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Architecture, Control, and Management of Optical Switching Networks

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Abstract: We present dynamic circuit switching (DCS) as a new paradigm for telecom backbone networks. DCS is well suited for optical networks and can support emerging services such as bandwidth-on-demand more efficiently than other switching technologies.

Keywords: optical network, dynamic circuit switching, bandwidth on demand, packet aggregation.

1. Introduction

With the emergence of bandwidth-hungry applications, our networks – particularly long-haul, telecom, backbone mesh networks – require high capacity and novel switching methods. Optical transmission can provide huge bandwidth. However, the gap between optical and electronic bandwidth is several orders of magnitude, so we need novel switching technologies and network architectures that can effectively match the needs of (electronic) bandwidth-hungry data applications with optical networking technologies.

Circuit switching (as in traditional telephony systems) and packet switching (as in the Internet) are well-established electronic switching technologies. Their optical counterparts, and variations, are being studied such as Optical Circuit Switching (OCS), Optical Packet Switching (OPS), and Optical Burst Switching (OBS). OCS-based network architectures are also operational today.

Note, however, that end-users and various applications generate "bursty traffic," which the network should handle efficiently. OPS is the all-optical equivalent of electronic packet switching, so in theory it should handle bursty traffic well. But OPS technologies are in their infancy, because high-speed buffering is challenging in optics. An end-to-end OCS path can be set up in a few tens of milliseconds, and it can provide deterministic bandwidth. OBS provides a balance between OPS and OCS: an out-of-band control message is sent along the route (to configure an all-optical circuit), just before the data burst (possibly consisting of several packets) is sent in the optical domain. Buffering in OBS is moved from the optical core (as for OPS) to the edges of the network. Although OCS is quite practical, it can benefit from more dynamism to handle bursty packet traffic.

Hence, we present a new switching architecture, called Dynamic Circuit Switching (DCS). Its optical implementation is called Dynamic Optical Circuit Switching (DOCS), whose architecture has been proposed and analyzed as the switching paradigm for the future Internet [1-3].

DCS can efficiently provide huge switching capacity to the edge packet applications. Therefore, it is a potential solution for transporting packets over high-bandwidth circuits which are established dynamically over our telecom network backbone. Packet traffic generated by users is aggregated at the network edges (shown as access network in Fig. 1), and dynamic high-speed bandwidth pipes are established through the network core, between the end-nodes (shown as boundary routers in Fig. 1). This architecture is flexible, i.e., it is suitable for dynamic demands, therefore it can provision bandwidth on-the-fly to emerging bandwidth-on-demand (BoD) services. Instead of signing a costly long-term contract with the Internet Service Provider (ISP), for a fixed bandwidth pipe (whose usage pattern can vary substantially with significant durations of idle times), the user can now dynamically "dial for bandwidth" on an as-needed basis. As studied in [1-2], packet switching is suitable for the bursty access networks, while the core should be circuit switched.

There are a multitude of applications that need to reserve bandwidth on demand. They could range from scientific grid computing applications to consumer applications, e.g., video-on-demand (VoD), IPTV, etc.

2. Dynamic Circuit Switching

DCS can be used as an additional technology for the backbone of the future large-scale networks. The strong points of this architecture are: compatibility with packet switching at the network edge, simplicity, cost-effectiveness and efficiency, and flexibility of allocating different bandwidth granularities, depending on the application needs.

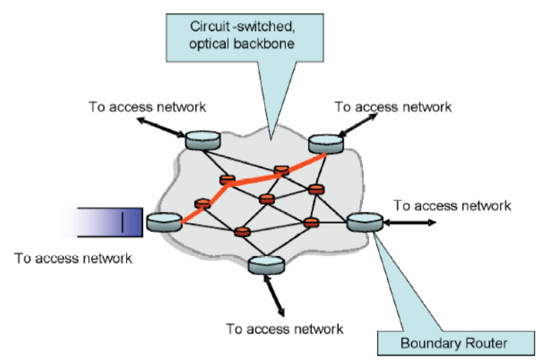

Fig. 1. Dynamic circuit switching [3].

Figure 1 (taken from [3]) shows an incarnation of DCS applied to an optical backbone (hence, it is called DOCS). It is a mesh network that consists of boundary routers at the edge of the network and a circuit-switched optical backbone. Whenever additional capacity is needed between two routers, the capacity of the optical path between the routers is dynamically increased, by establishing high-bandwidth pipes through the network core. Even though the bandwidth pipes, which are called lightpaths in optics, operate at a line rate of, say, 10 or 40 Gbps, the actual connection service pipes may be of different bandwidth granularities, depending on the application requirements. Therefore, by considering the network state to be the collection of all the lightpaths and their residual capacities, traffic-grooming approaches can be utilized to improve network utilization, i.e., a new incoming request is served either by using the residual capacities of the existing lightpaths and/or by establishing new lightpaths. The circuit must have fast setup time, as it may need to be set up and torn down frequently. This is achieved by having fast switch reconfiguration and fast signaling protocols.

Instead of using large and expensive routers in the network core as in today's Internet, the DCS architecture employs small and cheap dynamic circuit switches (which are well suited to optics as they require no per-packet processing or buffering). Circuit switches are simple. They require about 90% less hardware than an equivalent packet switch, and they have much higher switching capacity and cost about four times less than an equivalent packet switch. As phrased in [4], the best way to build a circuit switch is *"Start with a packet switch and throw most of it away"* [4]. Circuit switches perform well. They have very good service guarantees: guaranteed bandwidth and no queuing delay, which implies predictable packet delays. They are reliable and have fast restoration time (less than 50 ms). Dynamic optical circuit switches can be fabricated efficiently by using Photonic Integrated Circuits [3].

3. Applying DCS to a Deadline-Driven BoD Service

An important aspect in designing a DCS network is to consider the types of applications and services that may exist in these networks. Example applications include real-time applications, such as a large file download, with a maximum-transfer-time requirement, which a person can tolerate (say 5 sec). The file could be transferred in a much shorter time (of say 200 msec) if it is offered more bandwidth, but this may not make too much difference for the user. Also, there are flexible applications that require high bandwidth, but not instantaneously. Database/website backup is an example: a database backup could occur at any time during the time window 1 am – 5 am, with a 15-minute holding time. Both the file-transfer and website backup are characterized by a time when the data transfer must finish (a deadline).

Scheduling of dynamic deadline-driven requests (DDRs) for bandwidth-on-demand (BoD) service in a dynamic circuit-switched network is studied in [5]. Requests between two end-nodes can be scheduled at any time during a time window, as long as they meet their deadline. The network operator decides whether to accept or reject the request based on the current network state at the arrival time of the request, based on the request's holding time, H, and its deadline, D. If the deadline D is much larger than its holding time H, the request is very flexible; and it has more chances of being scheduled compared with a request with D close to H. If a request is accepted, the network operator will dynamically find a route and a scheduling time interval during which to transfer the data between the end-nodes.

In [5], two dynamic bandwidth-allocation algorithms, called DDR-FF (First-Fit) and DDR-TIR (Time-Interval Reconfiguration) are studied. DDR-TIR is based on the idea that network performance can be improved by reconfiguring the time intervals of previous requests that are already scheduled, but not yet in-service.

Figure 2 shows the performance of various scheduling algorithms for DDRs using DCS in a 24-node, US nationwide network, where traffic is uniform, DDR arrivals are independent, holding time H is constant (5 sec) for all requests, and deadline D is uniformly distributed over [25-145] sec. The deadline-driven approaches (DDR-FF and DDR-TIR) are compared with an immediate scheduling method, where, if the network has enough resources, the request is scheduled right away. In Fig. 2, the blocking probability for DDR-FF and DDR-TIR is the percentage of requests that could not be scheduled by their deadlines. We find that the two deadline-driven bandwidth-allocation algorithms achieve much better performance compared to Immediate Scheduling (which is deadline-unaware), and the reconfiguration approach (DDR-TIR) performs better than that which does not allow reconfiguration (DDR-FF).

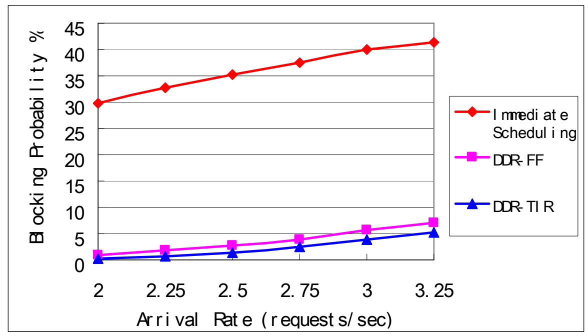

Fig. 2. Performance of immediate vs. deadline-driven request scheduling.

4. Conclusion

To conclude, deadline-driven requests (and advance reservation services in general) can help to improve the network performance and the user's quality of service. However, to allow these type of bandwidth requests, future networks need support for setting up large bandwidth pipes on demand, fast reconfigurability, and strict service guarantees, all of which can be met by the DCS architecture.

Reconsider the file-download example which could finish in 5 sec or 200 msec, depending on the bandwidth allocated to it. The operator of the DCS network can choose the bandwidth pipe thickness. Now, the operator has to also solve the problem of grooming different connections on to a wavelength circuit (lightpath). Thus, not only the time domain, but also the bandwidth-pipe thickness is an important dimension for the DCS network architecture.

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