Establishment and Management of Virtual End-to-End QoS Paths Through Modern Hybrid WANs with TeraPaths

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***Abstract*—The resource reservation capabilities offered by modern wide area networks, such as ESnet and Internet2, create a new network utilization model that coexists but drastically differs from the standard best-effort network paradigm. These capabilities enable the dedication of network resources to specific users/applications that may suffer from interruptions and other adverse effects because of the default best-effort behavior of networks. Extending the new capabilities through the local area networks of end sites and making them available to end users and applications in a useful, transparent, and scalable manner is a variation of the "last mile" problem. The TeraPaths project at Brookhaven National Laboratory is pioneering a framework that takes advantage of the new capabilities to establish and manage on-demand true end-to-end QoS-aware network paths dedicated to authorized data flows. In this paper, we examine the issues raised by the new end-to-end resource reservation-based networking paradigm and the implications/benefits for end users and applications.**

Keywords—End-to-end QoS networking; hybrid networks; network virtualization.

I. INTRODUCTION

Modern data intensive scientific applications, including high energy and nuclear physics, astrophysics, climate modeling, nanoscale materials science, and genomics, will soon be capable of generating data on the order of exabytes per year [1]. This data must be transferred, visualized, and analyzed by geographically distributed teams of scientists, imposing unprecedented demands on computing and especially networking resources. While such applications can capitalize on modern high-performance networking capabilities, they can be critically sensitive to the adverse effects of unpredictably occurring network congestion. Because network capacity is finite, competition among data flows may cause applications to suffer severe performance degradation and eventual disruption. When data delivery must conform to specific deadlines or application components need to interact in real time, the standard best-effort networking model is not always sufficient. To work effectively, these applications require resource availability guarantees. In the case of network, the requirement primarily translates to bandwidth guarantees, however, other Quality of Service (QoS) parameters may also be included, i.e., delay, jitter, etc. The Department of Energy (DOE) Office of Science identifies QoS as one the five top ranked issues essential to the success of distributed science [2].

Several available networking technologies, such as the Differentiated Services (DiffServ) [3], Integrated Services (IntServ) [4], Multi-Protocol Label Switching (MPLS) [5], and Generalized MPLS (GMPLS) [6] architectures, have the capability to address the issue of providing resource guarantees. In practice, however, the scope of network connections utilized by distributed applications spans multiple autonomous domains. These domains typically have different levels of heterogeneity in administrative policies and control plane and data plane technologies, making it difficult or impossible to provide network QoS guarantees using a single architecture across all domains. For example, Differentiated Services Code Point (DSCP) packet markings, used in the DiffServ architecture, are by default reset at ingress points of network domains. As such, the DiffServ architecture is ineffective across domains without prior inter-domain Service Level Agreements (SLAs) in effect and proper configuration of involved network devices.

Recent networking research and development efforts [9] – [12] adopt a hybrid solution to the problem, with individual network segments utilizing different underlying technologies. From the end user perspective, however, these technologies are seamlessly tied together to ensure end-to-end resource allocation guarantees. This hybrid solution creates a new networking model that transparently co-exists but fundamentally differs with the standard best-effort model. Under the new model, it is possible to allocate network resources through advance reservations and dedicate these resources to specific data flows. Each such flow (or flow group) is steered into its "own" virtual network path, which ensures that the flow will receive a pre-determined level of QoS in terms of bandwidth and/or other parameters. Virtual paths can comprise several physical network segments and span multiple administrative domains. These domains need to coordinate to establish the virtual path. Coordination takes place by means of interoperating web services. Each domain exposes a set of web services that enable the reservation of resources within a domain's network. Authorized users of these services, which can be another domain's services, can reserve network resources within the domain and associate them with specific data flows. When reservations activate across all domains between a flow's source and destination, a dedicated end-to-end virtual path spanning these domains is assembled. This path offers to the flow of interest a predetermined level of end-to-end QoS. The coordination of multiple network domains through web services is essentially a loosely coupled Service Oriented Architecture (SOA) for the network control plane, a network "service plane" [13].

End-to-end virtual paths can be viewed as consisting of three main segments: two end segments, one within each end site Local Area Network (LAN), and a middle segment spanning one or more Wide Area Network (WAN) domains.

In this paper, we consider the establishment of end-to-end virtual paths from the perspective of end sites. User applications run on end site systems, communicate with the rest of the world through end site LANs, and are subject to end site administrative policies. In the standard networking model, traffic through the WAN is subject to pre-existing SLAs between adjacent network domains. In the new advance resource reservation model, such SLAs are essentially dynamic, allowing end sites to utilize and – indirectly – manage WAN capabilities in a way that maximizes the benefit to the end user. The next section describes the two main projects that constitute the framework for the advance resource reservation model. Section 3 focuses on the differences between the two kinds of dedicated network paths through WAN domains supported by the framework, while Section 4 presents techniques necessary for the effective utilization of these dedicated WAN paths. Section 5 examines fault tolerance issues. Section 6 discusses related work. Finally, Section 7 presents our conclusions and future work directions.

II. Background

The framework for establishing end-to-end QoS-aware network paths encompasses web service-based systems that properly configure end site LAN and WAN domains (see figure 1). The capability for advance resource reservation is currently available between sites interconnected through the ESnet [7] and Internet2 [8] networks. In this section we give background information on the two projects that constitute this framework, the TeraPaths project and the OSCARS project.

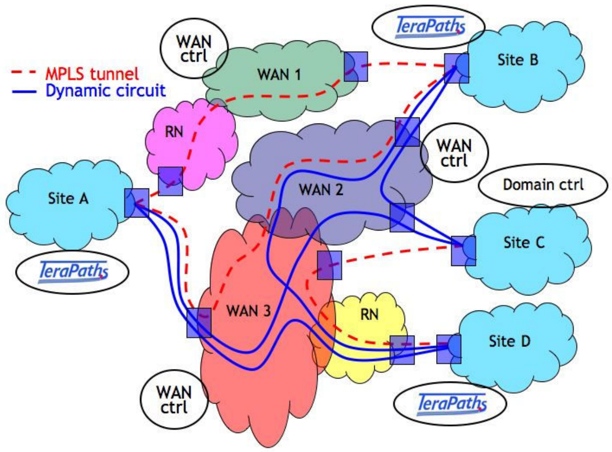

Fig. 1. The framework for establishing end-to-end paths. TeraPaths-controlled sites are interconnected with WAN MPLS tunnels and/or dynamic circuits. Some paths pass through regional networks that have long-term static configurations to accommodate QoS.

A. *The TeraPaths Project*

The DOE-funded TeraPaths project [9] at Brookhaven National Laboratory (BNL) combines DiffServ-based LAN QoS with WAN MPLS tunnels and dynamic circuits to establish end-to-end (host-to-host) virtual paths with QoS guarantees. These virtual paths prioritize, protect, and regulate network flows in accordance with site agreements and user requests, and prevent the disruptive effects that conventional network flows can bring to one another.

Providing an end-to-end virtual network path with QoS guarantees (e.g., guaranteed bandwidth) to a specific data flow requires the timely configuration of all network devices along the route between a given source and a given destination. In the general case, such a route passes through multiple administrative domains and there is no single control center able to perform the configuration of all devices involved. The TeraPaths system has a fully distributed, layered architecture (see figure 2) and interacts with the network with the perspective of end-sites of communities. The local network of each participating end-site is under the control of an End-Site Domain Controller module (ESDC). The site's network devices are under the control of one or more Network Device Controller modules (NDCs). NDCs play the role of a "virtual network engineer" in the sense that they securely expose a very specific set of device configuration commands to the ESDC module. The software is organized so that NDCs can be, if so required by tight security regulations, completely independently installed, configured, and maintained.

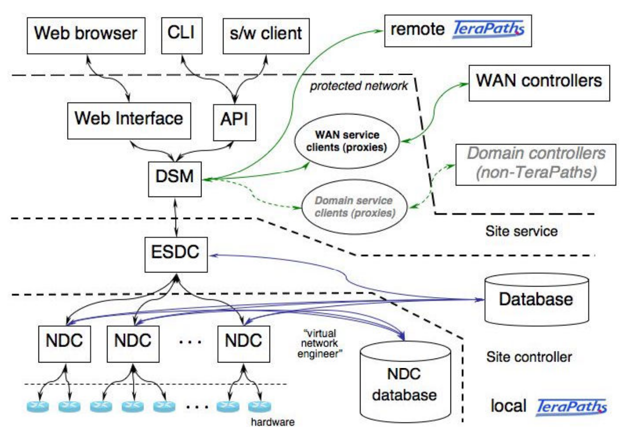

Fig. 2. The software architecture of TeraPaths. Services of remote network domains are invoked through "proxy" server modules.

A NDC encapsulates specific functionality of a network device and abstracts this functionality through a uniform interface while hiding the complexity of the actual configuration of heterogeneous hardware from higher software layers. A site's ESDC and NDC(s) are complemented by a Distributed Services Module (DSM), which is the core of the TeraPaths service. The DSM has the role of coordinating all network domains along the route between two end hosts (each host belonging to a different end-site) to timely enable the necessary segments and establish an end-to-end path. The DSM interfaces with all ESDCs (local and remote) to configure the path, starting within the end-site LANs (direct control) and proceeding to arrange the necessary path segments through WAN domains (indirect control). To interface with non-TeraPaths domain controllers, primarily for WAN domains but also for end-sites that are using other controlling software (e.g., Lambda Station [10]), the DSM uses auxiliary modules that encapsulate the functionality of the targeted domain controller by invoking the required API but exposing a standardized abstract interface. As such, these auxiliary modules appear to a DSM as a set of "proxy" WAN or end-site services with a uniform interface. It should be noted that the responsibility of selecting and engineering the path within a WAN domain belongs to the controlling system of that domain. TeraPaths can only indirectly affect such a path by providing preferences to the WAN controlling system, if that system offers such a capability.

Currently, TeraPaths follows a hybrid star/daisy chain coordination model where the initiating end-site first coordinates with the target site and then indirectly sets up a WAN path by contacting its primary WAN provider and relying on that provider's domain to coordinate, if necessary, with other WAN domains along the desired route. The hybrid coordination model was adopted as the most feasible since end site and WAN systems need only to interface/coordinate. Thus, no unified communication protocol is required, as in the case of the daisy chain model, and there is no centralization of control, as in the case of the star model. The hybrid model essentially splits the network in two large segments: the end sites and the WAN domains, with each segment coordinating with the other to setup a path.

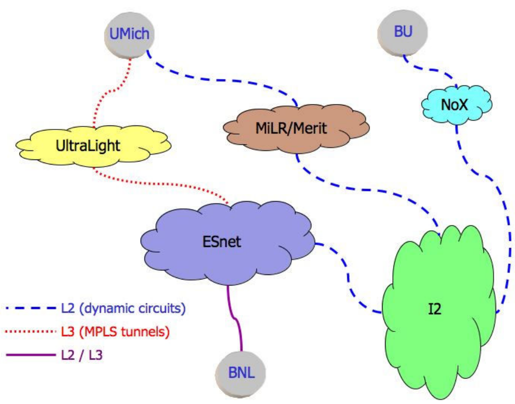

Fig. 3. The TeraPaths testbed encompasses subnets at BNL, UMich, and BU. Only BNL is directly connected to ESnet.

B. OSCARS

The DOE-funded On-demand Secure Circuit Advance Reservation System (OSCARS) [12] is a project initiated by ESnet. Initially, OSCARS could dynamically provision secure layer-3 (L3) circuits with guaranteed bandwidth in the form of MPLS tunnels, only within the ESnet domain.

Through collaboration between ESnet and Internet2, OSCARS evolved into a more general Inter-Domain Controller (IDC), a WAN domain controller, enabling adjacent WAN domains to interoperate and establish secure circuits spanning multiple domains via the use of a special protocol specifically developed for domain interoperation. While still capable of providing MPLS tunnels within ESnet, OSCARS can additionally provide guaranteed bandwidth layer-2 (L2) circuits within and between ESnet's Science Data Network (SDN) and Internet2's Dynamic Circuit Network (DCN). SDN and DCN are interconnected at New York and Chicago and bring together DOE laboratories and Universities across the United States.

Access to OSCARS circuit reservations is offered via a web interface. Additionally, the system's functionality is exposed through a web services API for automatic invocation from programs. The API includes basic primitives for establishing and managing circuit reservations (create, cancel, query, list) and L2-specific primitives to signal and teardown dynamic circuits. TeraPaths utilizes a client module to automatically submit circuit reservation requests and further manage these reservations on behalf of end site users/applications.

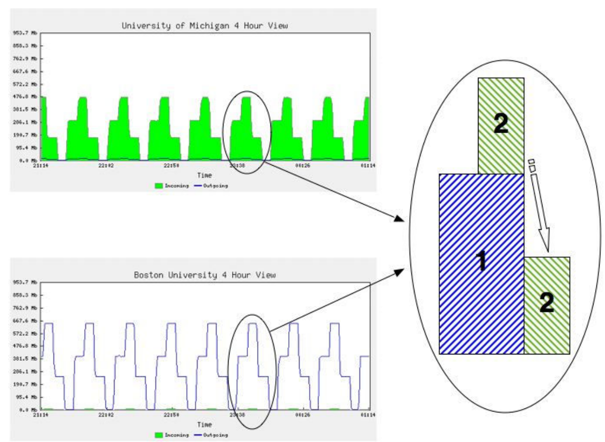

Fig. 4. Demonstration of flow bandwidth regulation at SuperComputing 2007 and Joint Techs winter 2008.

C. The TeraPaths Testbed

The TeraPaths project utilizes a multiple-site testbed for research, software development, and testing. Currently, the testbed encompasses subnets at three sites, BNL, University of Michigan (UMich) and Boston University (BU) (see figure 3). Each site runs its own instance of the TeraPaths service. All instances can interface with OSCARS interdomain controllers to setup MPLS tunnels through ESnet and dynamic circuits through ESnet and Internet2. Future end-sites will have similar interconnecting capabilities depending on which WAN they subscribe to (ESnet supports both L2 and L3 circuits, while Internet2 only L2). TeraPaths instances can regulate and guarantee the bandwidth of multiple flows between the testbed sites. These flows may utilize individual WAN circuits or may be grouped together, based on source and destination, into the same WAN circuit (which accommodates the aggregate bandwidth). Figure 4 shows a demonstration of flow bandwidth regulation for multiple periodic data transfers as monitored by Internet 2's perfSONAR system. The aggregate bandwidth passing through circuits between BNL, UMich, and BU is displayed. Two transfers take place during each period, with each transfer maintained at a guaranteed bandwidth level. The second transfer (2) starts later than the first (1) and continues after the latter finishes. Each flow is policed to its guaranteed bandwidth level preventing competition within the circuit. Use of DiffServ QoS in the end site LANs and dynamic WAN circuits ensures that presence of any other traffic does not affect the regulated flows.

III. Layer-3 vs. Layer-2

From the perspective of end sites, the requirements for utilizing a L2 or a L3 circuit are significantly different. In this section we discuss these requirements and related issues.

A. *MPLS Tunnels (L3)*

In the case the path through one or more WAN domains is established in the form of an MPLS tunnel (see figure 5a), admission control into the tunnel is done at the ingress device of the MPLS tunnel on the WAN side. Packets that belong to an authorized flow or group of flows are recognized based on source and destination IP address and possibly additional selection criteria (e.g., port numbers). The source end site essentially hands over all packets to the WAN but only those that belong to authorized flows enter their corresponding tunnel. The MPLS tunnel maintains the packet DSCP markings so that flows emerging at the egress of the tunnel receive differential treatment within the destination end site LAN.

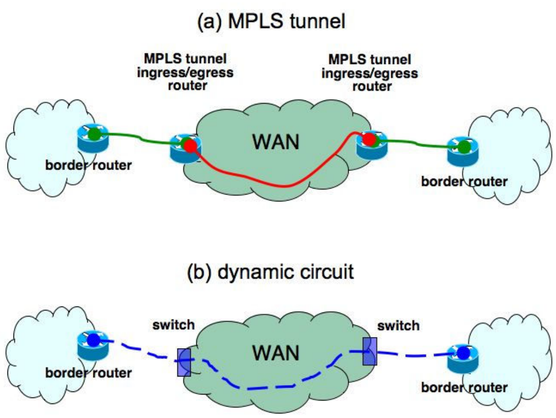

Fig. 5. WAN circuits: (a) MPLS tunnels vs. (b) L2 dynamic circuits.

B. *Dynamic Circuits (L2)*

The infrastructure for the utilization of dynamic L2 circuits is quite different (see figure 5b). In this case, the WAN circuit established between two end sites makes those sites members of the same Virtual LAN (VLAN). The interfaces of the end site border routers participating in the connection appear as if connected directly with a patch cable, i.e., there is a single hop between them. Forwarding authorized traffic to the VLAN assigned to the circuit is the responsibility of each end site's border router. Each router uses Policy Based Routing (PBR) to selectively forward authorized flow packets (identified by source and destination IP addresses and possibly other criteria, e.g., ports) into this VLAN. For bidirectional traffic through a circuit, the border routers have to be configured in a mirrored configuration so that the destination site's border router appears as the next hop to the source site's border router and vice versa.

C. *Related Issues*

When an end site gains access to a WAN domain through a Regional Network (RN) that cannot be dynamically configured through a domain controller, it is necessary to statically configure the RN's devices so that (a) DSCP markings are not reset at the boundaries and (b) VLANs are extended through the RN. The same techniques need to be used within an end site LAN for network devices that are along routes used by end-to-end paths but are not under direct TeraPaths control. The static configuration is applied only to those specific device interfaces that interconnect TeraPaths-controlled devices with WAN devices. We call such statically configured network segments "pass-through" segments, in the sense that they honor DSCP markings and allow extension of VLANs through them. Figure 6 gives an example of a "pass- through" setup.

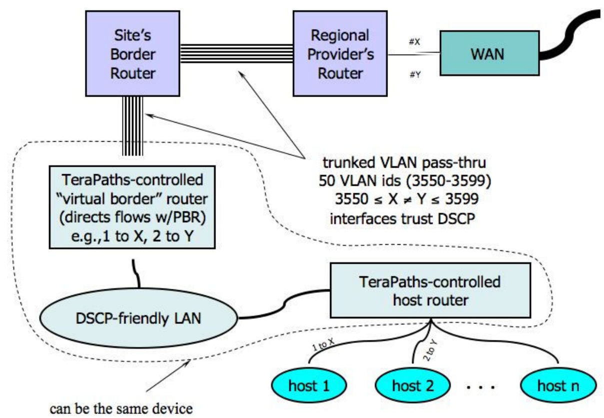

Fig. 6. Example pass-through configuration for the end site's regional network and border router. The router where circuit VLANs terminate plays the role of a "virtual border" router. If only one router is controlled by TeraPaths, this router both conditions and forwards authorized traffic.

In both L2 and L3 circuit cases, scalability issues must be considered because both technologies require all involved network devices to be configured to recognize specific data flows. Both MPLS tunnels and dynamic circuits are technologies well suited to establish special connections between WAN endpoints and accommodate qualifying traffic between sites connected to these endpoints. However, dedicating an MPLS tunnel or a dynamic circuit to each individual flow between a pair of end sites may cause severe scalability problems, especially in the case of dynamic circuits. With MPLS tunnels, scalability depends on the limitations and efficiency of the WAN hardware, while reserved bandwidth is allocated only when qualifying flows are present. MPLS tunnels are unidirectional, so bidirectional flows require two separate WAN reservations, one for each direction. With L2 dynamic circuits, additional restrictions apply. Because a circuit behaves as an Ethernet-based VLAN, a fundamental requirement is the utilization of the same VLAN tag along the entire route covered by the circuit. All network devices along the path must use the same VLAN tag. This is a severe restriction as current devices support a total of roughly 4,000 tags with several tag ranges reserved for device use and for administrative reasons. Therefore, only a small fraction of the overall tag range is actually available for utilizing dynamic circuits, furthermore, each domain may have its own tag subset. The establishment and utilization of a circuit between two end sites requires all domains along the path to have a common subset of tags. In the current implementation of TeraPaths, this is required so that no tag conflicts exist when setting up a circuit. This requirement may be relaxed in the future by exploiting VLAN renaming capabilities.

In the TeraPaths testbed there is an agreement that 50 VLAN tags, 3550-3599, are reserved for dynamic circuit use. Ensuring that no tag conflicts exist within the testbed is relatively easy, because all testbed sites are serviced by ESnet and Internet2, which form a composite domain that can be configured by contacting a single OSCARS instance. Thus, it is possible to rely on OSCARS to select an available VLAN tag within a range suitable for the end sites involved.

The limitation in the number of available VLAN tags and the additional properties of circuits to reserve bandwidth regardless of the presence of qualifying traffic and to be bidirectional make evident the need to treat L2 dynamic circuits as an "expensive" resource requiring sophisticated techniques to maximize utilization efficacy. Clearly, such circuits need to be viewed as "highways" between end sites. Flows with matching source and destination need to be grouped together and forwarded through common circuits, configured so that they accommodate the aggregate bandwidth of the grouped flows.

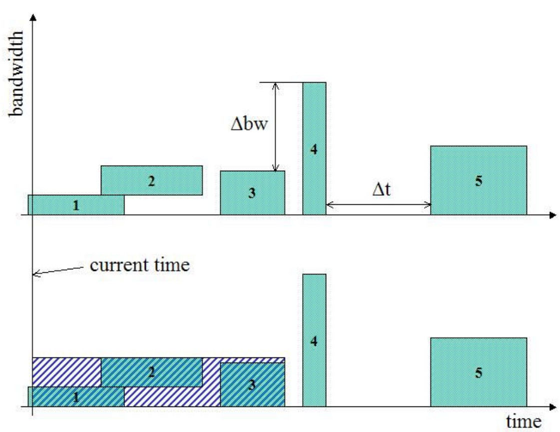

Fig. 7. Example of reservation consolidation. Unifying reservations #1, #2, and #3 is feasible, #4 has too big Δbw, #5 is too distant in the future.

IV. MANAGING WAN RESERVATIONS

Grouping together individual data flows or flow groups with common source and destination and forwarding them to a common WAN circuit with enough total bandwidth and duration to accommodate all flows can drastically reduce the number of circuits that are needed between a pair of end sites simultaneously and increase the availability of the dedicated paths. The first step of this approach is to decouple the end site reservations with the WAN reservations. End sites still reserve resources for individual flows, however multiple end site reservations can be accommodated by a single WAN circuit reservation as long as the aggregate duration and bandwidth can be determined. The level of reservation consolidation (or unification) needs to be controlled by suitable criteria to minimize waste of resources. Figure 7 shows an example of such criteria. If all reservations #1 through #5 were to be associated with a single encompassing WAN reservation, the resource waste would be significant because of the short but high-bandwidth reservation #4 and the distance in time between #4 and #5. Therefore, limits in the maximum difference in bandwidth between reservations (Δbw) and the time period between the end of one reservation and the beginning of the next (Δt) have to be taken into account when selecting which reservations should be consolidated.

The initiating ESDC needs to handle the WAN reservations on the one hand, and the configuration of both end sites on the other. Although basic WAN reservation primitives can be used for consolidating reservations, additional primitives may be necessary to streamline the process and make it effective. Using basic primitives, the ESDC can create a new WAN reservation (for a dynamic L2 circuit this requires at least one VLAN tag to be available) to accommodate a newly arrived reservation that fulfills the criteria to use a specific circuit. If the circuit is pending, the consolidated WAN reservations can be immediately cancelled. However, if the circuit is already active, all relevant traffic must be switched to the new VLAN before the cancellation. With L3 circuits, this switching is not necessary. A problem with this technique is that the submission of the new WAN reservation may fail due to lack of available bandwidth occupied by reservations that will be cancelled. A new WAN primitive, allowing the submission of a reservation while taking into account the simultaneous cancellation of a set of existing ones would greatly increase the efficacy of the technique.

If the WAN domain controller allows modification of its reservations to a certain degree, it is possible to extend a reservation time-wise and/or to modify its bandwidth. While time-wise modifications are straightforward and are contingent on resource availability, bandwidth modifications need to be considered not only with regard to when they should take place within active or pending reservations, but also with regard to what the repercussions will be for existing connections through an active circuit which may be interrupted during reconfiguration.

We consider here two optimization and consolidation techniques for WAN reservations. We assume that initially WAN reservations correspond 1-to-1 to end site reservations. However, committing a reservation and deactivating a reservation are events triggering an optimization and consolidation phase for the WAN reservations. In both event cases, active or pending reservations within specific time "distance" before the beginning and/or after the end of a new reservation can be selected for consolidation. These techniques are roughly analogous to disk buffering or caching, i.e., "read ahead" and "write behind". The goal of disk caching is to maximize the utilization of the disk and speed up access by buffering as much data as possible with read operations and before write operations. In a similar sense, selecting WAN reservations based on optimization criteria (e.g. reduce waste of resources) and consolidating them maximizes the utilization of a circuit and reduces the number of expensive create and teardown operations. We thus call these two techniques "create ahead" and "teardown behind."

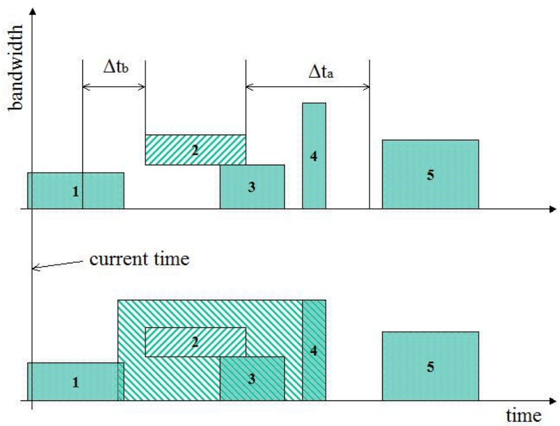

Fig. 8. An example of "create ahead". #2 is a new reservation. Circuit corresponding to #1 is modified to accommodate #2, #3, and #4 with a single reservation. #5 is too distant.

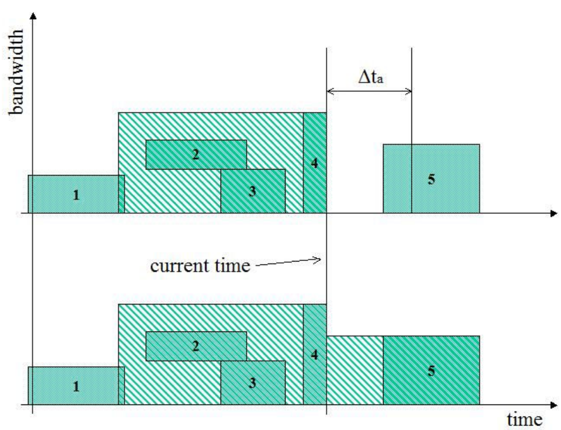

Fig. 9. An example of "teardown behind". When #4 expires, the circuit servicing #2, #3, and #4 is not torn down, but instead modified to accommodate #5.

"Create ahead" (see figure 8) selects WAN reservations within Δt_b before the start of a new reservation and Δt_a after the end of a new reservation for consolidation, if additional limits in bandwidth differences and time distance are met. To reduce waste of resources, the second technique "teardown behind" (see figure 9) modifies a unified reservation to conform to the bandwidth requirements at the time when the corresponding end site reservation expires by consolidating WAN reservations within Δt_a after the expiration of the end site reservation. The net result of the combination of the two techniques is to reduce the number of required circuits and the frequency of circuit creation and teardown operations for circuits between the same end sites while also reducing the waste of WAN resources.

V. Fault Tolerance Issues

In the event of a circuit failure, for any reason, flows that are being directed into that circuit will be interrupted, causing the corresponding applications to lose their connections. To prevent such situations, TeraPaths utilizes active circuit probing at the network device level. In this context, the end site network devices (border routers) that are the end points of a WAN circuit, periodically or on-demand exchange probes through that circuit for the duration of each related reservation. When a failure is detected, the immediate step is to stop forwarding traffic into the failed circuit and fall back to the standard IP network. The next step is to attempt to acquire a new circuit and redirect traffic back into it (see figure 10), while extending the reservations by the amount of time lost. The latter step is subject to WAN circuits becoming available again. Therefore, TeraPaths will keep trying for a pre-determined amount of time after which the reservation will be considered failed.

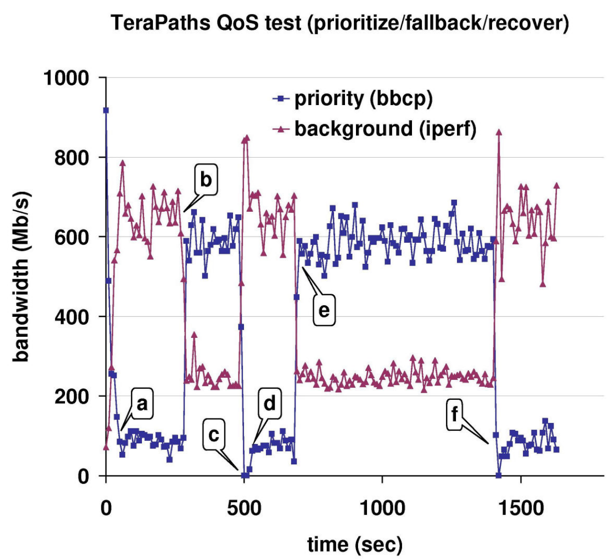

Fig. 10. Demonstration of recovery: (a) competing traffic causes drop in bandwidth, (b) QoS/circuit reservation active, (c) circuit failure, (d) fall back to best effort, (e) recovery (acquired new circuit), (f) end of reservation.

With frequent periodic probes, it is possible to catch a circuit failure early and attempt to remedy the problem so that applications don't lose their connections. This approach is transparent to applications, however, it can impose significant load on the network hardware with increasing number of reservations. Thus, only highly critical reservations should be safeguarded with frequent periodic probing. A more scalable solution is to make applications aware of the probing/recovery capabilities (TeraPaths exposes these capabilities through its API) and enable them to trigger probing and recovery on-demand.

VI. Related Work

Lambda Station [10] is a Fermi National Accelerator Laboratory (FNAL) project with the goal to provide specific data intensive applications with alternate network paths between local production computing resources and advanced high performance networks. The Lambda Station service selectively forwards authorized data flows to alternate network paths, allowing such flows to utilize premium high bandwidth connections between end sites.

Phoebus [11], an Internet2 project, is a framework and protocol for high-performance dynamic circuit networks. The Phoebus approach is to split the end-to-end network path into distinct segments at "adaptation" points located at backbone ingress and egress points, then find and create an optimized network path for a specific application from each such point. Application-generated traffic between end sites is redirected to the circuit network via Phoebus Gateways.

While TeraPaths, Lambda Station, and Phoebus are all "consumers" of WAN circuits through OSCARS, TeraPaths is unique in that it uses DiffServ QoS and traffic conditioning at the edges to provide QoS guarantees to each individual flow within a group of flows going through the same WAN circuit and utilizes WAN circuit reservation consolidation techniques to practically address scalability issues.

VII. Conclusion and Future Work

New network capabilities enable the establishment of end-to-end QoS-aware paths across multiple domains, paths that can be dedicated to individual data flows. Although the overall framework is in its first steps, the technology is promising as it coexists with standard best-effort networking and is accessible transparently to specific data flows. We discussed the issues involved with the utilization of WAN circuits from the perspective of end sites and presented techniques that the TeraPaths system utilizes for addressing the problem of scalability with increasing number of flows. Effective resolution of this problem will make the technology applicable to an ever-growing number of data flows between end sites and will enable effective network scheduling.

The TeraPaths team continues the research and development effort to improve the functionality and reliability of the TeraPaths framework, in close collaboration with the OSCARS developers. Our near future plans include study and evaluation of the reservation management techniques presented in this paper to adopt parameter ranges for practical use. In the longer term, we intend to incorporate the framework into a more general, application-centric network virtualization system. This system will provide individual applications with on-demand guaranteed network resources dedicated and tuned to their needs while isolating them from interference from other applications and strengthening security.

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