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Routing with multiple quality-of-services constraints: An approximation perspective

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ABSTRACT

Finding a path that satisfies multiple Quality-of-Service (QoS) constraints is vital to the deployment of current emerged services. However, existing algorithms are not very efficient and effective at finding such a path. Moreover, few works focus on three or more QoS constraints. In this paper, we present an enhanced version of fully polynomial time approximation scheme (EFPTAS) for multiconstrainted path optimal (MCOP) problem. Specifically, we make four major contributions. We first allow the proposed algorithm to construct an auxiliary graph, through which the QoS parameters on each of the finding path can be guaranteed not to exceed the given constraints. Then we adopt a concept, called nonlinear definition of path constraints in EFPTAS for reducing both time and space complexity. Also, we enable EFPTAS to run iteratively to facilitate a progressive refinement of the finding result. In addition to these, we identify some "deployment" issues for proposed algorithm, the essential steps that how and when the EFPTAS takes place are presented. By analyzing the proposed algorithm theoretically, we find that the presented EFPTAS can find a $(1+\varepsilon)$-approximation path in the network with time complexity $O(|E||V|/\varepsilon)$ (where $|E|$ is the number of edges and $|V|$ is the number of nodes), which outperforms the previous best-known algorithm for MCOP. We conduct an extensive comparison between the algorithm presented in this paper and previous best-known study experimentally, our results indicate that EFPTAS can find a path with low complexity and preferable quality.

1. Introduction

The last few years have witnessed the growth of various streaming media over the Internet, thanks to widespread deployment of the high-speed network technology. In parallel, real-time huge-volume data transfer applications (e.g. web broadcasting, video teleconferencing, and HDTV) also raise new challenges to current high-speed packet switching networks, one of the main issues is QoS routing, that is, select a path that guarantees various applications to meet multiple quality-of-service (QoS) requirements (Huang et al., 2010; Huang and Liu, 2010).

QoS routing consists of two functionalities: routing protocols that keep the network state information up to date and QoS routing algorithms that compute the constrained shortest paths based on the information provided by the routing protocols. This paper mainly concerns with the latter one. The algorithms for computing paths can be used in many scenarios, for example, constructing label-switching paths in MPLS, arranging service-delivering paths in IMS-enabled networks, establishing wavelength-switching paths in fiber-optics networks based on the QoS requirements in the service contracts, or applying together with RSVP (Zhang et al., 2002).

QoS metrics fall into two categories. The metrics of the path are obtained by adding (multiplying, in the case of reliability) the metrics of edges along the path, metrics such as delay, delay jitter, and hop count are called additive. QoS metrics like bandwidth are known as bottleneck parameters where the corresponding metric of the path is the smallest of the metrics of the edges along the path. Since problems involving bottleneck constraints are solvable (by omitting all links from the topology that does not satisfy one of the constraints), the additive parameters are focused only in this paper.

The problem of QoS routing is challenging because selecting paths that meet two or more additive QoS constraints is an NP-hard (Wang and Crowcroft, 1996). Such fundamental problem is usually known as multi-constrained path (MCP) problem. Currently, there has been much work involved in designing heuristic solutions for this problem. Sahni (1977) presented some general techniques for combinatorial approximation. Chen and Nahrstedt (1998), Chen et al. (2008) and Song and Sahni (2006) proposed various polynomial time algorithms for Delay Constrained Least Cost (DCLC) problem based on Sahni's study.

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Their algorithms resort to rounding and scaling to guarantee a solution within a factor $(1+\varepsilon)$ of the optimal solution. Xue (2000) and Juttner et al. (2001) presented the Lagrange relaxation method to approximate the DCLC by linear combination. Korkmaz and Krunz (2001) used a nonlinear function and proposed a randomized heuristic, their simulation results are rather good compared with other algorithms. Goel et al. (2001) presented an approximation algorithm for the single source all destinations delay sensitive DCLC routes problem. In Yuan (2002), Yuan presented a limited granularity heuristic and a limited path heuristic. Guerin and Orda (1999) provided efficient approximation algorithms for QoS routing with inaccurate information. Orda and Sprintson (2003) presented a precomputation scheme for QoS routing with two additive parameters. They also proposed different kinds of approximation algorithms for computing a pair of disjoint QoS paths recently Orda and Sprintson (2004). Kuipers et al. (2002) summarized the representative techniques for the DCLC. Besides, Mieghem and Kuipers (2004) provided four concepts of exact QoS routing algorithms, they even supposed that the NP-hard behavior of QoS routing would not happen in practical networks. However, we believe that future networking will support different kinds of QoS requirements (especially for multiple additive metrics) with the emerging of various services. Thus, it is essential to consider the NP-hard behavior of QoS routing.

In this area, another important technique ε-approximation algorithm, which can obtain an approximate, quantifiable solution to the optimal one, was extensively studied. Warburton (1987) was the first to derive a fully polynomial time approximation scheme (FPTAS) for DCLC on acyclic graphs. Hassin improved the Warburton's result with time complexity $O(|E||V|(|V|/\varepsilon)\log(|V|/\varepsilon))$ in Hassin (1992), where $|E|$ is the number of edges, $|V|$ is the number of nodes and ε is the approximation parameter. In addition, Lorenz and Raz (2001) presented a faster FPTAS with a time complexity of $O(|E||V|(\log\log|V|+1/\varepsilon))$. More recently, Xue et al. (2007), Xue et al. (2008) studied the different version of the Multiconstrained Path (MCP) Problem and presented an efficient approximation algorithm, which can solve the optimization version of MCP (also typically called MCOP, multiconstrained optimal path problem) with K constraints in $O(|E|(|V|/\varepsilon)^{K-1})$ time.

The above mentioned researches mainly focus on solving MCOP by the efficiency approximation algorithm rather than the bio-inspired heuristic such as Huang and Liu (2010). In this paper, we investigate MCOP from an approximation perspective. To the best of our knowledge, Xue's algorithm is currently the fastest for path establishment in multiconstrained QoS routing. However, the space complexity of his algorithm is relatively high, and the obtained path might not be precise enough. In this study we propose an Enhanced Fully Polynomial Time Approximation Scheme, named EFPTAS for multiconstrained optimal path (MCOP) problem. Our work can be regarded as an extension of Yuan (2002), Mieghem and Kuipers (2004), Lorenz and Raz (2001), Xue et al. (2007) and Xue et al. (2008). Specifically, we have made four major contributions.

- We adopt the technique of auxiliary graph, which can guarantee that the QoS parameters on each finding path do not exceed to the corresponding constraints.
- We employ the nonlinear definition of the path constraints to reduce the complexity of path-selecting and, hence, the network operating efficiency can be greatly enhanced.
- Instead of rounding each link weight into an integer, we enable limited iterations of the algorithm to facilitate a progressive refinement of result from approximation to precision.
- Some "deployable" facets are identified based on current real-world network environment to guarantee the deployability of the proposed algorithm. This is critical, as to our knowledge, there is no reported work in the literature on the deployment of QoS routing algorithm.[1]

We have theoretically analyzed the performance of the EFPTAS. Our results indicate that the proposed algorithm is superior to previous studies on both time and space complexity. We also have implemented EFPTAS and experimented with four specific networks (`NSFNet`, `NTTNet`, `CERNet`,[2] `CERNet-2`) and different scale of random networks. The experimental results show that EFPTAS can improve the network performance significantly for two representative services.

The rest of this paper is organized as follows. In the next section, we formally define the problem and notations. A typical work is also reviewed in this section. Section 3 presents the proposed approximation and its theoretical analysis as well as the deployment issues. In Section 4, we report experimental results obtained from different kinds of networks. Section 5 draws the conclusion of this paper.

2. Preliminaries

2.1. Problem formulation

Our notation and terminology are from Yuan (2002) and Mieghem and Kuipers (2004). A communication network with K QoS constraints can be represented by a connected graph $G(V,E,w_1,\ldots,w_K)$, where V is the set of $|V|$ vertices, E is the set of $|E|$ edges. Each edge has K weights, and $w_k(e)\geq 0$ is the kth weight of edge e, $\forall e\in E$, $1\leq k\leq K$. Let p be a path in G. Denote $w_k(p)$ as the sum of the kth weight on edges along p. We have the following definitions.

Definition 1. Multiconstrained Path (MCP) Problem. Consider an undirected graph $G(V,E)$, each edge associated with K positive real-valued edge weights $w_k(e)$, $1\leq k\leq M$. Let $W=(W_1,W_2,\ldots,W_K)$ be the K constraints, and $s,d\in V$ be the source and destination nodes. The MCP is to find a path p from s to d such that $w_k(p)\leq W_k$.

The path that satisfied $w_k(p)\leq W_k$ is said to *feasible path*. We use $\{p_f\}$ to denote all the feasible paths in $G(V,E)$.

Definition 2. Multiconstrained Optimal Path (MCOP) Problem. The MCOP problem is to find an optimal path p_{opt} among feasible paths $\{p_f\}$ in G from s to d and the smallest value of $\eta\in(0,1]$ such that $w_k(p_{opt})\leq\eta\cdot W_k$.

An algorithm is a $(1+\varepsilon)$-approximation algorithm (or simply, an approximation algorithm) for MCOP if the algorithm generates a source to destination path p such that $w_k(p)\leq(1+\varepsilon)\cdot\eta\cdot W_k$, the running time of the algorithm is bounded by a polynomial in the input size of the instance as well as in $1/\varepsilon$.

2.2. Auxiliary graph

Xue et al. provided an important methodology in their works Xue et al. (2007, 2008), that is, constructing an auxiliary graph. It transforms from an undirected graph G to a directed graph $G^{K,\tau}$. Each vertex $v\in G$ is associated with $(1+\tau)^{K-1}$ vertices (since each weight has been normalized $w_k(e)/W_k$, we could regard τ as the maximum integer of all constraints.) in $G^{K,\tau}$, i.e., $(u,C_2,\ldots,C_K)$,

[1] The QoS routing algorithm referred here is especially for the MCP which subjects to two or more *additive* constraints.

[2] CERNet: China Education and Research Network. http://www.cernet.edu.