ITC19/ Performance Challenges for Efficient Next Generation Networks 1215-1224
LIANG X.J. and XIN Z.H.(Editors)
V.B. IVERSEN and KUO G.S.(Editors)
Beijing University of Posts and Telecommunications Press

IP Network Design with End-to-End QoS Constraints: The VPN Case

Emilio C. G. Wille [1], Marco Mellia [2], Emilio Leonardi [2] and Marco Ajmone Marsan [2]

[1] Federal Center of Technological Education – Paraná
Department of Electronics, Av. Sete de Setembro 3165, Curitiba (PR), Brazil
e-mail: ecgwille@cefetpr.br
[2] Turim Polytechnic
Department of Electronics, Corso Duca degli Abruzzi 24 - 10129, Torino, Italy
e-mail: {mellia, emilio, ajmone}@mail.tlc.polito.it

Abstract. The traditional approaches to optimal design and planning of packet networks focus on the network-layer infrastructure, thus neglecting end-to-end Quality of Service (e2e QoS) issues, and Service Level Agreement (SLA) guarantees. This is quite inappropriate since the Internet today carries a wide range of critical telecommunication services. The challenge in the area is how to devise reasonable packet network design methodologies that allow the choice of the most adequate set of network resources, subject to e2e QoS constraints and, at the same time, consider the traffic dynamics of today's packet networks. In this paper we describe a simple methodology to tackle the packet network design problem, and illustrate an example of its application to the optimization of link capacities and routing in a corporate Virtual Private Network (VPN), where traffic is mostly due to TCP connections. An efficient Lagrangean relaxation based heuristic procedure is developed to find bounds and solutions for the considered problem, and numerical results for a variety of problem instances are reported.
Keywords: Networks design and planning, Mathematical programming/optimization.

1 INTRODUCTION

Packet network design is an old problem, that was extensively investigated in the early days of packet networks, starting with the seminal work of Kleinrock in the mid-sixties [1, 2]. The traditional approaches to optimal design and planning of packet networks focus on the network-layer infrastructure, thus neglecting end-to-end Quality of Service (e2e QoS) issues, and Service Level Agreement (SLA) guarantees. This is quite inappropriate, since the Internet today carries a wide range of critical telecommunication services, and design approaches based on end-to-end QoS are a must.

From the end user's point of view, QoS is driven by end-to-end performance parameters, such as data throughput, web page latency, transaction reliability, etc. Matching the user-layer QoS requirements to the network-layer performance parameters is not a straightforward task. The QoS perceived by end users in their access to Internet services is mainly driven by TCP, the reliable transport protocol of the Internet, whose congestion control algorithms dictate the latency of information transfer.

Additionally, the description of traffic patterns inside the Internet is a particularly delicate issue, since it is well known that IP packets do not arrive at router buffers following a Poisson process [3], but a higher degree of correlation exists. Traditionally, either $M/M/1$ or $M/M/1/B$ queueing models were considered as good representations of packet queueing elements in the network. The traffic flowing in IP networks is known to exhibit Long

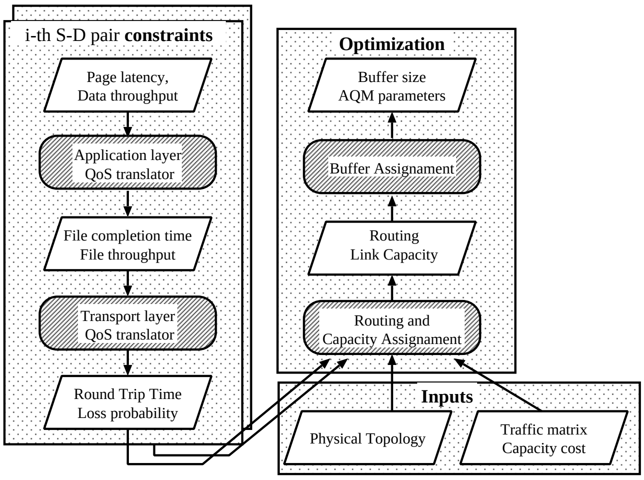

Fig. 1. Schematic Flow Diagram of the Network Design Methodology

Range Dependent (LRD) behaviors which cause queue dynamics to severely deviate from the above model predictions. For this reason, the usual approach of modeling packet networks as networks of $M/M/1$ queues [4–6] appears now inadequate for the design of such networks.

In this paper, we propose a packet network design and planning approach that considers the dynamics of packet networks, as well as the effect of protocols at the different layers of the Internet architecture on the e2e QoS experienced by end users. A refined IP traffic modeling technique, already presented in [7], that is both simple and capable of producing accurate performance estimates for general-topology packet networks loaded by realistic traffic patterns is considered. The main idea behind the approach consists in reproducing the effects of traffic correlations on network queueing elements by means of Markovian queueing models with *batch arrivals*. Hence, using $M_{[X]}/M/1$ like queues.

Since the routing and link capacities selection problems are closely interrelated, it is appropriate to jointly solve them in what is called the Capacity and Flow Assignment (CFA) problem. In this paper, we present a nonlinear mixed-integer programming formulation for the generic CFA problem and solve it in the case of corporate Virtual Private Network (VPNs). An efficient Lagrangean relaxation based heuristic procedure is developed to find bounds and solutions. When explicitly considering TCP traffic it is also necessary to tackle the Buffer Assignment (BA) problem.

The rest of the paper is organized as follows. Section 2 describes the general design methodology and provides the formulation of the optimization problem. Section 3 illustrates a Lagrangean relaxation of the problem, as well as a heuristic solution procedure. Numerical results are discussed and compared against results of *ns*-2 simulations in Section 4. Conclusions are given in Section 5.

2 THE IP NETWORK DESIGN METHODOLOGY

Fig. 1 shows the flow diagram of the proposed design methodology. Shaded, rounded boxes represent function blocks, while white parallelograms represent input/output of functions. There are three main blocks, which correspond to the classic blocks in constrained optimization problems: *constraints* (on the left), *inputs* (on the bottom right) and *optimization procedure* (on the top right). As constraints we consider, for every source/destination pair, the specification of user-layer QoS parameters, e.g., download latency for web pages or

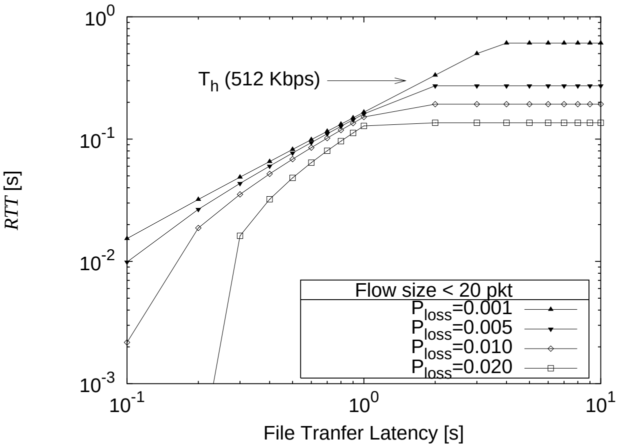

Fig. 2. *RTT* Constraints as given by the Transport Layer QoS Translator

links. A path from source node s to a destination node d is a subgraph of G and it is modeled as an open network of queues, where each queue represents an output interface of an IP router with its buffer. For a given link (i, j), the flow f_{ij} is defined as the effective quantity of information transported by this link, while its capacity C_{ij} is a measure of the maximal quantity of information that it can transmit. Flow and capacity are both expressed in bits per second (bps). Each buffer can accommodate a maximum of B_{ij} packets, and d_{ij} is the link physical length.

CFA formulation Different formulations of the CFA problem result by selecting i) the cost functions, ii) the routing model, and iii) the capacity constraints. It is important to note that for a given set of options a specific optimization technique must be applied to solve the problem. In this paper we focus on the VPN case, in which common assumptions are i) linear costs, ii) non-bifurcated routing, and iii) continuous capacities. Solution techniques for this sub case are presented in Section 3. Optimization techniques for the design of physical topologies, i.e. the non-continuous capacity case, are currently being investigated.

Our goal is to minimize the total link costs while determining the best route for the traffic that flows on each source/destination path, and meeting the maximum e2e packet delay constraint. The following optimization problem is thus formulated:

$$Z_{CFA} = \min \sum_{i,j} g_{ij}(C_{ij}) \tag{1}$$

subject to:

$$\sum_j \delta_{ij}^{sd} - \sum_j \delta_{ji}^{sd} = \begin{cases} 1 & \text{if } s = i \\ -1 & \text{if } d = i \\ 0 & \text{otherwise} \end{cases} \quad \forall\ (i, s, d) \tag{2}$$

$$K_1 \sum_{i,j} \frac{\delta_{ij}^{sd}}{C_{ij} - f_{ij}} \leq RTT_{sd} - K_2 \sum_{i,j} \delta_{ij}^{sd} d_{ij} \qquad \forall\ (s, d) \tag{3}$$

$$f_{ij} = \sum_{s,t} \delta_{ij}^{sd} \gamma_{sd} \qquad \forall\ (i, j) \tag{4}$$

$$\delta_{ij}^{sd} \in \{0, 1\} \qquad \forall\ (i, j, s, d); \qquad C_{ij} \geq f_{ij} \geq 0 \quad \forall\ (i, j) \tag{5}$$

The second step corresponds to linearize constraints (8) (by using a logical constraint). We use the new variables w_{ij}^{sd} (whose dimension is seconds per bit) for each link (i,j) on path (s,d). Thus we have the following problem:

$$Z_{CFA} = min\Big[\sum_{i,j} \frac{d_{ij}}{w_{ij}} + \sum_{i,j} \sum_{s,d} d_{ij}\delta_{ij}^{sd}\gamma_{sd}\Big]$$

subject to:

$$w_{ij}^{sd} \leq M_{sd}\delta_{ij}^{sd} \qquad \forall\ (i,j,s,d) \tag{11}$$

$$K_1 \sum_{i,j} w_{ij}^{sd} + K_2 \sum_{i,j} \delta_{ij}^{sd} d_{ij} \leq RTT_{sd} \qquad \forall\ (s,d) \tag{12}$$

$$w_{ij}^{sd} \geq 0 \qquad \forall\ (i,j,s,d) \tag{13}$$

and (2), (9), (10).

Note that constraints (11) force the packet delay of link (i,j) on path (s,d) to be 0 if the link is not used. The constant M_{sd} corresponds to the minimum value of w_{ij}^{sd} that is able to satisfy the packet delay constraints for path (s,d). We have $M_{sd} = RTT_{sd}/K_1$. We refer to this problem as problem P in the rest of this paper.

We now consider the Lagrangean relaxation of problem P obtained by dualizing constraints (11) and (12) using the nonnegative multipliers α_{ij}^{sd} and β_{sd}, respectively.

$$\begin{aligned} L(\alpha,\beta) = min \Bigg\{ & \sum_{i,j} \frac{d_{ij}}{w_{ij}} + \sum_{i,j} \sum_{s,d} d_{ij}\delta_{ij}^{sd}\gamma_{sd} + \sum_{s,d} \sum_{i,j} \alpha_{ij}^{sd} \left[(w_{ij}^{sd} - M_{sd}\delta_{ij}^{sd}) \right] \\ & + \sum_{s,d} \beta_{sd} \left[\sum_{i,j} (K_1 w_{ij}^{sd} + K_2 \delta_{ij}^{sd} d_{ij}) - RTT_{sd} \right] \Bigg\} \end{aligned} \tag{14}$$

subject to (2), (9), (10) and (13).

Problem $L(\alpha,\beta)$ can now be decomposed into two independent subproblems, $L_1(\alpha,\beta)$ and $L_2(\alpha,\beta)$, as follows:

$$L_1(\alpha,\beta) = min \sum_{s,d} \sum_{i,j} \delta_{ij}^{sd} (d_{ij}\gamma_{sd} - M_{sd}\alpha_{ij}^{sd} + K_2 d_{ij}\beta_{sd}) \tag{15}$$

subject to (2) and (10). And:

$$L_2(\alpha,\beta) = min \sum_{i,j} \Big(\frac{d_{ij}}{w_{ij}} + \sum_{s,d} w_{ij}^{sd} (\alpha_{ij}^{sd} + K_1\beta_{sd}) \Big) - \sum_{s,d} \beta_{sd} RTT_{sd} \tag{16}$$

subject to (9) and (13).

Subproblem $L_1(\alpha,\beta)$ can be further decomposed into $n * (n-1)$ shortest path problems (one for each source/destination pair) and solved using the classic Bellman-Ford's algorithm.

To be able to solve problem $L_2(\alpha,\beta)$, we decompose it into m independent subproblems (one for each link):

$$L_2^{(i,j)}(\alpha,\beta) = min \Big(\frac{d_{ij}}{w_{ij}} + w_{ij} \sum_{s,d} y_{ij}^{sd} (\alpha_{ij}^{sd} + K_1\beta_{sd}) \Big) \tag{17}$$

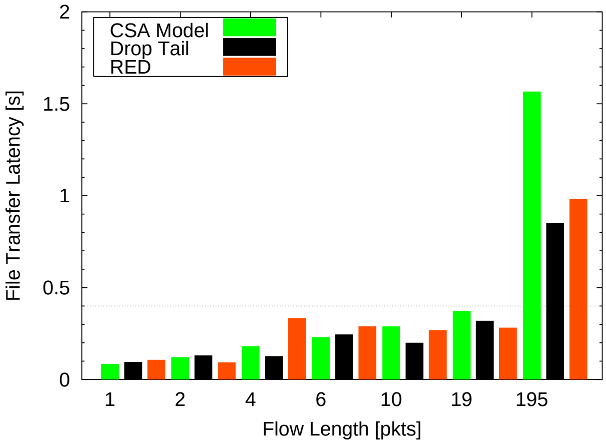

Fig. 3. Model and simulation results for latency; 5-link path from the 10-node network

4.1 10-Node Networks

In this first set of results we consider the dimensioning of a 10-nodes, 20-links network topology and its performance results. We considered a mixed traffic scenario where the flow length (ranging from 1 to 195 packets) follows the distribution related in [10]. We choose, for this case, the following target QoS constraints for all source/destination pairs: i) file latency $L_t \leq 0.4$ s for TCP flows shorter than 20 packets, ii) throughput $T_h \geq 512$ Kbps for TCP flows longer than 20 packets. Selecting $P_{loss} = 0.01$, we obtain a network-level design constraint equal to $RTT \leq 0.052$s (see Fig. 2) for all source-destination pairs. Each traffic relation offers an average aggregate traffic equal to $\hat{\gamma}_{sd} = 1$Mbps. Link propagation delays range from 0.25 ms to 1.5 ms . After solving the CFA problem, we solved the BA problem in both the DropTail and RED cases (see [11, 12]). The objective of the BA problem is to minimize buffer costs while keeping the total loss probability, experienced by all the flows routed on the path (s, d), below a maximum fixed P_{loss}. The average loss probability for the $M_{[X]}/M/1/B$ queue is evaluated by solving its Continuous Time Markov Chain (CTMC).

To validate the network design, we performed packet-level simulations (using the ns-2 simulator) to check whether the QoS constraints are actually met. In the experiments TCP connections are established at instants described by a Poisson process, choosing at random a server-client pair. Connection opening rates are determined so as to meet the offered traffic. We performed *path simulations* rather than simulating the entire network, i.e., we selected a path referring to a single source/destination pair, and simulated only links in that path, considering also interfering cross traffic. Among all possible source/destination pairs, we selected the longest path in the network, which comprises 5 links. Results are plotted in Fig. 3, which reports the file transfer latency for all flow size classes. The QoS constraint of 0.4s for the maximum latency is also shown. We can clearly see that model predictions and simulation results are in perfect agreement with specifications, since the latency constraint is satisfied for all flows shorter than 20 segments. Note also that longer flows obtain a much higher throughput than the target, because the flow transfer latency constraint is more stringent.

4.2 40-Node Networks

In this second set of results we consider the dimensioning of 40-node, 160-link network topologies and analise their costs. Link propagation delays are uniformly distributed be-

References

1. Kleinrock, L., "Queueing Systems, Volume II: Computer Applications", *Wiley Interscience*, New York, 1976.
2. Gerla, M., L. Kleinrock, "On the Topological Design of Distributed Computer Networks", *IEEE Transactions on Communications*, Vol.25, pp. 48-60, Jan. 1977.
3. V.Paxson, S.Floyd, "Wide-Area Traffic: The Failure of Poisson Modeling," *IEEE/ACM Transactions on Networking*, Vol.3, N.3, pp. 226-244, Jun. 1995.
4. K.T.Cheng, F.Y.S.Lin, "Minimax End-to-End Delay Routing and Capacity Assignment for Virtual Circuit Networks", *IEEE Globecom 95*, Singapore, pp. 2134-2138, Nov. 1995.
5. E. Rolland, A. Amiri, R. Barkhi, "Queueing Delay Guarantees in Bandwidth Packing", In *Computers and Operations Research*, Vol.26, pp. 921-935, 1999.
6. A.Gersht, R.Weihmayer, "Joint optimization of data network design and facility selection", *IEEE Journal on Selected Areas in Communications*, Vol.8, N.9, pp. 1667-1681, Dec. 1990.
7. M.Garetto, D.Towsley, "Modeling, Simulation and Measurements of Queuing Delay under Long-tail Internet Traffic", *ACM SIGMETRICS 2003*, San Diego, CA, June 2003.
8. N.Cardwell, S.Savage, T.Anderson, "Modeling TCP Latency", *IEEE Infocom 00*, Tel Aviv, IS, March 2000.
9. J.Padhye, V.Firoiu, D.Towsley, J.Kurose, "Modeling TCP Reno performance: a simple model and its empirical validation", *IEEE/ACM Trans. on Networking*, Vol.8, N.2, pp. 133-145, Apr. 2000.
10. M. Mellia, A. Carpani, R. Lo Cigno, "Measuring IP and TCP behavior on Edge Nodes", *IEEE Globecom 2002*, Taipei, TW, Nov. 2002.
11. E. Wille, *Design and Planning of IP Networks Under End-to-End QoS Constraints*, PhD Thesis, Politecnico di Torino, Available at http://www.tlc-networks.polito.it/mellia/papers/wille_phd.pdf
12. E.Wille, M.Garetto, M.Mellia, E.Leonardi, M.Ajmone Marsan, "Considering End-to-End QoS in IP Network Design", *NETWORKS 2004*, Vienna, June 13-16.
13. X.Chao, M.Miyazawa, M.Pinedo, *Queueing Networks, Customers, Signals and Product Form Solutions*, John Wiley, 1999.
14. M.Wright, "Interior methods for constrained optimization", *Acta Numerica*, Vol.1, pp. 341-407, 1992.
15. B.Gendron, T.G.Crainic, A.Frangioni, "Multicommodity Capacitated Network Design". B. Sansò and P. Soriano (eds), *Telecom. Network Planning*, pp. 1-19, Kluwer, MA, 1998.
16. A.M. Geoffrion, "Lagrangean relaxation and its uses in integer programming", *Mathematical Programming Study*, Vol.2, pp. 82-114, 1974.
17. A.Medina, A.Lakhina, I.Matta, J.Byers, "BRITE: Boston university representative internet topology generator", Boston University, http://cswww.bu.edu/brite, April 2001.