摘 要

通信技术的发展和新的应用类型的出现对网络互连的核心设备—路由器的性能和功能都提出了更高的要求。在过去十年中，Internet 迅速发展成为全球最大的数据网络，其骨干链路的带宽和流量都呈现爆炸性增长的态势，要求路由器能提供快速的分组转发技术；与此同时，随着 Internet 的商业化，用户对网络服务质量（Quality of Service）的要求也不断提高，需要路由器根据应用的需求提供多种类型的服务。如何在保证吞吐量的同时满足分组在带宽、延迟和丢失率等方面的要求是高性能路由器 QoS 技术所面临的主要问题。与传统的只提供无差别服务的路由器相比，支持 QoS 的高性能路由器不仅要利用交换和并行处理技术来提高系统的吞吐率，而且需要在体系结构、数据平面和控制平面的算法等方面进行改进，以满足 Internet 未来发展的要求。

本文主要从拥塞控制、接纳控制和输入排队调度算法等三个方面对高性能路由器中的 QoS 关键技术问题进行了研究，主要贡献有：

在拥塞控制方面，本文主要研究了如何利用路由器实现网络拥塞控制，提出了二阶段分布式拥塞控制方案，它将传统的基于末端系统的端到端控制分为核心网络控制和接入网络控制两个阶段，根据网络的具体情况分别控制拥塞。在核心网络拥塞控制的实现上，提出了基于速率和队列控制的近似公平带宽分配算法（RQ-AFB），主要面向当前的 Internet 结构，根据传输流的速率和队列长度动态地调整分组的丢弃概率，有效地解决了自适应和非自适应传输流之间的不公平带宽分配问题；此外，本文还提出了基于边界节点的聚集拥塞控制（EB-ACC），主要面向区分服务模型，通过在网络的边界节点引入自适应的流量调节算法，重点解决了聚集间的不公平性和拥塞崩溃问题。在接入网络拥塞控制的实现上，阐述了基于边界节点和基于主机的控制方案。

在接纳控制方面，提出了面向区分服务网络的接纳控制方案（DS-CAC），重点阐述了 DS-CAC 方案中的信令处理过程和在分布式环境下对连接请求的串行化处理，并给出了基于边界节点、基于带宽代理以及同时利用边界节点和带宽代理实现的方案；提出了一种保证统计型 QoS 的接纳控制算法，重点阐述了如何利用聚集到达速率二阶矩数字特征和 QoS 约束来估计路由器的可用带宽；此外，本文还研究了在网络资源不够用的情况下的连接接入问题，提出了 QoS 适应算法并应用到面向对象的视频流的传输中。

在输入排队调度方面，本文重点研究了支持多服务类的输入排队路由器的体系结构（MC-IQR），提出了支持多服务类的虚拟输出排队（MC-VOQ）结构和用于保证多种服务类 QoS 的层次调度结构，并在现有算法的基础上，给出了保证确定型的延迟服务和保证带宽服务的调度算法。

关键词：服务质量，路由器，队列管理，拥塞控制，接纳控制，输入排队，调度算法，拥塞检测，速率控制，公平性，带宽测量，区分服务，协议

Research on Key Techniques of Providing Quality-of-Services in High-Performance Router

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Advances in communication technologies and inventions in network applications have posed new challenges to performance and functionalities of Internet router. In the last decade, the Internet has evolved into the largest data communication network in the world, and its backbone network's bandwidth and traffic have been increasing explosively, which requires high-performance router to meet the demand of broadband physical link and to realize interconnection. Moreover, with the transformation into a commercial infrastructure, the Internet should provide meaningful QoS (Quality-of-Services) for different applications according to their requirements in the router. The main difficulty in developing QoS technologies for high-performance router is to solve the problem of how to guarantee the high throughput of router while simultaneously satisfy the QoS requirements of packets, such as bandwidth, delay and loss. Therefore, it is necessary to develop new high-performance router architecture and associated QoS algorithms in both data plane and control plane to deal with this new situation. Compared with traditional router with only best effort service, QoS-capable high-performance routers not only utilize switching and parallel processing to improve the system's throughput, but also need support from new QoS scheduling and control algorithms.

This thesis explores the key techniques of QoS in high-performance router from three aspects: congestion control, admission control and input-queued scheduling algorithms. The main contributions are given as follows:

Congestion control mechanism is one of the key techniques in maintaining the stability of the Internet. In this thesis, a new distributed congestion control scheme, Two-Phase Distributed Congestion Control, is put forward. The scheme divides the end-to-end congestion control into two phases: core network control and access network control. The two phases work independently and can select appropriate control mechanism according to the network's architecture. In the core network control, a novel active queue management algorithm, namely Rate and Queue controlled Approximate Fair Bandwidth allocation (RQ-AFB), is proposed to solve the unfair bandwidth sharing problem between adaptive and non-adaptive flows for the current Internet. RQ-AFB dynamically adjusts dropping probability of an incoming packet based on per-flow's estimated rate, fair allocated bandwidth and queue length. In addition, a new edge-to-edge control scheme, namely Edge-based Aggregation Congestion Control (EB-ACC) is put forward to solve the problem of

fairness among aggregates and congestion collapse for Differentiated Services (DiffServ) model. EB-ACC scheme adaptively adjusts sending rate of aggregate at ingress router based on a TCP throughput model and feedback of network congestion status from egress router. In access network control, two congestion control schemes, which are based on edge router and end host respectively, are discussed in detail.

Connection admission control is another key technology to provide QoS in router. In this thesis, a new Connection Admission Control (DS-CAC) scheme is proposed to provide quantitative QoS guarantees for DiffServ. The signaling process and serialization of connection's request in a distributed network are discussed in detail. Three implementation schemes of DS-CAC, i.e., Centralized CAC, Distributed CAC and Hybrid CAC, are presented. For admission control algorithm, a novel available bandwidth estimation algorithm, which is based on second moment property and QoS constraints at router, is proposed to provide statistical QoS for network traffic. In addition, a novel QoS adaptation algorithm is introduced in admission control to address the re-negotiation problem in the case of insufficient network resource. The QoS adaptation algorithm is applied to object-based video transmission over IP networks.

Input-queued scheduling algorithm is very important in improving the performance of router with cell-based switch fabric. This thesis proposes a new Multi-Class Input-Queued Router (MC-IQR) architecture to support DiffServ services. A new Multi-Class Virtual Output Queueing (MC-VOQ) structure is proposed to buffer packet from different service classes at the input port. In addition, two input-queued scheduling algorithms, which are based on hard-real-time and maximal weight matching respectively, are proposed to support delay-guaranteed service and bandwidth-guaranteed services.

Keywords: Quality-of-Services, router, buffer management, congestion control, admission control, input queueing, scheduling algorithm, congestion detection, rate control, fairness, bandwidth measurement, differentiated service, protocol