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Kemal Altinkemer
Purdue University

Indranil Bose
Purdue University

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Kemal Altinkemer & Indranil Bose
Krannert Graduate School of Management, Purdue University,
West Lafayette, IN - 47907.

Motivation

One of the fundamental problems related with frame relay and Asynchronous Transfer Mode (ATM) based backbone networks is to determine the routes to be used for delivering messages between each communicating pair of nodes when the capacities of the communication links and the topology of the network are known. This is referred to as the flow assignment problem. Most of the available literature on backbone networks has attempted to solve the flow assignment problem based on the assumption of a single communication link between nodes. In reality, multiple parallel links may be used between communicating nodes and decisions need to be made about which link to choose and when for routing messages through the network. This problem becomes even more complicated when the network supports different classes of traffic with a variety of delay requirements. Some examples of delay insensitive traffic would be some e-mail, ftp, remote login whereas real-time audio, and video could be regarded as delay sensitive traffic.

Problem Statement

The problem that we are studying is how to route messages having different delay sensitivities over a frame relay or ATM based fiber optic network with parallel links. We assume that the messages belong to different priority classes to account for the difference in delay requirements. There is evidence in the area of performance analysis of computer networks, Laue (1981), that strongly suggests that the overall performance can be significantly improved if messages are prioritized according to their delay requirements. This finding leads us to make the above assumption.

We also address the issue of how to decide what price to charge from the users who are requesting delivery of messages belonging to different priority classes. There is significant literature that details the benefits of using pricing of network services (Altinkemer and Srinivasan, 1994; Cocchi *et al.,* 1993; Gupta *et al.,* 1994; Mackie-Mason and Varian 1993). Priority pricing enables the users to decide when and what kind of service they need and at what priority. Backbone networks of today already suffer from congestion problems due to the tremendous increase in traffic in recent times. It seems evident that some pricing mechanism may provide an efficient resource allocation scheme that would maximize the value of the network usage. In our case, we decide on the priority prices to be paid by users requesting different service classes.

Significance of the Research

The problem addressed in our research is related to routing and pricing decisions in frame relay or ATM based fiber optic networks with parallel links. This problem is important since the delay on the parallel links are not additive. Hence, to meet delay guarantees for different priorities of traffic, routing of messages assumes critical importance. As more delay-sensitive applications (e.g. interactive television, real-time virtual simulations, telemedicine) come up in the future, pricing of network services according to priorities will also assume tremendous importance.

In our research, there will be fundamental contribution from queuing theory perspective. Calculation of mean waiting time for multiserver priority queues is known to be a complex problem. As part of our research we would obtain analytical expressions for mean waiting time of different priority classes with exponential arrival and fixed service time (i.e. priority M/D/k queues in case of ATM networks) and exponential service time (i.e. priority M/M/k queues in case of frame relay networks).

Problem Formulation

The inputs to our network routing and pricing process are given network topology, origin-destination traffic matrix, same capacities of the existing parallel links and their associated costs. The underlying assumptions are - Poisson interarrival rate for external messages, no node processing delay, an infinite buffer space and negligible propagation delays. For ATM based backbone networks the problem is modeled as a network of M/D/k queues where the 'k' parallel links are viewed as servers and the messages as customers. The service time is assumed to be a constant as ATM networks have fixed cell lengths (i.e. 53 bytes). For frame relay networks the problem is modeled approximately as a network of M/M/k queues. In frame relay networks there exists an upper bound on the maximum length of frames and as such a more exact description of the service distribution is a truncated exponential distribution. However, since we make use of Kleinrock's independence assumption to model our problem it may not be inappropriate to approximate the truncated exponential distribution by an exponential distribution, in addition. We believe that such approximations are tolerable for frame relay networks since we are interested in approximate but reasonable solutions. We also assume a nonpreemptive head-of-the-line priority discipline and static nonbifurcated routing. A single primary route is chosen for each message class generated by a given pair of origin-destination nodes. All routes are implicitly considered as explained in Gavish and Altinkemer (1990).

It is assumed that there are only two message classes. Although our model can be generalized to 'n' classes, we restrict ourselves to only two classes for the purpose of computational tractability. The two classes of traffic illustrate the natural distinction between 'low' and 'high' priority traffic. How much delay a priority class can tolerate is assumed to be an input parameter to our model. We also assume there is an upper bound on delay for different priority classes on links. One aim of the study is to find the sensitivity of routing decisions to the upper bounds on delays for the different message classes.

The link cost structure consists of fixed cost and variable cost. Fixed setup cost includes a fixed cost per unit of time and a term proportional to the link length. The variable cost is assumed to be proportional to the traffic and corresponds to the cost per message unit charged by the common carrier. Both fixed and variable cost is considered when modeling the problem from the perspective of the backbone network provider whereas only variable cost involved in leasing the links from a common carrier come into play when we model the problem from the standpoint of a user organization. There will be extensive computational tests which will measure performance for both scenarios.

Computational Methodology

We formulate the problem as a mixed integer program in a manner similar to that of Neuman (1992). The original problem is shown to belong to the NP-hard class. This motivates us to see the technique of Lagrangean relaxation for obtaining lower bounds on the optimal solution to the problem. By relaxing the original problem, one of the subproblems is identified to be a shortest path problem and the other subproblem is solved using numerical search methods. The Lagrange multipliers are updated using subgradient optimization and estimates of the "best" Lagrange multipliers that give the tightest lower bound of the objective function are used as prices for the priority classes. The details of the solution procedure for an ATM network with two parallel links when links are modeled as separate M/D/1 queues appear in Altinkemer and Bose (1996a). The waiting time expressions for priority M/D/k queue appears in Altinkemer *et al.* (1996b). These will be used for solving the routing and pricing problem in an ATM network with 'k' parallel links where links are modeled as M/D/k queues.

Future Work

We have formulated the problem of routing and pricing in the case of ATM networks with two parallel links. This formulation assumes that the messages form two separate queues (each queue having a single server) at the processing nodes. We need to perform computational tests to decide on the routes and priority prices for this case. A modified formulation for the same problem would be to assume that messages form a single queue at the processing node and are sent out on the first available link which is modeled as a server. Kleinrock (1975) remarked that a single queue with 'k' servers is more efficient (in terms of throughput) than 'k' separate queues each with a single server. It remains to be shown whether this observation holds for a network of queues. We would also have two separate formulations for frame relay networks and compare the routes and prices obtained by the two through numerical computations.

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