Traffic Engineering Solutions for Core Networks

A Paper in the Backbone Network and Business Solutions Series

TECHNICAL PAPER

ALCATEL

ARCHITECTS OF AN INTERNET WORLD
Abstract

An explosion of data in all its forms is changing the face of the global marketplace. Increasing numbers of adventurous Internet companies are offering new web-based products and services to consumer and corporate markets. As this market evolves, IP is emerging as the standard for global interworking, but a critical requirement is also becoming evident — the need for a true multiservice network that can support multiple applications via a single carrier. This network is the next generation network (NGN).

As this network emerges, backbone carriers must ensure that the IP core keeps up with increasing traffic volumes reliably and cost-effectively. In addition, they must prove their ability to integrate best-effort traffic with the quality of service (QoS) demands of real-time applications that need a predictable and protected service. This requires an intelligent and optimized mapping of customer traffic flows onto a physical topology over a geographic area — an operation known as traffic engineering (TE).

Traditionally, carriers have allowed interior gateway protocols (IGPs) to determine the shortest path to a destination but, today, new methods are emerging to improve load distribution, eliminate bottlenecks and facilitate greater network scalability. TE tools are designed to control the traffic flow through a network, offering services according to customers’ specific requirements while using network resources efficiently and economically.

Carriers are using several mechanisms for TE. This paper examines various TE mechanisms in different core environments, starting with the traditional router-based core. In this network, carriers could rely on the manipulation of routing metrics. This approach was appropriate when Internet backbones contained fewer routers and links, and less traffic. Today, metric manipulation is unsuitable for the growing Internet because this TE mechanism lacks scalability and does not provide even distribution of traffic based on bandwidth availability or traffic characteristics.

In an asynchronous transfer mode (ATM) overlay network, the path of ATM PVCs can be controlled so that transport resources are used more efficiently and strict QoS guarantees can be given. This introduces true QoS-aware TE into the network; however, the ATM overlay solution also presents some challenges for carriers in terms of the complexity of managing two technologies, the \( n \) squared PVC problem, core technology, triggered the quest for a new paradigm that would combine the control of ATM with the simplicity and the cost-effective scalability of IP. The answer was multiprotocol label switching (MPLS).

Alcatel’s core ATM/MPLS multiservice solution is based on the Alcatel 7670 Routing Switch Platform (RSP), a next generation routing switch that offers the reliability and services of an ATM core switch, integrated with a label switch router (LSR) to support IP services with MPLS. The Alcatel 7670 RSP allows network operators to scale their ATM clouds and evolve toward IP using MPLS as a stepping stone.

For IP core networks, MPLS provides a means to counter the limitations of shortest path routing by moving traffic onto label switched paths (LSPs). It establishes a virtual connection between two points on an IP network, maintaining the flexibility and simplicity of an IP network while exploiting the ATM-like advantage of a connection-oriented network.

As for MPLS TE, Alcatel recommends a combined offline/online TE solution. An online approach employs the core router itself for path computation and selection, using a constrained shortest path algorithm known as constraint-based routing or constrained shortest path first (CSPF) to compute shortest routes, taking into account certain constraints, such as available bandwidth. Path establishment takes place using a signaling component. Because online TE determines paths one at a time, the order in which the paths are calculated is critical in determining their physical routes across the network. A robust offline tool is still required to optimize the network globally because it simultaneously examines the total topology, including constraints and unique requirements, and performs global calculations to select and reshuffle optimal paths across the entire network.

Alcatel’s TE solution for MPLS is based on a high performance, fully MPLS-enabled core portfolio, giving network operators control and availability. This solution also includes the first centralized, fully automatic TE tool in the industry — the TE feature, which increases network fairness and throughput by as much as 20 percent and 25 percent, respectively. The TE feature offers intelligent adjustable path protection and can assist in network planning and disaster analysis through powerful simulations and what-if scenarios.

The combined online/offline TE solution enables service providers to gain control over their traffic by rolling out a stable and reliable network core that paves the way to the NGN.
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Alcatel's market leadership in optical transmission, multiservice switching and new generation routing enable us to help service providers put in place networks that will evolve into a transparent and coordinated data/optical next generation network.

This document is part of a series of technical papers on Alcatel's Backbone Network and Business Solutions. Through these papers, we illustrate that Alcatel understands the full breadth and depth of the backbone service provider’s issues and has solutions to address these challenges.
1. Introduction

Exponential Internet data traffic growth continues to drive the need for a new generation network architecture. Smart technology-savvy businesses are turning to the Internet to create a virtual global marketplace for new products and services. This widely acknowledged trend, despite the recent economic slowdown, is characterized by an explosion of data network traffic in all its forms.

This boom is occurring in both the consumer market, with Internet browsing, audio and video streaming, and in the corporate market, with virtual private networks (VPNs), local area network (LAN) interconnections, Internet access, intranets and extranets. Because most of these data services are based on the Internet protocol (IP), this technology is emerging as the standard for global interworking — but the changing face of the network is not only about IP. To support the specialized requirements of emerging applications, the current Internet must evolve into a reliable, truly "multiservice" network. It must be able to transport the multitude of different applications via a single, carrier grade network — the next generation network.

Unprecedented growth in users and applications, coupled with the emergence of broadband access networks, is presenting these carriers' carriers with a traffic increase of more than 100 percent every year. As the data network evolves into a critical communications network, backbone carriers must ensure that the core keeps up with phenomenal traffic volumes of any type, reliably and cost-effectively.

IP core networks are also expected to integrate best-effort data with the quality of service (QoS) demands of applications such as voice, interactive television, videoconferencing, etc. These real-time applications require a very predictable and protected service.

Addressing these challenges requires an optimized and intelligent mapping of customer traffic flows onto a physical topology over a geographic area. Until now, backbone wholesale carriers allowed the routing protocols — interior gateway protocols (IGPs) such as open shortest path first (OSPF) and intermediate system-to-intermediate system (IS-IS) — to determine which path traffic would follow, simply the shortest path to the destination. However, because of the network topology, this approach results in a load distribution that is far from optimal, causing recurrent points of congestion and bottlenecks. A few links are overutilized, while other subsets of the network remain underutilized, complicating network scalability.

Overdimensioning is a common solution to the problem of unforeseeable bottlenecks, but in today’s highly competitive environment for service provisioning, it does not provide an economically viable answer for the long term. As networks grow more quickly and customer demands increase, service providers need to approach the mapping of traffic flows onto physical topologies in a fundamentally different way, to control and support the traffic load more efficiently. In other words, service providers need to “get a grip” on their traffic, to be able to scale the network while fulfilling customer demands.

The goal of traffic engineering (TE) is exactly that: to control the traffic flow through a network, offering services according to customers’ specific requirements, while utilizing network resources in an economical way. Effective TE takes into account current and future traffic demand, as well as individual customer needs for bandwidth, QoS, reliability and availability, often governed by service level agreements (SLAs). The best TE solutions also allow for “what-if” scenarios that can be used for capacity and disaster risk analysis.

When integrated into a complete operations support system (OSS), a TE solution is the key to providing bandwidth brokerage. It offers the ability to control whether a new customer can be served with the required new connection (i.e., as part of a VPN, taking into account all QoS measures) and how this connection can be established.

This technical paper studies various TE mechanisms and their suitability for the next generation core. Metric adaptation, asynchronous transfer mode (ATM) and multiprotocol label switching (MPLS) are all mechanisms for TE. Alcatel's centralized, offline global TE solution is introduced, outlining its advantages over current techniques. The future direction of TE applications is addressed, as well as the integration of TE into a complete OSS. Along the way, the various mechanisms will be applied and illustrated in Alcatel TE solutions that are available today.
2. Traffic Engineering Solutions

2.1 Traffic Engineering Defined

TE is the mechanism for mapping customer data flows onto an existing physical topology. It implements a process for routing data through the network according to a view of resource availability and the current and expected traffic volume. The class of service (CoS) and QoS that the data requires could also be factored into this process.

TE may be under the control of manual operators, who monitor the state of the network and route the traffic or provision additional resources to compensate for problems as they arise. Alternatively, TE may be driven by automated processes reacting to information that has been fed back through routing protocols or other methods.

TE helps the network operator make the best use of available resources by spreading the traffic load over the physical links and allowing some links to be reserved for certain classes of traffic or for particular customers.

TE should give operators precise control over the placement of traffic flows within their own routed domains, called autonomous systems (ASs). It enables the operators to move traffic flows away from the shortest path selected by the IGP and onto a potentially less congested physical path across the AS, as shown in Figure 1.

Network operators can use TE to balance the traffic load over various links, routers, and switches in the network, so that none of these components is overutilized or underutilized. This load balancing enables them to exploit the economies of the bandwidth that has been provisioned across the entire network. TE should be thought of as assistance to the routing infrastructure — it provides additional information that can be used when forwarding traffic along alternate paths across the network.

2.2 Traffic Engineering in the Traditional Router-based Core

In the early 1990s, IP core networks consisted of routers interconnected by leased lines — T1 (1.5 Mb/s) and T3 (45 Mb/s) links. When the Internet began its growth spurt, the demand for bandwidth increased faster than the speed of individual network links. Service providers responded to this challenge by simply provisioning more links to provide additional bandwidth. At this point, TE in the router-based core became even more important to service providers because it would enable them to use the aggregated bandwidth more efficiently by load balancing the traffic over the available parallel or alternative paths.

2.2.1 Traffic engineering mechanism

In IP router-based cores, TE was achieved by simply manipulating routing metrics. Metric-based control was adequate because Internet backbones were much smaller in terms of the number of routers, number of links, and amount of traffic. Also, in the days before the tremendous popularity of the any-to-any World Wide Web (WWW), the Internet’s topological hierarchy forced traffic to flow across more deterministic paths, and events on the network did not create temporary hot spots.

Figure 1: IGP Shortest Path vs. Traffic Engineered Path
In Figure 2, assume that Network A sends a large amount of traffic to Network C and Network D. With the metrics shown in Figure 2, Links 1 and 2 might become congested because both the Network A-to-Network C and the Network A-to-Network D flows transit those links. If the network operator changed Link 4’s metric to “2”, the Network A-to-Network D flow would be moved to Link 4, but the Network A-to-Network C flow would remain on Links 1 and 2. As a result, the network hot spot would be fixed without causing problems in any other part of the network.

2.2.2 Limitations of a traditional routed core for traffic engineering
Metric-based traffic controls provided an adequate TE solution until the mid-1990s. By this time, however, many service providers networks had grown exponentially, and they simply could not move forward with either metric-based traffic controls or router-based cores. Traditional routed cores had begun to present a number of TE challenges:
- TE based on metric manipulation is not scalable. As core networks become more richly connected (that is, bigger, more thickly meshed and more redundant), it is difficult to ensure that a metric adjustment in one part of the network does not cause problems in another part. TE based on metric manipulation offers a trial-and-error approach rather than a scientific solution to an increasingly complex problem.

2.3 Traffic Engineering Through an ATM Overlay Network
Around the mid 1990s, the volume of Internet traffic escalated to a point at which network operators needed to migrate their networks to support trunks that were larger than T3 (45 Mb/s). Fortunately, at this time, OC-3/STM-1 ATM interfaces (155 Mb/s) became available for switches and routers. To obtain the required speed, operators redesigned their networks to use the higher speeds and traffic management features supported by a switched ATM core. Some service providers transitioned from a network of DS3 point-to-point links to routers with OC-3/STM-1 ATM segmentation and reassembly (SAR) interfaces at the edge and OC-3/STM-1 ATM switches in the core. Then, after a period of six to nine months, the links between core ATM switches were upgraded to OC-12/STM-4 (622 Mb/s). Other network operators began by increasing the mesh of their DS3 frame relay networks. When they began the transition from frame relay to ATM, they relied on OC-3/STM-1 at the edge but immediately deployed OC-12/STM-4 interswitch links in the core (see Figure 3 on page 4 for an example of the resulting mesh topology).

2.3.1 Traffic engineering mechanism
When IP runs over an ATM network, routers surround the edge of the ATM cloud. Each router communicates with every other router by a set of permanent virtual circuits (PVCs) that are configured across the ATM physical topology. The PVCs function as logical circuits, providing connectivity between edge routers. The routers do not have direct access to information describing the physical topology of the underlying ATM infrastructure; they recognize only the
individual PVCs that appear to them as simple point-to-point circuits between two routers. Figure 4 illustrates how the physical topology of an ATM core differs from a logical IP overlay topology.

In most cases, the PVC paths and attributes are globally controlled and optimized by a central network management system (NMS) based on link capacity and historical and anticipated traffic patterns. The NMS can also calculate a set of secondary PVCs to respond to failure conditions and offer path protection for critical applications. After the globally optimized PVC mesh has been calculated, the supporting configurations are downloaded to the routers and ATM switches to implement the single or double, full mesh logical topology (see Figure 5).

The ATM and IP networks meet when ATM PVCs are mapped to router subinterfaces. Subinterfaces on a router are associated with ATM PVCs, and then the routing protocol associates IP prefixes (routes) with the router subinterfaces.

Finally, ATM PVCs are integrated into the IP network by running the IGP across each of the PVCs to establish peer relationships and exchange routing information. Between any two routers, the IGP metric for the primary PVC is set
to be preferred over the backup PVC. This guarantees that the backup PVC is used only when the primary PVC is unavailable. When the primary PVC becomes available after an outage, traffic is automatically returned to it from the backup.

### 2.3.2 Benefits and limitations of ATM for TE

#### Benefits

ATM offers precise control over traffic as it flows across the core network. Many network operators rely on the deterministic performance and traffic management functionality that ATM switches provide to successfully manage the operation of a multiservice network. Indeed, besides transporting IP best-effort services, the ATM multiservice core is also capable of transporting delay-sensitive broadband applications.

Furthermore, an ATM-based core fully supports TE because it can explicitly route PVCs by provisioning an arbitrary virtual topology on top of the network’s physical topology. In this virtual topology, PVCs are routed to precisely distribute traffic across all links, making them evenly utilized. This approach eliminates the “traffic magnet” effect of least cost routing, which would result in overutilized and underutilized links.

Per PVC statistics provided by ATM switches enable operators to monitor traffic patterns for optimal PVC placement and management. Network designers initially provision each PVC to support specific TE objectives, and then constantly monitor the traffic load on each PVC.

If a given PVC begins to experience congestion, the operator has the necessary information to remedy the situation by modifying either the virtual or physical topology to accommodate shifting traffic loads.

#### Limitations

In the mid-1990s, ATM switches were selected for their unparalleled ability to provide high speed interfaces, deterministic performance, QoS and TE through the use of explicitly routed PVCs. Today, these features are still well appreciated to carry and aggregate the traffic coming from broadband access networks such as digital subscriber line (xDSL), local multipoint distribution system (LMDS), etc. In the Internet inner IP core, however, high-end IP core routers are beginning to support these same features. The latest advances in routing technology are causing service providers to evaluate the pros and cons of the ATM overlay model for the inner core — it provides perfect traffic control and absolute service guarantees but also implies higher operational costs and greater complexity.

An ATM overlay model requires that two different technologies — an ATM infrastructure and a logical IP overlay — be maintained and managed. Also, in a pure overlay model, routing and TE occur on different sets of systems — routing executes on the routers and TE runs on the ATM switches — making it difficult to fully integrate the two processes.
While ATM switches can currently scale up to high interface speeds of OC-192/STM-64, the deployment of these speeds in a cost-efficient way poses challenges. Service providers can scale the ATM cloud at their own speed, but must take into account the operational challenges of managing two technologies for IP service.

2.3.3 The Alcatel core ATM/MPLS multiservice solution

The emergence of broadband access solutions — DSL, LMDS, etc. — still imposes the need for a scalable ATM cloud to aggregate and carry broadband traffic. However, in the inner core, to an increasing degree, a pure IP routing solution offers the simplicity and scalability needed to cope with massive IP traffic growth cost-effectively. Consequently, in the edge or legacy ATM core, service providers see the need for a stable and proven ATM cloud, which will allow them to scale and provide an evolution to IP. Today, this environment requires multiprotocol routing switches that give service providers an efficient, scalable migration path.

Alcatel, a chief proponent of this evolution, has developed the Alcatel 7670 Routing Switch Platform (RSP) to ease the transition from ATM to pure IP. The Alcatel 7670 RSP is a next generation routing switch that offers the reliability and services of an ATM core switch integrated with a label switch router (LSR) to support IP services with MPLS. This platform allows service providers to scale the ATM cloud and evolve to IP using MPLS (discussed further in section 2.4) as a stepping stone. The Alcatel 7670 RSP eases the transition from ATM to IP/MPLS at the service provider’s own speed, allowing capacity for all protocols while not forcing networks into a specific technology.

To give service providers immediate, proven stability, QoS and traffic management, the Alcatel 7670 RSP is rich in ATM capabilities. Service providers can scale multiservice networks as required to meet strong growth in broadband access solutions and the demands of an increasing number of users. At the same time, the unit’s ability to function as a high performance LSR leverages the similarities between MPLS and ATM, as well as Alcatel’s worldwide reputation for carrier grade ATM equipment. With these capabilities, service providers can use the Alcatel 7670 RSP for ATM PVC TE, while also utilizing MPLS, the new TE paradigm.

For routing and signaling, the Alcatel 7670 RSP architecture provides dual shared control planes: IP/MPLS protocols and ATM protocols. This shared control infrastructure allows the service provider to optimize traffic management across multiple protocols (ATM, MPLS, IP) by using the same underlying management functions.

The multiprotocol nature of the Alcatel 7670 RSP also extends to the data plane, which encompasses the switch fabric and the line interface cards, and is designed to support packet-based and cell-based flows. By separating routing/system functions from packet forwarding functions, the Alcatel 7670 RSP achieves true wire-speed performance at all times. Figure 6 shows the functional components of the Alcatel 7670 RSP, including the structure of the control plane and data plane.

Alcatel network management and service assurance

The Alcatel 5620 Network Manager (NM), enriched with the Alcatel 5620 Performance Module and the Alcatel 5620 Service Level Agreement (SLA) Module (see Figure 7), support a comprehensive set of fault, configuration and performance management capabilities, as well as accounting and security functions to help the service provider manage a multiservice core. The Alcatel 5620 NM simplifies and automates provisioning of ATM PVCs and MPLS LSPs for TE or Layer 2 VPNs. Furthermore, the Alcatel 5620 NM allows operators to
specify primary and secondary paths with reserved bandwidth, so that critical paths can be protected and service guaranteed in the event of failover.

A network simulator is provided to test and model network resources during TE activities. This is useful for studying changes to the existing network, testing upgrade scenarios, and simulating network failures and re-route scenarios. The Alcatel 5620 NM also offers the traffic engineer a reporting system that generates statistics and information about traffic volume, network congestion and error conditions.

IP route exchange with an IGP requires direct peering/adjacency with all neighbors. Therefore, the network deploys a full mesh of ATM PVCs, which creates the traditional \( n^2 \) problem, that is, if the service provider has \( n \) routers, there is a need to add \( n-1 \) new PVCs every time a router is introduced into the network. If a service provider wants to use an ATM overlay to traffic engineer a small or moderately sized IP network, the \( n^2 \) problem is not a critical issue. However, for a predominantly IP router environment with hundreds of attached routers, the challenge is significant. Switched virtual connections (SVCs) provide a means of overcoming the \( n^2 \) problem for a primarily ATM environment, but service providers may still find it a challenge to manage them quickly and easily in an IP environment.

### 2.4 Traffic Engineering Using MPLS

When Internet usage took off in the early 1990s, the performance limitations of routers created serious network bottlenecks. The routers in the network core were replaced by ATM switches, which demonstrated superior forwarding performance and enhanced traffic management features. The Internet backbone architecture evolved into a set of low capacity edge routers interconnected by PVCs across an ATM network, overcoming the forwarding capacity limitations of routers. Moreover, this architecture allowed network operators to control traffic flows across their networks. The path of ATM PVCs across ATM networks could be managed to distribute traffic equally and use transport resources more efficiently. Thus, TE for IP networks was born.

Evolution of chip technology was an important factor in overcoming the forwarding capacity limitations of IP routers. Today, application specific integrated circuits (ASICs) and network processor units (NPUs) for IP address lookup can handle millions of packets per second, enabling terabit routers with interface capacities of up to OC-192/STM-64. In this respect, routers can outperform ATM switches and, gradually, the ATM core of IP backbones is being replaced by a meshed network of IP terabit routers. However, traffic flow is still bound to the shortest path routing decisions of IP routing protocols, leading to bottlenecks and underutilized network resources.

To counter the limitations of shortest path routing, the Internet Engineering Task Force (IETF) proposed MPLS — an algorithm that moves traffic away from the shortest path selected by the IGP onto label switched paths (LSPs). MPLS brings connection-oriented forwarding techniques together with the Internet’s routing protocols by establishing a virtual connection between two points on an IP network. The simplicity and flexibility of an IP network remain intact, while the ATM-like advantage of a connection-oriented network is exploited. This hybrid architecture can emulate connection-oriented services, but normal datagram mechanisms are used to deliver conventional IP services. Since the overhead required for connection emulation is incurred only for the services that require it, the cost of running the network is minimized.

![Figure 7: Alcatel Network Management and Service Assurance](image-url)
Using MPLS incorporates four key steps:
- Path computation
- Path establishment
- Path selection
- Packet forwarding

### 2.4.1 MPLS concepts

#### Path computation

The route taken by an LSP through the network is determined by path computation. This process can take place online in real time in the network nodes themselves, or offline on a workstation using a centralized application that determines routing plans on behalf of each router. Online (distributed) and/or offline (centralized) path computation is key to the optimization of traffic loads across the network and will be discussed in more detail in the next sections.

#### Path establishment: Label distribution

A path is established using one of two standardized signaling protocols: Resource reservation protocol (RSVP) with extensions, or constraint-based routed label distribution protocol (CR-LDP). During path setup, labels are exchanged between LSRs (i.e., routers that support MPLS), and these labels are used during packet forwarding. (see, “Path selection and packet forwarding” for further details).

Two kinds of paths can be established: explicit paths and shortest paths. Shortest paths form the normal IGP routes. An explicit path, however, is one whose route is determined in advance and can be different from the shortest path route. (In Figure 9, the explicit path is the solid line between the LSR in Los Angeles and the LSR in New York via the two other routers.) The ability to set up explicit paths is an important element of traffic engineering because it enables network operators to distribute the traffic load more evenly.

#### Path selection and packet forwarding

At an ingress LSR (i.e., the router where an LSP starts; in Figure 9, the LSR in Los Angeles), incoming packets are sent on the LSP according to their forwarding equivalence class (FEC). An FEC is a group of IP packets with the same destination and forwarding treatment. A packet can be assigned to an FEC based on parameters such as packet ingress point, or fields in the IP header (destination address, forwarding treatment such as Differentiated Services codepoint [DSCP]).

The FEC is encoded in a label — a short, fixed-length identifier that is attached to the packet. A transit LSR forwards packets based on the information contained in the label and the interface on which the packet came. The IP header is not consulted. The lookup in the label information base (LIB) determines the packet’s outgoing interface and new outgoing label. This process is called label swapping.

When the packet arrives at the egress LSR (i.e., the router where an LSR ends; in Figure 9, the LSR in New York), the router strips off the label and forwards the packet as a regular IP packet. That is, it determines the outgoing interface by looking up the destination address in its routing table.

#### Path protection

As a connection-oriented model, MPLS enables traffic to be redirected quickly from a broken connection to an alternative connection, and on to the same destination. In IP networks, restoration time is significantly longer because the routing protocols must converge before service can be restored.

MPLS allows network operators to choose between different path protection strategies. With fast rerouting, if a repair can be made locally to the device that detects the failure, then restoration can be made without serious service disruption. Fast restoration such as this can happen in the same time as SONET restoration.
However, fast restoration often creates non-optimal paths, so an active standby protection technique is also available. The ingress LSR is notified of the failure and nondisruptively redirects traffic to a more optimal path, using a make-before-break strategy in which a new connection is established before the old one is torn down.

Advantages of MPLS
Many people believe that MPLS in and of itself significantly enhances the forwarding performance of LSRs. It is more accurate to say that exact match lookups, such as those performed by MPLS and ATM switches, have historically been faster than the longest match lookups performed by IP routers. However, recent advances in silicon technology allow ASIC and NPU-based route look-up engines to run just as fast as MPLS or ATM VPI/VCI look-up engines.

The true benefit of MPLS technology is that it provides a clear separation between routing (that is, control) and forwarding (that is, moving data). This separation allows the deployment of a single forwarding algorithm that can be used for multiple services and traffic types. In the future, as service providers look to develop more and more new revenue generating services, the MPLS forwarding infrastructure can remain the same while new services are built by simply changing the way that packets are assigned to an LSP. For example, packets could be assigned to an LSP based on a combination of the destination subnetwork and application type, a combination of the source and destination subnetworks, a specific QoS requirement, an IP multicast group, or a VPN identifier. In this manner, new services can easily be migrated to operate over the common MPLS forwarding infrastructure.
2.4.2 Online MPLS traffic engineering, constraint-based routing

In online or distributed TE, LSRs are used for path computation and selection. Online computation typically uses an enhanced shortest path algorithm, or an adaptation generally denoted by constraint-based routing. Constraint-based routing is a class of routing algorithms that computes shortest routes through a network subject to a set of constraints and requirements, including bandwidth, delay (expressed as a maximum number of hops), and policy instruments, such as resource class attributes.

Since constraint-based routing considers not only the topology, but also additional link properties (i.e., maximum link bandwidth, currently reserved bandwidth, link colors, etc.), additional network resource attributes are flooded to the routers using extensions to the link state IGPs, such as OSPF and IS-IS. Constraint-based routing policy instruments enable network operators to assign links to a certain resource class, for example. An operator could assign transatlantic links to the resource class “Transatlantic,” overprovisioned links to resource class “Predictable,” satellite links to resource class “Satellite,” etc. When a customer asks for a low delay connection between offices in Brussels and Rome, an LSP can be set up with the constraints “exclude Transatlantic and Satellite” and “include Predictable.”

Traffic engineering information distribution

TE requires a mechanism to distribute information about the network topology, as well as dynamic information about the network load. This mechanism can be implemented by defining relatively simple extensions to the IGP so that link attributes are included as part of each router's link-state advertisement (LSA). IS-IS extensions can be supported by defining new type length values (TLVs), while OSPF extensions can be implemented with opaque LSAs.

The standard flooding algorithm used by the link-state IGP ensures that link attributes are flooded to all routers in the service provider’s routing domain (AS). Each LSR maintains network link attributes and topology information in a specialized TE database (TED), which is used exclusively for calculating explicit paths for the placement of LSPs across the physical topology.

The following TE extensions are added to the IGP advertisements:
- Maximum link bandwidth
- Maximum reservable link bandwidth
- Current bandwidth reservation
- Current bandwidth usage
- Link color

Path computation (CSPF, Constraint-based routing) and LSP setup

After network link attributes and topology information are flooded by the IGP and placed in the TED, each ingress LSR uses the TED to calculate the paths for its own set of LSPs across the routing domain. The path for each LSP can be represented by either a strict or loose explicit route. An explicit route is a preconfigured sequence of LSRs that should be part of the physical path of the LSP. If the ingress LSR specifies all the LSRs in the LSP, the LSP is identified as a strict explicit route. However, if the ingress LSR specifies only some of the LSRs in the LSP, the LSP is a loose explicit route. Support for strict and loose explicit routes allows the path computation process to be flexible whenever possible but constrained when necessary.

The ingress LSR determines the physical path for each LSP by applying a CSPF algorithm to the information in the TED. CSPF is a shortest path first algorithm that has been modified to take into account specific restrictions when calculating the shortest path across the network. (This is also referred to as constraint-based routing.)

Input into the CSPF algorithm includes:
- Topology link-state information learned from the IGP and maintained in the TED.
- Attributes associated with the state of network resources (such as total link bandwidth, reserved link bandwidth, available link bandwidth and link color) that are carried by IGP extensions and stored in the TED.
- Administrative attributes required to support traffic traversing the proposed LSP (such as bandwidth requirements, maximum hop count and administrative policy requirements) that are obtained from network operator configuration.

As CSPF considers each candidate node and link for a new LSP, it either accepts or rejects a specific path component based on resource availability and on whether selecting the component violates user policy constraints. The output of the CSPF calculation is an explicit route consisting of a sequence
of LSR addresses that provides the shortest path through the network that meets the constraints. This explicit route is then passed to the signaling component (RSVP extensions), which establishes the forwarding state in the LSRs along the LSP. The CSPF algorithm is repeated for each LSP that the ingress LSR is required to generate.

2.4.3 Limitations of online traffic engineering
The advantages of online TE stem mainly from the fact that it is fast and simple, and that it works in a dynamic fashion. Unfortunately, the advent of more complex services (such as DiffServ) and increasing performance and survivability demands reveal some of its drawbacks.

The disadvantages of online TE are related to the optimization that takes into account all traffic trunks in sequence as they are proposed to the network. This approach is not deterministic — the order in which LSPs are calculated plays a critical role in determining their physical paths across the network. There is no way of ensuring that the order in which the trunks are set up leads to an optimal solution. In fact, in many cases, much traffic is blocked because of this system. Suppose, for instance, that a large trunk on a long path is routed first. Many resources will be attributed to this trunk, so it is possible that there will be an inadequate number of remaining resources to handle the requirements of subsequent trunks. In order to react appropriately to changing traffic patterns, it is necessary to be able to reroute previously established trunks if they obstruct a better routing configuration.

This suboptimal condition becomes even more serious when traffic needs to be protected with backup paths. Online algorithms can handle the combined constraints of both a primary and a protection path. However, this is limited to a 1-to-1 protection mode — network operators must configure a dedicated backup path for every primary path. It is clear that far more efficient solutions can be achieved if protection bandwidth can be shared among trunks that have working paths that are assumed to be exempt from simultaneous failure. Indeed, most protection schemes consider only single link and/or node failures, in which case fully node and link disjoint working paths cannot fail simultaneously. Sharing protection capacity (in a so-called shared protection scheme) leads to more efficiency in the network. This requires a view of all trunks and their paths through the network. Network operators can overcome the limitations of online TE by combining it with offline centralized TE, as discussed in the next section.
Finally, the use of only online TE in QoS-aware networks is questionable. In such networks, some traffic flows need to be offered with low loss or low latency guarantees. Although online algorithms could be extended to take QoS requirements into account for each trunk, an online algorithm will not be able to estimate the impact of this new trunk on the QoS characteristics of existing trunks. This requires a view of all trunks, their paths, and the load changes along these paths when a new trunk is introduced.

Delay and delay jitter are typically related to buffer occupancy, which in turn is related to the load at each given node. Therefore, online algorithms cannot be used for the QoS provisioning required in a DiffServ network, which must be able to offer low loss or low latency guarantees to the flows that require them.

2.4.4 Offline traffic engineering

Despite the fast provisioning and reduced management effort resulting from online path calculation, an offline tool is required to optimize TE on a global scale. In most cases, a combination of offline (centralized) and online (distributed) TE is the most beneficial approach, combining the best of both mechanisms.

An offline tool simultaneously examines each link's resource constraints and the requirements of each ingress-to-egress LSP. The offline approach can take several minutes to several hours to complete; it performs global calculations, compares the results of each calculation and then selects the best solution for the network as a whole. The output of the offline calculation is a set of LSPs that optimizes the use of all network resources. After the offline calculation is completed, LSPs can be established in any order because each is created following the rules for a globally optimized solution. In offline TE, two applications exist: planning tools and fully interactive TE tools.

A planning tool is not connected to the core network and runs isolated from the network. Therefore, the operator must enter the topology and load information manually. With an isolated planning tool, many parameters can be taken into account while running the computation/optimization process, but after this process, the operator will need to configure the network elements manually according to the output of the planning tool. Planning tools are mainly applied when analyzing network extensions every three to six months. Conversely, a fully interactive TE tool is directly connected to the live network. It interacts with the network to discover elements, topology and load information. The computation process runs in an offline global optimization application and can be triggered by the operator or, in some cases, by the network itself (e.g., when congestion occurs). After the optimization process, the interactive tool proposes a new set of LSPs, which will be provisioned on the live network automatically after operator confirmation. Consequently, besides network extension planning, the interactive TE tool can be used to maximize throughput and to provision existing MPLS networks.

2.4.5 Offline traffic engineering complements online traffic engineering

The problems related to a distributed TE approach can be solved by expanding the network view of the edge nodes. Each node should know all trunks, their paths, and their QoS requirements. When configuring a new trunk, all other network nodes should be informed, requiring some additional extensions to the routing protocols.

Even if all routers have the same, complete view of the topology and the trunks, they must also use the same online algorithm, but in a network with routers from multiple vendors, this situation is unlikely. Therefore, a solely distributed approach cannot possibly meet all needs.

Consistent TE decisions require centralized control of the TE configuration. A centralized approach obviates the need for any routing protocol extensions, since the tool knows the paths of the trunks and the load that they create. Yet, this tool needs to solve the complex problem of engineering every trunk and respecting QoS parameters and protection levels while at the same time minimizing the amount of spare capacity for restoration purposes. This global optimization can be achieved through the use of linear programming-based algorithms, or with heuristics.

Heuristic algorithms work quickly because they tend to make intelligent assumptions about the problem, reducing the number of variables to be optimized. They provide excellent results for specific problems, but they are less flexible and may be incapable of dealing with complex problems when it is difficult to identify the assumptions for reducing the number of variables.
Linear programming-based algorithms, on the other hand, provide a mathematical framework for solving a generic class of problems, which makes them far more flexible and reusable than heuristics. They can deal with the complicated optimization problems that arise from multiple path routing or shared protection schemes. Alcatel provides an offline centralized TE tool based on linear programming that describes the TE problem by means of an objective function and a set of constraints. This tool and its operation are described in more detail in the next section.

2.4.6 Alcatel’s solution for MPLS traffic engineering

Alcatel proposes a combination of online distributed TE and offline centralized TE. This solution allows network operators to provision simple trunk demands quickly using online TE while maximizing network throughput and improving path protection with offline TE.

Alcatel’s backbone solutions support the described MPLS TE mechanisms. Alcatel’s TE solution also supports the Cisco GSR Series Routers as well as the Juniper M-series Internet backbone routers. To support the evolution towards MPLS TE in the terabit IP/MPLS core environment, Alcatel provides the Alcatel 7770 Routing Core Platform (RCP). Alcatel complements this solution with the Alcatel 7670 RSP for the multiservice ATM/MPLS/IP core.

For global offline TE, Alcatel has developed the Alcatel 5620 TE feature, part of the 5620 NM Traffic and Service Optimization (TOS) Module, which is the first interactive TE feature available in the industry. The 5620 NM is an open platform that interworks with the Alcatel portfolio, as well as products from other vendors.

The Alcatel 7770 RCP provides up to 640 Gb/s in a single rack configuration. This high end, high capacity IP backbone router is designed specifically for the inner core close to the optical transmission infrastructure. Together with Alcatel optical products such as the Alcatel 1660 Optical Cross Connect and the Alcatel 1640 Wavelength Multiplexer, the Alcatel 7770 RCP provides not only high performance IP routing, but also a complete, interoperable solution for all layers of the optical IP core.

The Alcatel 7770 RCP fully supports the TE approach described above. Its high performance MPLS and G-MPLS implementation enables hardware label swapping when used as a transit LSP node, and line rate classification and lookup when used as an ingress LSP node. Backup LSPs are supported by fast swapping at the ingress LSP node.

Signaling support is implemented by RSVP and CR-LDP protocols. Bandwidth can be specified using single or multiple parameters, including MaxBitRate, MeanBitRate and BurstSize. The Alcatel 7770 RCP supports QoS aspects, such as label inferred LSPs (L-LSPs) and E-LSPs (MPLS experimental bits inferred). In a transit node, all LSPs are mapped into DiffServ queues. In the ingress node, L-LSPs can be mapped into either the DiffServ queues or a separate queue, which enables the fairness of per-LSP shaping. This flexible mapping is possible because the Alcatel 7770 RCP provides up to 2,048 queues per termination board.

When the Alcatel 7770 RCP is used as a non-DiffServ node, all LSPs in a transit node will be put into one separate queue, different from the best effort queue. This queue can receive bandwidth guarantees, introducing the notion of “better best effort.”

Constraint-based routing calculations are performed by the LSP head-end node using a TE database created through updates via OSPF or IS-IS extensions. Supported constraints include available bandwidth, administrative color and number of hops. The maximum hop count limitation can be used to control, to some extent, the expected delay for the paths. It is also capable of calculating maximum disjoint backup paths.

Global offline optimization with the Alcatel 5620 TE feature provides offline optimization of the Alcatel IP core in combination with other vendors’ IP core routers. It is the first open, fully automatic, interactive, centralized TE feature in the industry.

During the offline TE process, the TE tool first discovers the topology automatically along with the information about established LSPs, dynamic traffic load, reservation status, etc. After the discovery phase, the tool uses an intelligent linear programming-based algorithm to translate the user traffic demands (articulated in SLAs) into a global set of LSPs that makes optimal use of the network resources. After calculating the set LSPs in line with the negotiated SLAs, the TE feature automatically provisions the trunks after operator confirmation. This process can deliver gains of up to 20 percent fairness and 25 percent throughput without extra investments in networking gear.

Besides optimizing the network to increase predictability, fairness and throughput, the TE tool can also enable service differentiators such as intelligent path protection or simulation of “what-if” scenarios to assist in network planning and disaster risk assessment.
The TE calculations use the following data for input:
- Network topology: Description of nodes and links
- Traffic trunks: Bandwidth requirements
- Optional set of existing bandwidth allocations: Existing LSPs

If LSPs already exist in the network, the network administrator may choose to leave these LSPs (or a subset of these LSPs) unaltered and optimize only the available network resources.

Using sophisticated algorithms pioneered by Alcatel, the TE feature gives a complete set of explicit paths for each traffic trunk, allowing network operators to achieve an optimal balance of network traffic. The TE feature calculates the SPF paths that result from normal IGP operation. From this, the tool extracts the explicit paths that are not SPF paths and later implements this subset of paths as core edge to core edge MPLS LSPs (strict explicit route) on the physical network.

Alcatel's TE feature does not aim to introduce a full mesh of explicit routes in the core. The existing Layer 3 hop-by-hop routing is preserved, while one of its deficiencies is compensated for by introducing a number of explicit routes. Optimization similar to that achieved by a full mesh is obtained, but without the vast management overhead. The network operator must accept the TE feature's proposed explicit routes, in order for the feature to establish these routes in the network.

The optimization calculation also produces a number of quantitative indicators that express the network performance when using the recommended set of explicit paths. These indicators include:
- Link load matrix: Represents the load on every link in the network
- Share matrix: Indicates maximum achievable trunk capacity without violating the bandwidth requirements of other traffic trunks
- Integrated share: Measures the possible aggregate throughput with the given topology and the given set of paths

The TE feature allows the network operator to reserve and allocate resources for a hot-standby backup path in advance, so that the path will be ready to use in the event of primary path failure. In basic implementations, network resources for the backup path are reserved and allocated at the time of failure of the primary path, increasing the network downtime.

The TE calculation also supports link color (enabling the network operator to specify, for example, that a certain trunk must be routed over Gold links only), administrative groups and maximum hop count limitation, as in the case of online calculation.

Furthermore, the Alcatel 5620 TE feature supports a complete QoS monitoring functionality. In this case, the tool uploads much more than the MPLS statistics from the network. All traffic in the network is quantifiable, and this real data is used as a starting point for TE path calculations. Traffic data is used as a feedback signal to drive the re-optimization of explicit routes, taking into account QoS constraints.

The Alcatel 7670 RSP and the Alcatel 7770 RCP fully support the QoS-aware TE feature by delivering the required monitoring data. For example, if there is a point of congestion in the network, the Alcatel 7770 RCP's two-level IP forwarding lookup can trace the source of traffic on any given link in order to determine which nodes are affected by the bottleneck.

The decision on SLA and service level specification (SLS) admission control will be closely bound to both intra- and inter-domain TE aspects (e.g., a new SLS can be accepted if the traffic configuration is optimized). Therefore, it is natural to integrate bandwidth brokerage functions with offline TE. For this reason, the Alcatel 5620 TE feature will evolve into a fully featured bandwidth broker (BB).

**Traffic engineering in the Alcatel OSS**

Offline TE solutions can be used as the basis for a set of value-added data applications for service providers. The Alcatel OSS consists of three major functional areas: service provisioning and activation, service assurance, and customer care and billing. TE is implemented in the areas of service provisioning and service assurance.

For service provisioning, TE plays an important role in the bandwidth brokerage function. It can calculate whether the network can meet a certain traffic demand with a promised QoS. As such, it is an integral part of customer-oriented service activation.
For service assurance, TE is used in a self-triggering mode. The Alcatel 5620 Performance Module and the Alcatel 5620 SLA Module predict when the network will be congested. When certain links in the network reach congestion, the Alcatel 5620 Performance and SLA Modules trigger the Alcatel 5620 TE feature to re-optimize and reconfigure the MPLS network.

TE is a key component of a complete OSS solution. It is a means to control the network's performance and, therefore, a way to achieve predictable service throughout the network.

The Alcatel 7770 RCP and the Alcatel 7670 RSP support MPLS, making up a complete framework for TE within and beyond the core. With the evolution to G-MPLS, this scope will expand to include the optical core with DWDM and optical cross connects. By combining the intelligence of TE with ATM, IP and the speed of optics, Alcatel will bring unprecedented cost savings and integration to the core of networks.

3. Conclusion

The Internet is quickly becoming a massive, critical communications network, supporting private and public services of all kinds. Operators of core networks are faced with the challenge of supporting huge traffic growth in a reliable and cost-effective way. Furthermore, the core is increasingly carrying a mix of best-effort traffic and QoS-demanding applications that need predictable and protected service.

Essentially, for the core, these challenges require an optimized and intelligent mapping of customer traffic flows onto a physical topology. TE provides a means of controlling traffic through a network, offering services according to customers' specific requirements, while still utilizing network resources economically.

In traditional routed cores, IGP s drive the decision on which path a traffic flow takes — the shortest path. This results in overutilized links in one part of the network, while another part is largely underutilized, complicating efficient scaling of the network. The only way to move traffic flows in this traditional routed core is by adapting the link metrics; however, this is a trial and error method which is impractical and ineffective for large core networks.

Deploying ATM networks gives ultimate control and predictability for core traffic flows. ATM allows for hardened and predictable end-to-end QoS guarantees. The path of ATM PVCs across the ATM network can be controlled so that transport resources are used more efficiently. Furthermore, today ATM is well suited to aggregating and carrying traffic reliably from emerging broadband access networks (DSL, LMDS).

ATM overlay networks, however, experience limitations in the Internet backbone environment. The complexity of managing two technologies and the $n$ squared PVC problem led some service providers to seek a new TE mechanism — a paradigm that combined the control of ATM with the simplicity and cost-effective scalability of IP. This new paradigm is MPLS.

Alcatel is an expert in the multiprotocol environment, driven by the emergence of broadband access technologies, and has responded to its challenges with the Alcatel 7670 RSP. This next generation routing switch offers the reliability and services of an ATM core switch integrated with an LSR to support IP services with MPLS. This platform allows network operators to scale their ATM clouds and evolve towards IP using MPLS as a stepping stone. The solution fully supports Alcatel's network management and service assurance solution, which provides the information and control to enable service providers to cut costs and increase revenues.

Meanwhile, the evolution of chip technology overcame the forwarding capacity limitations of traditional CPU-based routers. Today, ASICs and NPUs for IP forwarding can handle millions of packets per second and enable stable and predictable terabit routers with interface capacities of up to OC-192/STM-64. Adding MPLS to these predictable IP routers makes it possible to engineer traffic tunnels to avoid congestion and fully utilize all available resources in the IP core network.

With online distributed MPLS TE, the path computation or path selection is done within an LSR. On-line computation typically uses an enhanced shortest path algorithm known constraint-based routing or CSPF. This algorithm computes shortest routes considering a set of constraints and requirements. After the path selection, the path (LSP) is set up using a signaling component such as RSVP with extensions, or CR-LDP.

Despite the fast provisioning and reduced management effort resulting from online path calculation, an offline centralized TE feature is still required to optimize TE globally. Online computation calculates one LSP at a time, making the order in which an LSP is calculated critical in determining its path across the network.
An offline centralized tool simultaneously examines the total topology, all links’ resource constraints and the requirements of each traffic trunk (LSP). Then the TE feature performs global calculations, compares the results of each calculation, and selects the best solution for the network as a whole. The output of the offline calculation is a set of LSPs that optimizes utilization of all network resources. After the offline calculation is completed, the LSPs can be established in any order because each is installed following the rules for the globally optimized solution.

Alcatel offers a total solution for MPLS TE, including MPLS-enabled switched routers and support for G-MPLS. Alcatel integrates an entire core portfolio, including the company’s own products and those of its partners, into a comprehensive solution that supports online and offline TE. All products are standards-based, stable, predictable wire-speed platforms designed around ASICs and NPUs, giving network operators control and scalability.

Furthermore, the Alcatel 5620 TE feature is the industry’s first centralized, fully automatic TE tool. This feature optimizes the IP core as a whole, increasing fairness and throughput by as much as 20 percent and 25 percent respectively, without extra investments in networking gear. The Alcatel 5620 TE feature also offers intelligent adjustable path protection and can assist in network planning and disaster analysis through powerful simulations and “what-if” scenarios.

The TE mechanisms and solutions described in this paper present a view on moving to more efficient, scalable core networks. Alcatel’s combined online/offline TE solution enables service providers to finally get a complete grip on their network traffic. This control allows them to satisfy the demands of customer traffic flows by rolling out a stable and reliable network core that paves the way to the next generation network.
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<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>AS</td>
<td>autonomous system</td>
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<tr>
<td>ATM</td>
<td>asynchronous transfer mode</td>
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<td>BB</td>
<td>bandwidth broker</td>
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<td>CoS</td>
<td>class of service</td>
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<td>CR-LDP</td>
<td>constraint-based routed label distribution protocol</td>
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<td>CSPF</td>
<td>constrained shortest path first</td>
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<td>DSL</td>
<td>digital subscriber line</td>
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<td>FEC</td>
<td>forwarding equivalence class</td>
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<td>IETF</td>
<td>Internet Engineering Task Force</td>
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<td>IGP</td>
<td>interior gateway protocol</td>
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<td>IP</td>
<td>Internet protocol</td>
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<td>LAN</td>
<td>local area network</td>
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<td>LMDS</td>
<td>local multipoint distribution system</td>
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<td>LSA</td>
<td>link state advertisement</td>
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<td>LSP</td>
<td>label switched path</td>
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<td>LSR</td>
<td>label switch router</td>
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<td>MPLS</td>
<td>multiprotocol label switching</td>
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<td>NGN</td>
<td>next generation network</td>
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<td>NMS</td>
<td>network management system</td>
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<td>OSS</td>
<td>operations support system</td>
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<td>PVC</td>
<td>permanent virtual circuit</td>
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<td>QoS</td>
<td>quality of service</td>
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<td>RSVP</td>
<td>resource reservation protocol</td>
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<td>SLS</td>
<td>service level specification</td>
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<td>SVC</td>
<td>switched virtual circuit</td>
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<td>TE</td>
<td>traffic engineering</td>
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<td>TED</td>
<td>TE database</td>
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<td>TLV</td>
<td>type length value</td>
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<td>VPN</td>
<td>virtual private network</td>
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<td>WWW</td>
<td>World Wide Web</td>
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