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Overview and Principles of Internet Traffic Engineering

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Abstract

This document describes the principles of traffic engineering (TE) in

the Internet. The document is intended to promote better

understanding of the issues surrounding traffic engineering in IP

networks and the networks that support IP networking, and to provide

a common basis for the development of traffic engineering

capabilities for the Internet. The principles, architectures, and

methodologies for performance evaluation and performance optimization

of operational networks are also discussed.

This work was first published as RFC 3272 in May 2002. This document

obsoletes RFC 3272 by making a complete update to bring the text in

line with best current practices for Internet traffic engineering and

to include references to the latest relevant work in the IETF.

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1. Introduction

This document describes the principles of Internet traffic

engineering (TE). The objective of the document is to articulate the

general issues and principles for Internet traffic engineering, and

where appropriate to provide recommendations, guidelines, and options

for the development of online and offline Internet traffic

engineering capabilities and support systems.

This document provides a terminology and taxonomy for describing and

understanding common Internet traffic engineering concepts.

Even though Internet traffic engineering is most effective when

applied end-to-end, the focus of this document is traffic engineering

within a given domain (such as an autonomous system). However,

because a preponderance of Internet traffic tends to originate in one

autonomous system and terminate in another, this document also

provides an overview of aspects pertaining to inter-domain traffic

engineering.

This work was first published as [RFC3272] in May 2002. This

document obsoletes [RFC3272] by making a complete update to bring the

text in line with best current practices for Internet traffic

engineering and to include references to the latest relevant work in

the IETF. It is worth noting around three fifths of the RFCs

referenced in this document post-date the publication of RFC 3272.

Appendix C provides a summary of changes between RFC 3272 and this

document.

1.1. What is Internet Traffic Engineering?

One of the most significant functions performed by the Internet is

the routing of traffic from ingress nodes to egress nodes.

Therefore, one of the most distinctive functions performed by

Internet traffic engineering is the control and optimization of the

routing function, to steer traffic through the network.

Internet traffic engineering is defined as that aspect of Internet

network engineering dealing with the issues of performance evaluation

and performance optimization of operational IP networks. Traffic

engineering encompasses the application of technology and scientific

principles to the measurement, characterization, modeling, and

control of Internet traffic [RFC2702], [AWD2].

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It is the performance of the network as seen by end users of network

services that is paramount. The characteristics visible to end users

are the emergent properties of the network, which are the

characteristics of the network when viewed as a whole. A central

goal of the service provider, therefore, is to enhance the emergent

properties of the network while taking economic considerations into

account. This is accomplished by addressing traffic oriented

performance requirements while utilizing network resources

economically and reliably. Traffic oriented performance measures

include delay, delay variation, packet loss, and throughput.

Internet traffic engineering responds to network events. Aspects of

capacity management respond at intervals ranging from days to years.

Routing control functions operate at intervals ranging from

milliseconds to days. Packet level processing functions operate at

very fine levels of temporal resolution, ranging from picoseconds to

milliseconds while reacting to the real-time statistical behavior of

traffic.

Thus, the optimization aspects of traffic engineering can be viewed

from a control perspective, and can be both pro-active and reactive.

In the pro-active case, the traffic engineering control system takes

preventive action to protect against predicted unfavorable future

network states, for example, by engineering backup paths. It may

also take action that will lead to a more desirable future network

state. In the reactive case, the control system responds to correct

issues and adapt to network events, such as routing after failure.

Another important objective of Internet traffic engineering is to

facilitate reliable network operations [RFC2702]. Reliable network

operations can be facilitated by providing mechanisms that enhance

network integrity and by embracing policies emphasizing network

survivability. This reduces the vulnerability of services to outages

arising from errors, faults, and failures occurring within the

network infrastructure.

The optimization aspects of traffic engineering can be achieved

through capacity management and traffic management. In this

document, capacity management includes capacity planning, routing

control, and resource management. Network resources of particular

interest include link bandwidth, buffer space, and computational

resources. In this document, traffic management includes:

1. nodal traffic control functions such as traffic conditioning,

queue management, scheduling

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2. other functions that regulate traffic flow through the network or

that arbitrate access to network resources between different

packets or between different traffic streams.

One major challenge of Internet traffic engineering is the

realization of automated control capabilities that adapt quickly and

cost effectively to significant changes in network state, while still

maintaining stability of the network. Performance evaluation can

assess the effectiveness of traffic engineering methods, and the

results of this evaluation can be used to identify existing problems,

guide network re-optimization, and aid in the prediction of potential

future problems. However, this process can also be time consuming

and may not be suitable to act on short-lived changes in the network.

Performance evaluation can be achieved in many different ways. The

most notable techniques include analytical methods, simulation, and

empirical methods based on measurements.

Traffic engineering comes in two flavors: either a background process

that constantly monitors traffic and optimizes the use of resources

to improve performance; or a form of a pre-planned optimized traffic

distribution that is considered optimal. In the later case, any

deviation from the optimum distribution (e.g., caused by a fiber cut)

is reverted upon repair without further optimization. However, this

form of traffic engineering relies upon the notion that the planned

state of the network is optimal. Hence, in such a mode there are two

levels of traffic engineering: the TE-planning task to enable optimum

traffic distribution, and the routing task keeping traffic flows

attached to the pre-planned distribution.

As a general rule, traffic engineering concepts and mechanisms must

be sufficiently specific and well-defined to address known

requirements, but simultaneously flexible and extensible to

accommodate unforeseen future demands.

1.2. Components of Traffic Engineering

As mentioned in Section 1.1, Internet traffic engineering provides

performance optimization of operational IP networks while utilizing

network resources economically and reliably. Such optimization is

supported at the control/controller level and within the data/

forwarding plane.

The key elements required in any TE solution are as follows:

1. Policy

2. Path steering

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3. Resource management

Some TE solutions rely on these elements to a lesser or greater

extent. Debate remains about whether a solution can truly be called

traffic engineering if it does not include all of these elements.

For the sake of this document, we assert that all TE solutions must

include some aspects of all of these elements. Other solutions can

be classed as "partial TE" and also fall in scope of this document.

Policy allows for the selection of next hops and paths based on

information beyond basic reachability. Early definitions of routing

policy, e.g., [RFC1102] and [RFC1104], discuss routing policy being

applied to restrict access to network resources at an aggregate

level. BGP is an example of a commonly used mechanism for applying

such policies, see [RFC4271] and [RFC8955]. In the traffic

engineering context, policy decisions are made within the control

plane or by controllers, and govern the selection of paths. Examples

can be found in [RFC4655] and [RFC5394]. Standard TE solutions may

cover the mechanisms to distribute and/or enforce polices, but

specific policy definition is generally unspecified.

Path steering is the ability to forward packets using more

information than just knowledge of the next hop. Examples of path

steering include IPv4 source routes [RFC0791], RSVP-TE explicit

routes [RFC3209], and Segment Routing [RFC8402]. Path steering for

TE can be supported via control plane protocols, by encoding in the

data plane headers, or by a combination of the two. This includes

when control is provided by a controller using a southbound (i.e.,

controller to router) control protocol.

Resource management provides resource aware control and forwarding.

Examples of resources are bandwidth, buffers, and queues, all of

which can be managed to control loss and latency.

Resource reservation is the control aspect of resource management.

It provides for domain-wide consensus about which network

resources are used by a particular flow. This determination may

be made at a very course or very fine level. Note that this

consensus exists at the network control or controller level, not

within the data plane. It may be composed purely of accounting/

bookkeeping, but it typically includes an ability to admit,

reject, or reclassify a flow based on policy. Such accounting can

be done based on any combination of a static understanding of

resource requirements, and the use of dynamic mechanisms to

collect requirements (e.g., via [RFC3209]) and resource

availability (e.g., via [RFC4203]).

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Resource allocation is the data plane aspect of resource

management. It provides for the allocation of specific node and

link resources to specific flows. Example resources include

buffers, policing, and rate-shaping mechanisms that are typically

supported via queuing. It also includes the matching of a flow

(i.e., flow classification) to a particular set of allocated

resources. The method of flow classification and granularity of

resource management is technology specific. Examples include

Diffserv with dropping and remarking [RFC4594], MPLS-TE [RFC3209],

and GMPLS based label switched paths [RFC3945], as well as

controller-based solutions [RFC8453]. This level of resource

control, while optional, is important in networks that wish to

support congestion management policies to control or regulate the

offered traffic to deliver different levels of service and

alleviate congestion problems, or those networks that wish to

control latencies experienced by specific traffic flows.

1.3. Scope

The scope of this document is intra-domain traffic engineering. That

is, traffic engineering within a given autonomous system in the

Internet. This document discusses concepts pertaining to intra-

domain traffic control, including such issues as routing control,

micro and macro resource allocation, and the control coordination

problems that arise consequently.

This document describes and characterizes techniques already in use

or in advanced development for Internet traffic engineering. The way

these techniques fit together is discussed and scenarios in which

they are useful will be identified.

Although the emphasis in this document is on intra-domain traffic

engineering, in Section 7, an overview of the high level

considerations pertaining to inter-domain traffic engineering will be

provided. Inter-domain Internet traffic engineering is crucial to

the performance enhancement of the global Internet infrastructure.

Whenever possible, relevant requirements from existing IETF documents

and other sources are incorporated by reference.

1.4. Terminology

This section provides terminology which is useful for Internet

traffic engineering. The definitions presented apply to this

document. These terms may have other meanings elsewhere.

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Busy hour: A one hour period within a specified interval of time

(typically 24 hours) in which the traffic load in a network or

sub-network is greatest.

Congestion: A state of a network resource in which the traffic

incident on the resource exceeds its output capacity over an

interval of time.

Congestion avoidance: An approach to congestion management that

attempts to obviate the occurrence of congestion.

Congestion control: An approach to congestion management that

attempts to remedy congestion problems that have already occurred.

Constraint-based routing: A class of routing protocols that take

specified traffic attributes, network constraints, and policy

constraints into account when making routing decisions.

Constraint-based routing is applicable to traffic aggregates as

well as flows. It is a generalization of QoS routing.

Demand side congestion management: A congestion management scheme

that addresses congestion problems by regulating or conditioning

offered load.

Effective bandwidth: The minimum amount of bandwidth that can be

assigned to a flow or traffic aggregate in order to deliver

'acceptable service quality' to the flow or traffic aggregate.

Hot-spot: A network element or subsystem which is in a state of

congestion.

Inter-domain traffic: Traffic that originates in one Autonomous

system and terminates in another.

Metric: A parameter defined in terms of standard units of

measurement.

Measurement methodology: A repeatable measurement technique used to

derive one or more metrics of interest.

Network survivability: The capability to provide a prescribed level

of QoS for existing services after a given number of failures

occur within the network.

Offline traffic engineering: A traffic engineering system that

exists outside of the network.

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Online traffic engineering: A traffic engineering system that exists

within the network, typically implemented on or as adjuncts to

operational network elements.

Performance measures: Metrics that provide quantitative or

qualitative measures of the performance of systems or subsystems

of interest.

Performance metric: A performance parameter defined in terms of

standard units of measurement.

Provisioning: The process of assigning or configuring network

resources to meet certain requests.

QoS routing: Class of routing systems that selects paths to be used

by a flow based on the QoS requirements of the flow.

Service Level Agreement (SLA): A contract between a provider and a

customer that guarantees specific levels of performance and

reliability at a certain cost.

Service Level Objective (SLO): A key element of an SLA between a

provider and a customer. SLOs are agreed upon as a means of

measuring the performance of the Service Provider and are outlined

as a way of avoiding disputes between the two parties based on

misunderstanding.

Stability: An operational state in which a network does not

oscillate in a disruptive manner from one mode to another mode.

Supply-side congestion management: A congestion management scheme

that provisions additional network resources to address existing

and/or anticipated congestion problems.

Traffic characteristic: A description of the temporal behavior or a

description of the attributes of a given traffic flow or traffic

aggregate.

Traffic engineering system: A collection of objects, mechanisms, and

protocols that are used together to accomplish traffic engineering

objectives.

Traffic flow: A stream of packets between two end-points that can be

characterized in a certain way. A micro-flow has a more specific

definition A micro-flow is a stream of packets with the same

source and destination addresses, source and destination ports,

and protocol ID.

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Traffic matrix: A representation of the traffic demand between a set

of origin and destination abstract nodes. An abstract node can

consist of one or more network elements.

Traffic monitoring: The process of observing traffic characteristics

at a given point in a network and collecting the traffic

information for analysis and further action.

Traffic trunk: An aggregation of traffic flows belonging to the same

class which are forwarded through a common path. A traffic trunk

may be characterized by an ingress and egress node, and a set of

attributes which determine its behavioral characteristics and

requirements from the network.

2. Background

The Internet must convey IP packets from ingress nodes to egress

nodes efficiently, expeditiously, and economically. Furthermore, in

a multiclass service environment (e.g., Diffserv capable networks -

see Section 4.1.4), the resource sharing parameters of the network

must be appropriately determined and configured according to

prevailing policies and service models to resolve resource contention

issues arising from mutual interference between packets traversing

through the network. Thus, consideration must be given to resolving

competition for network resources between traffic streams belonging

to the same service class (intra-class contention resolution) and

traffic streams belonging to different classes (inter-class

contention resolution).

2.1. Context of Internet Traffic Engineering

The context of Internet traffic engineering includes:

1. A network domain context that defines the scope under

consideration, and in particular the situations in which the

traffic engineering problems occur. The network domain context

includes network structure, network policies, network

characteristics, network constraints, network quality attributes,

and network optimization criteria.

2. A problem context defining the general and concrete issues that

traffic engineering addresses. The problem context includes

identification, abstraction of relevant features, representation,

formulation, specification of the requirements on the solution

space, and specification of the desirable features of acceptable

solutions.

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3. A solution context suggesting how to address the issues

identified by the problem context. The solution context includes

analysis, evaluation of alternatives, prescription, and

resolution.

4. An implementation and operational context in which the solutions

are instantiated. The implementation and operational context

includes planning, organization, and execution.

The context of Internet traffic engineering and the different problem

scenarios are discussed in the following subsections.

2.2. Network Domain Context

IP networks range in size from small clusters of routers situated

within a given location, to thousands of interconnected routers,

switches, and other components distributed all over the world.

At the most basic level of abstraction, an IP network can be

represented as a distributed dynamic system consisting of:

o a set of interconnected resources which provide transport services

for IP traffic subject to certain constraints

o a demand system representing the offered load to be transported

through the network

o a response system consisting of network processes, protocols, and

related mechanisms which facilitate the movement of traffic

through the network (see also [AWD2]).

The network elements and resources may have specific characteristics

restricting the manner in which the traffic demand is handled.

Additionally, network resources may be equipped with traffic control

mechanisms managing the way in which the demand is serviced. Traffic

control mechanisms may be used to:

o control packet processing activities within a given resource

o arbitrate contention for access to the resource by different

packets

o regulate traffic behavior through the resource.

A configuration management and provisioning system may allow the

settings of the traffic control mechanisms to be manipulated by

external or internal entities in order to exercise control over the

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way in which the network elements respond to internal and external

stimuli.

The details of how the network carries packets are specified in the

policies of the network administrators and are installed through

network configuration management and policy based provisioning

systems. Generally, the types of service provided by the network

also depend upon the technology and characteristics of the network

elements and protocols, the prevailing service and utility models,

and the ability of the network administrators to translate policies

into network configurations.

Internet networks have three significant characteristics:

o they provide real-time services

o they are mission critical

o their operating environments are very dynamic.

The dynamic characteristics of IP and IP/MPLS networks can be

attributed in part to fluctuations in demand, to the interaction

between various network protocols and processes, to the rapid

evolution of the infrastructure which demands the constant inclusion

of new technologies and new network elements, and to transient and

persistent faults which occur within the system.

Packets contend for the use of network resources as they are conveyed

through the network. A network resource is considered to be

congested if, for an interval of time, the arrival rate of packets

exceed the output capacity of the resource. Congestion may result in

some of the arriving packets being delayed or even dropped.

Congestion increases transit delay, delay variation, may lead to

packet loss, and reduces the predictability of network services.

Clearly, congestion is highly undesirable. Combating congestion at a

reasonable cost is a major objective of Internet traffic engineering.

Efficient sharing of network resources by multiple traffic streams is

a basic operational premise for the Internet. A fundamental

challenge in network operation is to increase resource utilization

while minimizing the possibility of congestion.

The Internet has to function in the presence of different classes of

traffic with different service requirements. RFC 2475 provides an

architecture for Differentiated Services (Diffserv) and makes this

requirement clear [RFC2475]. The RFC allows packets to be grouped

into behavior aggregates such that each aggregate has a common set of

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behavioral characteristics or a common set of delivery requirements.

Delivery requirements of a specific set of packets may be specified

explicitly or implicitly. Two of the most important traffic delivery

requirements are capacity constraints and QoS constraints.

Capacity constraints can be expressed statistically as peak rates,

mean rates, burst sizes, or as some deterministic notion of effective

bandwidth. QoS requirements can be expressed in terms of:

o integrity constraints such as packet loss

o temporal constraints such as timing restrictions for the delivery

of each packet (delay) and timing restrictions for the delivery of

consecutive packets belonging to the same traffic stream (delay

variation).

2.3. Problem Context

There are several large problems associated with operating a network

described in the previous section. This section analyzes the problem

context in relation to traffic engineering. The identification,

abstraction, representation, and measurement of network features

relevant to traffic engineering are significant issues.

A particular challenge is to formulate the problems that traffic

engineering attempts to solve. For example:

o how to identify the requirements on the solution space

o how to specify the desirable features of solutions

o how to actually solve the problems

o how to measure and characterize the effectiveness of solutions.

Another class of problems is how to measure and estimate relevant

network state parameters. Effective traffic engineering relies on a

good estimate of the offered traffic load as well as a view of the

underlying topology and associated resource constraints. A network-

wide view of the topology is also a must for offline planning.

Still another class of problem is how to characterize the state of

the network and how to evaluate its performance. The performance

evaluation problem is two-fold: one aspect relates to the evaluation

of the system-level performance of the network; the other aspect

relates to the evaluation of resource-level performance, which

restricts attention to the performance analysis of individual network

resources.

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In this document, we refer to the system-level characteristics of the

network as the "macro-states" and the resource-level characteristics

as the "micro-states." The system-level characteristics are also

known as the emergent properties of the network. Correspondingly, we

refer to the traffic engineering schemes dealing with network

performance optimization at the systems level as "macro-TE" and the

schemes that optimize at the individual resource level as "micro-TE."

Under certain circumstances, the system-level performance can be

derived from the resource-level performance using appropriate rules

of composition, depending upon the particular performance measures of

interest.

Another fundamental class of problem concerns how to effectively

optimize network performance. Performance optimization may entail

translating solutions for specific traffic engineering problems into

network configurations. Optimization may also entail some degree of

resource management control, routing control, and capacity

augmentation.

2.3.1. Congestion and its Ramifications

Congestion is one of the most significant problems in an operational

IP context. A network element is said to be congested if it

experiences sustained overload over an interval of time. Congestion

almost always results in degradation of service quality to end users.

Congestion control schemes can include demand-side policies and

supply-side policies. Demand-side policies may restrict access to

congested resources or dynamically regulate the demand to alleviate

the overload situation. Supply-side policies may expand or augment

network capacity to better accommodate offered traffic. Supply-side

policies may also re-allocate network resources by redistributing

traffic over the infrastructure. Traffic redistribution and resource

re-allocation serve to increase the 'effective capacity' of the

network.

The emphasis of this document is primarily on congestion management

schemes falling within the scope of the network, rather than on

congestion management systems dependent upon sensitivity and

adaptivity from end-systems. That is, the aspects that are

considered in this document with respect to congestion management are

those solutions that can be provided by control entities operating on

the network and by the actions of network administrators and network

operations systems.

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2.4. Solution Context

The solution context for Internet traffic engineering involves

analysis, evaluation of alternatives, and choice between alternative

courses of action. Generally the solution context is based on making

reasonable inferences about the current or future state of the

network, and making decisions that may involve a preference between

alternative sets of action. More specifically, the solution context

demands reasonable estimates of traffic workload, characterization of

network state, derivation of solutions which may be implicitly or

explicitly formulated, and possibly instantiating a set of control

actions. Control actions may involve the manipulation of parameters

associated with routing, control over tactical capacity acquisition,

and control over the traffic management functions.

The following list of instruments may be applicable to the solution

context of Internet traffic engineering.

o A set of policies, objectives, and requirements (which may be

context dependent) for network performance evaluation and

performance optimization.

o A collection of online and possibly offline tools and mechanisms

for measurement, characterization, modeling, and control traffic,

and control over the placement and allocation of network

resources, as well as control over the mapping or distribution of

traffic onto the infrastructure.

o A set of constraints on the operating environment, the network

protocols, and the traffic engineering system itself.

o A set of quantitative and qualitative techniques and methodologies

for abstracting, formulating, and solving traffic engineering

problems.

o A set of administrative control parameters which may be

manipulated through a Configuration Management (CM) system. The

CM system itself may include a configuration control subsystem, a

configuration repository, a configuration accounting subsystem,

and a configuration auditing subsystem.

o A set of guidelines for network performance evaluation,

performance optimization, and performance improvement.

Determining traffic characteristics through measurement or estimation

is very useful within the realm the traffic engineering solution

space. Traffic estimates can be derived from customer subscription

information, traffic projections, traffic models, and from actual

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measurements. The measurements may be performed at different levels,

e.g., at the traffic-aggregate level or at the flow level.

Measurements at the flow level or on small traffic aggregates may be

performed at edge nodes, when traffic enters and leaves the network.

Measurements for large traffic-aggregates may be performed within the

core of the network.

To conduct performance studies and to support planning of existing

and future networks, a routing analysis may be performed to determine

the paths the routing protocols will choose for various traffic

demands, and to ascertain the utilization of network resources as

traffic is routed through the network. Routing analysis captures the

selection of paths through the network, the assignment of traffic

across multiple feasible routes, and the multiplexing of IP traffic

over traffic trunks (if such constructs exist) and over the

underlying network infrastructure. A model of network topology is

necessary to perform routing analysis. A network topology model may

be extracted from:

o network architecture documents

o network designs

o information contained in router configuration files

o routing databases

o routing tables

o automated tools that discover and collate network topology

information.

Topology information may also be derived from servers that monitor

network state, and from servers that perform provisioning functions.

Routing in operational IP networks can be administratively controlled

at various levels of abstraction including the manipulation of BGP

attributes and interior gateway protocol (IGP) metrics. For path

oriented technologies such as MPLS, routing can be further controlled

by the manipulation of relevant traffic engineering parameters,

resource parameters, and administrative policy constraints. Within

the context of MPLS, the path of an explicitly routed label switched

path (LSP) can be computed and established in various ways including:

o manually

o automatically, online using constraint-based routing processes

implemented on label switching routers

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o automatically, offline using constraint-based routing entities

implemented on external traffic engineering support systems.

2.4.1. Combating the Congestion Problem

Minimizing congestion is a significant aspect of Internet traffic

engineering. This subsection gives an overview of the general

approaches that have been used or proposed to combat congestion.

Congestion management policies can be categorized based upon the

following criteria (see [YARE95] for a more detailed taxonomy of

congestion control schemes):

1. Congestion Management based on Response Time Scales

\* Long (weeks to months): Expanding network capacity by adding

new equipment, routers, and links takes time and is

comparatively costly. Capacity planning needs to take this

into consideration. Network capacity is expanded based on

estimates or forecasts of future traffic development and

traffic distribution. These upgrades are typically carried

out over weeks or months, or maybe even years.

\* Medium (minutes to days): Several control policies fall within

the medium timescale category. Examples include:

a. Adjusting routing protocol parameters to route traffic

away or towards certain segments of the network.

b. Setting up or adjusting explicitly routed LSPs in MPLS

networks to route traffic trunks away from possibly

congested resources or toward possibly more favorable

routes.

c. Re-configuring the logical topology of the network to make

it correlate more closely with the spatial traffic

distribution using, for example, an underlying path-

oriented technology such as MPLS LSPs or optical channel

trails.

Many of these adaptive schemes rely on measurement systems. A

measurement system monitors changes in traffic distribution,

traffic loads, and network resource utilization and then

provides feedback to the online or offline traffic engineering

mechanisms and tools so that they can trigger control actions

within the network. The traffic engineering mechanisms and

tools can be implemented in a distributed or centralized

fashion. A centralized scheme may have global visibility into

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the network state and may produce more optimal solutions.

However, centralized schemes are prone to single points of

failure and may not scale as well as distributed schemes.

Moreover, the information utilized by a centralized scheme may

be stale and might not reflect the actual state of the

network. It is not an objective of this document to make a

recommendation between distributed and centralized schemes:

that is a choice that network administrators must make based

on their specific needs.

\* Short (picoseconds to minutes): This category includes packet

level processing functions and events that are recorded on the

order of several round trip times. It also includes router

mechanisms such as passive and active buffer management. All

of these mechanisms are used to control congestion or signal

congestion to end systems so that they can adaptively regulate

the rate at which traffic is injected into the network. One

of the most popular active queue management schemes,

especially for TCP traffic, is Random Early Detection (RED)

[FLJA93]. During congestion (but before the queue is filled),

the RED scheme chooses arriving packets to "mark" according to

a probabilistic algorithm which takes into account the average

queue size. A router that does not utilize explicit

congestion notification (ECN) [FLOY94] can simply drop marked

packets to alleviate congestion and implicitly notify the

receiver about the congestion. On the other hand, if the

router supports ECN, it can set the ECN field in the packet

header. Several variations of RED have been proposed to

support different drop precedence levels in multi-class

environments [RFC2597]. RED provides congestion avoidance

which is not worse than traditional Tail-Drop (TD) queue

management (drop arriving packets only when the queue is

full). Importantly, RED reduces the possibility of global

synchronization where retransmission burst become synchronized

across the whole network, and improves fairness among

different TCP sessions. However, RED by itself cannot prevent

congestion and unfairness caused by sources unresponsive to

RED, e.g., UDP traffic and some misbehaved greedy connections.

Other schemes have been proposed to improve the performance

and fairness in the presence of unresponsive traffic. Some of

those schemes (such as Longest Queue Drop (LQD) and Dynamic

Soft Partitioning with Random Drop (RND) [SLDC98]) were

proposed as theoretical frameworks and are typically not

available in existing commercial products.

2. Congestion Management: Reactive Versus Preventive Schemes

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\* Reactive: Reactive (recovery) congestion management policies

react to existing congestion problems. All the policies

described above for the long and medium time scales can be

categorized as being reactive. They are based on monitoring

and identifying congestion problems that exist in the network,

and on the initiation of relevant actions to ease a situation.

\* Preventive: Preventive (predictive/avoidance) policies take

proactive action to prevent congestion based on estimates and

predictions of future congestion problems. Some of the

policies described for the long and medium time scales fall

into this category. Preventive policies do not necessarily

respond immediately to existing congestion problems. Instead,

forecasts of traffic demand and workload distribution are

considered, and action may be taken to prevent potential

future congestion problems. The schemes described for the

short time scale can also be used for congestion avoidance

because dropping or marking packets before queues actually

overflow would trigger corresponding TCP sources to slow down.

3. Congestion Management: Supply-Side Versus Demand-Side Schemes

\* Supply-side: Supply-side congestion management policies

increase the effective capacity available to traffic in order

to control or reduce congestion. This can be accomplished by

increasing capacity or by balancing distribution of traffic

over the network. Capacity planning aims to provide a

physical topology and associated link bandwidths that match or

exceed estimated traffic workload and traffic distribution

subject to traffic forecasts and budgetary or other

constraints. If the actual traffic distribution does not fit

the topology derived from capacity panning, then the traffic

can be mapped onto the topology by using routing control

mechanisms, by applying path oriented technologies (e.g., MPLS

LSPs and optical channel trails) to modify the logical

topology, or by employing some other load redistribution

mechanisms.

\* Demand-side: Demand-side congestion management policies

control or regulate the offered traffic to alleviate

congestion problems. For example, some of the short time

scale mechanisms described earlier as well as policing and

rate-shaping mechanisms attempt to regulate the offered load

in various ways.

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2.5. Implementation and Operational Context

The operational context of Internet traffic engineering is

characterized by constant changes that occur at multiple levels of

abstraction. The implementation context demands effective planning,

organization, and execution. The planning aspects may involve

determining prior sets of actions to achieve desired objectives.

Organizing involves arranging and assigning responsibility to the

various components of the traffic engineering system and coordinating

the activities to accomplish the desired TE objectives. Execution

involves measuring and applying corrective or perfective actions to

attain and maintain desired TE goals.

3. Traffic Engineering Process Models

This section describes a generic process model that captures the

high-level practical aspects of Internet traffic engineering in an

operational context. The process model is described as a sequence of

actions that must be carried out to optimize the performance of an

operational network (see also [RFC2702], [AWD2]). This process model

may be enacted explicitly or implicitly, by a software process or by

a human.

The traffic engineering process model is iterative [AWD2]. The four

phases of the process model described below are repeated as a

continual sequence.

o Define the relevant control policies that govern the operation of

the network.

o Acquire measurement data from the operational network.

o Analyze the network state and characterize the traffic workload.

Proactive analysis identifies potential problems that could

manifest in the future. Reactive analysis identifies existing

problems and determines their causes.

o Optimize the performance of the network. This involves a decision

process which selects and implements a set of actions from a set

of alternatives given the results of the three previous steps.

Optimization actions may include the use of techniques to control

the offered traffic and to control the distribution of traffic

across the network.

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3.1. Components of the Traffic Engineering Process Model

The key components of the traffic engineering process model are as

follows.

1. Measurement is crucial to the traffic engineering function. The

operational state of a network can only be conclusively

determined through measurement. Measurement is also critical to

the optimization function because it provides feedback data which

is used by traffic engineering control subsystems. This data is

used to adaptively optimize network performance in response to

events and stimuli originating within and outside the network.

Measurement in support of the TE function can occur at different

levels of abstraction. For example, measurement can be used to

derive packet level characteristics, flow level characteristics,

user or customer level characteristics, traffic aggregate

characteristics, component level characteristics, and network

wide characteristics.

2. Modeling, analysis, and simulation are important aspects of

Internet traffic engineering. Modeling involves constructing an

abstract or physical representation which depicts relevant

traffic characteristics and network attributes. A network model

is an abstract representation of the network which captures

relevant network features, attributes, and characteristic.

Network simulation tools are extremely useful for traffic

engineering. Because of the complexity of realistic quantitative

analysis of network behavior, certain aspects of network

performance studies can only be conducted effectively using

simulation.

3. Network performance optimization involves resolving network

issues by transforming such issues into concepts that enable a

solution, identification of a solution, and implementation of the

solution. Network performance optimization can be corrective or

perfective. In corrective optimization, the goal is to remedy a

problem that has occurred or that is incipient. In perfective

optimization, the goal is to improve network performance even

when explicit problems do not exist and are not anticipated.

4. Review of TE Techniques

This section briefly reviews different traffic engineering approaches

proposed and implemented in telecommunications and computer networks

using IETF protocols and architectures. The discussion is not

intended to be comprehensive. It is primarily intended to illuminate

existing approaches to traffic engineering in the Internet. A

historic overview of traffic engineering in telecommunications

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networks is provided in Appendix A, while Appendix B describes

approaches in other standards bodies.

4.1. Overview of IETF Projects Related to Traffic Engineering

This subsection reviews a number of IETF activities pertinent to

Internet traffic engineering.

4.1.1. Constraint-Based Routing

Constraint-based routing refers to a class of routing systems that

compute routes through a network subject to the satisfaction of a set

of constraints and requirements. In the most general case,

constraint-based routing may also seek to optimize overall network

performance while minimizing costs.

The constraints and requirements may be imposed by the network itself

or by administrative policies. Constraints may include bandwidth,

hop count, delay, and policy instruments such as resource class

attributes. Constraints may also include domain specific attributes

of certain network technologies and contexts which impose

restrictions on the solution space of the routing function. Path

oriented technologies such as MPLS have made constraint-based routing

feasible and attractive in public IP networks.

The concept of constraint-based routing within the context of MPLS

traffic engineering requirements in IP networks was first described

in [RFC2702] and led to developments such as MPLS-TE [RFC3209] as

described in Section 4.1.6.

Unlike QoS routing (for example, see [RFC2386] and [MA]) which

generally addresses the issue of routing individual traffic flows to

satisfy prescribed flow-based QoS requirements subject to network

resource availability, constraint-based routing is applicable to

traffic aggregates as well as flows and may be subject to a wide

variety of constraints which may include policy restrictions.

4.1.1.1. IGP Flexible Algorithms (Flex-Algos)

The traditional approach to routing in an IGP network relies on the

IGPs deriving "shortest paths" over the network based solely on the

IGP metric assigned to the links. Such an approach is often limited:

traffic may tend to converge toward the destination, possibly causing

congestion; and it is not possible to steer traffic onto paths

depending on the end-to-end qualities demanded by the applications.

To overcome this limitation, various sorts of traffic engineering

have been widely deployed (as described in this document), where the

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TE component is responsible for computing the path based on

additionalcmetrics and/or constraints. Such paths (or tunnels) need

to be installed in the routers' forwarding tables in addition to, or

as a replacement for the original paths computed by IGPs. The main

drawback of these TE approaches is the additional complexity of

protocols and management, and the state that may need to be

maintained within the network.

IGP flexible algorithms (flex-algos) [I-D.ietf-lsr-flex-algo] allow

IGPs to construct constraint-based paths over the network by

computing constraint- based next hops. The intent of flex-algos is

to reduce TE complexity by letting an IGP perform some basic TE

computation capabilities. Flex-algo includes a set of extensions to

the IGPs that enable a router to send TLVs that:

o describe a set of constraints on the topology

o identify calculation-type

o describe a metric-type that is to be used to compute the best

paths through the constrained topology.

A given combination of calculation-type, metric-type, and constraints

is known as a "Flexible Algorithm Definition" (or FAD). A router

that sends such a set of TLVs also assigns a specific identifier (the

Flexible Algorithm) to the specified combination of calculation-type,

metric-type, and constraints.

There are two use cases for flex-algo: in IP networks

[I-D.ietf-lsr-ip-flexalgo] and in segment routing networks

[I-D.ietf-lsr-flex-algo]. In the first case, flex-algo computes

paths to an IPv4 or IPv6 address, in the second case, flex-algo

computes paths to a prefix SID (see Section 4.1.16).

There are many use cases where flex-algo can bring big value, such

as:

o Expansion of functionality of IP Performance metrics [RFC5664]

when points of interest could instantiate specific constraint-

based routing (flex-algo) based on the measurement results.

o Nested usage of flex-algo and TE extensions for IGP (see

Section 4.1.11) when we can form 'underlay' by means of flex-algo

and 'overlay' by TE.

o Flex-algo in SR-MPLS (Section 4.1.16) is a base use case when we

can easily benefit from TE-like topology that will be built

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without external TE component on routers or PCE (see

Section 4.1.13).

o Building of network slices

[I-D.nsdt-teas-ietf-network-slice-definition] where particular

IETF network slice SLO can be guaranteed by flex-algo.

4.1.2. Integrated Services

The IETF developed the Integrated Services (Intserv) model that

requires resources, such as bandwidth and buffers, to be reserved a

priori for a given traffic flow to ensure that the quality of service

requested by the traffic flow is satisfied. The Integrated Services

model includes additional components beyond those used in the best-

effort model such as packet classifiers, packet schedulers, and

admission control. A packet classifier is used to identify flows

that are to receive a certain level of service. A packet scheduler

handles the scheduling of service to different packet flows to ensure

that QoS commitments are met. Admission control is used to determine

whether a router has the necessary resources to accept a new flow.

The main issue with the Integrated Services model has been

scalability [RFC2998], especially in large public IP networks which

may potentially have millions of active micro-flows in transit

concurrently.

A notable feature of the Integrated Services model is that it

requires explicit signaling of QoS requirements from end systems to

routers [RFC2753]. The Resource Reservation Protocol (RSVP) performs

this signaling function and is a critical component of the Integrated

Services model. RSVP is described in Section 4.1.3.

4.1.3. RSVP

RSVP is a soft state signaling protocol [RFC2205]. It supports

receiver initiated establishment of resource reservations for both

multicast and unicast flows. RSVP was originally developed as a

signaling protocol within the Integrated Services framework (see

Section 4.1.2) for applications to communicate QoS requirements to

the network and for the network to reserve relevant resources to

satisfy the QoS requirements [RFC2205].

In RSVP, the traffic sender or source node sends a PATH message to

the traffic receiver with the same source and destination addresses

as the traffic which the sender will generate. The PATH message

contains: (1) a sender traffic specification describing the

characteristics of the traffic, (2) a sender template specifying the

format of the traffic, and (3) an optional advertisement

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specification which is used to support the concept of One Pass With

Advertising (OPWA) [RFC2205]. Every intermediate router along the

path forwards the PATH message to the next hop determined by the

routing protocol. Upon receiving a PATH message, the receiver

responds with a RESV message which includes a flow descriptor used to

request resource reservations. The RESV message travels to the

sender or source node in the opposite direction along the path that

the PATH message traversed. Every intermediate router along the path

can reject or accept the reservation request of the RESV message. If

the request is rejected, the rejecting router will send an error

message to the receiver and the signaling process will terminate. If

the request is accepted, link bandwidth and buffer space are

allocated for the flow and the related flow state information is

installed in the router.

One of the issues with the original RSVP specification was

Scalability. This is because reservations were required for micro-

flows, so that the amount of state maintained by network elements

tends to increase linearly with the number of micro-flows. These

issues are described in [RFC2961] which also modifies and extends

RSVP to mitigate the scaling problems to make RSVP a versatile

signaling protocol for the Internet. For example, RSVP has been

extended to reserve resources for aggregation of flows, to set up

MPLS explicit label switched paths (see Section 4.1.6), and to

perform other signaling functions within the Internet. [RFC2961]

also describes a mechanism to reduce the amount of Refresh messages

required to maintain established RSVP sessions.

4.1.4. Differentiated Services

The goal of Differentiated Services (Diffserv) within the IETF was to

devise scalable mechanisms for categorization of traffic into

behavior aggregates, which ultimately allows each behavior aggregate

to be treated differently, especially when there is a shortage of

resources such as link bandwidth and buffer space [RFC2475]. One of

the primary motivations for Diffserv was to devise alternative

mechanisms for service differentiation in the Internet that mitigate

the scalability issues encountered with the Intserv model.

Diffserv uses the Differentiated Services field in the IP header (the

DS field) consisting of six bits in what was formerly known as the

Type of Service (TOS) octet. The DS field is used to indicate the

forwarding treatment that a packet should receive at a transit node

[RFC2474]. Diffserv includes the concept of Per-Hop Behavior (PHB)

groups. Using the PHBs, several classes of services can be defined

using different classification, policing, shaping, and scheduling

rules.

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For an end-user of network services to utilize Differentiated

Services provided by its Internet Service Provider (ISP), it may be

necessary for the user to have an SLA with the ISP. An SLA may

explicitly or implicitly specify a Traffic Conditioning Agreement

(TCA) which defines classifier rules as well as metering, marking,

discarding, and shaping rules.

Packets are classified, and possibly policed and shaped at the

ingress to a Diffserv network. When a packet traverses the boundary

between different Diffserv domains, the DS field of the packet may be

re-marked according to existing agreements between the domains.

Differentiated Services allows only a finite number of service

classes to be specified by the DS field. The main advantage of the

Diffserv approach relative to the Intserv model is scalability.

Resources are allocated on a per-class basis and the amount of state

information is proportional to the number of classes rather than to

the number of application flows.

The Diffserv model deals with traffic management issues on a per hop

basis. The Diffserv control model consists of a collection of micro-

TE control mechanisms. Other traffic engineering capabilities, such

as capacity management (including routing control), are also required

in order to deliver acceptable service quality in Diffserv networks.

The concept of Per Domain Behaviors has been introduced to better

capture the notion of Differentiated Services across a complete

domain [RFC3086].

4.1.5. QUIC

QUIC [I-D.ietf-quic-transport] is a UDP-based multiplexed and secure

transport protocol. QUIC provides applications with flow-controlled

streams for structured communication, low-latency connection

establishment, and network path migration.

QUIC is a connection-oriented protocol that creates a stateful

interaction between a client and server. QUIC uses a handshake

procedure that combines negotiation of cryptographic and transport

parameters. This is a key differentiation from other transport

protocols.

Endpoints communicate in QUIC by exchanging QUIC packets that use a

customized framing for protection. Most QUIC packets contain frames,

which carry control information and application data between

endpoints. QUIC authenticates all packets and encrypts as much as is

practical. QUIC packets are carried in UDP datagrams to better

facilitate deployment within existing systems and networks.

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Application protocols exchange information over a QUIC connection via

streams, which are ordered sequences of bytes. Two types of stream

can be created: bidirectional streams, which allow both endpoints to

send data; and unidirectional streams, which allow a single endpoint

to send data. A credit-based scheme is used to limit stream creation

and to bound the amount of data that can be sent.

QUIC provides the necessary feedback to implement reliable delivery

and congestion control to avoid network congestion.

4.1.6. Multiprotocol Label Switching (MPLS)

MPLS is an advanced forwarding scheme which also includes extensions

to conventional IP control plane protocols. MPLS extends the

Internet routing model and enhances packet forwarding and path

control [RFC3031].

At the ingress to an MPLS domain, Label Switching Routers (LSRs)

classify IP packets into Forwarding Equivalence Classes (FECs) based

on a variety of factors, including, e.g., a combination of the

information carried in the IP header of the packets and the local

routing information maintained by the LSRs. An MPLS label stack

entry is then prepended to each packet according to their forwarding

equivalence classes. The MPLS label stack entry is 32 bits long and

contains a 20-bit label field.

An LSR makes forwarding decisions by using the label prepended to

packets as the index into a local next hop label forwarding entry

(NHLFE). The packet is then processed as specified in the NHLFE.

The incoming label may be replaced by an outgoing label (label swap),

and the packet may be forwarded to the next LSR. Before a packet

leaves an MPLS domain, its MPLS label may be removed (label pop). A

Label Switched Path (LSP) is the path between an ingress LSRs and an

egress LSRs through which a labeled packet traverses. The path of an

explicit LSP is defined at the originating (ingress) node of the LSP.

MPLS can use a signaling protocol such as RSVP or LDP to set up LSPs.

MPLS is a very powerful technology for Internet traffic engineering

because it supports explicit LSPs which allow constraint-based

routing to be implemented efficiently in IP networks [AWD2]. The

requirements for traffic engineering over MPLS are described in

[RFC2702]. Extensions to RSVP to support instantiation of explicit

LSP are discussed in [RFC3209].

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4.1.7. Generalized MPLS (GMPLS)

GMPLS extends MPLS control protocols to encompass time-division

(e.g., Synchronous Optical Network / Synchronous Digital Hierarchy

(SONET/SDH), Plesiochronous Digital Hierarchy (PDH), Optical

Transport Network (OTN)), wavelength (lambdas), and spatial switching

(e.g., incoming port or fiber to outgoing port or fiber) as well as

continuing to support packet switching. GMPLS provides a common set

of control protocols for all of these layers (including some

technology-specific extensions) each of which has a diverse data or

forwarding plane. GMPLS covers both the signaling and the routing

part of that control plane and is based on the Traffic Engineering

extensions to MPLS (see Section 4.1.6).

In GMPLS, the original MPLS architecture is extended to include LSRs

whose forwarding planes rely on circuit switching, and therefore

cannot forward data based on the information carried in either packet

or cell headers. Specifically, such LSRs include devices where the

switching is based on time slots, wavelengths, or physical ports.

These additions impact basic LSP properties: how labels are requested

and communicated, the unidirectional nature of MPLS LSPs, how errors

are propagated, and information provided for synchronizing the

ingress and egress LSRs.

4.1.8. IP Performance Metrics

The IETF IP Performance Metrics (IPPM) working group has developed a

set of standard metrics that can be used to monitor the quality,

performance, and reliability of Internet services. These metrics can

be applied by network operators, end-users, and independent testing

groups to provide users and service providers with a common

understanding of the performance and reliability of the Internet

component 'clouds' they use/provide [RFC2330]. The criteria for

performance metrics developed by the IPPM working group are described

in [RFC2330]. Examples of performance metrics include one-way packet

loss [RFC7680], one-way delay [RFC7679], and connectivity measures

between two nodes [RFC2678]. Other metrics include second-order

measures of packet loss and delay.

Some of the performance metrics specified by the IPPM working group

are useful for specifying SLAs. SLAs are sets of service level

objectives negotiated between users and service providers, wherein

each objective is a combination of one or more performance metrics,

possibly subject to certain constraints.

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4.1.9. Flow Measurement

The IETF Real Time Flow Measurement (RTFM) working group produced an

architecture that defines a method to specify traffic flows as well

as a number of components for flow measurement (meters, meter

readers, manager) [RFC2722]. A flow measurement system enables

network traffic flows to be measured and analyzed at the flow level

for a variety of purposes. As noted in RFC 2722, a flow measurement

system can be very useful in the following contexts:

o understanding the behavior of existing networks

o planning for network development and expansion

o quantification of network performance

o verifying the quality of network service

o attribution of network usage to users.

A flow measurement system consists of meters, meter readers, and

managers. A meter observes packets passing through a measurement

point, classifies them into groups, accumulates usage data (such as

the number of packets and bytes for each group), and stores the usage

data in a flow table. A group may represent any collection of user

applications, hosts, networks, etc. A meter reader gathers usage

data from various meters so it can be made available for analysis. A

manager is responsible for configuring and controlling meters and

meter readers. The instructions received by a meter from a manager

include flow specifications, meter control parameters, and sampling

techniques. The instructions received by a meter reader from a

manager include the address of the meter whose date is to be

collected, the frequency of data collection, and the types of flows

to be collected.

4.1.10. Endpoint Congestion Management

[RFC3124] provides a set of congestion control mechanisms for the use

of transport protocols. It is also allows the development of

mechanisms for unifying congestion control across a subset of an

endpoint's active unicast connections (called a congestion group). A

congestion manager continuously monitors the state of the path for

each congestion group under its control. The manager uses that

information to instruct a scheduler on how to partition bandwidth

among the connections of that congestion group.

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4.1.11. TE Extensions to the IGPs

[RFC5305] describes the extensions to the Intermediate System to

Intermediate System (IS-IS) protocol to support TE, similarly

[RFC3630] specifies TE extensions for OSPFv2 ([RFC5329] has the same

description for OSPFv3).

The idea of redistribution TE extensions such as link type and ID,

local and remote IP addresses, TE metric, maximum bandwidth, maximum

reservable bandwidth and unreserved bandwidth, admin group in IGP is

a common for both IS-IS and OSPF.

The difference is in the details of their transmission: IS-IS uses

the Extended IS Reachability TLV (type 22) and Sub-TLVs for those TE

parameters, OSPFv2 uses Opaque LSA [RFC5250] type 10 (OSPFv3 uses

Intra-Area-TE-LSA) with two top-level TLV (Router Address and Link)

also with Sub-TLVs for that purpose.

IS-IS also uses the Extended IP Reachability TLV (type 135, which

have the new 32 bit metric) and the TE Router ID TLV (type 134).

Those Sub-TLV details are described in [RFC8570] for IS-IS and in

[RFC7471] for OSPFv2 ([RFC5329] for OSPFv3).

4.1.12. Link-State BGP

In a number of environments, a component external to a network is

called upon to perform computations based on the network topology and

current state of the connections within the network, including

traffic engineering information. This is information typically

distributed by IGP routing protocols within the network (see

Section 4.1.11.

The Border Gateway Protocol (BGP) Section 7 is one of the essential

routing protocols that glue the Internet together. BGP Link State

(BGP-LS) [RFC7752] is a mechanism by which link-state and traffic

engineering information can be collected from networks and shared

with external components using the BGP routing protocol. The

mechanism is applicable to physical and virtual IGP links, and is

subject to policy control.

Information collected by BGP-LS can be used to construct the Traffic

Engineering Database (TED, see Section 4.1.20) for use by the Path

Computation Element (PCE, see Section 4.1.13), or may be used by

Application-Layer Traffic Optimization (ALTO) servers (see

Section 4.1.15).

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4.1.13. Path Computation Element

Constraint-based path computation is a fundamental building block for

traffic engineering in MPLS and GMPLS networks. Path computation in

large, multi-domain networks is complex and may require special

computational components and cooperation between the elements in

different domains. The Path Computation Element (PCE) [RFC4655] is

an entity (component, application, or network node) that is capable

of computing a network path or route based on a network graph and

applying computational constraints.

Thus, a PCE can provide a central component in a traffic engineering

system operating on the Traffic Engineering Database (TED, see

Section 4.1.20) with delegated responsibility for determining paths

in MPLS, GMPLS, or Segment Routing networks. The PCE uses the Path

Computation Element Communication Protocol (PCEP) [RFC5440] to

communicate with Path Computation Clients (PCCs), such as MPLS LSRs,

to answer their requests for computed paths or to instruct them to

initiate new paths [RFC8281] and maintain state about paths already

installed in the network [RFC8231].

PCEs form key components of a number of traffic engineering systems.

More information about the applicability of PCE can be found in

[RFC8051], while [RFC6805] describes the application of PCE to

determining paths across multiple domains. PCE also has potential

use in Abstraction and Control of TE Networks (ACTN) (see

Section 4.1.17), Centralized Network Control [RFC8283], and Software

Defined Networking (SDN) (see Section 5.3.2).

4.1.14. Multi-Layer Traffic Engineering

Networks are often arranged as layers. A layer relationship may

represent the interaction between technologies (for example, an IP

network operated over an optical network), or the relationship

between different network operators (for example, a customer network

operated over a service provider's network). Note that a multi-layer

network does not imply the use of multiple technologies, although

some form of encapsulation is often applied.

Multi-layer traffic engineering presents a number of challenges

associated with scalability and confidentiality. These issues are

addressed in [RFC7926] which discusses the sharing of information

between domains through policy filters, aggregation, abstraction, and

virtualization. That document also discusses how existing protocols

can support this scenario with special reference to BGP-LS (see

Section 4.1.12).

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PCE (see Section 4.1.13) is also a useful tool for multi-layer

networks as described in [RFC6805] and [RFC8685]. Signaling

techniques for multi-layer traffic engineering are described in

[RFC6107].

See also Appendix A.3.1 for a discussion of how the overlay model has

been important in the development of traffic engineering.

4.1.15. Application-Layer Traffic Optimization

This document describes various TE mechanisms available in the

network. However, distributed applications in general and, in

particular, bandwidth-greedy P2P applications that are used, for

example, for file sharing, cannot directly use those techniques. As

per [RFC5693], applications could greatly improve traffic

distribution and quality by cooperating with external services that

are aware of the network topology. Addressing the Application-Layer

Traffic Optimization (ALTO) problem means, on the one hand, deploying

an ALTO service to provide applications with information regarding

the underlying network (e.g., basic network location structure and

preferences of network paths) and, on the other hand, enhancing

applications in order to use such information to perform better-than-

random selection of the endpoints with which they establish

connections.

The basic function of ALTO is based on abstract maps of a network.

These maps provide a simplified view, yet enough information about a

network for applications to effectively utilize them. Additional

services are built on top of the maps. [RFC7285] describes a

protocol implementing the ALTO services as an information-publishing

interface that allows a network to publish its network information

such as network locations, costs between them at configurable

granularities, and end-host properties to network applications. The

information published by the ALTO Protocol should benefit both the

network and the applications. The ALTO Protocol uses a REST-ful

design and encodes its requests and responses using JSON [RFC8259]

with a modular design by dividing ALTO information publication into

multiple ALTO services (e.g., the Map service, the Map-Filtering

Service, the Endpoint Property Service, and the Endpoint Cost

Service).

[RFC8189] defines a new service that allows an ALTO Client to

retrieve several cost metrics in a single request for an ALTO

filtered cost map and endpoint cost map. [RFC8896] extends the ALTO

cost information service so that applications decide not only 'where'

to connect, but also 'when'. This is useful for applications that

need to perform bulk data transfer and would like to schedule these

transfers during an off-peak hour, for example.

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[I-D.ietf-alto-performance-metrics] introducing network performance

metrics, including network delay, jitter, packet loss rate, hop

count, and bandwidth. The ALTO server may derive and aggregate such

performance metrics from BGP-LS (see Section 4.1.12) or IGP-TE (see

Section 4.1.11), or management tools, and then expose the information

to allow applications to determine 'where' to connect based on

network performance criteria. ALTO WG is evaluating the use of

network TE properties while making application decisions for new use-

cases such as Edge computing and Datacenter interconnect.

4.1.16. Segment Routing with MPLS Encapsulation (SR-MPLS)

Segment Routing (SR) [RFC8402] leverages the source routing and

tunneling paradigms. The path a packet takes is defined at the

ingress and the packet is tunneled to the egress. A node steers a

packet through a controlled set of instructions, called segments, by

prepending the packet with an SR header: a label stack in MPLS case.

A segment can represent any instruction, topological or service-

based, thanks to the MPLS architecture [RFC3031]. Labels can be

looked up in a global context (platform wide) as well as in some

other context (see "context labels" in Section 3 of [RFC5331]).

4.1.16.1. Base Segment Routing Identifier Types

Segments are identified by Segment Identifiers (SIDs). There are

four types of SID that are relevant for traffic engineering.

Prefix SID: Uses the SR Global Block (SRGB), must be unique within

the routing domain SRGB, and is advertised by an IGP. The Prefix-

SID can be configured as an absolute value or an index.

Node SID: A Prefix SID with the 'N' (node) bit set. It is

associated with a host prefix (/32 or /128) that identifies the

node. More than 1 Node SID can be configured per node.

Adjacency SID: Locally significant by default, an Adjacency SID can

be made globally significant through use of the 'L' flag. It

identifies a unidirectional adjacency. In most implementations

Adjacency SIDs are automatically allocated for each adjacency.

They are always encoded as an absolute (not indexed) value.

Binding SID: A Binding SID has two purposes:

1. Mapping Server in ISIS

The SID/Label Binding TLV is used to advertise the mappings

of prefixes to SIDs/Labels. This functionality is called

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the Segment Routing Mapping Server (SRMS). The behavior of

the SRMS is defined in [RFC8661]

2. Cross-connect (label to FEC mapping)

This is fundamental for multi-domain/multi-layer operation.

The Binding SID identifies a new path available at the

anchor point. It is always local to the originator, must

not be present at the top of the stack, and must be looked

up in the context of the Node SID. It could be provisioned

through Netconf/Restconf, PCEP, BGP, or the CLI.

4.1.16.2. Segment Routing Policy

SR Policy [I-D.ietf-spring-segment-routing-policy] is an evolution of

Segment Routing to enhance the TE capabilities. It is a framework

that enables instantiation of an ordered list of segments on a node

for implementing a source routing policy with a specific intent for

traffic steering from that node.

An SR Policy is identified through the tuple <headend, color,

endpoint>. The headend is the IP address of the node where the

policy is instantiated. The endpoint is the IP address of the

destination of the policy. The color is an index that associates the

SR Policy with an intent (e.g., low-latency).

The headend node is notified of SR Policies and associated SR paths

via configuration or by a extensions to protocols such as PCEP

[RFC8664] or BGP [I-D.ietf-idr-segment-routing-te-policy]. Each SR

path consists of a Segment-List (an SR source-routed path), and the

headend uses the endpoint and color parameters to classify packets to

match the SR policy and so determine along which path to forward

them. If an SR Policy is associated with a set of SR paths, each is

associated with a weight for weighted load balancing. Furthermore,

multiple SR Policies may be associated with a set of SR paths to

allow multiple traffic flows to be placed on the same paths.

An SR Binding SID (BSID) are also be associated with each candidate

path associated with an SR Policy, or with the SR Policy itself. The

headend node installs a BSID-keyed entry in the forwarding plane and

assigns it the action of steering packets that match the entry to the

selected path of the SR Policy. This steering can be done in various

ways:

o SID Steering: Incoming packets have an active SID matching a local

BSID at the headend.

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o Per-destination Steering: Incoming packets match a BGP/Service

route which indicates an SR Policy.

o Per-flow Steering: Incoming packets match a forwarding array (for

example, the classic 5-tuple) which indicates an SR Policies.

o Policy-based Steering: Incoming packets match a routing policy

which directs them to an SR Policy.

4.1.17. Network Virtualization and Abstraction

One of the main drivers for Software Defined Networking (SDN)

[RFC7149] is a decoupling of the network control plane from the data

plane. This separation has been achieved for TE networks with the

development of MPLS/GMPLS (see Section 4.1.6 and Section 4.1.7) and

the Path Computation Element (PCE) (Section 4.1.13). One of the

advantages of SDN is its logically centralized control regime that

allows a global view of the underlying networks. Centralized control

in SDN helps improve network resource utilization compared with

distributed network control.

Abstraction and Control of TE Networks (ACTN) [RFC8453] defines a

hierarchical SDN architecture which describes the functional entities

and methods for the coordination of resources across multiple

domains, to provide end-to-end traffic engineered services. ACTN

facilitates end-to-end connections and provides them to the user.

ACTN is focused on:

o Abstraction of the underlying network resources and how they are

provided to higher-layer applications and customers.

o Virtualization of underlying resources for use by the customer,

application, or service. The creation of a virtualized

environment allows operators to view and control multi-domain

networks as a single virtualized network.

o Presentation to customers of networks as a virtual network via

open and programmable interfaces.

The ACTN managed infrastructure is built from traffic engineered

network resources, which may include statistical packet bandwidth,

physical forwarding plane sources (such as wavelengths and time

slots), forwarding and cross-connect capabilities. The type of

network virtualization seen in ACTN allows customers and applications

(tenants) to utilize and independently control allocated virtual

network resources as if resources as if they were physically their

own resource. The ACTN network is "sliced", with tenants being given

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a different partial and abstracted topology view of the physical

underlying network.

4.1.18. Network Slicing

An IETF Network Slice is a logical network topology connecting a

number of endpoints using a set of shared or dedicated network

resources [I-D.nsdt-teas-ietf-network-slice-definition]. The

resources are used to satisfy specific Service Level Objectives

(SLOs) specified by the consumer.

IETF Network Slices are created and managed within the scope of one

or more network technologies (e.g., IP, MPLS, optical). They are

intended to enable a diverse set of applications that have different

requirements to coexist on the same network infrastructure. IETF

Network Slices are defined such that they are independent of the

underlying infrastructure connectivity and technologies used. This

is to allow an IETF Network Slice consumer to describe their network

connectivity and relevant objectives in a common format, independent

of the underlying technologies used.

An IETF Network Slice is a well-defined composite of a set of

endpoints, the connectivity requirements between subsets of these

endpoints, and associated service requirements. The service

requirements are expressed in terms of quantifiable characteristics

or service level objectives (SLOs). SLOs along with terms Service

Level Indicator (SLI) and Service Level Agreement (SLA) are used to

define the performance of a service at different levels

[I-D.nsdt-teas-ietf-network-slice-definition].

The concept of an IETF network slice is consistent with an enhanced

VPN (VPN+) [I-D.ietf-teas-enhanced-vpn]. That is, from a consumer's

perspective it looks like a VPN connectivity matrix with additional

information about the level of service required between endpoints,

while from an operator's perspective it looks like a set of routing

or tunneling instructions with the network resource reservations

necessary to provide the required service levels as specified by the

SLOs.

IETF network slices are not, of themselves, TE constructs. However,

a network operator that offers IETF network slices is likely to use

many TE tools in order to manage their network and provide the

services.

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4.1.19. Deterministic Networking

Deterministic Networking (DetNet) [RFC8655] is an architecture for

applications with critical timing and reliability requirements. The

layered architecture particularly focuses on developing DetNet

service capabilities in the data plane [RFC8938]. The DetNet service

sub-layer provides a set of Packet Replication, Elimination, and

Ordering Functions (PREOF) functions to provide end-to-end service

assurance. The DetNet forwarding sub-layer provides corresponding

forwarding assurance (low packet loss, bounded latency, and in-order

delivery) functions using resource allocations and explicit route

mechanisms.

The separation into two sub-layers allows a greater flexibility to

adapt Detnet capability over a number of TE data plane mechanisms

such as IP, MPLS, and Segment Routing. More importantly it

interconnects IEEE 802.1 Time Sensitive Networking (TSN)

[I-D.ietf-detnet-ip-over-tsn] deployed in Industry Control and

Automation Systems (ICAS).

DetNet can be seen as a specialized branch of TE, since it sets up

explicit optimized paths with allocation of resources as requested.

A DetNet application can express its QoS attributes or traffic

behavior using any combination of DetNet functions described in sub-

layers. They are then distributed and provisioned using well-

established control and provisioning mechanisms adopted for traffic-

engineering.

In DetNet, a considerable state information is required to maintain

per flow queuing disciplines and resource reservation for a large

number of individual flows. This can be quite challenging for

network operations during network events such as faults, change in

traffic volume or re-provisioning. Therefore, DetNet recommends

support for aggregated flows, however, it still requires large amount

of control signaling to establish and maintain DetNet flows.

4.1.20. Network TE State Definition and Presentation

The network states that are relevant to the traffic engineering need

to be stored in the system and presented to the user. The Traffic

Engineering Database (TED) is a collection of all TE information

about all TE nodes and TE links in the network, which is an essential

component of a TE system, such as MPLS-TE [RFC2702] and GMPLS

[RFC3945]. In order to formally define the data in the TED and to

present the data to the user with high usability, the data modeling

language YANG [RFC7950] can be used as described in [RFC8795].

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4.1.21. System Management and Control Interfaces

The traffic engineering control system needs to have a management

interface that is human-friendly and a control interfaces that is

programmable for automation. The Network Configuration Protocol

(NETCONF) [RFC6241] or the RESTCONF Protocol [RFC8040] provide

programmable interfaces that are also human-friendly. These

protocols use XML or JSON encoded messages. When message compactness

or protocol bandwidth consumption needs to be optimized for the

control interface, other protocols, such as Group Communication for

the Constrained Application Protocol (CoAP) [RFC7390] or gRPC, are

available, especially when the protocol messages are encoded in a

binary format. Along with any of these protocols, the data modeling

language YANG [RFC7950] can be used to formally and precisely define

the interface data.

The Path Computation Element Communication Protocol (PCEP) [RFC5440]

is another protocol that has evolved to be an option for the TE

system control interface. The messages of PCEP are TLV-based, not

defined by a data modeling language such as YANG.

4.2. Content Distribution

The Internet is dominated by client-server interactions, principally

Web traffic although in the future, more sophisticated media servers

may become dominant. The location and performance of major

information servers has a significant impact on the traffic patterns

within the Internet as well as on the perception of service quality

by end users.

A number of dynamic load balancing techniques have been devised to

improve the performance of replicated information servers. These

techniques can cause spatial traffic characteristics to become more

dynamic in the Internet because information servers can be

dynamically picked based upon the location of the clients, the

location of the servers, the relative utilization of the servers, the

relative performance of different networks, and the relative

performance of different parts of a network. This process of

assignment of distributed servers to clients is called traffic

directing. It is an application layer function.

Traffic directing schemes that allocate servers in multiple

geographically dispersed locations to clients may require empirical

network performance statistics to make more effective decisions. In

the future, network measurement systems may need to provide this type

of information.

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When congestion exists in the network, traffic directing and traffic

engineering systems should act in a coordinated manner. This topic

is for further study.

The issues related to location and replication of information

servers, particularly web servers, are important for Internet traffic

engineering because these servers contribute a substantial proportion

of Internet traffic.

5. Taxonomy of Traffic Engineering Systems

This section presents a short taxonomy of traffic engineering systems

constructed based on traffic engineering styles and views as listed

below and described in greater detail in the following subsections of

this document.

o Time-dependent versus State-dependent versus Event-dependent

o Offline versus Online

o Centralized versus Distributed

o Local versus Global Information

o Prescriptive versus Descriptive

o Open Loop versus Closed Loop

o Tactical versus Strategic

5.1. Time-Dependent Versus State-Dependent Versus Event-Dependent

Traffic engineering methodologies can be classified as time-

dependent, state-dependent, or event-dependent. All TE schemes are

considered to be dynamic in this document. Static TE implies that no

traffic engineering methodology or algorithm is being applied - it is

a feature of network planning, but lacks the reactive and flexible

nature of traffic engineering.

In time-dependent TE, historical information based on periodic

variations in traffic (such as time of day) is used to pre-program

routing and other TE control mechanisms. Additionally, customer

subscription or traffic projection may be used. Pre-programmed

routing plans typically change on a relatively long time scale (e.g.,

daily). Time-dependent algorithms do not attempt to adapt to short-

term variations in traffic or changing network conditions. An

example of a time-dependent algorithm is a global centralized

optimizer where the input to the system is a traffic matrix and

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multi-class QoS requirements as described [MR99]. Another example of

such a methodology is the application of data mining to Internet

traffic [AJ19] which enables the use of various machine learning

algorithms to identify patterns within historically collected

datasets about Internet traffic, and to extract information in order

to guide decision-making, and to improve efficiency and productivity

of operational processes.

State-dependent TE adapts the routing plans based on the current

state of the network which provides additional information on

variations in actual traffic (i.e., perturbations from regular

variations) that could not be predicted using historical information.

Constraint-based routing is an example of state-dependent TE

operating in a relatively long time scale. An example operating in a

relatively short timescale is a load-balancing algorithm described in

[MATE]. The state of the network can be based on parameters flooded

by the routers. Another approach is for a particular router

performing adaptive TE to send probe packets along a path to gather

the state of that path. [RFC6374] defines protocol extensions to

collect performance measurements from MPLS networks. Another

approach is for a management system to gather the relevant

information directly from network elements using telemetry data

collection "publication/subscription" techniques [RFC7923]. Timely

gathering and distribution of state information is critical for

adaptive TE. While time-dependent algorithms are suitable for

predictable traffic variations, state-dependent algorithms may be

applied to increase network efficiency and resilience to adapt to the

prevailing network state.

Event-dependent TE methods can also be used for TE path selection.

Event-dependent TE methods are distinct from time-dependent and

state-dependent TE methods in the manner in which paths are selected.

These algorithms are adaptive and distributed in nature and typically

use learning models to find good paths for TE in a network. While

state-dependent TE models typically use available-link-bandwidth

(ALB) flooding for TE path selection, event-dependent TE methods do

not require ALB flooding. Rather, event-dependent TE methods

typically search out capacity by learning models, as in the success-

to-the-top (STT) method. ALB flooding can be resource intensive,

since it requires link bandwidth to carry LSAs, processor capacity to

process LSAs, and the overhead can limit area/Autonomous System (AS)

size. Modeling results suggest that event-dependent TE methods could

lead to a reduction in ALB flooding overhead without loss of network

throughput performance [I-D.ietf-tewg-qos-routing].

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5.2. Offline Versus Online

Traffic engineering requires the computation of routing plans. The

computation may be performed offline or online. The computation can

be done offline for scenarios where routing plans need not be

executed in real-time. For example, routing plans computed from

forecast information may be computed offline. Typically, offline

computation is also used to perform extensive searches on multi-

dimensional solution spaces.

Online computation is required when the routing plans must adapt to

changing network conditions as in state-dependent algorithms. Unlike

offline computation (which can be computationally demanding), online

computation is geared toward relative simple and fast calculations to

select routes, fine-tune the allocations of resources, and perform

load balancing.

5.3. Centralized Versus Distributed

Under centralized control there is a central authority which

determines routing plans and perhaps other TE control parameters on

behalf of each router. The central authority periodically collects

network-state information from all routers, and sends routing

information to the routers. The update cycle for information

exchange in both directions is a critical parameter directly

impacting the performance of the network being controlled.

Centralized control may need high processing power and high bandwidth

control channels.

Distributed control determines route selection by each router

autonomously based on the router's view of the state of the network.

The network state information may be obtained by the router using a

probing method or distributed by other routers on a periodic basis

using link state advertisements. Network state information may also

be disseminated under exception conditions. Examples of protocol

extensions used to advertise network link state information are

defined in [RFC5305], [RFC6119], [RFC7471], [RFC8570], and [RFC8571].

See also Section 4.1.11.

5.3.1. Hybrid Systems

In practice, most TE systems will be a hybrid of central and

distributed control. For example, a popular MPLS approach to TE is

to use a central controller based on an active, stateful PCE, but to

use routing and signaling protocols to make local decisions at

routers within the network. Local decisions may be able to respond

more quickly to network events, but may result in conflicts with

decisions made by other routers.

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Network operations for TE systems may also use a hybrid of offline

and online computation. TE paths may be precomputed based on stable-

state network information and planned traffic demands, but may then

be modified in the active network depending on variations in network

state and traffic load. Furthermore, responses to network events may

be precomputed offline to allow rapid reactions without further

computation, or may be derived online depending on the nature of the

events.

Lastly, note that a fully functional TE system is likely to use all

aspects of time-dependent, state-dependent, and event-dependent

methodologies as described in Section 5.1.

5.3.2. Considerations for Software Defined Networking

As discussed in Section 4.1.17, one of the main drivers for SDN is a

decoupling of the network control plane from the data plane

[RFC7149]. However, SDN may also combine centralized control of

resources, and facilitate application-to-network interaction via an

application programming interface (API) such as [RFC8040]. Combining

these features provides a flexible network architecture that can

adapt to network requirements of a variety of higher-layer

applications, a concept often referred to as the "programmable

network" [RFC7426].

The centralized control aspect of SDN helps improve global network

resource utilization compared with distributed network control, where

local policy may often override global optimization goals. In an SDN

environment, the data plane forwards traffic to its desired

destination. However, before traffic reaches the data plane, the

logically centralized SDN control plane often determines the end-to-

end path the application traffic will take in the network.

Therefore, the SDN control plane needs to be aware of the underlying

network topology, capabilities and current node and link resource

state.

Using a PCE-based SDN control framework [RFC7491], the available

network topology may be discovered by running a passive instance of

OSPF or IS-IS, or via BGP-LS [RFC7752], to generate a TED (see

Section 4.1.20). The PCE is used to compute a path (see

Section 4.1.13) based on the TED and available bandwidth, and further

path optimization may be based on requested objective functions

[RFC5541]. When a suitable path has been computed the programming of

the explicit network path may be performed using either end-to-end

signaling protocol [RFC3209] or per-hop with each node being directly

programmed [RFC8283] by the SDN controller.

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By utilizing a centralized approach to network control, additional

network benefits are also available, including Global Concurrent

Optimization (GCO) [RFC5557]. A GCO path computation request will

simultaneously use the network topology and set of new end-to-end

path requests, along with their respective constraints, for optimal

placement in the network. Correspondingly, a GCO-based computation

may be applied to recompute existing network paths to groom traffic

and to mitigate congestion.

5.4. Local Versus Global

Traffic engineering algorithms may require local and global network-

state information.

Local information is the state of a portion of the domain. Examples

include the bandwidth and packet loss rate of a particular path, or

the state and capabilities of a network link. Local state

information may be sufficient for certain instances of distributed

control TE.

Global information is the state of the entire TE domain. Examples

include a global traffic matrix, and loading information on each link

throughout the domain of interest. Global state information is

typically required with centralized control. Distributed TE systems

may also need global information in some cases.

5.5. Prescriptive Versus Descriptive

TE systems may also be classified as prescriptive or descriptive.

Prescriptive traffic engineering evaluates alternatives and

recommends a course of action. Prescriptive traffic engineering can

be further categorized as either corrective or perfective.

Corrective TE prescribes a course of action to address an existing or

predicted anomaly. Perfective TE prescribes a course of action to

evolve and improve network performance even when no anomalies are

evident.

Descriptive traffic engineering, on the other hand, characterizes the

state of the network and assesses the impact of various policies

without recommending any particular course of action.

5.5.1. Intent-Based Networking

Intent is defined in [I-D.irtf-nmrg-ibn-concepts-definitions] as a

set of operational goals (that a network should meet) and outcomes

(that a network is supposed to deliver), defined in a declarative

manner without specifying how to achieve or implement them. This

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definition is based on [RFC7575] where, in the context of Autonomic

Networks, it is described as "an abstract, high-level policy used to

operate a network."

Thus, intent-based management or Intent-Based Networking (IBN) is the

concept of operating a network based on the concept of intent.

Intent-Based Networking aims to produce networks that are simpler to

manage and operate, requiring only minimal intervention. Networks

have no way of automatically knowing operational goals nor which

instances of networking services to support, thus the operator's

intent needs to be communicated to the network.

More specifically, intent is a declaration of operational goals that

a network should meet and outcomes that the network is supposed to

deliver, without specifying how to achieve them. Those goals and

outcomes are defined in a purely declarative way: they specify what

to accomplish, not how to achieve it. Intent applies two concepts:

o It provides data abstraction: users and operators do not need to

be concerned with low-level device configuration.

o It provides functional abstraction: users and operators do not

need to be concerned with how to achieve a given intent. What is

specified is the desired outcome which is converted by the

management system into the actions that will achieve the outcome.

Intent-Based Networking is applicable to traffic engineering because

many of the high-level objectives may be expressed as "intent." For

example, load balancing, delivery of services, and robustness against

failures. The intent is converted by the management system into

traffic engineering actions within the network.

5.6. Open-Loop Versus Closed-Loop

Open-loop traffic engineering control is where control action does

not use feedback information from the current network state. The

control action may use its own local information for accounting

purposes, however.

Closed-loop traffic engineering control is where control action

utilizes feedback information from the network state. The feedback

information may be in the form of historical information or current

measurement.

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5.7. Tactical versus Strategic

Tactical traffic engineering aims to address specific performance

problems (such as hot-spots) that occur in the network from a

tactical perspective, without consideration of overall strategic

imperatives. Without proper planning and insights, tactical TE tends

to be ad hoc in nature.

Strategic traffic engineering approaches the TE problem from a more

organized and systematic perspective, taking into consideration the

immediate and longer term consequences of specific policies and

actions.

6. Recommendations for Internet Traffic Engineering

This section describes high-level recommendations for traffic

engineering in the Internet in general terms.

The recommendations describe the capabilities needed to solve a

traffic engineering problem or to achieve a traffic engineering

objective. Broadly speaking, these recommendations can be

categorized as either functional or non-functional recommendations.

o Functional recommendations describe the functions that a traffic

engineering system should perform. These functions are needed to

realize traffic engineering objectives by addressing traffic

engineering problems.

o Non-functional recommendations relate to the quality attributes or

state characteristics of a traffic engineering system. These

recommendations may contain conflicting assertions and may

sometimes be difficult to quantify precisely.

6.1. Generic Non-functional Recommendations

The generic non-functional recommendations for Internet traffic

engineering are listed in the paragraphs that follow. In a given

context, some of these recommendations may be critical while others

may be optional. Therefore, prioritization may be required during

the development phase of a traffic engineering system to tailor it to

a specific operational context.

Usability: Usability is a human aspect of traffic engineering

systems. It refers to the ease with which a traffic engineering

system can be deployed and operated. In general, it is desirable

to have a TE system that can be readily deployed in an existing

network. It is also desirable to have a TE system that is easy to

operate and maintain.

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Automation: Whenever feasible, a TE system should automate as many

TE functions as possible to minimize the amount of human effort

needed to analyze and control operational networks. Automation is

particularly important in large-scale public networks because of

the high cost of the human aspects of network operations and the

high risk of network problems caused by human errors. Automation

may entail the incorporation of automatic feedback and

intelligence into some components of the TE system.

Scalability: Public networks continue to grow rapidly with respect

to network size and traffic volume. Therefore, to remain

applicable as the network evolves, a TE system should be scalable.

In particular, a TE system should remain functional as the network

expands with regard to the number of routers and links, and with

respect to the traffic volume. A TE system should have a scalable

architecture, should not adversely impair other functions and

processes in a network element, and should not consume too many

network resources when collecting and distributing state

information, or when exerting control.

Stability: Stability is a very important consideration in TE systems

that respond to changes in the state of the network. State-

dependent TE methodologies typically include a trade-off between

responsiveness and stability. It is strongly recommended that

when a trade-off between responsiveness and stability is needed,

it should be made in favor of stability (especially in public IP

backbone networks).

Flexibility: A TE system should allow for changes in optimization

policy. In particular, a TE system should provide sufficient

configuration options so that a network administrator can tailor

the system to a particular environment. It may also be desirable

to have both online and offline TE subsystems which can be

independently enabled and disabled. TE systems that are used in

multi-class networks should also have options to support class

based performance evaluation and optimization.

Visibility: Mechanisms should exist as part of the TE system to

collect statistics from the network and to analyze these

statistics to determine how well the network is functioning.

Derived statistics such as traffic matrices, link utilization,

latency, packet loss, and other performance measures of interest

which are determined from network measurements can be used as

indicators of prevailing network conditions. The capabilities of

the various components of the routing system are other examples of

status information which should be observable.

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Simplicity: A TE system should be as simple as possible and easy to

use (i.e., have clean, convenient, and intuitive user interfaces).

Simplicity in user interface does not necessarily imply that the

TE system will use naive algorithms. When complex algorithms and

internal structures are used, the user interface should hide such

complexities from the network administrator as much as possible.

Interoperability: Whenever feasible, TE systems and their components

should be developed with open standards-based interfaces to allow

interoperation with other systems and components.

Security: Security is a critical consideration in TE systems. Such

systems typically exert control over functional aspects of the

network to achieve the desired performance objectives. Therefore,

adequate measures must be taken to safeguard the integrity of the

TE system. Adequate measures must also be taken to protect the

network from vulnerabilities that originate from security breaches

and other impairments within the TE system.

The remaining subsections of this section focus on some of the high-

level functional recommendations for traffic engineering.

6.2. Routing Recommendations

Routing control is a significant aspect of Internet traffic

engineering. Routing impacts many of the key performance measures

associated with networks, such as throughput, delay, and utilization.

Generally, it is very difficult to provide good service quality in a

wide area network without effective routing control. A desirable TE

routing system is one that takes traffic characteristics and network

constraints into account during route selection while maintaining

stability.

Shortest path first (SPF) IGPs are based on shortest path algorithms

and have limited control capabilities for TE [RFC2702], [AWD2].

These limitations include:

1. Pure SPF protocols do not take network constraints and traffic

characteristics into account during route selection. For

example, IGPs always select the shortest paths based on link

metrics assigned by administrators) so load sharing cannot be

performed across paths of different costs. Using shortest paths

to forward traffic may cause the following problems:

\* If traffic from a source to a destination exceeds the capacity

of a link along the shortest path, the link (and hence the

shortest path) becomes congested while a longer path between

these two nodes may be under-utilized

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\* The shortest paths from different sources can overlap at some

links. If the total traffic from the sources exceeds the

capacity of any of these links, congestion will occur.

\* Problems can also occur because traffic demand changes over

time, but network topology and routing configuration cannot be

changed as rapidly. This causes the network topology and

routing configuration to become sub-optimal over time, which

may result in persistent congestion problems.

2. The Equal-Cost Multi-Path (ECMP) capability of SPF IGPs supports

sharing of traffic among equal cost paths between two nodes.

However, ECMP attempts to divide the traffic as equally as

possible among the equal cost shortest paths. Generally, ECMP

does not support configurable load sharing ratios among equal

cost paths. The result is that one of the paths may carry

significantly more traffic than other paths because it may also

carry traffic from other sources. This situation can result in

congestion along the path that carries more traffic. Weighted

ECMP (WECMP) (see, for example, [I-D.ietf-bess-evpn-unequal-lb])

provides some mitigation.

3. Modifying IGP metrics to control traffic routing tends to have

network-wide effects. Consequently, undesirable and

unanticipated traffic shifts can be triggered as a result. Work

described in Section 8 may be capable of better control [FT00],

[FT01].

Because of these limitations, new capabilities are needed to enhance

the routing function in IP networks. Some of these capabilities are

summarized below.

o Constraint-based routing computes routes to fulfill requirements

subject to constraints. This can be useful in public IP backbones

with complex topologies. Constraints may include bandwidth, hop

count, delay, and administrative policy instruments such as

resource class attributes [RFC2702], [RFC2386]. This makes it

possible to select routes that satisfy a given set of

requirements. Routes computed by constraint-based routing are not

necessarily the shortest paths. Constraint-based routing works

best with path-oriented technologies that support explicit

routing, such as MPLS.

Constraint-based routing can also be used as a way to distribute

traffic onto the infrastructure, including for best effort

traffic. For example, congestion problems caused by uneven

traffic distribution may be avoided or reduced by knowing the

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reservable bandwidth attributes of the network links and by

specifying the bandwidth requirements for path selection.

o A number of enhancements to the link state IGPs are needed to

allow them to distribute additional state information required for

constraint-based routing. The extensions to OSPF are described in

[RFC3630], and to IS-IS in [RFC5305]. Some of the additional

topology state information includes link attributes such as

reservable bandwidth and link resource class attribute (an

administratively specified property of the link). The resource

class attribute concept is defined in [RFC2702]. The additional

topology state information is carried in new TLVs and sub-TLVs in

IS-IS, or in the Opaque LSA in OSPF [RFC5305], [RFC3630].

An enhanced link-state IGP may flood information more frequently

than a normal IGP. This is because even without changes in

topology, changes in reservable bandwidth or link affinity can

trigger the enhanced IGP to initiate flooding. A trade-off

between the timeliness of the information flooded and the flooding

frequency is typically implemented using a threshold based on the

percentage change of the advertised resources to avoid excessive

consumption of link bandwidth and computational resources, and to

avoid instability in the TED.

o In a TE system, it is also desirable for the routing subsystem to

make the load splitting ratio among multiple paths (with equal

cost or different cost) configurable. This capability gives

network administrators more flexibility in the control of traffic

distribution across the network. It can be very useful for

avoiding/relieving congestion in certain situations. Examples can

be found in [XIAO] and [I-D.ietf-bess-evpn-unequal-lb].

o The routing system should also have the capability to control the

routes of subsets of traffic without affecting the routes of other

traffic if sufficient resources exist for this purpose. This

capability allows a more refined control over the distribution of

traffic across the network. For example, the ability to move

traffic away from its original path to another path (without

affecting other traffic paths) allows the traffic to be moved from

resource-poor network segments to resource-rich segments. Path

oriented technologies such as MPLS-TE inherently support this

capability as discussed in [AWD2].

o Additionally, the routing subsystem should be able to select

different paths for different classes of traffic (or for different

traffic behavior aggregates) if the network supports multiple

classes of service (different behavior aggregates).

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6.3. Traffic Mapping Recommendations

Traffic mapping is the assignment of traffic workload onto pre-

established paths to meet certain requirements. Thus, while

constraint-based routing deals with path selection, traffic mapping

deals with the assignment of traffic to established paths which may

have been generated by constraint-based routing or by some other

means. Traffic mapping can be performed by time-dependent or state-

dependent mechanisms, as described in Section 5.1.

An important aspect of the traffic mapping function is the ability to

establish multiple paths between an originating node and a

destination node, and the capability to distribute the traffic

between the two nodes across the paths according to some policies. A

pre-condition for this scheme is the existence of flexible mechanisms

to partition traffic and then assign the traffic partitions onto the

parallel paths as noted in [RFC2702]. When traffic is assigned to

multiple parallel paths, it is recommended that special care should

be taken to ensure proper ordering of packets belonging to the same

application (or micro-flow) at the destination node of the parallel

paths.

Mechanisms that perform the traffic mapping functions should aim to

map the traffic onto the network infrastructure to minimize

congestion. If the total traffic load cannot be accommodated, or if

the routing and mapping functions cannot react fast enough to

changing traffic conditions, then a traffic mapping system may use

short time scale congestion control mechanisms (such as queue

management, scheduling, etc.) to mitigate congestion. Thus,

mechanisms that perform the traffic mapping functions complement

existing congestion control mechanisms. In an operational network,

traffic should be mapped onto the infrastructure such that intra-

class and inter-class resource contention are minimized (see

Section 2).

When traffic mapping techniques that depend on dynamic state feedback

(e.g., MATE [MATE] and such like) are used, special care must be

taken to guarantee network stability.

6.4. Measurement Recommendations

The importance of measurement in traffic engineering has been

discussed throughout this document. A TE system should include

mechanisms to measure and collect statistics from the network to

support the TE function. Additional capabilities may be needed to

help in the analysis of the statistics. The actions of these

mechanisms should not adversely affect the accuracy and integrity of

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the statistics collected. The mechanisms for statistical data

acquisition should also be able to scale as the network evolves.

Traffic statistics may be classified according to long-term or short-

term timescales. Long-term traffic statistics are very useful for

traffic engineering. Long-term traffic statistics may periodicity

record network workload (such as hourly, daily, and weekly variations

in traffic profiles) as well as traffic trends. Aspects of the

traffic statistics may also describe class of service characteristics

for a network supporting multiple classes of service. Analysis of

the long-term traffic statistics may yield other information such as

busy hour characteristics, traffic growth patterns, persistent

congestion problems, hot-spot, and imbalances in link utilization

caused by routing anomalies.

A mechanism for constructing traffic matrices for both long-term and

short-term traffic statistics should be in place. In multi-service

IP networks, the traffic matrices may be constructed for different

service classes. Each element of a traffic matrix represents a

statistic about the traffic flow between a pair of abstract nodes.

An abstract node may represent a router, a collection of routers, or

a site in a VPN.

Traffic statistics should provide reasonable and reliable indicators

of the current state of the network on the short-term scale. Some

short term traffic statistics may reflect link utilization and link

congestion status. Examples of congestion indicators include

excessive packet delay, packet loss, and high resource utilization.

Examples of mechanisms for distributing this kind of information

include SNMP, probing tools, FTP, IGP link state advertisements, and

Netconf/Restconf, etc.

6.5. Network Survivability

Network survivability refers to the capability of a network to

maintain service continuity in the presence of faults. This can be

accomplished by promptly recovering from network impairments and

maintaining the required QoS for existing services after recovery.

Survivability is an issue of great concern within the Internet

community due to the demand to carry mission critical traffic, real-

time traffic, and other high priority traffic over the Internet.

Survivability can be addressed at the device level by developing

network elements that are more reliable; and at the network level by

incorporating redundancy into the architecture, design, and operation

of networks. It is recommended that a philosophy of robustness and

survivability should be adopted in the architecture, design, and

operation of traffic engineering that control IP networks (especially

public IP networks). Because different contexts may demand different

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levels of survivability, the mechanisms developed to support network

survivability should be flexible so that they can be tailored to

different needs. A number of tools and techniques have been

developed to enable network survivability including MPLS Fast Reroute

[RFC4090], RSVP-TE Extensions in Support of End-to-End GMPLS Recovery

[RFC4872], and GMPLS Segment Recovery [RFC4873].

The impact of service outages varies significantly for different

service classes depending on the duration of the outage which can

vary from milliseconds (with minor service impact) to seconds (with

possible call drops for IP telephony and session time-outs for

connection oriented transactions) to minutes and hours (with

potentially considerable social and business impact). Different

duration outages have different impacts depending on the throughput

of the traffic flows that are interrupted.

Failure protection and restoration capabilities are available in

multiple layers as network technologies have continued to evolve.

Optical networks are capable of providing dynamic ring and mesh

restoration functionality at the wavelength level. At the SONET/SDH

layer survivability capability is provided with Automatic Protection

Switching (APS) as well as self-healing ring and mesh architectures.

Similar functionality is provided by layer 2 technologies such as

Ethernet.

Rerouting is used at the IP layer to restore service following link

and node outages. Rerouting at the IP layer occurs after a period of

routing convergence which may require seconds to minutes to complete.

Path-oriented technologies such a MPLS ([RFC3469]) can be used to

enhance the survivability of IP networks in a potentially cost

effective manner.

An important of multi-layer survivability is that technologies at

different layers may provide protection and restoration capabilities

at different granularities in terms of time scales and at different

bandwidth granularity (from packet-level to wavelength level).

Protection and restoration capabilities can also be sensitive to

different service classes and different network utility models.

Coordinating different protection and restoration capabilities across

multiple layers in a cohesive manner to ensure network survivability

is maintained at reasonable cost is a challenging task. Protection

and restoration coordination across layers may not always be

feasible, because networks at different layers may belong to

different administrative domains.

The following paragraphs present some of the general recommendations

for protection and restoration coordination.

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o Protection and restoration capabilities from different layers

should be coordinated to provide network survivability in a

flexible and cost effective manner. Avoiding duplication of

functions in different layers is one way to achieve the

coordination. Escalation of alarms and other fault indicators

from lower to higher layers may also be performed in a coordinated

manner. The order of timing of restoration triggers from

different layers is another way to coordinate multi-layer

protection/restoration.

o Network capacity reserved in one layer to provide protection and

restoration is not available to carry traffic in a higher layer:

it is not visible as spare capacity in the higher layer. Placing

protection/restoration functions in many layers may increase

redundancy and robustness, but it can result in significant

inefficiencies in network resource utilization. Careful planning

is needed to balance the trade-off between the desire for

survivablity and the optimal use of resources.

o It is generally desirable to have protection and restoration

schemes that are intrinsically bandwidth efficient.

o Failure notifications throughout the network should be timely and

reliable if they are to be acted on as triggers for effective

protection and restoration actions.

o Alarms and other fault monitoring and reporting capabilities

should be provided at the right network layers so that the

protection and restoration actions can be taken in those layers.

6.5.1. Survivability in MPLS Based Networks

Because MPLS is path-oriented, it has the potential to provide faster

and more predictable protection and restoration capabilities than

conventional hop by hop routed IP systems. Protection types for MPLS

networks can be divided into four categories.

o Link Protection: The objective of link protection is to protect an

LSP from the failure of a given link. Under link protection, a

protection or backup LSP (the secondary LSP) follows a path that

is disjoint from the path of the working or operational LSP (the

primary LSP) at the particular link where link protection is

required. When the protected link fails, traffic on the working

LSP is switched to the protection LSP at the head-end of the

failed link. As a local repair method, link protection can be

fast. This form of protection may be most appropriate in

situations where some network elements along a given path are

known to be less reliable than others.

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o Node Protection: The objective of node protection is to protect an

LSP from the failure of a given node. Under node protection, the

secondary LSP follows a path that is disjoint from the path of the

primary LSP at the particular node where node protection is

required. The secondary LSP is also disjoint from the primary LSP

at all links attached to the node to be protected. When the

protected node fails, traffic on the working LSP is switched over

to the protection LSP at the upstream LSR directly connected to

the failed node. Node protection covers a slightly larger part of

the network compared to link protection, but is otherwise

fundamentally the same.

o Path Protection: The goal of LSP path protection (or end-to-end

protection) is to protect an LSP from any failure along its routed

path. Under path protection, the path of the protection LSP is

completely disjoint from the path of the working LSP. The

advantage of path protection is that the backup LSP protects the

working LSP from all possible link and node failures along the

path, except for failures of ingress or egress LSR. Additionally,

path protection may be more efficient in terms of resource usage

than link or node protection applied at every jop along the path.

However, path protection may be slower than link and node

protection because the fault notifications have to be propagated

further.

o Segment Protection: An MPLS domain may be partitioned into

multiple subdomains (protection domains). Path protection is

applied to the path of each LSP as it crosses the domain from its

ingress to the domain to where it egresses the domain. In cases

where an LSP traverses multiple protection domains, a protection

mechanism within a domain only needs to protect the segment of the

LSP that lies within the domain. Segment protection will

generally be faster than end-to-end path protection because

recovery generally occurs closer to the fault and the notification

doesn't have to propagate as far.

See [RFC3469] and [RFC6372] for a more comprehensive discussion of

MPLS based recovery.

6.5.2. Protection Options

Another issue to consider is the concept of protection options. We

use notation such as "m:n protection", where m is the number of

protection LSPs used to protect n working LSPs. In all cases except

1+1 protection, the resources associated with the protection LSPs can

be used to carry preemptable best-effort traffic when the working LSP

is functioning correctly.

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o 1:1 protection: One working LSP is protected/restored by one

protection LSP.

o 1:n protection: One protection LSP is used to protect/restore n

working LSPs. Only one failed LSP can be restored at any time.

o n:1 protection: One working LSP is protected/restored by n

protection LSPs, possibly with load splitting across the

protection LSPs. This may be especially useful when it is not

feasible to find one path for the backup that can satisfy the

bandwidth requirement of the primary LSP.

o 1+1 protection: Traffic is sent concurrently on both the working

LSP and a protection LSP. The egress LSR selects one of the two

LSPs based on local policy (usually based on traffic integrity).

When a fault disrupts the traffic on one LSP, the egress switches

to receive traffic from the other LSP. This approach is expensive

in how it consumes network but recovers from failures most

rapidly.

6.6. Traffic Engineering in Diffserv Environments

Increasing requirements to support multiple classes of traffic in the

Internet, such as best effort and mission critical data, calls for IP

networks to differentiate traffic according to some criteria and to

give preferential treatment to certain types of traffic. Large

numbers of flows can be aggregated into a few behavior aggregates

based on some criteria based on common performance requirements in

terms of packet loss ratio, delay, and jitter, or in terms of common

fields within the IP packet headers.

Differentiated Services (Diffserv) [RFC2475] can be used to ensure

that SLAs defined to differentiate between traffic flows are met.

Classes of service (CoS) can be supported in a Diffserv environment

by concatenating per-hop behaviors (PHBs) along the routing path. A

PHB is the forwarding behavior that a packet receives at a Diffserv-

compliant node, and it can be configured at each router. PHBs are

delivered using buffer management and packet scheduling mechanisms

and require that the ingress nodes use traffic classification,

marking, policing, and shaping.

Traffic engineering can compliment Diffserv to improve utilization of

network resources. Traffic engineering can be operated on an

aggregated basis across all service classes [RFC3270], or on a per

service class basis. The former is used to provide better

distribution of the traffic load over the network resources (see

[RFC3270] for detailed mechanisms to support aggregate traffic

engineering). The latter case is discussed below since it is

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specific to the Diffserv environment, with so called Diffserv-aware

traffic engineering [RFC4124].

For some Diffserv networks, it may be desirable to control the

performance of some service classes by enforcing relationships

between the traffic workload contributed by each service class and

the amount of network resources allocated or provisioned for that

service class. Such relationships between demand and resource

allocation can be enforced using a combination of, for example:

o TE mechanisms on a per service class basis that enforce the

relationship between the amount of traffic contributed by a given

service class and the resources allocated to that class.

o Mechanisms that dynamically adjust the resources allocated to a

given service class to relate to the amount of traffic contributed

by that service class.

It may also be desirable to limit the performance impact of high

priority traffic on relatively low priority traffic. This can be

achieved, for example, by controlling the percentage of high priority

traffic that is routed through a given link. Another way to

accomplish this is to increase link capacities appropriately so that

lower priority traffic can still enjoy adequate service quality.

When the ratio of traffic workload contributed by different service

classes varies significantly from router to router, it may not be

enough to rely on conventional IGP routing protocols or on TE

mechanisms that are not sensitive to different service classes.

Instead, it may be desirable to perform traffic engineering,

especially routing control and mapping functions, on a per service

class basis. One way to accomplish this in a domain that supports

both MPLS and Diffserv is to define class specific LSPs and to map

traffic from each class onto one or more LSPs that correspond to that

service class. An LSP corresponding to a given service class can

then be routed and protected/restored in a class dependent manner,

according to specific policies.

Performing traffic engineering on a per class basis may require per-

class parameters to be distributed. It is common to have some

classes share some aggregate constraints (e.g., maximum bandwidth

requirement) without enforcing the constraint on each individual

class. These classes can be grouped into class-types, and per-class-

type parameters can be distributed to improve scalability. This also

allows better bandwidth sharing between classes in the same class-

type. A class-type is a set of classes that satisfy the following

two conditions:

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o Classes in the same class-type have common aggregate requirements

to satisfy required performance levels.

o There is no requirement to be enforced at the level of an

individual class in the class-type. Note that it is,

nevertheless, still possible to implement some priority policies

for classes in the same class-type to permit preferential access

to the class-type bandwidth through the use of preemption

priorities.

See [RFC4124] for detailed requirements on Diffserv-aware traffic

engineering.

6.7. Network Controllability

Offline and online (see Section 5.2) TE considerations are of limited

utility if the network cannot be controlled effectively to implement

the results of TE decisions and to achieve the desired network

performance objectives.

Capacity augmentation is a coarse-grained solution to TE issues.

However, it is simple and may be advantageous if bandwidth is

abundant and cheap. However, bandwidth is not always abundant and

cheap, and additional capacity might not always be the best solution.

Adjustments of administrative weights and other parameters associated

with routing protocols provide finer-grained control, but this

approach is difficult to use and imprecise because of the the way the

routing protocols interact occur across the network.

Control mechanisms can be manual (e.g., static configuration),

partially-automated (e.g., scripts), or fully-automated (e.g., policy

based management systems). Automated mechanisms are particularly

useful in large scale networks. Multi-vendor interoperability can be

facilitated by standardized management systems (e.g., YANG models) to

support the control functions required to address TE objectives.

Network control functions should be secure, reliable, and stable as

these are often needed to operate correctly in times of network

impairments (e.g., during network congestion or security attacks).

7. Inter-Domain Considerations

Inter-domain TE is concerned with performance optimization for

traffic that originates in one administrative domain and terminates

in a different one.

BGP [RFC4271] is the standard exterior gateway protocol used to

exchange routing information between autonomous systems (ASes) in the

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Internet. BGP includes a sequential decision process that calculates

the preference for routes to a given destination network. There are

two fundamental aspects to inter-domain TE using BGP:

o Route Redistribution: Controlling the import and export of routes

between ASes, and controlling the redistribution of routes between

BGP and other protocols within an AS.

o Best path selection: Selecting the best path when there are

multiple candidate paths to a given destination network. This is

performed by the BGP decision process, selecting preferred exit

points out of an AS towards specific destination networks taking a

number of different considerations into account. The BGP path

selection process can be influenced by manipulating the attributes

associated with the process, including NEXT-HOP, WEIGHT, LOCAL-

PREFERENCE, AS-PATH, ROUTE-ORIGIN, MULTI-EXIT-DESCRIMINATOR (MED),

IGP METRIC, etc.

Route-maps provide the flexibility to implement complex BGP policies

based on pre-configured logical conditions. They can be used to

control import and export policies for incoming and outgoing routes,

control the redistribution of routes between BGP and other protocols,

and influence the selection of best paths by manipulating the

attributes associated with the BGP decision process. Very complex

logical expressions that implement various types of policies can be

implemented using a combination of Route-maps, BGP-attributes,

Access-lists, and Community attributes.

When considering inter-domain TE with BGP, note that the outbound

traffic exit point is controllable, whereas the interconnection point

where inbound traffic is received typically is not. Therefore, it is

up to each individual network to implement TE strategies that deal

with the efficient delivery of outbound traffic from its customers to

its peering points. The vast majority of TE policy is based on a

"closest exit" strategy, which offloads interdomain traffic at the

nearest outbound peering point towards the destination AS. Most

methods of manipulating the point at which inbound traffic enters a

are either ineffective, or not accepted in the peering community.

Inter-domain TE with BGP is generally effective, but it is usually

applied in a trial-and-error fashion because a TE system usually only

has a view of the available network resources within one domain (an

AS in this case). A systematic approach for inter-domain TE requires

cooperation between the domains. Further, what may be considered a

good solution in one domain may not necessarily be a good solution in

another. Moreover, it is generally considered inadvisable for one

domain to permit a control process from another domain to influence

the routing and management of traffic in its network.

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MPLS TE-tunnels (LSPs) can add a degree of flexibility in the

selection of exit points for inter-domain routing by applying rhe

concept of relative and absolute metrics. If BGP attributes are

defined such that the BGP decision process depends on IGP metrics to

select exit points for inter-domain traffic, then some inter-domain

traffic destined to a given peer network can be made to prefer a

specific exit point by establishing a TE-tunnel between the router

making the selection and the peering point via a TE-tunnel and

assigning the TE-tunnel a metric which is smaller than the IGP cost

to all other peering points.

Similarly to intra-domain TE, inter-domain TE is best accomplished

when a traffic matrix can be derived to depict the volume of traffic

from one AS to another.

8. Overview of Contemporary TE Practices in Operational IP Networks

This section provides an overview of some traffic engineering

practices in IP networks. The focus is on aspects of control of the

routing function in operational contexts. The intent here is to

provide an overview of the commonly used practices: the discussion is

not intended to be exhaustive.

Service providers apply many of the traffic engineering mechanisms

described in this document to optimize the performance of their IP

networks. These techniques include capacity planning for long

timescales; routing control using IGP metrics and MPLS, as well as

path planning and path control using MPLS and Segment Routing for

medium timescales; and traffic management mechanisms for short

timescale.

Capacity planning is an important component of how a service provider

plans an effective IP network. These plans may take the following

aspects into account: location of and new links or nodes, existing

and predicted traffic patterns, costs, link capacity, topology,

routing design, and survivability.

Performance optimization of operational networks is usually an

ongoing process in which traffic statistics, performance parameters,

and fault indicators are continually collected from the network.

This empirical data is analyzed and used to trigger TE mechanisms.

Tools that perform what-if analysis can also be used to assist the TE

process by reviewing scenarios before a new set of configurations are

implemented in the operational network.

Real-time intra-domain TE using the IGP is done by increasing the

OSPF or IS-IS metric of a congested link until enough traffic has

been diverted away from that link. This approach has some

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limitations as discussed in Section 6.2. Intra-domain TE approaches

([RR94] [FT00] [FT01] [WANG]) take traffic matrix, network topology,

and network performance objectives as input, and produce link metrics

and load-sharing ratios. These processes open the possibility for

intra-domain TE with IGP to be done in a more systematic way.

Administrators of MPLS-TE networks specify and configure link

attributes and resource constraints such as maximum reservable

bandwidth and resource class attributes for the links in the domain.

A link state IGP that supports TE extensions (IS-IS-TE or OSPF-TE) is

used to propagate information about network topology and link

attributes to all routers in the domain. Network administrators

specify the LSPs that are to originate at each router. For each LSP,

the network administrator specifies the destination node and the

attributes of the LSP which indicate the requirements that are to be

satisfied during the path selection process. The attributes may

include and explicit path for the LSP to follow, or originating

router uses a local constraint-based routing process to compute the

path of the LSP. RSVP-TE is used as a signaling protocol to

instantiate the LSPs. By assigning proper bandwidth values to links

and LSPs, congestion caused by uneven traffic distribution can be

avoided or mitigated.

The bandwidth attributes of an LSP relates to the bandwidth

requirements of traffic that flows through the LSP. The traffic

attribute of an LSP can be modified to accommodate persistent shifts

in demand (traffic growth or reduction). If network congestion

occurs due to some unexpected events, existing LSPs can be rerouted

to alleviate the situation or network administrator can configure new

LSPs to divert some traffic to alternative paths. The reservable

bandwidth of the congested links can also be reduced to force some

LSPs to be rerouted to other paths. A traffic matrix in an MPLS

domain can also be estimated by monitoring the traffic on LSPs. Such

traffic statistics can be used for a variety of purposes including

network planning and network optimization.

Network management and planning systems have evolved and taken over a

lot of the responsibility for determining traffic paths in TE

networks. This allows a network-wide view of resources, and

facilitates coordination of the use of resources for all traffic

flows in the network. Initial solutions using a PCE to perform path

computation on behalf of network routers have given way to an

approach that follows the SDN architecture. A stateful PCE is able

to track all of the LSPs in the network and can redistribute them to

make better use of the available resources. Such a PCE can forms

part of a network orchestrator that uses PCEP or some other

southbound interface to instruct the signaling protocol or directly

program the routers.

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Segment routing leverages a centralized TE controller and either an

MPLS or IPv6 forwarding plane, but does not need to use a signaling

protocol or management plane protocol to reserve resources in the

routers. All resource reservation is logical within the controller,

and not distributed to the routers. Packets are steered through the

network using segment routing.

As mentioned in Section 7, there is usually no direct control over

the distribution of inbound traffic to a domain. Therefore, the main

goal of inter-domain TE is to optimize the distribution of outbound

traffic between multiple inter-domain links. When operating a global

network, maintaining the ability to operate the network in a regional

fashion where desired, while continuing to take advantage of the

benefits of a global network, also becomes an important objective.

Inter-domain TE with BGP begins with the placement of multiple

peering interconnection points that are in close proximity to traffic

sources/destination, and offer lowest cost paths across the network

between the peering points and and the sources/destinations. Some

location-decision problems that arise in association with inter-

domain routing are discussed in [AWD5].

Once the locations of the peering interconnects have been determined

and implemented, the network operator decides how best to handle the

routes advertised by the peer, as well as how to propagate the peer's

routes within their network. One way to engineer outbound traffic

flows in a network with many peering interconnects is to create a

hierarchy of peers. Generally, the shortest AS paths will be chosen

to forward traffic but BGP metrics can be used to prefer some peers

and so favor particular paths. Preferred peers are those peers

attached through peering interconnects with the most available

capacity. Changes may be needed, for example, to deal with a

"problem peer" who is difficult to work with on upgrades or is

charging high prices for connectivity to their network. In that

case, the peer may be given a reduced preference. This type of

change can affect a large amount of traffic, and is only used after

other methods have failed to provide the desired results.

When there are multiple exit points toward a given peer, and only one

of them is congested, it is not necessary to shift traffic away from

the peer entirely, but only from the one congested connections. This

can be achieved by using passive IGP-metrics, AS-path filtering, or

prefix filtering.

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9. Security Considerations

This document does not introduce new security issues.

Network security is, of course, an important issue. In general, TE

mechanisms are security neutral: they may use tunnels which can

slightly help protect traffic from inspection and which, in some

cases, can be secured using encryption; they put traffic onto

predictable paths within the network that may make it easier to find

and attack; they increase the complexity or operation and management

of the network; and they enable traffic to be steered onto more

secure links or to more secure parts of the network.

The consequences of attacks on the control and management protocols

used to operate TE networks can be significant: traffic can be

hijacked to pass through specific nodes that perform inspection, or

even to be delivered to the wrong place; traffic can be steered onto

paths that deliver quality that is below the desired quality; and,

networks can be congested or have resources on key links consumed.

Thus, it is important to use adequate protection mechanisms on all

protocols used to deliver TE.

Certain aspects of a network may be deduced from the details of the

TE paths that are used. For example, the link connectivity of the

network, and the quality and load on individual links may be assumed

from knowing the paths of traffic and the requirements they place on

the network (for example, by seeing the control messages or through

path- trace techniques). Such knowledge can be used to launch

targeted attacks (for example, taking down critical links) or can

reveal commercially sensitive information (for example, whether a

network is close to capacity). Network operators may, therefore,

choose techniques that mask or hide information from within the

network.

10. IANA Considerations

This draft makes no requests for IANA action.

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Appendix A. Historic Overview

A.1. Traffic Engineering in Classical Telephone Networks

This subsection presents a brief overview of traffic engineering in

telephone networks which often relates to the way user traffic is

steered from an originating node to the terminating node. This

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subsection presents a brief overview of this topic. A detailed

description of the various routing strategies applied in telephone

networks is included in the book by G. Ash [ASH2].

The early telephone network relied on static hierarchical routing,

whereby routing patterns remained fixed independent of the state of

the network or time of day. The hierarchy was intended to

accommodate overflow traffic, improve network reliability via

alternate routes, and prevent call looping by employing strict

hierarchical rules. The network was typically over-provisioned since

a given fixed route had to be dimensioned so that it could carry user

traffic during a busy hour of any busy day. Hierarchical routing in

the telephony network was found to be too rigid upon the advent of

digital switches and stored program control which were able to manage

more complicated traffic engineering rules.

Dynamic routing was introduced to alleviate the routing inflexibility

in the static hierarchical routing so that the network would operate

more efficiently. This resulted in significant economic gains

[HUSS87]. Dynamic routing typically reduces the overall loss

probability by 10 to 20 percent (compared to static hierarchical

routing). Dynamic routing can also improve network resilience by

recalculating routes on a per-call basis and periodically updating

routes.

There are three main types of dynamic routing in the telephone

network. They are time-dependent routing, state-dependent routing

(SDR), and event dependent routing (EDR).

In time-dependent routing, regular variations in traffic loads (such

as time of day or day of week) are exploited in pre-planned routing

tables. In state-dependent routing, routing tables are updated

online according to the current state of the network (e.g., traffic

demand, utilization, etc.). In event dependent routing, routing

changes are triggers by events (such as call setups encountering

congested or blocked links) whereupon new paths are searched out

using learning models. EDR methods are real-time adaptive, but they

do not require global state information as does SDR. Examples of EDR

schemes include the dynamic alternate routing (DAR) from BT, the

state-and-time dependent routing (STR) from NTT, and the success-to-

the-top (STT) routing from AT&T.

Dynamic non-hierarchical routing (DNHR) is an example of dynamic

routing that was introduced in the AT&T toll network in the 1980's to

respond to time-dependent information such as regular load variations

as a function of time. Time-dependent information in terms of load

may be divided into three timescales: hourly, weekly, and yearly.

Correspondingly, three algorithms are defined to pre-plan the routing

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tables. The network design algorithm operates over a year-long

interval while the demand servicing algorithm operates on a weekly

basis to fine tune link sizes and routing tables to correct forecast

errors on the yearly basis. At the smallest timescale, the routing

algorithm is used to make limited adjustments based on daily traffic

variations. Network design and demand servicing are computed using

offline calculations. Typically, the calculations require extensive

searches on possible routes. On the other hand, routing may need

online calculations to handle crankback. DNHR adopts a "two-link"

approach whereby a path can consist of two links at most. The

routing algorithm presents an ordered list of route choices between

an originating switch and a terminating switch. If a call overflows,

a via switch (a tandem exchange between the originating switch and

the terminating switch) would send a crankback signal to the

originating switch. This switch would then select the next route,

and so on, until there are no alternative routes available in which

the call is blocked.

A.2. Evolution of Traffic Engineering in Packet Networks

This subsection reviews related prior work that was intended to

improve the performance of data networks. Indeed, optimization of

the performance of data networks started in the early days of the

ARPANET. Other early commercial networks such as SNA also recognized

the importance of performance optimization and service

differentiation.

In terms of traffic management, the Internet has been a best effort

service environment until recently. In particular, very limited

traffic management capabilities existed in IP networks to provide

differentiated queue management and scheduling services to packets

belonging to different classes.

In terms of routing control, the Internet has employed distributed

protocols for intra-domain routing. These protocols are highly

scalable and resilient. However, they are based on simple algorithms

for path selection which have very limited functionality to allow

flexible control of the path selection process.

In the following subsections, the evolution of practical traffic

engineering mechanisms in IP networks and its predecessors are

reviewed.

A.2.1. Adaptive Routing in the ARPANET

The early ARPANET recognized the importance of adaptive routing where

routing decisions were based on the current state of the network

[MCQ80]. Early minimum delay routing approaches forwarded each

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packet to its destination along a path for which the total estimated

transit time was the smallest. Each node maintained a table of

network delays, representing the estimated delay that a packet would

experience along a given path toward its destination. The minimum

delay table was periodically transmitted by a node to its neighbors.

The shortest path, in terms of hop count, was also propagated to give

the connectivity information.

One drawback to this approach is that dynamic link metrics tend to

create "traffic magnets" causing congestion to be shifted from one

location of a network to another location, resulting in oscillation

and network instability.

A.2.2. Dynamic Routing in the Internet

The Internet evolved from the ARPANET and adopted dynamic routing

algorithms with distributed control to determine the paths that

packets should take en-route to their destinations. The routing

algorithms are adaptations of shortest path algorithms where costs

are based on link metrics. The link metric can be based on static or

dynamic quantities. The link metric based on static quantities may

be assigned administratively according to local criteria. The link

metric based on dynamic quantities may be a function of a network

congestion measure such as delay or packet loss.

It was apparent early that static link metric assignment was

inadequate because it can easily lead to unfavorable scenarios in

which some links become congested while others remain lightly loaded.

One of the many reasons for the inadequacy of static link metrics is

that link metric assignment was often done without considering the

traffic matrix in the network. Also, the routing protocols did not

take traffic attributes and capacity constraints into account when

making routing decisions. This results in traffic concentration

being localized in subsets of the network infrastructure and

potentially causing congestion. Even if link metrics are assigned in

accordance with the traffic matrix, unbalanced loads in the network

can still occur due to a number factors including:

o Resources may not be deployed in the most optimal locations from a

routing perspective.

o Forecasting errors in traffic volume and/or traffic distribution.

o Dynamics in traffic matrix due to the temporal nature of traffic

patterns, BGP policy change from peers, etc.

The inadequacy of the legacy Internet interior gateway routing system

is one of the factors motivating the interest in path oriented

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technology with explicit routing and constraint-based routing

capability such as MPLS.

A.2.3. ToS Routing

Type-of-Service (ToS) routing involves different routes going to the

same destination with selection dependent upon the ToS field of an IP

packet [RFC2474]. The ToS classes may be classified as low delay and

high throughput. Each link is associated with multiple link costs

and each link cost is used to compute routes for a particular ToS. A

separate shortest path tree is computed for each ToS. The shortest

path algorithm must be run for each ToS resulting in very expensive

computation. Classical ToS-based routing is now outdated as the IP

header field has been replaced by a Diffserv field. Effective

traffic engineering is difficult to perform in classical ToS-based

routing because each class still relies exclusively on shortest path

routing which results in localization of traffic concentration within

the network.

A.2.4. Equal Cost Multi-Path

Equal Cost Multi-Path (ECMP) is another technique that attempts to

address the deficiency in the Shortest Path First (SPF) interior

gateway routing systems [RFC2328]. In the classical SPF algorithm,

if two or more shortest paths exist to a given destination, the

algorithm will choose one of them. The algorithm is modified

slightly in ECMP so that if two or more equal cost shortest paths

exist between two nodes, the traffic between the nodes is distributed

among the multiple equal-cost paths. Traffic distribution across the

equal-cost paths is usually performed in one of two ways: (1) packet-

based in a round-robin fashion, or (2) flow-based using hashing on

source and destination IP addresses and possibly other fields of the

IP header. The first approach can easily cause out- of-order packets

while the second approach is dependent upon the number and

distribution of flows. Flow-based load sharing may be unpredictable

in an enterprise network where the number of flows is relatively

small and less heterogeneous (for example, hashing may not be

uniform), but it is generally effective in core public networks where

the number of flows is large and heterogeneous.

In ECMP, link costs are static and bandwidth constraints are not

considered, so ECMP attempts to distribute the traffic as equally as

possible among the equal-cost paths independent of the congestion

status of each path. As a result, given two equal-cost paths, it is

possible that one of the paths will be more congested than the other.

Another drawback of ECMP is that load sharing cannot be achieved on

multiple paths which have non-identical costs.

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A.2.5. Nimrod

Nimrod was a routing system developed to provide heterogeneous

service specific routing in the Internet, while taking multiple

constraints into account [RFC1992]. Essentially, Nimrod was a link

state routing protocol to support path oriented packet forwarding.

It used the concept of maps to represent network connectivity and

services at multiple levels of abstraction. Mechanisms allowed

restriction of the distribution of routing information.

Even though Nimrod did not enjoy deployment in the public Internet, a

number of key concepts incorporated into the Nimrod architecture,

such as explicit routing which allows selection of paths at

originating nodes, are beginning to find applications in some recent

constraint-based routing initiatives.

A.3. Development of Internet Traffic Engineering

A.3.1. Overlay Model

In the overlay model, a virtual-circuit network, such as Synchronous

Optical Network / Synchronous Digital Hierarchy (SONET/SDH), Optical

Transport Network (OTN), or Wavelength Division Multiplexing (WDM),

provides virtual-circuit connectivity between routers that are

located at the edges of a virtual-circuit cloud. In this mode, two

routers that are connected through a virtual circuit see a direct

adjacency between themselves independent of the physical route taken

by the virtual circuit through the ATM, frame relay, or WDM network.

Thus, the overlay model essentially decouples the logical topology

that routers see from the physical topology that the ATM, frame

relay, or WDM network manages. The overlay model based on ATM or

frame relay enables a network administrator or an automaton to employ

traffic engineering concepts to perform path optimization by re-

configuring or rearranging the virtual circuits so that a virtual

circuit on a congested or sub-optimal physical link can be re-routed

to a less congested or more optimal one. In the overlay model,

traffic engineering is also employed to establish relationships

between the traffic management parameters (e.g., Peak Cell Rate,

Sustained Cell Rate, and Maximum Burst Size for ATM) of the virtual-

circuit technology and the actual traffic that traverses each

circuit. These relationships can be established based upon known or

projected traffic profiles, and some other factors.

Appendix B. Overview of Traffic Engineering Related Work in Other SDOs

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B.1. Overview of ITU Activities Related to Traffic Engineering

This section provides an overview of prior work within the ITU-T

pertaining to traffic engineering in traditional telecommunications

networks.

ITU-T Recommendations E.600 [ITU-E600], E.701 [ITU-E701], and E.801

[ITU-E801] address traffic engineering issues in traditional

telecommunications networks. Recommendation E.600 provides a

vocabulary for describing traffic engineering concepts, while E.701

defines reference connections, Grade of Service (GoS), and traffic

parameters for ISDN. Recommendation E.701 uses the concept of a

reference connection to identify representative cases of different

types of connections without describing the specifics of their actual

realizations by different physical means. As defined in

Recommendation E.600, "a connection is an association of resources

providing means for communication between two or more devices in, or

attached to, a telecommunication network." Also, E.600 defines "a

resource as any set of physically or conceptually identifiable

entities within a telecommunication network, the use of which can be

unambiguously determined" [ITU-E600]. There can be different types

of connections as the number and types of resources in a connection

may vary.

Typically, different network segments are involved in the path of a

connection. For example, a connection may be local, national, or

international. The purposes of reference connections are to clarify

and specify traffic performance issues at various interfaces between

different network domains. Each domain may consist of one or more

service provider networks.

Reference connections provide a basis to define grade of service

(GoS) parameters related to traffic engineering within the ITU-T

framework. As defined in E.600, "GoS refers to a number of traffic

engineering variables which are used to provide a measure of the

adequacy of a group of resources under specified conditions." These

GoS variables may be probability of loss, dial tone, delay, etc.

They are essential for network internal design and operation as well

as for component performance specification.

GoS is different from quality of service (QoS) in the ITU framework.

QoS is the performance perceivable by a telecommunication service

user and expresses the user's degree of satisfaction of the service.

QoS parameters focus on performance aspects observable at the service

access points and network interfaces, rather than their causes within

the network. GoS, on the other hand, is a set of network oriented

measures which characterize the adequacy of a group of resources

under specified conditions. For a network to be effective in serving

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its users, the values of both GoS and QoS parameters must be related,

with GoS parameters typically making a major contribution to the QoS.

Recommendation E.600 stipulates that a set of GoS parameters must be

selected and defined on an end-to-end basis for each major service

category provided by a network to assist the network provider with

improving efficiency and effectiveness of the network. Based on a

selected set of reference connections, suitable target values are

assigned to the selected GoS parameters under normal and high load

conditions. These end-to-end GoS target values are then apportioned

to individual resource components of the reference connections for

dimensioning purposes.

Appendix C. Summary of Changes Since RFC 3272

The changes to this document since RFC 3272 are substantial and not

easily summarized as section-by-section changes. The material in the

document has been moved around considerably, some of it removed, and

new text added.

The approach taken here is to list the table of content of both the

previous RFC and this document saying, respectively, where the text

has been place and where the text came from.

C.1. RFC 3272

1.0 Introduction: Edited in place in Section 1.

1.1 What is Internet Traffic Engineering?: Edited in place in

Section 1.1.

1.2 Scope: Moved to Section 1.3.

1.3 Terminology: Moved to Section 1.4 with some obsolete terms

removed and a little editing.

2.0 Background: Retained as Section 2 with some text removed.

2.1 Context of Internet Traffic Engineering: Retained as

Section 2.1.

2.2 Network Context: Rewritten as Section 2.2.

2.3 Problem Context: Rewritten as Section 2.3.

2.3.1 Congestion and its Ramifications: Retained as

Section 2.3.1.

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2.4 Solution Context: Edited as Section 2.4.

2.4.1 Combating the Congestion Problem: Reformatted as

Section 2.4.1.

2.5 Implementation and Operational Context: Retained as

Section 2.5.

3.0 Traffic Engineering Process Model: Retained as Section 3.

3.1 Components of the Traffic Engineering Process Model: Retained

as Section 3.1.

3.2 Measurement: Merged into Section 3.1.

3.3 Modeling, Analysis, and Simulation: Merged into Section 3.1.

3.4 Optimization: Merged into Section 3.1.

4.0 Historical Review and Recent Developments: Retained as

Section 4, but the very historic aspects moved to Appendix A.

4.1 Traffic Engineering in Classical Telephone Networks: Moved to

Appendix A.1.

4.2 Evolution of Traffic Engineering in the Internet: Moved to Ap

pendix A.2.

4.2.1 Adaptive Routing in ARPANET: Moved to Appendix A.2.1.

4.2.2 Dynamic Routing in the Internet: Moved to

Appendix A.2.2.

4.2.3 ToS Routing: Moved to Appendix A.2.3.

4.2.4 Equal Cost Multi-Path: Moved to Appendix A.2.4.

4.2.5 Nimrod: Moved to Appendix A.2.5.

4.3 Overlay Model: Moved to Appendix A.3.1.

4.4 Constraint-Based Routing: Retained as Section 4.1.1, but

moved into Section 4.1.

4.5 Overview of Other IETF Projects Related to Traffic

Engineering:

Retained as Section 4.1 with many new subsections.

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4.5.1 Integrated Services: Retained as Section 4.1.2.

4.5.2 RSVP: Retained as Section 4.1.3 with some edits.

4.5.3 Differentiated Services: Retained as Section 4.1.4.

4.5.4 MPLS: Retained as Section 4.1.6.

4.5.5 IP Performance Metrics: Retained as Section 4.1.8.

4.5.6 Flow Measurement: Retained as Section 4.1.9 with some

reformatting.

4.5.7 Endpoint Congestion Management: Retained as Section 4.1.10.

4.6 Overview of ITU Activities Related to Traffic Engineering: Moved

to Appendix B.1.

4.7 Content Distribution: Retained as Section 4.2.

5.0 Taxonomy of Traffic Engineering Systems: Retained as Section 5.

5.1 Time-Dependent Versus State-Dependent: Retained as

Section 5.1.

5.2 Offline Versus Online: Retained as Section 5.2.

5.3 Centralized Versus Distributed: Retained as Section 5.3 with

additions.

5.4 Local Versus Global: Retained as Section 5.4.

5.5 Prescriptive Versus Descriptive: Retained as Section 5.5 with

additions.

5.6 Open-Loop Versus Closed-Loop: Retained as Section 5.6.

5.7 Tactical vs Strategic: Retained as Section 5.7.

6.0 Recommendations for Internet Traffic Engineering: Retained as

Section 6.

6.1 Generic Non-functional Recommendations: Retained as

Section 6.1.

6.2 Routing Recommendations: Retained as Section 6.2 with edits.

6.3 Traffic Mapping Recommendations: Retained as Section 6.3.

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6.4 Measurement Recommendations: Retained as Section 6.4.

6.5 Network Survivability: Retained as Section 6.5.

6.5.1 Survivability in MPLS Based Networks: Retained as

Section 6.5.1.

6.5.2 Protection Option: Retained as Section 6.5.2.

6.6 Traffic Engineering in Diffserv Environments: Retained as

Section 6.6 with edits.

6.7 Network Controllability: Retained as Section 6.7.

7.0 Inter-Domain Considerations: Retained as Section 7.

8.0 Overview of Contemporary TE Practices in Operational IP Networks:

Retained as Section 8.

9.0 Conclusion: Removed.

10.0 Security Considerations: Retained as Section 9 with

considerable new text.

C.2. This Document

o Section 1: Based on Section 1 of RFC 3272.

\* Section 1.1: Based on Section 1.1 of RFC 3272.

\* Section 1.2: New for this document.

\* Section 1.3: Based on Section 1.2 of RFC 3272.

\* Section 1.4: Based on Section 1.3 of RFC 3272.

o Section 2: Based on Section 2. of RFC 3272.

\* Section 2.1: Based on Section 2.1 of RFC 3272.

\* Section 2.2: Based on Section 2.2 of RFC 3272.

\* Section 2.3: Based on Section 2.3 of RFC 3272.

+ Section 2.3.1: Based on Section 2.3.1 of RFC 3272.

\* Section 2.4: Based on Section 2.4 of RFC 3272.

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+ Section 2.4.1: Based on Section 2.4.1 of RFC 327

\* Section 2.5: Based on Section 2.5 of RFC 3272.

o Section 3: Based on Section 3 of RFC 3272.

\* Section 3.1: Based on Sections 3.1, 3.2, 3.3, and 3.4 of RFC

3272.

o Section 4: Based on Section 4 of RFC 3272.

\* Section 4.1: Based on Section 4.5 of RFC 3272.

+ Section 4.1.1: Based on Section 4.4 of RFC 3272.

- Section 4.1.1.1: New for this document.

+ Section 4.1.2: Based on Section 4.5.1 of RFC 3272.

+ Section 4.1.3: Based on Section 4.5.2 of RFC 3272.

+ Section 4.1.4: Based on Section 4.5.3 of RFC 3272.

+ Section 4.1.5: New for this document.

+ Section 4.1.6: Based on Section 4.5.4 of RFC 3272.

+ Section 4.1.7: New for this document.

+ Section 4.1.8: Based on Section 4.5.5 of RFC 3272.

+ Section 4.1.9: Based on Section 4.5.6 of RFC 3272.

+ Section 4.1.10: Based on Section 4.5.7 of RFC 3272.

+ Section 4.1.11: New for this document.

+ Section 4.1.12: New for this document.

+ Section 4.1.13: New for this document.

+ Section 4.1.14: New for this document.

+ Section 4.1.15: New for this document.

+ Section 4.1.16: New for this document.

- Section 4.1.16.1: New for this document.

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- Section 4.1.16.2: New for this document.

+ Section 4.1.17: New for this document.

+ Section 4.1.18: New for this document.

+ Section 4.1.19: New for this document.

+ Section 4.1.20: New for this document.

+ Section 4.1.21: New for this document.

\* Section 4.2: Based on Section 4.7 of RFC 3272.

o Section 5: Based on Section 5 of RFC 3272.

\* Section 5.1: Based on Section 5.1 of RFC 3272.

\* Section 5.2: Based on Section 5.2 of RFC 3272.

\* Section 5.3: Based on Section 5.3 of RFC 3272.

+ Section 5.3.1: New for this document.

+ Section 5.3.2: New for this document.

\* Section 5.4: Based on Section 5.4 of RFC 3272.

\* Section 5.5: Based on Section 5.5 of RFC 3272.

+ Section 5.5.1: New for this document.

\* Section 5.6: Based on Section 5.6 of RFC 3272.

\* Section 5.7: Based on Section 5.7 of RFC 3272.

o Section 6: Based on Section 6 of RFC 3272.

\* Section 6.1: Based on Section 6.1 of RFC 3272.

\* Section 6.2: Based on Section 6.2 of RFC 3272.

\* Section 6.3: Based on Section 6.3 of RFC 3272.

\* Section 6.4: Based on Section 6.4 of RFC 3272.

\* Section 6.5: Based on Section 6.5 of RFC 3272.

+ Section 6.5.1: Based on Section 6.5.1 of RFC 3272.

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+ Section 6.5.2: Based on Section 6.5.2 of RFC 3272.

\* Section 6.6: Based on Section 6.6. of RFC 3272.

\* Section 6.7: Based on Section 6.7 of RFC 3272.

o Section 7: Based on Section 7 of RFC 3272.

o Section 8: Based on Section 8 of RFC 3272.

o Section 9: Based on Section 10 of RFC 3272.

o Appendix A: New for this document.

\* Appendix A.1: Based on Section 4.1 of RFC 3272.

\* Appendix A.2: Based on Section 4.2 of RFC 3272.

+ Appendix A.2.1: Based on Section 4.2.1 of RFC 3272.

+ Appendix A.2.2: Based on Section 4.2.2 of RFC 3272.

+ Appendix A.2.3: Based on Section 4.2.3 of RFC 3272.

+ Appendix A.2.4: Based on Section 4.2.4 of RFC 3272.

+ Appendix A.2.5: Based on Section 4.2.5 of RFC 3272.

\* Appendix A.3: New for this document.

+ Appendix A.3.1: Based on Section 4.3 of RFC 3272.

o Appendix B: New for this document.

\* Appendix B.1: Based on Section 4.7 of RFC 3272.

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