the initial network topology (Consistent from RRU to CU). The purple and green lines represent the topology of the traffic predicted by the ML engine for the next two periods. Fig.2 e) Shows the comparison of light resource utilization in BH between our scheme and the traditional solution for three time periods. And Fig.2 d) shows faulty node recovery based on dual-migration experimental topology. Fig.2 f) shows the time to failure recovery, with results below the second level. According to Fig.2 e, f), the average utilization rate of optical resources in three periods has improved from 45.1% to 70.5%. The network recovery delay is 0.669s.

We propose the cross-layer restructuring with ML scheme that fully uses the flexibility of optical layer and cognitive enhancement and decision deduction of ML to realize high utilization and reliability.

5. Relevance

In this demo, ML-assisted cross-layer network restructuring for 5G/B5G transport is proved to be effective, which covers the "whole chain", including traffic prediction, network topology rebuilding, mitigation-based fast failure recovery. The proposed novel IP-optical integration architecture and testbed fully used the flexible optical networks to achieve "5G/B5G Transport Changes as Traffic Changes", resulting in high utilization efficiency and high reliability. This demo is specifically designed for OFC audience, mainly for Operators, vendors and general academia.

6. Acknowledgments

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