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Contentionless transmission in buffer-less slotted optical packet switched networks

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ABSTRACT

Contention of optical packets in optical packet switched (OPS) networks is a major problem, and it is even more critical in buffer-less OPS networks. In this paper, an innovative contention avoidance technique is proposed which uses combination of special traffic shaping at ingress switches and special time slot reservation technique through the path of traffic flows in core network. This novel protocol is called contentionless transmission OPS (CLTOPS) suitable for buffer-less slotted OPS networks. Performance evaluations show that the CLTOPS can outperform the original slotted-OPS architecture in terms of packet loss rate (PLR) performance, with or without using wavelength conversion. It is shown that there is a trade-off between the amount of improvement in PLR and additional delay applied to the users' packets at the ingress switches buffers. However, appropriate parameters can be selected to make the additional delay tolerable for users' applications.

1. Introduction

Internet is expanding exponentially in terms of both the number of users and volume of user application's traffic demands, and therefore, high-speed and high-throughput backbone networks are necessary to support these demands. One of the most promising techniques for high-speed backbone networks is all-Optical Packet Switched (OPS) networks. OPS utilizes high bandwidth of Dense Wavelength Division Multiplexing (DWDM) and it can potentially present a good channel utilization due to multiplexing of many optical packets with different destinations as long as channels can be efficiently filled without excessive loss rate. This makes OPS suitable for IP traffic [1,2]. We use slotted OPS due to its optical packet alignment and synchronization at core switches needed for CLTOPS [3].

The most important issue in OPS is contention of optical packets in core switches that cause packet loss in the network. Contention among optical packets arises when there is more than one optical packet that wants to exit a core switch through the same output fiber on the same wavelength and at the same time [4,5]. When contention occurs in a core switch, only one of the contending optical packets can be sent on desired output fiber and wavelength, and the others are dropped unless contention resolution schemes are deployed.

Contention resolution is performed in three domains: (1) time domain by buffering contending optical packets in fiber delay line (FDL); (2) wavelength domain by converting contending optical packets wavelengths to unused wavelengths at desired output fibers; and (3) space domain by using deflection routing which sends deflected optical packets through alternate routes [4,6]. Combining two or more domains can provide better performance results [3].

Buffering of optical packets in an OPS core switch is performed by sending them through some fiber (called FDL) in which both ends of the fiber are connected to the core switch and the optical packets will circulate and return back to the switch after experiencing an amount of delay equal to propagation time in the fiber. This technique requires bulky FDLs with many limitations such as being able only to access packets when they circulate the entire FDL, extra impairments and attenuations experienced by optical packets, and out of order arrival of optical packets at egress switches. Thus some researchers are interested in the OPS that do not use FDLs for contention resolution (called buffer-less OPS) [4,7–9].

Contention resolution with wavelength conversion is suitable for OPS because of imposing no additional delay, jitter and packet reordering. Tunable Wavelength Converters (TWCs) are very expensive devices, and therefore, OPS architectures prefer to use shared TWCs such as shared-per-node (SPN) architecture to decrease the number of wavelength converters (WCs) [10]. It is hard to make full range WCs (FRWC) with a reasonable price as

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the number of wavelengths increases [11]. This is why OPS should use limited range WCs (LRWC) which convert an input wavelength to the set of adjacent wavelengths in which the set is determined by conversion degree (d). In LRWC, if wavelengths are in range {1,2,...,w} and input wavelength is λ_i, the output wavelength can be selected to any of min(1, $i - d$) to max($i + d$, w) wavelengths [6,12].

Contention resolution using deflection routing is not so common in OPS because it heavily depends on the degree of connections between core switches. It may cause out of ordering of optical packets, optical packet looping around the network, and network congestion at high traffic loads [5,13].

Hardware-based and software based contention avoidance techniques are used to reduce packet loss rate (PLR) in core switches. Hardware-based schemes reduce PLR by increasing network resources while traffic load remains the same (such as using multi-fiber links and additional wavelengths). Software-based schemes (such as aggregation of IP packets at ingress switches; traffic smoothing and shaping at the network edge; traffic pacing at hosts and edges [14]; and load balancing) decrease burstiness by regulating transmitted traffic to the network [4,6,14–18].

PLR of general OPS mesh networks with buffer-less core switches that use no wavelength conversion is high at medium to high traffic loads [19]. Even the use of limited number of LRWCs or even FRWCs cannot reduce PLR at high network loads to acceptable ranges [11,18,19]. That is why retransmission in OPS network is employed to reduce the PLR of IP packets to an acceptable range [20]. We do not implement retransmission by OPS network in our work and leave loss handling to other network layers.

1.1. Related work

The work in [21] uses traffic smoothing in edge switches by rate prediction and renegotiation at regular intervals in slotted OPS. It shapes traffic by sending each stream with equally spaced optical packets with fixed bit rates for a short period. Here, edge switches acquire knowledge of scheduling and routing information of relevant paths through the network during renegotiation intervals, and try to shift dispatched optical packet streams to free evenly spaced time-slots in the path. Contention may arise for scheduled streams because of imperfection in knowledge and timing of edge switches. Core switches use FDLs to shift contending streams. Those streams buffered in FDLs become unevenly spaced after passing through multiple core switches. The work in [22] addresses these issues by decomposing one smoothed flow into multiple equally spaced sub-flows with different rates. However, this technique also uses FDLs in core switches, but each sub-flow packets are buffered in a way that relative positions between low-rate sub-flows and high-rate sub-flows of the same flow almost remains the same, and the traffic remains smoothed after passing multiple core switches.

Fractional lambda switching (FλS) is another dynamic all-optical switching technique which transmits and dynamically switches fractions of each wavelength called time frames (TFs). However, unlike OPS, TFs are switched based on reservation tables in each core switch. TFs are identified based on their arrival times at each switch. Thus in order to identify arriving TFs, FλS requires clock of all switches to be synchronized with high accuracy using Common Time Reference (CTR) such as GPS. FλS is a circuit based switching suitable for circuit based application traffic like streaming and voice over IP (VOIP). To establish a new connection between an ingress and an egress switch, the ingress switch sends the availability vector of its output link to the next switching node in the path. Each switching node shifts the arriving availability vector with integer number of TFs of the connection link delay and applies the AND logical operation with its output port availability vector and then sends the resulting vector to the next switch in the path. When the vector reaches the egress switch, the egress switch picks required number of remaining available TFs for the new connection and informs the ingress switch with the selected TFs. IP packets also can be sent through unused parts of existing connections [23–25]. This switching technique requires call establishment that is not suitable for bursty IP traffic. FλS has almost zero PLR which motivate us to utilize its idea in slotted OPS for transmitting bursty IP traffic with lower PLR.

1.2. Objective and contribution

Our objective is to use slot reservation technique through the paths of the core network for IP traffic in a slotted-OPS network. This requires ingress buffering to smooth IP traffic while controlling buffering delay of IP packets.

Our contribution is to propose a new technique called contentionless transmission in buffer-less slotted OPS networks (CLTOPS) which uses special traffic smoothing and buffering technique in ingress switches to make regular streams for bursty IP traffic and control the maximum buffering delay by sending aggregated packets waiting for a long time as unreserved optical packets. We also use slot reservation to assure no contention and dropping of reserved optical packets using an innovative signaling method and special reservation method relying on natural characteristics of the slotted OPS which eliminates the need for CTR and clock (time reference) synchronization among the network switches. CLTOPS has better performance and lower PLR without using any additional hardware while controlling buffering delay.

See Appendix A for a list of general symbols and notations that will be used in this paper.

2. Network model, definitions, and assumptions

Fig. 1 shows our OPS node architecture data plane. The network model is an all-optical slotted packet-switched network with diameter D, $n_e + 1$ edge switches (with electronic buffers), and $n_c + 1$ all-optical wavelength-selective cross-connect switches (called core switches from now on). Note that D equals to the maximum number of hops among existing routes in the optical network under study. There is no restriction on the relation between n_e and n_c where each core switch may be connected to zero, one, or more edge switches. Each core switch uses N_{WC} shared-per-node (SPN) WCs for contention resolution. No optical buffer is used for contention resolution in a core switch. Clearly, there are n_e egress (destination) switches seen by an ingress (transmitter) switch.

Each fiber in the network carries W data wavelengths (each with rate B bits/s) and one additional wavelength for control purposes (i.e., an out-band signaling). Since there are W wavelengths in the network, an $n \times n$ core switch has W strictly non-blocking switch fabrics inside where the size of each switch fabric is $n \times n$.

As stated, the network follows slotted-OPS operation. Each time-slot duration is S_T which includes a small time-gap (called slot-offset) of duration S_G and an optical packet of duration S_P. The gap includes guard time, processing time at the core switch, and switching time. There is only one service class and all client packets are treated as best effort class in the optical network. Still, the network model can be modified to support QoS for IP packets [26]. That is, by prioritization of arriving IP packets at ingress switches, high priority IP packets are mostly transmitted in high priority optical packets (i.e., reserved optical packets in CLTOPS) which reduces their PLR.

Each ingress switch has n_e electronic buffers called aggregation buffers where each one holds arriving IP packets with the same