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ABSTRACT

TCP/IP represents the reference standard for the implementation of interoperable communication networks. Nevertheless, the layering principle at the basis of interoperability severely limits the performance of data communication networks, thus requiring proper configuration and management in order to provide effective management of traffic flows. This paper presents a brief survey related to network optimization using Traffic Engineering algorithms, aiming at providing additional insight to the different alternatives available in the scientific literature.

1. INTRODUCTION TO NETWORK OPTIMIZATION

The focus of the paper is on the concept of network optimization, i.e. the process by which optimal performance can be achieved. The optimum may be defined by a specific institution such as an ISP or industry, or an objective function that models specific goals.

The factors that define the optimal performance will vary with the situation to which the optimization process is applied. Some examples of factors that may be optimized are cost, raw materials used, time required and pollution caused. Optimization may be aimed at obtaining local and global optima, depending on the type of problem addressed.

In this scenario, a communication network is typically characterized by a graph G = (V,A), where *V* is the set of nodes (vertices) and *A* the set of links (arcs, edges). Most packet communication networks can be described as an augmented graph with two parameters: link flow λ_i and link transmission capacity C_i. The physical meaning of λ_i is the traffic arrival rate in link *i*, expressed in data units per second, and C_i has the same units as λ_i. The objective of a network optimization problem is to optimize one of two types of indices: the *operating index*, e.g. delay *T* of packets or the number of packets in the system, and the *capital index*, e.g. cost *D* of required capacity. The entities to be adjusted, called the *design variables*, can be for example traffic flows and link capacity.

Given topology and offered traffic requirements, with constraints that link flows are not greater than link capacity, three generic problems of optimization can be formulated:

1) The *capacity assignment* (CA) problem:

- To minimize *T*
- To adjust C_i
- Under constraint *D*

In generic capacity assignment (CA) models, the network topology, the traffic matrix, and the link flow vector are given. The capital index is to be optimized, with link capacity as design variable, subject to the operating index constraint.

In most cases, the CA models take the formulation of *nonlinear programming* (NLP), and numerical procedures have to be employed to solve the problem. However, it was shown that an analytical solution is available if the objective function is linear and the average flow delay approximately follows the Poisson assumption. The Poisson model is still an appropriate approximation for traffic patterns in virtual circuit switching such as call-connection scenarios and in datagram switching such as *TELNET* or *FTP* applications.

2) The *flow assignment* (FA) problem:

- Given C_i
- To minimize T
- To adjust λ_i

In several applications, there are multiple classes of offered traffic (like CBR, VBR, UBR, and ABR flows) to be transmitted over paths connecting a set of *origin–destination* (OD) pairs. Therefore, there is a need to further express link flows by path flows *xk* associated with traffic classes. This is feasible because usually the total number of *xk* is greater than the total number of λ_i. Accordingly, the design variables become *xk*, and the induced model is based on the path–node incidence. Mathematically, a network optimization problem with the path–node incidence can be described by the *multi-commodity* (MC) model, a representative paradigm developed in the theory of network flows. For a B-ISDN paradigm, the concept of commodity classes is associated with traffic classes.

Models based on the path–node incidence may have another important property: the Poisson assumption is still reasonably applicable. This is because a path is typically an end-to-end connection and several types of traffic can be described by the Poisson pattern at the connection layer.

3) The *capacity and flow assignment* (CFA) problem:

- To minimize T
- To adjust C_i and λ_i
- Under constraint D

In specific scenarios, the statistics of traffic usually do not significantly change over time. For this reason, such a network model just needs to characterize its performance parameters in terms of mean values, for example the average delay of all data packets over a path.

Consequently, the parameters needed in such formulations are also presented in terms of mean values such as the average arrival rate, the average inter-arrival time, or the average cost. However, it should be pointed out that this type of approach cannot effectively describe all types of network scenarios and does not capture the dynamic behaviour of network and traffic. One of the most important example is perhaps the *asynchronous transfer mode* (ATM). An ATM network is supposed to support applications with diverse rates such as *constant, variable, available*, and *unspecified bit rate* due to its different behaviour in forwarding data to the nodes. Different clients may demand different *quality of service* (QoS). Advanced features such as *congestion control* and *self-healing* introduce additional complexity. In these circumstances, the approach that uses mean values of parameters may no longer be reasonably valid because simply taking the average of random parameters may result in the *probabilistic infeasibility* of the solution.

2. INTRODUCTION TO TRAFFIC ENGINEERING

Internet traffic engineering is usually defined as the aspect of Internet network engineering that deals with the issue of performance optimization of operational IP networks through management of traffic and assignment of paths and resources to data flows in particular. The same definition can still be used in other networking scenarios (Apple-talk, IPx…).

Traffic engineering (TE) can also be defined as the process of mapping traffic flows onto an existing physical topology.

One of the typical utilization of Traffic engineering is an ISP balancing the traffic load on different links, router, and switches in the network, so that none resource is over-utilized or under-utilized. In this way, ISPs can exploit the economies of the bandwidth that are provisioned across the entire network and enhance the operation, performance, efficiency and reliability of the network.

Traffic engineering should be viewed as assistance to the routing infrastructure, that provides additional information used in forwarding traffic along alternate paths across the network, so it joins concepts of routing (OSI Layer 3) and link level resource allocation (OSI Layer 2).

Supported by emerging technologies, especially Multi-Protocol Label Switching (MPLS), TE performs provisioning and admission control functions to optimize network operators' objectives.

There are many possible ways of classifying the TE algorithms and techniques depending on which aspect of optimization is pointed out. The TE mechanism takes two complementary forms, on-line and offline:

- On-line TE is state-dependent and applies on a short time-scale.
- Off-line TE applies on a longer time-scale and considers statistical behaviour of traffic demands aggregated over all connections.

By combining this demand information with a centralized view of network topology and link capacities, off-line TE selects routes and provisions resources on the selected routes for satisfying the demands.

On-line schemes usually try to minimise the probability of blocking future requests, while off-line ones try to minimise the load or the utilisation of the links, or try to maximise available bandwidth.

Such decisions are globally optimized for demands of various service types and origin-destination pairs such as for QoS classes. The solution of the off-line optimization can be used as a reference point for on-line operations.

2.1 TE OBJECTIVES AND METRICS

Given the type of the network to be engineered and an estimate of the traffic matrix to be routed on it, the problem is to find a routing scheme that optimises the network, with the joint goal of good user performance and efficient use of network resources.

Recalling the model of network presented in section 1, it is possible to represent its nodes and arcs with routers and links. Each arc has a capacity and traffic on the network is represented by a traffic matrix D which together with every pair of nodes associates the value of the traffic demand, i.e. the traffic that flows from a given node to another one.

A traffic engineering algorithm aims at finding "good paths" between each pair of source and destination nodes to route corresponding traffic flow. The definition of "good paths" is related to what the algorithm aims to optimise on the network. Generally, a good set of paths will be one that optimises a pre-defined objective function.

Once the paths are chosen, we can associate with each arc a load L_a, which is the total load on the arc, i.e. the sum over all demands of the amount of traffic sent over a link.

The utilisation and available bandwidth of a link a are, respectively:

$$U_a = L_a / C_a$$

$$BW_a = L_a - C_a .$$

Another important parameter is the maximum flow that can be sent from one node to another one in the residual network, i.e. when the whole traffic matrix is routed on the network.

TE metrics can be analyzed at three different levels:

- Link level: Minimization of delay, utilization and bandwidth
- Origin-Destination level: Minimization of path delay i.e. sum of the delays of all links on the path and the maximal link utilisation on the corresponding path and Maximization of the residual max flow between an OD pair of nodes
- Network level (Link and OD level): Many techniques, for example mean link utilization or max-flows

The delay of a link is composed of three components: the propagation delay (which can be considered a constant value), the transmission delay (inversely proportional to the link capacity) and the queuing delay (which increases with the link load).

	Metric characterising good current state	Metric characterising likely good future
$\text{Link}_{(a)}$	$Delay_a$	u_a, ABW_a
$\text{Path}_{(s,t)}$	$\sum_{a \in \mathcal{P}(s,t)} Delay_a$	θ_{st}, $max_{a \in \mathcal{P}(s,t)} u_a$
Network	$\frac{\sum_{a \in A} Delay_a}{\lvert A \rvert}$, $\frac{\sum_{a \in A} l_a \times Delay_a}{AllTr}$	$min_{(s,t)} \theta_{st}$, $max_{a \in A} u_a$ $\sum_{(s,t)} \theta_{st}$

Table 1: Levels of optimization and corresponding metrics [11]

2.2 TE ALGORITHMS

Most conventional routing protocols base their path computation only on one additive link metric, which typically results in *shortest-path routing*. However, some protocols allow more than one type of metric being taken into account when calculating the forwarding paths.

OSPF is a good example of single metric routing protocol, while *EIGRP* can be viewed as a demonstration of a multiple-metric protocol.

In the *Enhanced Interior Gateway Routing Protocol* (EIGRP), every interface (i.e., link) has four different metric types associated with it for path computation. However, for path computations only one metric is used at a time Using many different metrics, it would be possible to compute four different routing tables (one for each metric type) and then forward packets according to one of the schemes. To guarantee consistency among all routers, this would require that IP packets are marked appropriately and that every router applies the same forwarding scheme. In practice, this feature is not used and routes are computed only for one additive metric type.

The first two parameters are assigned statically, while the third and the fourth are determined by the routers during network operation. When a router computes the path towards a destination, it considers a combination of such metrics.

The following represents a summary of the main routing algorithms for TE. It should be clarified at this point that several additional solutions are available in the literature, but only the most significant are presented in this paper.

Fortz

In [1], B. Fortz et al. try to find an optimal set of IGP weights, such that classical shortest path first algorithms (taking in consideration modified metrics) lead to a good routing scheme. A cost is associated with each link of the network. This cost is a convex piecewise linear function of the link load. The objective function to minimise is the sum over all links of this cost.

There is no OD pair consideration in this objective function.

MIRA

In [13], Kodialam et al. introduce the concept of minimum interference routing. They propose an objective function which is a weighted sum of the max-flows over all possible source-destination pairs on the residual topology. Their online algorithm, called MIRA, is a heuristic that tries to maximise this objective function.

The amount of traffic that can be routed on the residual network is in fact the sum over all links of the available bandwidth. Indeed, one obvious (and degenerated) solution to the max throughput problem is to associate traffic only with the pairs of nodes that are located at the edges of a link, as the available bandwidth on the corresponding link can be associated with such pairs.

The weights associated with ingress-egress pairs are administrative weights that determine the relative importance of the ingress-egress pairs to the network administrator. Behind this objective function, the goal is to minimise the blocking probability of a future new request, without information about it. The idea is that if the max-flow between one source and one destination decreases, this means that the maximum request that can be accepted between these two nodes decreases as well.

There is no embedded metric characterising a "good" current state.

Blanchy

In [14], Blanchy et al. present an online heuristic traffic engineering algorithm to optimise a load balancing objective function. This function is the variance on the link utilisation and, as such, represents the deviation from the optimal load balancing situation. To limit the length of the paths of a pure load balancing function, they add a "shortest path" term and arrive at the consequent objective function.

The approach is interesting because the (weighted) combination of both terms will give more importance to the load-balancing term if the deviation is high enough to justify the detour, else it will let the "shortest path" term minimise the resources used. The weighted factor allows to give more importance to one aspect or to the other. This objective function does not directly include TE metrics, it does not include a delay contribution and there is no consideration about OD pairs. The traffic minimisation term tries to minimise the path length.

Delay

In [15], Elwalid et al. associate a cost with each link, in order to minimise the total cost (which is the sum of the link cost over all links). The cost of a link is a function of the link load. They assume that this function is convex. The paper assumes that a natural choice for the link cost is the delay, so that the network-wide cost function or the (unweighted) mean link delay - if the propagation delay is not taken into account.

Degrande

In [16], Degrande et al. propose to maximise an objective function which is given by the combination of four terms: F(airness), T(hroughput), B(alance) and (network) U(tilisation).

A weighting coefficient (named CF, CT, CB or CU) is associated to each term to give more influence to one or another. Fairness and Throughput are traffic oriented objectives, while Balance and Utilisation are resource oriented objectives. The utilisation term will minimise the size of the paths. There is no OD pair consideration and no delay contribution in this objective function. We will refer to this objective function as Umax.

In fact, inverse capacity routing (recommended by CISCO) gives the optimal value of U. We will thus refer to this objective function as InvCap

The following table briefly summarized the objective functions to be minimised as they are presented in the reviewed papers.

	Score Function (to be minimised)
$Fortz$	$\sum_{a \in A} \phi_a$
$MIRA$	$-\sum_{(s,t)} \theta_{st}$
$Blanchy$	$\sum_{a \in A}(u_a - u_{mean})^2 + \alpha \sum_{a \in A}(u_a)^2$
$MeanDelay$	$\sum_{a \in A} \frac{1}{c_a - l_a}$
$WMeanDelay$	$\sum_{a \in A} \frac{l_a}{c_a - l_a}$
$InvCap$	$\sum_{a \in A} u_a$
u_{max}	u_{max}
$Degrande$	$C_B.u_{max} + C_U.\sum_{a \in A} u_a$
$MinHop$	$\sum_{a \in A} l_a$

Table 2: Objectves functions and metrics for TE routing

3. INTERDOMAIN - INTRADOMAIN TE

A further classification of TE schemes can be based on their locality, distinguishing techniques applicable between different domains (or Autonomous Systems – AS) or within a single domain. The locality of TE provides different constraints and most often different goals.

3.1 INTERDOMAIN TE

Many algorithms for TE routing on *Interior* Gateway Protocols (IGPs), such as OSPF, IS-IS, and MPLS, control the flow of traffic within a single Autonomous System (AS).

In practice, though, most traffic in a large backbone network traverses multiple domains, making interdomain routing an important part of traffic engineering.

Interdomain TE should be implemented for the following reasons:

• *Congested edge link:* The links between domains are common points of congestion in the Internet. Upon detecting an overloaded edge link, an operator can change the interdomain paths to direct some of the traffic to a less congested link.

• *Upgraded link capacity:* Operators of large IP backbones frequently install new, higher-bandwidth links between domains. Exploiting the additional capacity may require routing changes that divert traffic travelling via other edge links to the new link.

• *Violation of peering agreement:* An AS pair may have a business arrangement that restricts the amount of traffic they exchange; for example, the outbound and inbound traffic may have to stay within a factor of 1.5. If this ratio is exceeded, an AS may need to direct some traffic to a different neighbour.

Designing an inter-domain protocol that satisfies both the algorithmic and policy requirements represents a very challenging task. There is an inherent conflict between the economic need for *fully-informed* and *private* routing policies and the structural need for robust routing algorithms.

One could consider a spectrum of designs making different tradeoffs.

The Border Gateway Protocol (BGP) takes an extreme position in this design space that all routing policies must be private; no policy information is transmitted in route updates, leaving policy to be implemented entirely by local filters whose contents are kept secret. As a result, BGP suffers from inherent algorithmic problems, including poor scalability, minimal fault isolation, and slow convergence due to uninformed path exploration.

3.2 INTRADOMAIN TE

Traffic engineering depends on having a set of performance objectives that guide the selection of paths, as well as effective mechanisms for the routers to select paths that satisfy these objectives. Most large IP networks run Interior Gateway Protocols (IGPs) such as OSPF (Open Shortest Path First) or IS-IS (Intermediate System-Intermediate System) that select paths based on static link weights. These weights are typically configured by the network operators. Routers use such protocols to exchange link weights and construct a complete view of the topology inside the AS. Then, each router computes shortest paths (where the length of a path is the sum of the weights on the links) and creates a table that controls the forwarding of each IP packet to the next hop in its route.

4. AUXILIARY ALGORITHMS FOR TE

Several TE algorithms need the traffic matrix to be calculated or estimated through on-line simulations of the network.

An interesting work [4] explains how to optimise the traffic matrix to be used in a routing algorithm independently from the chosen routing protocol. Specifically, the paper proposes to divide the traffic matrix into N equal sub-matrices, called *strata*, for which the routing scheme can be independently chosen. The sum of the N strata is obviously equal to the original traffic matrix. The routing scheme of each stratum is computed considering the network state resulting of the routing of lower strata.

5. SUMMARY

Based on the above considerations, it is possible to briefly classify the overviewed approaches on the basis of their core features (see Table 3).

Protocol/Algorithm	Type of Optimization	Network Topology	TE Domain	Main Parameters	Reference
FORTZ	Routing OSPF - ISIS	Traditional IP	Intradomain	OSPF weights	[1]
BCTE	QoS Routing	MPLS	Intradomain	Call blocking prob Path load	[2]
DART	Dynamic Routing	Scalable ad Hoc & Mesh	Intradomain	Overhead – Throughput – Network size	[3]
"Dividing TM"	Pre-Routing Traffic matrix splitting	M-ISIS MPLS	Intradomain	Computation time	[4]
MIN-MAX Load	Routing OSPF - ISIS	Traditional IP	Intradomain	Max Load $\frac{traffic}{opt.traffic}$	[5]
HLP	Hybrid hierarchical Routing	Autonomous systems connection	Interdomain	Link-state + Path vector	[6]
"Smart TE"	Smart Routing with Genetic algorithm for TE	Autonomous systems connection	Interdomain	Minimizing Maximum Link Utilization and Load-balancing	[7]
Least Path Interference	Hybrid Routing	Traditional IP	Intradomain	offline path interference estimation + online path finding	[8]
Minimum Interference	Online Routing	MPLS	Intradomain	link-state information + capacity information for path selection	[9]

SP (stochastic programming)	Capacity & Flow	ATM networks (not only)	Intradomain	Congestion and link flows modelling	[10]

Table 3: Algorithms for TE - Network optimization

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