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The Square Root Multipliers Algorithm for Discrete Capacity and Buffer Assignment problems in Elastic Traffic Networks

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ABSTRACT

This paper discusses a novel approach for the dimensioning of packet networks, under the constraints of end-to-end Quality-of-Service (QoS) requirements. The network modeling also considers the dynamic behavior of today's networks traffic. In particular, the proposed approach considers multilink networks where discrete capacities are the decision variables. This Discrete Capacity Assignment (DCA) problem can be classified as a constrained combinatorial optimization problem and therefore it is NP-complete. In order to solve the problem, we propose the *Square Root Multipliers Algorithm* (SRMA) followed by a Randomized Rounding (RR) method. We also enforce loss probability constraints by properly choosing buffer sizes, therefore facing the Buffer Assignment (BA) problem. To evaluate the performance of our approach, SRMA/RR results are compared with the optimal solutions found by an exhaustive search (ES) procedure. Analytical results for a variety of problem instances are reported, and a verification is performed based on simulations conducted with the software *NS*-2. The results suggest that the proposed approach provides a quite efficient method to obtain near-optimal solutions with small computational effort.

1. Introduction

Nowadays, TCP/IP (Transmission Control Protocol/Internet Protocol) is the most widely used set of protocols of the Internet. New Internet services is a growing area that is facing the need for Quality-of-Service (QoS) guarantees and appropriate tools for monitoring and enforcement of QoS contracts between clients and service providers. Traditional dimensioning approaches, extensively investigated in the early days of packet networks [1], focused on the network-layer infrastructure, neglecting end-to-end (e2e) Quality-of-Service issues, and Service Level Agreement (SLA) guarantees. In addition, many investigations reveled that Internet traffic is correlated, which can be partly due to TCP control mechanisms [2,3]. Consequently, satisfactory solutions for IP network design and dimensioning are not yet available.

In [4], the authors proposed a 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. The proposed approach firstly maps the end-user performance constraints into transport-layer performance constraints, and then into network-layer performance constraints. This mapping process is then considered together with a refined TCP/IP traffic modeling technique, previously presented in [5], that is both simple and capable of producing accurate performance estimates for general-topology packet networks loaded by elastic traffic patterns. However, in [4], the optimization procedure relied on continuous transmission capacities. Generally, this is not the case in real-world systems. Hence, in this paper, we present and solve the Discrete Capacity Assignment (DCA) problem subject to e2e QoS constraints, where transmission capacities are picked from a set of discrete values. This leads to a constrained combinatorial optimization problem, classified as NP-complete [6]. We first solve the DCA problem (properly selecting the capacity of links) considering the e2e delay constraints only. Then we enforce loss probability constraints by properly choosing buffer sizes, therefore facing the Buffer Assignment (BA) problem. In order to find solutions for the problems, we propose the *Square Root Multipliers Algorithm* (SRMA). In the DCA problem, SMRA is followed by a Randomized Rounding (RR) method. Randomized Rounding is a powerful method in the design and analysis of approximation algorithms. An approximation algorithm runs in polynomial time and determines a feasible solution which is demonstrably good [7]. To evaluate the performance of our proposed approach, SRMA/RR results (and its effectiveness) will be compared with the optimal solutions found by an exhaustive search (ES) procedure.

It is worthy to note that the DCA problem was proposed in [8] and the BA problem corresponds to that of [9]. In [8], DCA problems were solved by use of a discrete Particle Swarm Optimization

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(PSO). Although near-optimal DCA solutions were obtained, the effective use of PSO in combinatorial spaces remains an open problem [10]. In [11], in order to solve the BA problem, the original multi-constrained problem was decomposed into a number of single constrained problems. Afterwards, the single solutions were appropriately combined producing a near-optimal solution to the original problem. In this work, the proposed solution methods are completely different and innovative.

The remainder of this paper is structured as follows. Section 2 presents network and queue models, as well as, the mathematical formulation of DCA and BA problems. The problems are solved based on the use of the SRMA proposed in Section 3. In Section 4, a set of numerical results is discussed. Analytical results are presented, and a verification is performed based on simulations conducted with the software *NS*-2 [12]. Finally, conclusions and future work are drawn in Section 5.

2. Problem statement

2.1. Network and queueing models

The network infrastructure is represented by a graph $G=(V, E)$ in which V is a set of vertices (with cardinality N_V) and E is a set of edges (with cardinality N_E). Each node represents a network router and the edges represent physical links connecting a router to another. For a given link (ij) connecting router i to router j, we define C_{ij} the capacity of the link (in bps), f_{ij} the total traffic flow (in bps), the link utilization $\rho_{ij}=f_{ij}/C_{ij}$, and B_{ij} the buffer size (*drop-tail* queue), in packets. The traffic requirements and the traffic routing uniquely determine the flow of each link. The average traffic requirements between nodes are represented by a traffic matrix $\Gamma=\{\gamma_{sd}\}$, where the traffic γ_{sd} between a node pair (sd) represents the average number of bps sent from source s to destination d. We consider that, for each source/destination pair, the traffic is transmitted over exactly one directed path in the network (non-bifurcated routing). Each path is determined by a routing algorithm and stored in a set of paths Π (with cardinality N_P). Let $\Delta=\{\delta_{ij}^{sd}\}$ be a matrix whose elements are equal to one if link (ij) is in the path (sd) or zero, otherwise. Thus, the flow on link (ij) results from the sum of all flows routed on that link, i.e., $f_{ij}=\sum_{sd}\delta_{ij}^{sd}\gamma_{sd}$.

According to [3], arrivals of IP packets at routers do not follow a Poisson process. However, there is a correlation degree, which can be partly due to the TCP control mechanisms. Thus, we adopt $M_{[X]}/M/1/\infty$ and $M_{[X]}/M/1/B$ queues with *batch arrivals*, where $[X]$ is the distribution of batch (i.e., a packet burst) sizes, to model the elastic traffic induced by TCP. Packet lengths are exponentially distributed with mean $1/\mu$ (bits/packet). This model has been extensively studied and has proved highly accurate in assessing the behavior of queues fed with elastic traffic [13].

2.2. The Discrete Capacity Assignment problem

In this subsection we present the Discrete Capacity Assignment problem, i.e., the selection of the link capacities [8]. We consider a linear cost function, non-bifurcated routing, discrete capacities, and e2e delay constraints. Given the network topology comprising routers and links, the traffic requirements, and the routing, the DCA problem is formulated as the following optimization problem:

$$Z_{DCA}=\min\sum_{(ij)\in E}d_{ij}C_{ij} \tag{1}$$

subject to the constraints:

$$\overline{T}_{sd}=\sum_{(ij)\in E}\delta_{ij}^{sd}\overline{T}(C_{ij})\le Delay_{sd},\quad \forall\ (sd)\in\Pi \tag{2}$$

$$C_{ij}>f_{ij}>0,\quad \forall\ (ij)\in E \tag{3}$$

$$C_{ij}\in S,\quad \forall\ (ij)\in E \tag{4}$$

The objective function (1) represents the total link cost, which is the sum of the cost functions of all links (ij). The link cost is a linear function of the capacity ($d_{ij}C_{ij}$), where d_{ij} is the physical length of the link (in km, for example). Eq. (2) is the e2e packet delay constraint for each source/destination pair. It says that the total amount of delay $\overline{T}_{sd}$ experienced by all the flows routed on path (sd) should not exceed $Delay_{sd}$. For the DCA problem we consider infinite buffer queues. Hence, packets experience delays caused by router queues which average value, $\overline{T}(C_{ij})$, is given (according to [14]) by the following expression:

$$\overline{T}(C_{ij})=\frac{K}{\mu}\frac{1}{C_{ij}-f_{ij}}\quad with\quad K=\frac{\overline{X}+\overline{X^2}}{2\overline{X}} \tag{5}$$

where $\overline{X}$ and $\overline{X^2}$ are the first and second moments of the batch size distribution $[X]$. Constraints (3) are non–negativity constraints. Constraints (4) are integrality constraints, where S corresponds to a set (with cardinality N_S) of discrete capacities.

We notice that the above stated DCA problem is a constrained combinatorial optimization problem, and is known to be NP-complete [6]. Finding the optimal solution becomes impractical in most cases and therefore heuristics are proposed to find admissible solutions.

2.3. The Buffer Assignment problem

By explicitly considering elastic traffic, we also need to consider the impact of finite buffers, therefore facing the Buffer Assignment problem. The objective is to minimize the total buffer cost considering the traffic that flows on each source/destination path, while meeting the maximum allowed packet loss probability [9]. This gives the following mathematical formulation:

$$Z_{BA}=\min\sum_{(ij)\in E}\eta_{ij}B_{ij} \tag{6}$$

subject to the constraints:

$$P_{sd}=\sum_{(ij)\in E}\delta_{ij}^{sd}p(B_{ij})\le P_{loss}^{sd},\quad \forall\ (sd)\in\Pi \tag{7}$$

$$B_{ij}\ge 0,\quad \forall\ (ij)\in E \tag{8}$$

The objective function (6) represents the sum of the buffer cost functions. The buffer cost is a linear function of the buffer size ($\eta_{ij}B_{ij}$), where η_{ij} is a constant of proportionality (in \$/pkt, for example). Eq. (7) is the loss probability constraint for each source/destination node pair. It says that the total loss probability experienced by all the flows routed on the path (sd) should not exceed the maximum fixed P_{loss}^{sd} (i.e., the maximum allowed loss probability for path (sd)). Here $p(B_{ij})$ is the packet loss probability for link (ij) (evaluated by means of the $M_{[X]}/M/1/B$ queue). We note also that the first part of Eq. (7) is based on the assumption that link losses are independent. Eq. (8) is a non-negativity constraint. We observe that the BA problem, considering continuous buffer sizes, can be classified as a constrained convex minimization problem; therefore, there is a global optimum [9]. A method to solve the BA problem can be found in [11], however the method proposed in this work is much more simple.

3. Solution method

In this section we present our approach to solve the DCA and BA problems.