Service Provisioning in WSS-based Wavelength-Convertible All-Optical Spine-Leaf Data Center Networks

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***Abstract*—We consider deploying tunable wavelength converters（TWCs）in the wavelength selective switch (WSS) based all-optical data center network with spine-leaf topology. We investigate its routing, wavelength, and time slot allocation (RWTA) optimization problem and propose two different lightpath provisioning strategies, which are WSS reconfiguration first-based (WRF) and wavelength conversion first-based (WCF) strategies. We evaluate the performance of these two strategies through simulations and find that the proposed WCF strategy can significantly reduce the overall task completion time (TCT) and the number of WSS reconfigurations.**

Keywords—data center network, all optical switching, tunable wavelength converter, WSS reconfiguration, RWTA

I. INTRODUCTION

With fast growth of Internet traffic demands, traditional data center networks (DCNs) based on electronic switches are suffering from low switching capacity, poor scalability, and high energy consumption due to the limit to Moore's Law. To tackle these issues, optical switching technology is being adopted as a key enabling technology for next generation DCNs due to its high bandwidth, low latency, and low energy consumption [1-2]. In [3], we have proposed an all-optical spine leaf (AOSL) DCN architecture, in which $N \times N$ WSSs are employed to replace all the electronic switches. This AOSL DCN is based on a typical cascading switch architecture and has no wavelength conversion capacity, thereby having to follow the wavelength continuity constraint when provisioning lightpath connections. This constraint may lead to wavelength collision even if there are sufficient free wavelengths on the fiber links of a lightpath, which causes the wastage of wavelength resources. Therefore, to avoid wavelength collision and improve wavelength utilization, it is significant to consider the wavelength conversion capability in the WSS-based AOSL DCN.

In this paper, we introduce the wavelength conversion capability to the WSS-based AOSL DCN through deploying tunable wavelength converters (TWCs) between leaf and spine WSSs, called *wavelength-convertible AOSL DCN*. To efficient utilize its wavelength resources, we investigate the routing, wavelength, and time slot allocation (RWTA) problem and develop heuristic algorithms for lightpath connection provisioning. Specifically, two strategies, i.e., the WSS reconfiguration first-based (WRF) and the wavelength conversion first-based (WCF) strategies, are proposed and investigated. Simulation results show that the proposed WCF strategy can significantly improve the performance of the wavelength-convertible AOSL DCN in terms of the overall task completion time (TCT) and the number of WSS reconfigurations.

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II. WAVELENGTH-CONVERTIBLE AOSL DATA CENTER NETWORK

Fig. 1 shows the architecture of WSS-based wavelength-convertible AOSL DCN, in which one TWC module is deployed before each input port of a spine WSS. We represent this wavelength-convertible AOSL DCN as $G(l, s, p, f, k)$, where l and s are the numbers of leaf and spine WSSs, respectively, p is the number of parallel fibers, f is the number of servers connected to each leaf WSS, and k is the number of spine WSSs that each port is deployed with a TWC module. The port counts of leaf and spine WSSs can be calculated as $p \times (s + f)$ and $p \times l$, respectively, and the total number of server nodes connected to the network is $l \times f$.

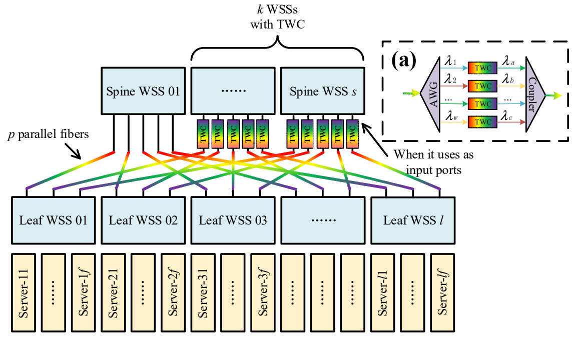

Fig. 1. A WSS-based wavelength-convertible AOSL DCN.

WSSs and TWCs bring flexibility in provisioning lightpaths on different wavelengths for the wavelength-convertible AOSL DCN, thereby avoiding wavelength contention on WSS ports and eliminating the wavelength continuity constraint on each lightpath. Specifically, once a lightpath request is blocked due to insufficient free wavelengths along its route, we can try two approaches to improve eligible wavelengths, i.e., wavelength conversion and WSS reconfiguration. In the first approach, the TWC module traversed by a lightpath is employed to convert signals from one wavelength to another, allowing the lightpath to use different wavelengths before and after the TWC module. Therefore, as long as there are free wavelengths on the fiber links, we can always establish a lightpath. In contrast, the second approach is to reconfigure the ports of the leaf and spine WSSs traversed by the lightpath to eliminate wavelength collision on these WSS ports. This approach can release more wavelength available for lightpath provisioning along the route. In addition, for better efficiency, we may jointly employ the two approaches when one approach fails to set up a lightpath. This however leads to an important problem, i.e., how to efficiently combine these two approaches to provision lightpaths.

III. Lightpath Service Provisioning in a Wavelength-Convertible AOSL DCN

We consider the RWTA problem in the context of a WSS-based wavelength-convertible AOSL DCN, for which heuristic algorithms are developed to efficiently provision lightpaths. Specifically, given a service request (s, d, T), where s, d, and T represent the source server, destination server, and the holding time of the request (in units of time slots), respectively. First, we employ a link disjoint *k-shortest* routing algorithm to find *k* candidate routes between the server pair (s, d). For each candidate route, we try to find a common free wavelength along the route with T continuous time slots. If such a wavelength is found, it will be assigned to set up the lightpath. Otherwise, we need to try the wavelength conversion and WSS reconfiguration approaches to improve wavelength availability along the route. Here, we consider two strategies, i.e., the WSS reconfiguration first-based (WRF) and the wavelength conversion first-based (WCF) strategies.

A. WSS Reconfiguration First-based (WRF) Strategy

When a lightpath request is blocked, this strategy first try to reconfigure WSSs to improve the wavelength availability along a candidate route. Specifically, it first reconfigures the port of the first leaf WSS traversed by the candidate route, and then checks the wavelength availability. If there is at least one free wavelength available in T continuous TSs along the route, the first available free wavelength is selected for lightpath establishment. Otherwise, it continues to use the TWC module to convert wavelengths in the middle of the route. If successful, we set up a new lightpath. Otherwise, we repeat this process for the remaining WSSs on the route. Its pseudocode is given as follows.

WSS Reconfiguration First-based Strategy

Input: Demand (s, d, T), r, t // r is the candidate route for lightpath provisioning between server pair (s, d) and t is the index of starting time slot that a lightpath can be set up between the server pair (s, d)

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For p ∈ P_r //P_r is the set of leaf and spine WSS ports traversed by route r
    Reconfigure the WSS port p;
    t = t + t'; //t' is the WSS reconfiguration delay
    Update the wavelength availability along the route r according to the status of each wavelength;
    ω* = θ(r, t, T) ; // θ(r, t, T) finds the first available wavelength in time slots [t, t + T − 1] on the fiber links traversed by path r.
    If ω*! = NULL, then
        Use wavelength ω* to set up a lightpath along path r in time slots [t, t + T − 1];
        Break;
    Else
        If δ(r, t, T) ==1, then //If at least one wavelength is available before and after the TWC module traversed by r in time slots [t, t + T − 1 ], δ(r, t, T) ==1; Otherwise, δ(r, t, T)==0.
            Set up a lightpath along path r in time slots [ t , t + T − 1 ] by converting the first available wavelength before the TWC module to the first available wavelength after the TWC module;
            Break;
        End If
    End If
End For
```

B. Wavelength Conversion First-based (WCF) Strategy

The WRF strategy needs to reconfigure many WSS ports, which may lead to the increase of the task completion time of all the services due to WSS reconfiguration delay. To avoid this, we consider another strategy to improve the wavelength availability for lightpath provisioning. Here, we first try wavelength conversion when a lightpath service request is blocked. Specifically, if there is no a free wavelength available along a candidate route for lightpath provisioning, we try to convert the first available wavelength before the TWC module to the first available wavelength after the TWC module on the route. If successful, we establish a lightpath. Otherwise, we try to reconfigure each WSS port traversed by the route. After a WSS port reconfigured, we then try to select a free wavelength on the route in T continuous TSs. If it is found, we then employ the wavelength to set up a lightpath. Otherwise, we repeat this process until all the WSS ports traversed by the route are reconfigured. The pseudocode of the strategy is as follows.

Wavelength Conversion First-based Strategy

Input: Demand (s, d, T), r, t

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If δ(r, t, T)==1, then
    Set up a lightpath along path r in time slots [t, t + T − 1];
Else
    For p ∈ P_r
        Reconfigure WSS port p;
        t = t + t';
        Update the wavelength availability along route r;
        ω* = θ(r, t, T);
        If ω*! = NULL, then
            Use wavelength ω* to set up a lightpath along path r in time slots[t, t + T − 1];
            Break;
        End If
    End For
End If
```

IV. SIMULATIONS AND PERFORMANCE ANALYSES

To evaluate the performance of the proposed heuristic algorithms, we consider a test network $G(3,3,1,10,3)$, where all the three spine WSSs are deployed with TWC modules before each input port. Some assumptions are made as follows. The number of servers connected to a WSS port is one and the number of tunable transceivers on each server is two. The number of available wavelengths in the DCN is nine. The holding time of each service request is randomly generated within the range of [1, 200] TSs. Here, we assume that each TWC can convert any input wavelength to any other wavelength, i.e., full wavelength conversion (FWC), and WSS is reconfigured based on the non-all-stop (NAS) [4] model, under which each port of a WSS can be independently reconfigured at any time and the services carried on the port are not interrupted. The WSS reconfiguration delay is assumed to be 10 TSs [5] and the wavelength conversion delay is not considered (according to [6]). The heuristic algorithms are implemented in JAVA.

A. Performance of Lightpath Provisioning Strategies

In this section, we first compare the performance of different lightpath provisioning strategies in terms of overall task completion time (TCT) and total number of WSS reconfigurations. Here, the overall TCT is defined as the task completion time of all the services, and the total number of WSS reconfigurations is defined as the sum of all the WSS reconfigurations. Based on $G(3,3,1,10,3)$, Fig. 2 shows the related results where the number of lightpath service requests increases from 100 to 1000. For performance comparison, we also specially evaluate a non-wavelength-conversion (NWC) strategy to provision lightpaths, which does not allow any wavelength conversion when setting up lightpaths. Legends "NWC," "WRF," and "WCF" correspond to the results of NWC, WRF, and WCF strategies, respectively. For all the strategies, we see that the numbers of overall TCT increases with an increasing number of lightpath service requests. This is because a larger number of service requests requires to assign more TSs to complete all the services. Also, comparing the three strategies, we note that WCF strategy can always reduce the overall TCT by almost 5.3% and 7.8% and the total number of WSS reconfigurations by up to 14.5% and 15.7%, compared to the NWC and WRF strategies, respectively. This is because the WCF strategy always try to avoid WSS reconfigurations, which helps reduce the number of WSS reconfigurations, thereby reducing the delay caused by reconfiguration in the overall TCT.

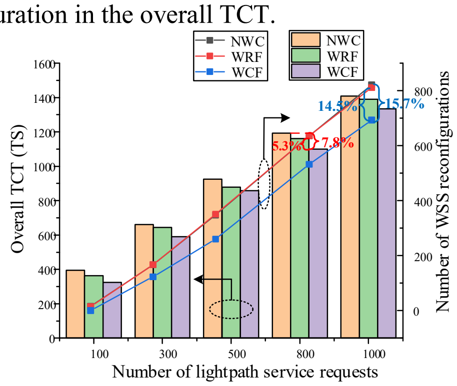

Fig. 2. Performance comparison of different provisioning strategies

B. Impact of Number of Spine WSSs Deployed with TWC Modules

We also evaluate how the number of TWC modules deployed can impact the overall TCT performance of the wavelength-convertible AOSL DCN. Fig. 3 shows the results of $G(3,3,1,10,1)$, $G(3,3,1,10,2)$, and $G(3,3,1,10,3)$, where the number of spine WSSs deployed with TWC modules before each input port increases from 1 to 3. Legends "WCF_1," "WCF_2," and "WCF_3" represent the results of one spine WSS deployed with TWC modules, two spine WSSs deployed with TWC modules, and three spine WSSs deployed with TWC modules, respectively. We note that, as the number of spine WSSs deployed with TWC modules increases, both the overall TCT and the total number of WSS reconfigurations reduces. This is because more TWC modules allows greater flexibility on lightpath provisioning, which can help improve wavelength utilization and reduce the number of WSS reconfigurations. In addition, we observe that the case with only one spine WSS deployed with TWC modules can always achieve a performance similar to the case of deploying TWC modules for all spine WSSs in terms of overall TCT and the total number of WSS reconfigurations. This observation is useful for designing a cost-effective WSS-based wavelength-convertible AOSL DCN, i.e., it is not necessary to deploy TWC modules before the input ports of each spine WSSs to achieve a wavelength utilization close to a full-wavelength-convertible AOSL DCN.

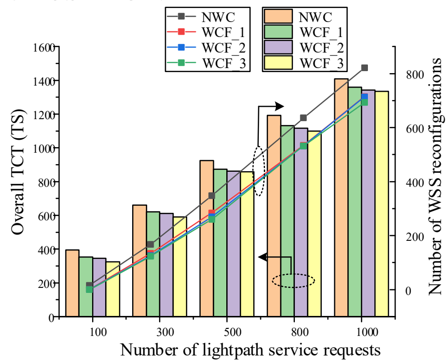

Fig. 3. Impact of number of spine WSSs deployed with TWC modules

V. CONCLUSION

We considered a WSS-based wavelength-convertible all-optical spine-leaf DCN and investigated its corresponding RWTA problem. Two different strategies, including the WSS reconfiguration first-based (WRF) and the wavelength conversion first-based (WCF) strategies, are developed to efficiently set up lightpaths. Simulation results show that the WCF strategy is efficient to significantly reduce the total TCT and the total number of WSS reconfigurations compared with the WRF strategy.

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