# End-to-End QoS Network Design

## Quality of Service for Rich-Media & Cloud Networks

Second Edition

**Tim Szigeti**, CCIE No. 9794
**Robert Barton**, CCIE No. 6660
**Christina Hattingh**
**Kenneth Briley Jr.**, CCIE No. 9754

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## About the Authors

**Tim Szigeti**, CCIE No. 9794, is a senior technical leader in the Systems Design Unit at Cisco Systems, where his role is to design network architectures for enterprise mobility solutions. He has specialized in quality of service technologies for the past 15 years, during which time he has authored many technical papers, design guides, and two Cisco Press books: *End-to-End QoS Network Design* (version 1) and *Cisco TelePresence Fundamentals*.

**Robert Barton**, CCIE No. 6660, is located in Vancouver, where he lives with his wife and two children. He graduated from the University of British Columbia with a degree in engineering physics, and is a registered professional engineer. Rob holds dual CCIEs, in Routing and Switching and Security, and was also the first CCDE in Canada. Rob joined Cisco from ArrowPoint Communications, where he worked as a data center specialist supporting many of the largest corporations in Canada. In the time since ArrowPoint was acquired by Cisco, Rob has worked as a public sector systems engineer, primarily focused on wireless and security architectures. Currently, Rob is working on SmartGrid network technologies, including smart meter and intelligent substation design.

**Christina Hattingh** spent 13 years as a senior member of the technical staff in Unified Communications (UC) in the Enterprise Networking Routing Group (formerly Services Routing Technology Group or SRTG) at Cisco Systems. The SRTG products, including the Cisco 2900/3900 and 2800/3800 series ISR platforms and their predecessors, were the first Cisco platforms to converge voice, data, and video traffic and services on IP networks by offering TDM gateway interfaces, WAN interfaces, call control, and QoS features. The ISR series of routers often live at smaller remote offices and therefore at the edge of the WAN, where the need for QoS services is most sensitive. In this role, Christina spoke at Cisco Live conferences, trained Cisco sales staff and Cisco resale partners on router-based UC technologies, authored several Cisco Press books, and advised customers on UC network deployment and design, including QoS designs and helping them through the TDM to SIP trunk industry transition.

**Kenneth Briley, Jr.**, CCIE No. 9754 is a technical lead in the Network Operating Systems Technology Group at Cisco Systems. For over 10 years, he has specialized in quality of service design and implementation in customer environments, alignment of QoS features and functions, and the marketing of new products that leverage QoS technologies. During this time, he has written several deployment guides and whitepapers, presented at Cisco Live, and most recently has focused on the convergence of wired and wireless quality of service.

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# About the Technical Reviewers

**John Johnston**, previously CCIE No. 5232, is a technical marketing engineer for Cisco Systems. His focus is on mobile security technology and design validation. John has more than 19 years of experience in IP internetworking, including the design and implementation of enterprise networks. Before joining Cisco Systems, John provided network design support for Fortune 500 companies. He holds a BSEE from the UNC-Charlotte.

**Roland Saville** is a Technical Leader for the Systems Development Unit (SDU) at Cisco, focused on developing best-practice design guides for enterprise network deployments. He has more than 18 years of experience at Cisco as a Systems Engineer, Product Manager, Consulting Systems Engineer, Technical Marketing Engineer, and Technical Leader. During that time, he has focused on a wide range of technology areas, including the integration of voice and video onto network infrastructures, network security, wireless LAN networking, RFID, energy management, Cisco TelePresence, and BYOD. He has also spent time focusing on the retail market segment. Prior to Cisco, he spent eight years as a Communications Analyst for Chevron Corporation. Roland holds a bachelor's of science degree in electrical engineering from the University of Idaho and an MBA degree from Santa Clara University. He co-authored the book *Cisco TelePresence Fundamentals*, is a member of the IEEE, and has 12 U.S. patents.

# Dedications

**Tim Szigeti:**

I find myself in a dedication dilemma.

On the one hand, I already went to great lengths to explain why *not* dedicating the first edition of this book to my wife would have been a fatal mistake. Since then, I've gone on to dedicate my second book to my son, and now I have a beautiful daughter who deserves a dedication too (and whose arrival, incidentally, actually delayed the release of this edition by a couple of months).

So, the question becomes: Are dedications—as their definition implies—*exclusive* to a given book? Or can these be edition-specific? Or perhaps the more important question is: Do I really think it wise to get into a debate over semantics with my wife, who has a double-major in both English and philosophy?

So I'll play the political game and try to weakly rationalize a compromise: The first edition of this book was dedicated to Lella. The second will be to Lella 2.0, or as she's more commonly known, Isla.

Besides, I've already witnessed how much my daughter values my books. For example, over the past few months, she's had two copies of my previous book under her crib, slightly elevating one end to alleviate nighttime gas. Since she wakes up happy and smiling every morning, I'll infer from this her appreciation of the practical benefits of my work. Furthermore, she's always ready to gnaw and drool on my books until they're nice and soggy, and since pure happiness is expressed during the process, I'll attribute this to her esteem of the quality of the authorship.

And so, to my beautiful little girl, I wish to dedicate to you this work. I really don't know how I ever managed to finish it, seeing as how little you let me sleep over the past few months! I know you'll probably never read it, but that's not the point. I just want you to know you were always on my mind and made working on it virtually impossible! And I'm so very happy it's all done with now, so that I can spend more time playing with you and letting you continue wrapping me tightly around your tiny little finger!

### Rob Barton:

This book is dedicated to my two wonderful boys, Adrian and Matthew. It's not that I expect you to actually pick up the book and try to become QoS experts, or that I am even trying to encourage you toward a career in network design or engineering, although these are noble pursuits. Rather, the lesson that writing this book has reminded me of is that you only grow as a person when you recognize the space you are in and make the decision to do something new. Oftentimes, we don't know what direction our efforts will take us in, but when you make the mindful choice to do something that is difficult, challenging, and can cause you more than a little pain along the way, you grow. No muscle ever grew without the fibers being damaged through exercise, and so is it too with all aspects of life. My hope is that this book will inspire you throughout your life to look for opportunities for growth—be it artistic, mental, professional, physical, or spiritual. This book is for you.

### Christina Hattingh:

To Robert Verkroost and my parents for their unfailing encouragement and support.

### Kenneth Briley, Jr.:

As this is my first book, I'd like to heed Tim's advice and dedicate it to my beautiful wife Mirah for fear of the aforementioned transgression. To Mirah, who incidentally read and approved this dedication, and her countless hours devoted to resolving numerous grammatical errors and listening to me drone on about how incredibly interesting QoS is. To our growing family; Lukas, Erik and Max: please don't grow up too fast, and remember that all things are possible.

## Acknowledgments

**Tim Szigeti:**

First, I'd like to thank all the readers of the first edition who made it the success that it has become. There aren't many technology books that are still being steadily purchased nearly 10 years after their release. And a special thanks to the reviewers who have posted comments for it; I cannot express the pride and appreciation I felt when I saw five-star ratings for our book on Amazon. Thank you!

Thanks to my director, Neil Anderson, for long recognizing the critical role of QoS across all our networking systems and solutions and ensuring that it was always properly addressed. Thanks, too, to Greg Edwards in helping to define and articulate various end-to-end QoS strategies.

Thank you Fred Baker for your guidance and direction in both defining and interpreting various QoS standards. Thanks, too, to James Polk for continuing to push the envelope in the IETF to define what tomorrow's QoS models are going to look like.

I'd like to thank the Vancouver Cisco office lab administrator, Mojan Mobasser, for all her diligence in sourcing and arranging access to equipment. Similar thanks are extended to Dawid Brink for letting me use his Nexus boxes—no questions asked!

Farther east, I'd also like to extend thanks to the Toronto Bell Canada team for allowing me extended access to their ASR and CRS labs. Similar thanks, but in the opposite geographic direction, go out to Lim Fung in our Singapore office for providing me access to his labs also.

I'd like to extend sincere thanks to Tim Stevenson for his amazing technical expertise, particularly relating to data center platforms. You really helped demystify a lot of hardware architectural questions I was grappling with. Thanks, Tim!

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Additionally, I'd like to thank Lucien Avramov for sharing his work on data center QoS and allowing me to borrow from it. Thank you too, Mike Herbert—wherever you are—for getting the ball rolling in this area.

I'd like to thank also the Cisco product teams that listened to the feedback we offered as a result of producing this book so as to continue to improve our QoS feature sets. This includes Albert Mitchell and the Catalyst 2K/3K team for implementing our latest designs into a new version of AutoQoS. Thanks also to Sarath Subrahmanya and Ramachandra Murthy in India for taking to heart our suggestions on WLC QoS feature enhancements. Kudos also go out to Oz Ben-Rephael and team in Israel for continuing to develop NBAR2 application signatures, including for our own Jabber application.

Thanks to the Cisco Press team. Brett Bartow: Thanks for taking on this project and allowing us to thoroughly update and expand on our original work in a comprehensive manner. We appreciate that you didn't blow a gasket when we exceeded our targeted

page count again, again, and again—to a final tune of target +50%! Thanks also for delaying this publication by a couple of months, letting me focus on my family as my daughter was born.

Thank you Chris Cleveland for making the review process so easy. Your comments and accommodation were very much appreciated and really helped polish this work. Thank you, too, Seth Kerney for coordinating the copy review. And also thanks to Vanessa Evans for ensuring that we always had everything we needed at every step of the way.

I'd like to extend exceptional thanks to our technical editors Roland Saville and John Johnston. Roland: You're one of the smartest persons I've had the pleasure of working with—and in so many fields. I don't know how your brain doesn't explode! You know I like to think of you as a "philosopher engineer," because you can take almost any design recommendation and find the corner-case counterargument where it breaks downs and doesn't apply. That's critically important to the process because by seeing from a distance where things can break you continually save us tremendous amounts of time in the lab, as well as ensuring the overall quality of the final designs. Thank you, too, JJ! You allowed me unfettered access to your massive labs in RTP and helped me along every step of the way. Your attention to detail is so impressive that I'm nearly spooked by your ability to catch the tiniest errors while reviewing hundreds of pages of configurations!

Finally, I owe a great deal of gratitude to my co-authors:

Ken: Thanks for your impressive knowledge and flexibility that you demonstrated by being able to jump right in and seamlessly adapt your research to our work in such an intuitive and cohesive manner. I've enjoyed working with you on many projects for the past decade and look forward to many more collaborations. Thanks again, Ken!

Christina: Thanks so much for coming out of retirement to work on one more project. Even though you're on the road more than Jack Kerouac these days, it was a real pleasure working with you again! Thanks for donning your QoS hat for us once again and bringing all your knowledge and experience to the table to help make this such a solid work.

Rob: Over the past 20 years we've been friends, classmates, roommates, workmates, "second-best" men at each other's weddings, and now co-authors. Your courage and determination are very inspiring. I honestly don't know if I would have taken my CCIE if I hadn't watched you do it. Same goes with running half-marathons (and one-day marathons!) Thanks for all your tremendous work on this project. It certainly was not for the faint-hearted, as every time we turned around we seemed to uncover yet another rabbit hole of technical issues that required yet more research and testing to be done. Thanks for sticking with it and seeing it through, Rob. But then again, that's just the kind of friend you are.

**Rob Barton:**

To begin, I would like to thank my very forgiving colleagues in the Cisco Vancouver office who have suffered through two years of trying to depend on an attention divided systems engineer who was more interested in solving theoretical QoS problems

than in helping his customers. Special thanks to my Cisco account team partner, Mike MacDonald, for his long-suffering patience, my manager, Ralph Wright, who enthusiastically supported this effort and always offered many words of encouragement, and to my director, Bill Kastelic, who eagerly gave me the flexibility to do this project. None of this would have been possible without the support from you guys.

I would also like to thank my lab administrator, Mojan Mobasser, for helping to get lab gear when I needed it the most. Testing these QoS solutions involved a lot of lab time, and without your support we would not have been able to build and test these solutions.

Special thanks goes out to Ian Procyk and my co-author Ken Briley who helped test some of the more difficult wireless scenarios. As well, I would like to thank Larry Ross for the many hours of emails and phone conversations discussing various wireless QoS solutions with me. Also thanks goes out to Kangwarn Chinthammit for helping with the AVC section review, and Scott Wainer who helped with the GET VPN work. All you guys were like my technical conscious during this project.

I'd also like to thank Bruno Wollmann from Terra-Comm Solutions who, while discussing my presentation at Cisco Live last year, introduced me to the concept of combining DMVPN with GET VPN to solve a real-world performance issue related to VoIP, which I think has made a great addition to the GET VPN chapter.

Chris Cleveland and Brett Bartow, thanks so much for your hard work on this project and supporting us all the way through. This project turned into a much bigger undertaking than any of us had expected, and instead of trying to apply your own QoS mechanism on our output, you let the creative juices flow, and in the end helped support a substantial work of technical literature.

Lastly, I'd like to thank Tim Szigeti. Not only have you been one of my closest friends for more than 20 years, you are also an inspiring engineer. Yes, I said engineer, the word you always tease me with. I can clearly remember the day this project started two and a half years ago; we were rewarding ourselves with a well-earned breakfast at the White Spot after one of our half-marathon training runs. I was complaining that your first edition of the End-to-End QoS book, while being a great book, was hopelessly out of date. Your response to me was unforgettable: "So why don't you help me write a new one?" That day was the start of this project, and although it was a long and difficult undertaking, it has also been an immensely rewarding experience. Thanks, Tim!

**Kenneth Briley, Jr.:**

First off I'd like to thank Roland Saville, for his guidance and clever insight when we worked through QoS on the Converged Access platforms.

To Stephen Orr, wireless is now awesome, before it was an illusion – thanks for the brilliant and oh so colorful commentary.

Many thanks to Tripti Agarwal, Saravanan Radhakrishnan, Anuj Kumar, and Bhavana Kudipudi without that team we would have never been able to deliver such a versatile platform.

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**Part XI: Appendixes (Online)**

**Appendix A AutoQoS for Medianet**

**Appendix B Control Plane Policing**

## Introduction

"Aren't we done with QoS yet?"

That's a question I get from time-to-time, which I like to answer along the lines of "As soon as we're done with availability and security, we'll be done with QoS also."

What I'm trying to express—although cheekily—is that although QoS has been around for a while, it is a foundational network infrastructure technology (the same as high-availability technologies and security technologies). And these foundational technologies will always prove to be integral components of any networking system, being present at the platform level, at the place in-the network (PIN) level and ultimately at the end-to-end network level.

Furthermore, such foundational network technologies are constantly evolving and expanding to meet new business and technical requirements. Such has been the case with QoS since the first edition of this work was published nearly 10 years ago.

For example, consider just one QoS-dependent application: video.

In 2004, there were really only two flavors of video traversing most enterprise networks: streaming video (unidirectional flows that benefited from both network- and application-level buffering to offset variations in transmission delays) and video conferencing (bidirectional 384-Kbps or 768-Kbps streams between dedicated hardware-based systems). So, we went into our massive Cisco Validation Labs in Research Triangle Park in North Carolina and hammered out best-practice designs to accommodate these two categories of video. We were done, right?

Wrong.

In the years that followed, codec and hardware advances made video production more cost-efficient and accessible, such that today nearly everyone with a smartphone has the ability to shoot high-definition video anytime and anywhere. Similarly, with the advent of social networking websites, video sharing and distribution suddenly became possible by anyone, anywhere (and that on a global scale!). Finally, video consumption also became possible anytime, anywhere, and on any device—thanks to advances in hardware and in wireless networking technologies.

That being the case, video is now the most dominant type of network traffic on the Internet and is expected to reach 90 percent within in a few years. Furthermore, there are many new forms and variations of video traffic, such as TelePresence, IP video surveillance, desktop video, and digital signage (just to name a few). And each of these types of video has unique service level requirements that must be met to ensure a high quality of experience by the end user. And thus, we circle back to QoS, which represents the enabling technologies to provide this quality of experience.

And that's just one application.

Advances in areas of data center and cloud networking, in addition to wireless networking, all have had corresponding impacts on QoS network designs.

Hence, a new edition of this book.

Another reason behind this second edition is to reflect the evolution of industry standards relating to QoS. Cisco has long advocated following industry standards and recommendations whenever deploying QoS, because this simplifies QoS designs, extends QoS policies beyond an administrative domain, and improves QoS policy effectiveness between administrative domains. Therefore, new standards, RFCs, and proposals have had—and will continue to have—a major impact on current and future strategic QoS designs.

A third key reason behind this new edition is that every network platform detailed in the original book has been replaced or significantly upgraded. So, the latest platforms (at the time of this writing) have been featured in this second version, with over a dozen Cisco product families being represented. In fact, nearly every design chapter features a different Cisco platform that suits the role being discussed, whether the role is a data center virtual switch, a branch router, a wireless LAN controller, a campus distribution switch, a WAN aggregator, a service provider core router, or so on.

And finally, QoS is a comprehensive and complex subject, one that entails a significant amount of fundamental technological concepts as well as platform-specific implementation detail. Therefore, it is often valuable for network administrators to have a single common reference on the subject, such as this book, which overviews all the relevant tools, presents various end-to-end strategies, and details platform-specific design recommendations for every major shipping Cisco platform.

And no, we're not done with QoS yet!

## Objectives of This Book

The main objective of this book is to present—in a comprehensive and cohesive manner—the many aspects of quality of service design, including an overview of the tools, strategic and tactical design recommendations, and platform-specific configuration details. Therefore, novice to advanced network administrators alike can benefit from this volume as a single handy reference on this topic.

In addition, this exercise has produced multiple platform-specific configurations that can be viewed as QoS templates. As such, these templates can be considered roughly 80 percent of a generic enterprise or service provider QoS solution (borrowing from Pareto's 80/20 rule), to which another 20 percent of customizing and tailoring can be done to reach a final customer-specific solution. Considerations and rationales behind the presented designs are all explained so that administrators are fully informed of the rationale behind the designs and therefore can confidently modify these to meet their own specific requirements and constraints.

A key approach that we've used throughout this configuration-rich book is to incorporate inline explanations of configurations. In this way, QoS-relevant commands are highlighted and detailed line-by-line to explicate the function of each element and clarify how these parts make up the solution as a whole.

To complement these line-by-line design recommendations, related verification commands are also incorporated. These verification commands are presented in context with the design examples, with specific details of what-to-look-for being highlighted and explained. These verification examples are therefore significantly richer in relevance than most such examples presented in hardware/software documentation, and they allow network administrators to confirm quickly whether the recommended designs have been deployed correctly.

Finally, each design section has a case study chapter at the end that ties together many of the strategic principles, tactical recommendations, and platform-specific considerations that have been presented within the section. These case studies illustrate how to take generic and abstract design concepts and mold them to meet specific customer requirements. These case studies are indicative of what can be expected in real-life production environments. Each of these case study examples spans multiple devices, thus highlighting critical interrelationships. Furthermore, all case study chapters form respective parts of a single integrated end-to-end QoS network design.

## Who Should Read This Book?

The primary reader of this book is the network administrator tasked with deploying QoS technologies. By extension, this group may also include other related IT professionals, such as systems administrators, audio/video specialists, VoIP specialists, and operations staff.

In addition, some readers may include technical decision makers tasked with evaluating the strategy and feasibility of QoS deployments, in addition to the drafting of implementation plans and phases toward these goals.

Yet another group of readers includes system engineers, partners, trainers, and other networking professionals who need to ramp-up technically on QoS technologies and designs, both for practical deployment purposes and to achieve various Cisco certifications.

Prerequisites are minimal, as the opening section of this book covers QoS technologies in high-to-mid-level technical detail, including protocols, tools, and relevant standards. In addition, each chapter includes extensive references for Additional Reading for more detailed information for readers unfamiliar with specific concepts discussed.

Because the content of the book ranges from a high level to a very low level of technical detail, it is suitable for a wide range of audiences, from intermediate to expert.

## How This Book Is Organized

This book is organized into 39 chapters distributed across 8 parts, and includes 2 appendixes. Although this book can be read cover to cover, this organization allows readers to easily identify chapters of direct interest, thus facilitating the use of this book as a handy reference work. The eight parts of this book are described below:

**Part I, "QoS Design Overview,"** introduces readers to QoS technologies, presenting a brief history and an architectural framework for these tools. Following this, groups of QoS tools are overviewed, including classification and marking tools, policing and shaping tools, queuing and dropping tools, bandwidth-reservation tools, and advanced tools like Medianet and application visibility and control.

**Part II, "QoS Design Strategies,"** breaks away from a purely technical discussion to take a higher-level view of how business requirements drive QoS design. Application service-level requirements are analyzed, as are strategic QoS design best practices. This section concludes with the first case study chapter, illustrating the considerations that factor into defining an end-to-end QoS design strategy.

**Part III, "Campus QoS Design,"** begins the exercise applying strategic QoS models to a tactical place in the network (PIN), which in this case is the enterprise campus. Campus-specific design considerations and recommendations are discussed at length, and subsequent chapters specialize in design recommendations for the access, distribution, and core layers of the campus network. A campus QoS design case study chapter completes the section.

**Part IV, "Wireless LAN QoS Design,"** applies the strategic QoS models to the enterprise wireless LAN. Because WiFi is a unique media, as compared to the rest of the network, additional concepts need to be covered to explain how QoS can be achieved over-the-air. These considerations include the introduction of the Enhanced Distributed Coordination Function as well as IEEE 802.11e/Wireless Multimedia QoS. Following this, QoS design chapters address both the centralized wireless LAN controller deployment model and the new wired-and-wireless converged access deployment model. The section finishes with a WLAN QoS design case study.

**Part V, "Data Center QoS Design,"** continues the application of QoS strategies, but this time to the data center network. Because of the convergence of storage-area networks and local-area networks within the data center, certain protocols require a completely lossless service that traditional QoS tools cannot guarantee. Therefore, data center-specific QoS tools are discussed, including the data center bridging toolset, which can be leveraged to guarantee such a lossless service. Following this, QoS design chapters address the virtual access layer, access and aggregation layers, and the core layer of data center networks. This part closes with a data center QoS design case study.

**Part VI, "WAN and Branch QoS Design,"** expands the scope of discussion beyond the local area and applies strategic QoS principles to the wide-area network. QoS designs are presented for both WAN aggregation routers and for branch routers. This part ends with a WAN QoS design case study.

**Part VII, "MPLS VPN QoS Design,"** continues the wide-area discussion but addresses QoS strategies for MPLS VPN networks, taking the perspectives of both the enterprise customer and the service provider into account in the end-to-end design. Design chapters are presented for the enterprise customer-edge router, the provider-edge router and the provider core routers. This section finishes with a case study on MPLS VPN QoS design.

**Part VIII, "IPsec QoS Design,"** concludes the discussion by applying strategic QoS principles to IPsec VPNs. QoS designs are detailed for both Dynamic Multipoint VPNs and Group Encrypted Transport VPNs.

An overview on each of the 39 chapters (and the 2 appendixes) follows.

- **Chapter 1, "Introduction and Brief History of QoS and QoE":** Provides a brief history lesson on quality of service and quality of experience evolution, introducing fundamental QoS concepts, standards, and the evolutionary changes necessitating a second edition of this book.
- **Chapter 2, "IOS-Based QoS Architectural Framework and Syntax Structure":** Overviews how QoS tools interrelate, and introduces Cisco's IOS-based Modular QoS command-line interface (MQC), the common syntax structure for configuring QoS across most Cisco platforms.
- **Chapter 3, "Classification and Marking Tools":** Describes the various classification options for distinguishing one packet from another, which is the requisite first step in providing differentiated services. Also discussed are various marking options so that packets do not have to be reclassified at every network node.
- **Chapter 4, "Policing, Shaping, and Markdown Tools":** Discusses various tools that can be used to meter and regulate packet flows, including policers (which drop excess traffic), shapers (which delay excess traffic) and markers (which re-mark excess traffic).
- **Chapter 5, "Congestion Management and Avoidance Tools":** Considers options on how to deal with bottlenecks in the network, by addressing both queuing tools (to determine which packets get priority or preferential treatment during congestion), and early-dropping tools (to reduce the probability of congestion).
- **Chapter 6, "Bandwidth-Reservation Tools":** Introduces the concepts of bandwidth reservations and endpoint/infrastructure signaling to communicate how and when such reservations are to be made.
- **Chapter 7, "QoS in IPv6 Networks":** Examines IPv6 packet formats, classification and marking options, and how QoS tools are to be configured in IPv6 networks or in mixed IPv4 and IPv6 networks.
- **Chapter 8, "Medianet":** Gives a brief overview of the Medianet architecture, with particular focus on the aspects of Medianet specific to QoS configuration and monitoring.
- **Chapter 9, "Application Visibility and Control":** Presents deep packet inspection technologies for application identification, classification, and monitoring and how these can be used within the network.
- **Chapter 10, "Business and Application QoS Requirements":** Examines current business trends impacting QoS designs and various application-class QoS requirements.

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