Abstract:

IP service, leased-line service and POTS service have been the three long-standing communication service offerings of providers. Recently, both commercial and research-and-education network (REN) providers have started offering optical dynamic circuit services (DCS). This paper reviews these services, differentiates DCS from leased-line services, offers a classification of DCS, and proposes two new types of DCS. DCS are classified into two types: Specified-Duration Scheduled (SDS) and Unspecified-Duration Unscheduled (UDU). SDS service is less flexible than UDU service in that it requires users to specify call durations, and is more complex (needs reservation schedulers), but it is the only efficient option if link bandwidth is divided into a small number of channels (e.g., 1-Gbps circuits on a 10-Gbps link for fast transfers of large files). For SDS offerings, if the mean call duration is small, then a distributed scheduler implementation may be required to handle the high call arrival load required to maintain high utilization levels. Finally, SDS is classified into two sub-types: Specified Start Time (SST) and Earliest Start Time (EST), based on whether the user can only accept a start time from within its own specified set of start times, or whether it can accept any, preferably earliest, start time. The SST sub-type is useful for applications requiring the co-scheduling of network bandwidth with other resources, while the EST sub-type is ideal for file transfers.

1. Introduction

Three types of communication services are in widespread use today: (i) IP service, (ii) leased line and Virtual Private Network (VPN) service, and (iii) Plain Old Telephone Service (POTS). The services are represented on top of the horizontal line in Figure 1 with increasing resource usage (rate-hop-duration product) per allocation, and correspondingly decreasing levels of sharing, as one moves toward the left. With IP service, an “allocation” is only for the transmission of a single packet on a single hop (link) as IP service is connectionless, which implies that there is no flow-based multi-hop resource allocation. As an example, if the link technology is Ethernet, the maximum rate-hop-duration product/allocation with IP service is only 1518 bytes (maximum transmission unit plus header and trailer bytes). Next to IP service in Figure 1 is POTS, which offers users 64 kbps for short durations (on average, 3 minutes per telephone call). This allocation is on multiple hops (from calling to called parties), and hence the average rate-hop-duration product/allocation is $1.37 \alpha \text{ MB}$, where $\alpha$ is the number of hops on the end-to-end circuit. At the other extreme in Figure 1 is leased-line service. Even a relatively low-rate 1.544-
Mbps T1 line leased for 1 year results in a rate-hop-duration product allocation of $5.54\alpha \ TB$, where $\alpha$ is again the number of hops on the end-to-end leased circuit. The term “hop” can be interpreted in multiple ways (e.g., count or not count physical links within a logical connection between two IP routers, POTS switches, or leased-line switches), but as long as it is consistent for the services being compared, the rate-hop-duration product/allocation increases as one moves to the left in Figure 1. VPN services are a generalization of leased line service, e.g., VPNs could be multipoint, while leased lines are typically point-to-point. While POTS and IP services are purchased by residential and business customers, leased-line services are typically purchased only by businesses due to high costs.

Dynamic circuit services, introduced by both commercial and research-and-education network providers, fill the gap in rate-hop-duration product/allocation between the typical 100GB-TB allocations made with leased line service, and the MB-level allocations of POTS. Hence, we position it between these two services in Figure 1, and add it below the horizontal line to represent its relative newness of introduction. The objective of this paper is to review current optical dynamic circuit service (DCS) offerings, discuss potential new dynamic circuit services, and offer example applications for different types of DCS.

![Figure 1: A spectrum of communication services](image)

Section 2 reviews the three basic services offered today: IP service, leased-line service and POTS. Section 3 defines and classifies Dynamic Circuit Services (DCS) into various types. Existing dynamic circuit services offered by commercial providers and research-and-education network providers are reviewed in Section 4. Two potential new optical dynamic circuit services are discussed in Section 5, and Section 6 summarizes the paper.

2. **IP service, POTS, and leased-line service**

In this section, we review different types of network equipment, and then discuss the type of networks used to support the three basic services offered today: IP, leased-line, and POTS.
Figure 2: A classification of switches

<table>
<thead>
<tr>
<th>Multiplexing in the data plane</th>
<th>Circuit multiplexing</th>
<th>Packet multiplexing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Admission control in the control plane</td>
<td>position based (port, time, lambda)</td>
<td>header based</td>
</tr>
<tr>
<td>Connection-oriented (CO) - admission control</td>
<td>Circuit switch e.g., telephone, SONET, WDM, SDM</td>
<td>Virtual-circuit (VC) switch e.g., MPLS, ATM, PBBTE</td>
</tr>
<tr>
<td>Connectionless (CL) - no admission control</td>
<td>Not an option</td>
<td>Connectionless packet switch e.g., Ethernet</td>
</tr>
</tbody>
</table>

Figure 2 shows a classification of switches. Starting with the top left quadrant, consider **circuit switches**. The multiplexing scheme used in the data plane is based on “position,” i.e., space (port), time and/or wavelength, and the “positions” of incoming data frames are used to determine how to switch the frames to appropriate outgoing links. When position-based multiplexing is used in the data plane, admission control is mandatory in the control plane. This is because specific positions have to be selected on each link of the end-to-end path for each multiplexed flow, and switches need to be configured with incoming-to-outgoing position mapping information before user data can be transmitted. This explains why the bottom left quadrant in Figure 2 is not an option. In packet switches, incoming packets are demultiplexed and switched to appropriate outgoing links based on information carried in the packet headers. These switches can be operated with or without admission control. The former are referred to as **virtual-circuit (VC) switches** and the latter as **connectionless packet switches**.

The seminal paper that introduced the TCP/IP internetworking solution used the term “gateways” as an “interface between networks” [1], where each network consists of one or more switches interconnecting data sources and sinks. The IP router is the most widely deployed gateway. It operates in connectionless mode, and forwards packets from one network to another. A new type of “gateway” has emerged recently to interconnect circuit/VC networks. This is referred to as a **Multi-Service Provisioning Platform (MSPP)**. Given the low cost of Ethernet line cards in routers and the dominance of Ethernet network interface cards in computers, Synchronous Optical NETwork/Synchronous Digital Hierarchy (SONET/SDH) and Wavelength Division Multiplexed (WDM) circuit switch vendors added Ethernet line cards to their circuit switches, creating these new entities called MSPPs. Circuits/VCs need to be provisioned across MSPPs prior to data transfer, making them “circuit/VC gateways.” Based on the provisioned information, port/VLAN ID filtered Ethernet frames are mapped onto SONET/WDM circuits or Multi-Protocol Label Switched (MPLS) virtual circuits.

**IP services** are offered across connectionless packet internetworks primarily using IP routers. In contrast, **POTS service** is offered across a time-division multiplexed circuit network, while **leased line/VPN services** are offered across circuit/VC internetworks that consist of circuit
switches (e.g., SONET/SDH and/or WDM), virtual-circuit switches (e.g., MPLS and VLANs), and increasingly circuit/VC gateways (e.g., MSPPs).

Figure 3 illustrates a leased line obtained from a service provider that operates a network of optical circuit/VC switches and gateways extending between customer edge devices I and III. To obtain a leased line/VPN, a customer identifies the endpoints, bandwidth, and holding time (duration). Typically, a service provider will advertise the availability of leased-line services to only those locations that already have cabling, copper or fiber, in place. If necessary, required interface cards/ports can be purchased after the leased-line request is received by the service provider. For example, often service providers will deploy WDM equipment but not purchase 10GigE or OC192 transponders until a request for a leased line warrants the purchase. Holding times (lease lengths) are usually on the order of years, which allows for 1-2 months of “setup” delays that could be incurred in procuring interface cards/ports. Also, there is no “call blocking”: all requests can be accommodated given the long setup time.

![Figure 3: Leased lines in contrast with DCS access links](image)

3. **Definition and classification of dynamic circuit services (DCS)**

**Definition:** How does a “dynamic circuit service” differ from a leased-line service? As shown in Figure 3, a dynamic circuit service (DCS) requires that customers connect into a circuit/VC switch/gateway of the DCS provider. These are shown as “DCS access links” in Figure 3. If a customer edge device, such as II in Figure 3, does not have a DCS access link, then other customers cannot request dynamic circuits to this customer. Therefore, the key difference between dynamic circuit service and leased-line service is as follows. Dynamic circuit service requires a customer to first purchase a long-duration DCS access link between the customer network/device and the provider network, and then, issue requests, on an as-needed basis, for
circuits, specifying the endpoints (all of which need to have also purchased DCS access links a priori), circuit rate, and optionally, duration. In contrast, in a leased line service, a customer sets up only one contract with the provider, in which the circuit endpoints, bandwidth, and duration are specified all at once. The DCS access link is comparable to an IP access link, whether residential or enterprise. Just as both residential and enterprise customers incur an annual charge just for the IP access link whether or not any IP packets are sent across this link into the service provider’s IP-routed network, the same is currently true for DC services. Another difference between DCS and leased-line services is that with DCS, network planning to meet a (low) target call blocking rate becomes difficult if there is no maximum holding time for circuits. Finally, with DCS, a request for a circuit can be rejected (blocked). A particular service provider may choose to operate a DCS at low link utilizations, in which case call blocking probability can be close to 0, but typically, if revenue maximization is a business goal, the network should be designed to allow for some call blocking.

In summary, a dynamic circuit service (DCS) is defined as one in which customers (i) purchase DCS access links with capacities within a service-provider specified range \((C_{\text{min}}, C_{\text{max}})\), and (ii) request circuits on an as-needed basis to other DCS customers for holding times within a service-provider specified range \((h_{\text{min}}, h_{\text{max}})\) and service-provider specified circuit-rate range \((r_{\text{min}}, r_{\text{max}})\). Thus, while the distinction between “leased (static) circuit” and “dynamic circuit” is difficult to make in absolute terms (holding durations are often cited, but the exact demarcation point is difficult to pinpoint), the distinction between “leased line service” and “dynamic circuit service” is much more evident.

Classification: We classify dynamic circuit services into two broad categories: Specified-Duration Scheduled (SDS) and Unspecified-Duration Unscheduled (UDU). The key differences are (i) SDS call requests are required to specify duration, while in UDU service there is no such requirement, and (ii) there is no reservation scheduler in the UDU service, while such a scheduler is required for SDS service. Call durations are required for SDS because a reservation scheduler cannot schedule a starting time for a new request without knowing when all ongoing calls will terminate. The other two combinations are not likely to be deployed, because scheduling unspecified-duration calls is not feasible, and there appears to be no value in specifying durations but not scheduling calls (as it constrains users with no apparent gain).

More commonly used terms are Book-Ahead (BA) or Advance-Reservation (AR) for the SDS service, and Immediate- or Instantaneous-Request (IR) for UDU service. But as noted in [2], book-ahead (BA) calls are those “that announce their call holding times” and non-BA calls or IR calls are those “that do not announce their holding times.” Therefore the names “Specified-Duration” and “Unspecified-Duration” are more representative of these services, especially since BA calls can request an immediate start time. The “Scheduled (Unscheduled)” part of the names represents the presence (absence) of a scheduler to handle the specified-duration (unspecified-duration) service.
When is it feasible to have just the more flexible UDU service and when does an SDS service become necessary? If the number of channels $m$ into which shared link capacity (for example, the capacities of links within the optical circuit/VC internetwork of Figure 3) is divided is smaller than the number required to meet a given link utilization goal and blocking probability, then SDS is essential. Using the single-link Erlang-B formula, we see that with UDU service, the call blocking probability is 23% at 80% utilization when $m=10$. To obtain a (much lower) call blocking probability of at most 10%, at the same desired utilization of 80%, SDS should be employed if $m \leq 22$.

The disadvantage of SDS is that users have to specify call durations and the system becomes more complex by having to operate a reservation scheduler. Note that the important parameter $m$ depends upon the application and link capacity. For example, if 1-Gbps circuits are required per call across a 10-Gbps link for fast file transfers, then $m$ is 10. The value of $m$ is determined by the bottleneck link rate among DCS access-link capacities in the range $(C_{min}, C_{max})$ and capacities of links within the DCS provider networks, as well as maximum circuit rate, $r_{max}$, as per the above definition of dynamic circuit service.

**Two sub-types of SDS:** Reserving link bandwidth ahead of time is useful in situations where other resources have to be co-scheduled; for example, a distance-learning class time has to be selected based on students’/instructor’s availabilities, and once this time is known, circuits can be requested for the class duration ahead of time. We refer to this sub-type of SDS as **Specified Start Time (SST).** Multiple start-time options could be specified in the call request, and the scheduler either admits the call allocating resources for the requested call duration starting at one of the user-specified start times, or rejects the call for a lack of resources at all the specified start times. A second use is strictly to achieve “call queueing” (scheduling the call for a delayed start if resources are currently unavailable). This is of particular value for file transfers. We refer to this sub-type of SDS service as **Earliest Start Time (EST)** because the scheduler schedules the request for the earliest available start time. With both SST and EST, the requested call specifies duration, and the call is “scheduled” to start at some specific start time. In contrast, with UDU service a call (circuit request) would be rejected if bandwidth is unavailable at the time of arrival of the call request. A rejection would require the file-transfer application or other end host software to keep issuing call requests after random wait periods. On the other hand, with EST SDS service, the call could effectively be assigned a delayed start time, saving computational resources at the end hosts, and achieving call seniority based fairness objectives. The performance metric of interest for SST service is call blocking probability, while for EST service it is mean waiting time (delay). Hybrid combinations of these two sub-types may be useful in the future, though for currently identifiable **applications**, SST and EST seem to be sufficient. Video-conferencing, distance-learning, remote visualization, and remote instrument control, are examples of SST applications, while file transfer is the primary EST application.

**Centralized or distributed implementation of SDS:** For long-held circuits, on the order of hours, for applications such as video conferencing, distance learning, remote instrument control,
and very large (tera- to peta-byte) file transfers, the aggregate call arrival rate is likely to be small. Since maximum link utilization is $\lambda/m\mu$, where $m$ is the number of channels into which the link capacity is divided, the larger the mean call duration ($1/\mu$), the smaller the call arrival rate ($\lambda$) required to operate at a given utilization level. When the call arrival rate is small, a centralized scheduler will be sufficient to handle the call load. However, as most providers will not want to divulge topology information to their peers, typically one scheduler is deployed per administrative domain [3].

In contrast, for general-purpose file transfers, on the order of hundreds of MBs to GBs, with Gbps circuits, call durations are on the order of seconds. This means the call arrival rates need to be large for links engineered to achieve the same (high) utilization. For such applications, distributed scheduling will be required. While some of the processing capacity in a distributed system will be expended in signaling message exchanges between the schedulers, the overall call handling throughput can be higher than in a centralized system. As an example, consider how the POTS service handles telephone calls. Calls between New York (NY) and Boston are handled by the call processors built into the switch controllers at the NY, Boston and intermediate switches, while call processors in the switches in other parts of the country are unaware of these NY-Boston calls. This natural partitioning of the workload allows for a distributed implementation to handle higher call arrival rates than in a centralized implementation.

Furthermore, the call setup delay, which is an overhead, can be larger for long-duration circuits than short-duration circuits. A centralized scheduler will likely incur longer call setup delays than distributed scheduling. Thus, the desired call duration range, $[h_{min}, h_{max})$, as in the above definition of dynamic circuit service, determines whether or not the SDS service should be implemented with a centralized scheduler (one per domain) or a distributed solution.

A distributed solution can be defined by adding time-related parameters to signaling protocols, such as RSVP-TE (e.g., call duration), and routing protocols, such as OSPF-TE.

4. Existing optical dynamic circuit services

The only type of DCS offered today, by both commercial operators and research-and-education network (REN) operators, is the Specified-Duration Scheduled (SDS) service with Specified Start Time (SST) requests. The commercial service is intra-domain, while the REN service is inter-domain. Also, there is a difference in the minimum duration, e.g., the Verizon DCS service requires circuits to be requested for a minimum duration of 1 day, while Internet2 allows customers to request circuits for durations as small as 1 minute, although most requests are for longer duration.

4.1 Commercial offerings

Commercial service providers, such as AT&T and Verizon, are now offering their customers a dynamic circuit service. Verizon’s service is referred to as “bandwidth on demand (BOD)” [4].
The DCS access link shown in Figure 3 is called a “BoD facility” in the Verizon offering, which states: “The BoD Facility is a flat rated charge, billed monthly. The BoD Facility carries a 2 year minimum commitment.” Customers can purchase OC12, OC48 or OC192 links as their BoD facilities. Customers can request circuits with Just-in-Time (JiT) provisioning that ingress and egress on BoD facilities. This service is referred to as “BoD Network Transport ON-NET.” With virtual concatenation, it allows customers to request “DS3, OC3c, OC12c, OC48c, GigE-1 (50Mbps), GigE-3 (150 Mbps), GigE-6 (300 Mbps), GigE-9 (450 Mbps), GigE-12 (600 Mbps) and GigE-Full rate capacities” [4]. Charging for these dynamic circuits obtained through the BoD Network Transport ON-Net service are noted as “flat-rate” with “month-to-month billing,” but the service description in [4] also notes that it is “pro-rated on a daily basis to the extent the rate element is in service for less than one month.” Effectively, this means that the minimum duration for this service is one day. Customers have to enter an agreement with Verizon, referred to as a “Master Services Agreement (MSA),” to obtain the BoD facility in the first place before dynamic circuits can be requested between any two BoD facilities for a per-day or longer usage.

AT&T’s Optical Mesh Service (OMS) also is a dynamic circuit service [5]. It states that “access to the AT&T network is predefined and static,” which is the DCS access link shown in Figure 3. Rates supported for the DCS access link are OC3, OC12, and OC48, and dynamic circuit speeds are STS1, STS3c and STS12c. Applications anticipated in [5] are disaster recovery, video on demand, FTP file transfers/bulk transfers, backbone network capacity adjustment and bandwidth on demand, which is explained as the ability for customers to “eliminate the need to have multiple, dedicated optical ports at each site to support a fully meshed environment.”

The backbone network capacity adjustment application noted in the AT&T OMS site [5] is effectively a traffic engineering/network engineering application [6]. We explain this using the Internet2 network diagram shown in Figure 4 as an example. Internet2 leases wavelengths from Level 3 for all the inter-city links shown in Figure 4. Instead of obtaining these leased circuits, it could use a service such as Verizon’s BoD or AT&T’s OMS in the following manner. It could have DCS access links from each of its IP routers to a Verizon or AT&T circuit/virtual-circuit switch at the same PoP. Based on its changing traffic patterns, Internet2 could dynamically create circuits between any two routers instead of using the fixed topology shown in Figure 4. For example, instead of connecting the New York router to Chicago and Washington routers, it could create a circuit from New York directly to the Atlanta router or even to the Los Angeles router. Such flexibility is thought to be required to handle unpredictable (e.g., disaster) events or special events. Recovery from failures are typically handled in a two-phase mode, with a fast (<50ms) recovery on to backup circuits, and then a recomputation of a new primary/backup circuit pair [7]. With the BoD or OMS service, an ISP such as Internet2 would have more flexibility than with fixed leased lines as is the current solution.

There are two factors in current networks that can influence the use of dynamic circuits for the traffic engineering/network engineering application. First, IP-routed networks are overprovisioned [8]. Service providers operate their links at less than 50% utilization both to
absorb sudden surges as in the REN community (e.g., Internet2 has a stated “headroom practice” of operating links at a maximum of 25-30% utilization to “enable researchers to engage in unpredictable large-bandwidth applications” [9]), and for handling rerouted circuits in case of failures (an often cited reason by commercial providers for light link loads). Second, operations divisions of service providers typically have strong resistance to change the network topology because of the potential for "route flaps" and drastic changes in the end-end packet latency (e.g., greater than 10ms). As dynamic circuit service is relatively new, the growth of its usage base for this and other applications remains to be seen.

4.2 Research-and Education Network (REN) offerings

This section describes how core research-and-education network (REN) operators have recently added optical dynamic circuit (DC) services to their IP service offering. The DC service is predominantly used by eScience projects for applications such as transfers of large files (on the order of terabytes to petabytes) as in the Large Hadron Collider (LHC) experimental projects, and for other applications such as remote visualization and remote instrument control. Two US-wide core RENs, ESnet and Internet2, have each deployed an optical dynamic circuit network to complement their existing IP-routed networks [3]. NLR, another US-wide provider, offers Layer-1 and Layer-2 services in addition to IP-routed (Layer-3) services [10]. Similar deployments have been made internationally, e.g., Europe’s AutoBAHN [11], Japan’s JGN2plus [12], and Canada’s UCLP [13], among others.

In this section, we describe Internet2’s dynamic circuit service as an example, and then describe the control-plane architecture and protocols, which were jointly developed by DANTE (Europe), Internet2 (US), Canarie (Canada) and ESnet (US). Finally, we describe a project called Lambda Station [14] that demonstrates how these DC services are used by end-user applications.

4.2.1 Internet2’s network

Figure 4 shows Internet2’s network, which consists of Juniper T640 IP routers and Ciena CD-CI Ethernet-SONET MSPPs, shown as Interoperable On demand Network (ION) nodes (ION is the new name chosen by Internet2 for its dynamic circuit network). Two wavelengths are leased by Internet2 on its entire national footprint, one to interconnect ION nodes, and the second to interconnect IP routers. Connector networks, such as regional REN providers or large enterprises, connect via separate links into a T640 for their IP-routed service and into a CD-CI for their DC service. For DCS, the minimum circuit duration is 1 minute, $r_{\text{min}} = 50\text{Mbps}$ and $r_{\text{max}} = 10\text{Gbps}$.
4.2.2 Control-plane software to support the book-ahead service

Figure 5 shows the control plane software architecture for the SDS service (with a per-domain centralized design). The Inter-domain Controller (IDC) is responsible for handling requests for bandwidth. It implements the IDC Protocol (IDCP) [15]. IDCP consists of message exchanges between domains to support the scheduling and provisioning of inter-domain circuits. In addition, it supports inter-domain topology exchange and circuit monitoring.

Phase 1 – Resource (bandwidth) scheduling: Figure 5 shows an example of “Daisy-Chain Messaging” in which IDC protocol messages are passed from one IDC to another in a chain-like fashion through a sequence of domains. The daisy chain is initiated when an end-user sends a request to the IDC of Domain 1 (i.e., the first one in the path from source to destination). The request is a createReservation message, which has the following mandatory parameters: startTime, endTime, bandwidth, endpoint addresses for “Source” and “Destination” of the circuit (see Figure 5), and an indicator of whether the end-user wants automatic circuit creation at the startTime (called “automatic signaling”) or if the end-user will issue an explicit createPath message (called “message signaling”). In addition, a few optional parameters are supported. The IDC, using its domain topology information obtained from its domain controller, and status information about current reservations in its own database for all links within its domain, determines whether or not the new request can be accommodated. If the requested bandwidth is available on all links of a path traversing its domain, it will accept the request; if not, the request will be rejected. If the request is accepted, the IDC will send a message to the next domain’s IDC.
in the daisy chain. The next-domain IDC is identified based on the destination address in the request and the topology exchanges that have previously occurred between the IDCs. If all IDCs on the end-to-end path accept the request, the end-user will receive a positive response to its *createReservation* message; if not, it will receive a reject response.

**Figure 5: Control-plane architecture for book-ahead service (per-domain centralized design) [15]**

**Phase 2 - Circuit provisioning:** For accepted reservations in which message-based signaling is the chosen option, the end-user must issue a *createPath* message to initiate the provisioning of the circuit at the *startTime*. For automated signaling, the circuit will be provisioned automatically at the *startTime* by the IDC. Within each domain, the IDC communicates with its domain controller, which in turn communicates with the network switches (not shown in Figure 5, but located in the “Network” clouds) to provision the circuit across these switches. Signaling proceeds in the same daisy-chain fashion with each IDC signaling the next-domain IDC to provision the circuit through its domain.

**Phase 3 - Data transfer:** When the circuit is completely provisioned, the “Source” host in Figure 5 can start sending data to the “Destination” host.

**Phase 4 – Circuit release:** A *teardownPath* message is sent by the end-user (message signaling) or IDC (automatic signaling) at the scheduled *endTime* for the reservation. Each IDC communicates with its domain controller, which in turn communicates with the switches to release the circuit, and IDC-to-IDC signaling is used in the same daisy-chain fashion as for scheduling and circuit provisioning.

### 4.2.3 Lambda Station software

This section answers an important question of how the dynamic circuit services offered by these core networks can be used by end-user applications that run on hosts that are physically located deep inside enterprises and, hence, have direct connectivity only to the enterprises’ IP-routed
networks. The Lambda Station solution [14] and software was specifically developed to support one of the LHC experimental projects (based in Fermilab in the Chicago area), but the solution is equally applicable to other eScience and general-purpose applications. It offers a programmatic interface that makes it possible to upgrade existing application software to communicate with the Lambda Stations without manual intervention.

Lambda Station servers are control-plane software processes running on off–the-shelf hosts within enterprise networks (shown as “Lambda Station Server” in Figure 6). Client software, which enables communication with the Lambda Station, is integrated into existing applications such as dCache/Storage Resource Manager (SRM) [16], which is used to move files into storage systems. Either before starting a file transfer or while one is in progress, the dCache/SRM application sends a circuit request to the Lambda Station server. The Lambda Station server sends a scheduling request to the IDC of the optical dynamic circuit network to which its enterprise network is connected, e.g., ESNet’s IDC in Figure 6. If successful, just before reservation activation time (startTime), it issues CLI or TL1 commands, as appropriate, to its enterprise IP router(s) to set specific source/destination pair based routing table entries for appropriate redirection of the dCache/SRM-specific data flow. Not all enterprise routers need to be configured; only the routers at which the flow’s path will deviate from the normal IP-routed path. The LambdaStation server maintains an abstract representation of the enterprise network infrastructure, and uses it to make local router configuration changes necessary to achieve the appropriate rerouting of traffic. The flow’s packets use the newly established dynamic circuit for transit through the wide-area core network. In Figure 6, the dashed line through the ESnet OSCARs and Internet2 DCS networks is shown as extending end-to-end between the clusters running the dCache/SRM application. This does not imply that it is an end-to-end dynamic circuit as the enterprises have not deployed dynamic circuit networks. Instead, within the enterprise networks, flow-specific IP routes are configured to lead packets to the entry point for the wide-area circuit, and from the exit point of the circuit to the destination at the far end enterprise.
5. Potential new dynamic circuit services

This section discusses two potential new dynamic circuit services. **SDS service with EST requests** are ideal for transfers of files with sizes on the order of hundreds of MBs to GBs (thus, smaller than the sizes for which the REN SDS is designed). If allocated circuit rates are significant fractions of shared link capacities (e.g., 1/20th or higher), call durations for files in this size range will be on the order of seconds, assuming link rates on the order of 10Gbps. Since call durations are short, a distributed scheduler implementation is required as described in Section 3. Examples of file transfer **applications** that require movement of files in this size range include storage applications such as backup storage and disaster recovery, Content Delivery Networks (CDN) that replicate Web content in regional servers for faster delivery to end users, and video file movement in support of IPTV services. A set of algorithms for a distributed scheduler implementation is described in [17].

Another potential new dynamic circuit service is the **UDU service**, which is envisioned as a high-speed POTS service, with per-circuit rates that are small fractions of link capacities (e.g., smaller than 1/20th). As noted in Section 3, while UDU service provides users the flexibility of not having to specify call durations and does not incur the complexity of a reservation scheduler, it can be deployed efficiently only if $m$, the number of channels into which link capacity is divided, is large. Therefore, UDU service is suitable for **applications** such as high-quality video telephony and cloud computing (e.g., Google Apps) that require moderate rates and have short...
call holding durations. In the CHEETAH project [18], the UDU mode of dynamic circuit services was studied in depth. Questions regarding the optimal rate to allocate per file transfer from a consideration of individual delays vs. system averages were answered under homogeneous and heterogeneous rate allocation schemes. Also, the use of the UDU service for file transfers in the Web application was demonstrated by implementing (i) a signaling client that communicated with built-in RSVP-TE controllers in off-the-shelf Ethernet-SONET circuit/VC gateways, (ii) a Circuit TCP (CTCP) transport protocol for use on the circuits after they are established, and (iii) a CGI solution to eliminate the need to modify Web clients and servers.

Another ongoing effort is the DARPA CORONET project in which network architectures are being studied to support a variety of dynamic guaranteed-bandwidth services at the wavelength level and at finer levels of granularity [7]. This can potentially lead to other new forms of DCS.

6. Summary

Different types of dynamic circuit services (DCS) can be implemented to augment today’s offering of IP, leased-line, and POTS services. Both commercial and research-and-education network providers offer a Specified-Duration Scheduled (SDS) dynamic circuit service with Specified Start Time (SST) requests. They differ in the scope (intra- vs. inter-domain, respectively) as well as the minimum/maximum call durations allowed. The circuit rate relative to link capacity is the critical parameter in determining whether an Unspecified-Duration Unscheduled (UDU) service, which does not require a reservation scheduler nor users to provide call durations, can be offered at reasonable call blocking rates and link utilization levels, or whether SDS is required. For SDS, an additional parameter, circuit holding time, further determines whether a centralized scheduler is sufficient to handle the call arrival load and required call setup delay (an overhead that should be kept at a small fraction of the circuit holding times), or whether a distributed scheduling solution is required. Potential new applications for an SDS service with Earliest Start Time (EST) requests, and the UDU (high-speed POTS) dynamic circuit services, are identified.

Acknowledgment

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References


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