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寬頻網際網路服務品質保證(II)

子計畫七：寬頻網際網路規劃與容量管理(II)／林永松

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一、摘要

As the traffic demands are increasing over time, the rerouting approach may not be applicable, which results in the necessity of capacity augmentation. Henceforth, we focus on the network servicing of virtual circuit network, that is to jointly consider the link capacity assignment and the routing problem in virtual circuit network where the objective is to minimize the total link installation cost with considering the average and end-to-end delay constraints. The concavity associated with the capacity cost function makes this problem more complicated than rerouting problem. The basic approach to the algorithm development is Lagrangean relaxation in conjunction with optimization-based add drop heuristics. In the computational experiments, it is shown that the proposed algorithm calculates solutions that are reasonably good in an hour of CPU time for networks with up to 26 nodes. And the solution quality is better in small network size and loose delay constraints.

Keywords: network planning, capacity augmentation, QoS routing

二、緣由與目的

To ensure user-perceived end-to-end QoS requirement is one of the most important issues in providing modern network services, which typically requires sophisticated design of routing and capacity management policies.

Most of existing networks face a common challenge, to satisfy more and more new traffic demand and QoS requirements. However, the existing link capacity may not be sufficient even performing rerouting. As a result, the network operators have to make a link capacity augmentation plan in order to satisfy the traffic requirements. As a result, the link capacity is also a decision variable. Hence, we jointly consider link capacity assignment and routing problem at the same time.

However, for most of the network operators, it is not easy to have a good routing and capacity augmentation plan due to the complicated QoS requirements. In addition, the routing also requires sophisticated design to of routing and capacity management policies. They often take the approaches of buying the equipment vendors solutions, which is mostly over-engineering. By using this rigorous mathematical optimization technique, we could provide alternative cost-efficient solutions to the network operators.

In [2], Cheng and Lin took a user-optimization approach and considered a fairness issue by minimizing the maximum individual end-to-end packet delay in virtual circuit networks. In [3], Yen and Lin considered both system and user perspectives typically in virtual circuit networks. More precisely, they considered the virtual circuit routing problem of minimizing the average packet delay subject to end-to-end packet delay constraints for users, which is an extension of [2]. In these previous researches, the link capacity is fixed such that could not meet more and more traffic into the network.

三、數學模型及其演算法

Mathematical notations are as follows.

V: $=\{1,2,\ldots,N\}$, the set of nodes in the graph

L: the set of communication links in the communication network

W: the set of Origin-Destination (O-D) pairs in the network

$¥_w$ **:**(packets/sec): the arrival rate of new traffic for each O-D pair $w \in W$, which is modeled as a Poisson process for illustration purpose

P_w: a given set of simple directed paths from the origin to the destination of O-D pair w

$¢_{pl}$: the indicator function which is 1 if link l is on path p and 0 otherwise

D_w: the maximum allowable end-to-end delay for O-D pair w

$\Psi_l(C_l)$: the link assignment cost for link $l \in L$, with respect to the link capacity C_l

K: the maximum allowable average cross network delay

A_l: the candidate set of link capacity assignment for link $l \in L$

Decision variables are depicted as follows

x_p: a routing decision variable which is 1 when path $p \in P_w$ is used to transmit the packets for O-D pair w and 0 otherwise

g_l: the aggregate flow over link l, which is equal to $\sum_{p \in P_w} \sum_{w \in W} x_p ¥_w ¢_{pl}$

f_l: the estimated flow over link l, which is equal to g_l

C_l**:** (packets/sec), the capacity of each link $l \in L$

$$Z_{IP} = \min \sum_{l \in L} \Psi_l(C_l) \qquad \text{(IP)}$$

subject to:

$$\frac{1}{\sum_{w \in W} ¥_w} \sum_{l \in L} \frac{f_l}{C_l - f_l} \le K \qquad (1)$$

$$\sum_{l \in L} \frac{y_{wl}}{C_l - f_l} \le D_w \qquad \forall w \in W \qquad (2)$$

$$\sum_{p \in P_w} x_p = 1 \qquad \forall w \in W \qquad (3)$$

$$x_p = 0 \text{ or } 1 \qquad \forall p \in P_w, w \in W \qquad (4)$$

$$\sum_{p \in P_w} x_p ¢_{pl} \le y_{wl} \qquad \forall w \in W, l \in L \qquad (5)$$

$$y_{wl} = 0 \text{ or } 1 \qquad \forall w \in W, l \in L \qquad (6)$$

$$g_l \le f_l \qquad \forall l \in L \qquad (7)$$

$$0 \le f_l \le C_l \qquad \forall l \in L \qquad (8)$$

$$C_l \in A_l \qquad \forall l \in L. \qquad (9)$$

As shown in (IP), the objective is to minimize the total link installation cost in order to satisfy the average and end-to-end delay requirements.

The algorithm development is based upon Lagrangean relaxation. We dualize Constraints (1), (2), (5) and (7) to obtain the following Lagrangean relaxation problem (LR).

$$Z_D = \min \sum_{l \in L} \Psi_l(C_l) + a\left(\frac{1}{\sum_{w \in W} r_w} \sum_{l \in L} \frac{f_l}{C_l - f_l} - K\right) + \sum_{w \in W} b_w\left(\sum_{l \in L} \frac{y_{wl}}{C_l - f_l} - D_w\right) + \sum_{w \in W} \sum_{l \in L} c_{wl}\left(\sum_{p \in P_x} x_p ¢_{pl} - y_{wl}\right) + \sum_{l \in L} d_l(g_l - f_l) \qquad \text{(LR)}$$

subject to:

$$\sum_{p \in P_w} x_p = 1 \qquad \forall w \in W \qquad (10)$$

$$x_p = 0 \text{ or } 1 \qquad \forall p \in P_w, w \in W \qquad (11)$$

$$y_{wl} = 0 \text{ or } 1 \qquad \forall w \in W, l \in L \qquad (12)$$

$$0 \le f_l \le C_l \qquad \forall l \in L \qquad (13)$$

$$C_l \in A_l \qquad \forall l \in L. \qquad (14)$$

We can decompose (LR) into two independent subproblems.

Subproblem 1: for x_p

$$\min \sum_{w \in W} \sum_{p \in P_w} \sum_{l \in L} (c_{wl} + d_l ¥_w) x_p ¢_{pl} \qquad \text{(SUB1)}$$

subject to (10) and (11).

Subproblem 2: for C_l, y_{wl} and f_l

$$\min \left[\sum_{l \in L} \left(\Psi_l(C_l) + \frac{a}{\sum_{w \in W} ¥_w} \frac{f_l}{C_l - f_l} + \frac{\sum_{w \in W} b_w y_{wl}}{C_l - f_l} - \sum_{w \in W} c_{wl} y_{wl} - d_l f_l\right) - aK - D_w \sum_{w \in W} b_w\right] \qquad \text{(SUB2)}$$

subject to (12), (13) and (14).

(SUB1) can be further decomposed into $|W|$ independent shortest path problem with nonnegative arc weights. It can be easily solved by the Dijkstra's algorithm. The $-aK \; -D_w \sum_{w \in W} b_w$ term in the objective function of (SUB2) could be dropped first and added back to the objective value since it will not affect the optimal solution of (SUB2). (SUB2) is a complicated problem due to the coupling of three decision variables, y_{wl}, f_l and C_l. Due to the possible limited candidate set of each link capacity configuration, we could exhaustive search all possible link capacity to identify the optimal solution with respect to the corresponding y_{wl} and f_l. Then the question lies in how we could find the optimal solution of y_{wl} and f_l to (SUB2) when the link capacity is constant. It is still a very difficult problem due to the coupling of two decision variables, y_{wl} and f_l, at the third term, $\frac{\sum_{w \in W} b_w y_{wl}}{C_l - f_l}$, of the objective function in (SUB5.4.1).

In [3], we proposed the algorithm to locate the optimal y_{wl} and f_l when the link capacity is fixed. Therefore, the optimal solution procedure to solve (SUB2) is proposed as follows:

Step 1. Exhaustive search all link capacity configuration for link $l \in L$. For each link capacity configuration, C_l,

Step 1.1. Solve ($\frac{b_w}{C_l - f_l} - c_{wl} = 0$) for each O-D pair w, call them the break points of f_l.

Step 1.2. Sorting these break points and denoted as $f_l^1, f_l^2, .., f_l^n$

Step 1.3. At each interval, $f_l^i \le f_l \le f_l^{i+1}$, $y_{wl}(f_l)$ is 1 if $\frac{b_w}{C_l - f_l} - c_{wl} \le 0$ and is 0 otherwise.

Step 1.4. Within the interval, $f_l^i \le f_l \le f_l^{i+1}$, let u_l be $\sum_{w \in W} b_w y_{wl}(f_l)$, v_l be $\sum_{w \in W} c_{wl} y_{wl}(f_l)$ and z_l be $\frac{a}{\sum_{w \in W} ¥_w}$, then the local minimal is either at the boundary point, f_l^i or f_l^{i+1}, or at point $f_l^* = C_l - \sqrt{\frac{z_l * C_l + u_l}{d_l}}$.

Step 1.5. The minimum solution with respect to this link capacity configuration, C_l could be found by comparing these local minimum points.

Step 2. The global minimum solution could be found by comparing the minimum solution with respect to each link capacity configuration.

According to the algorithms proposed above, we could successfully solve the Lagrangean relaxation problem optimally. By using the weak Lagrangean duality theorem, we could caculate the tightest lower bound and solve the dual problem by using the subgradient method [1].

To obtain the primal solutions to the (IP), the solutions to the routing assignment determined in (LR) are considered. In order to satisfy the average and end-to-end delay constraints, the add-drop heuristic are proposed.

The **add-drop** heuristic is depicted as follows.

Add heuristic:

a) Among all the links where their link capacity are not equal to the largest candidate link capacity, identify the most congested link. If all the links have the largest capacity configuration, stop the whole add heuristic process, else augment the link capacity on this link to the next higher link capacity configuration.

b) Verify the average cross network delay, if the average cross network delay is still violated, go to a) again.

Drop heuristic:

a) For a link, first decrease the link capacity to next lower capacity in the capacity configuration. Verify the capacity constraint, average cross network delay constraint and end-to-end delay constraints for all O-D pairs. If these constraints are all satisfied, then this link capacity could be decreased successfully, else augment the link capacity back to its original capacity configuration.

b) Repeat a) for all links in the network.

The computational experiments for the algorithms developed above are coded in C++ and performed on a PC with INTEL^{TM} PⅢ-800 CPU. We tested the algorithm for 3 networks -- ARPA, GTE, OCT with 21, 12 and 26 nodes.

TABLE 1 – Solution quality for ARPA network topology

Network topology	K (msec)	D_w (msec)	Lower bound	Upper bound	Error gap (%)
ARPA	50	100	2627	3814	45
	60	120	2618	3571	36
	70	140	2612	3431	31
	80	160	2609	3295	26
	90	180	2606	3177	21
	100	200	2605	3085	18
	110	220	2603	3010	15
	120	240	2601	2917	12

TABLE 2 – Solution quality for GTE network topology

Network topology	K (msec)	D_w (msec)	Lower bound	Upper bound	Error gap (%)
GTE	20	40	2501	3294	31
	30	60	2500	2799	11
	40	80	2500	2500	0
	50	100	2500	2500	0
	60	120	2500	2500	0

TABLE 3 – Solution quality for OCT network topology

Network topology	K (msec)	D_w (msec)	Lower bound	Upper bound	Error gap (%)
OCT	50	100	3383	4998	47
	60	120	3335	4812	44
	70	140	3333	4650	39
	80	160	3308	4532	37
	90	180	3298	4401	33
	100	200	3307	4279	29
	110	220	3274	4213	28
	120	240	3262	4096	25

四、計畫成果自評

Besides rerouting, capacity augmentation is also an important approach to address the increasing traffic demand and QoS requirements in network servicing. In this study, we jointly consider the capacity assignment and routing assignment in virtual circuit network. Besides the nonconvexity associated with the end-to-end delay constraints, the concavity associated with the capacity cost in the objective function makes this problem more complicated. As shown in the computational experiments, we have successfully solved this problem by using the proposed rigorous approaches.

五、參考文獻

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