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NETWORK ROUTING

Algorithms, Protocols, and Architectures

DEEPANKAR MEDHI

KARTHIKEYAN RAMASAMY

MORGAN KAUFMANN

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Algorithms, Protocols, and Architectures

Deepankar Medhi

Karthikeyan Ramasamy

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Foreword

My involvement with computer networking started with TheoryNet (1977), an e-mail system for theoretical computer scientists. Later (1981) I helped lead the computer science network (CSNET) project, which eventually connected most academic and many industrial computer research groups. In the early days, our efforts were primarily focused on providing connectivity and being able to use applications such as e-mail, ftp, and telnet. However, even in the simple (by today's standards) environment of the 1970s and early 1980s (Arpanet, CSNET, and other experimental Internet networks), getting routing "right" turned out to be quite challenging.

I was fortunate to be part of the NSFNET regional/backbone model development. This is when I began to fully understand the significance of routing in a large-scale multi-domain network and, in particular, the central role of policy issues in such a decentralized environment. Over the past decade, as the Internet became ubiquitous and global in scale, routing has become ever more important. Packets must be forwarded efficiently from one end of the world to the other with minimal perception of delay. This has required tremendous efforts on many fronts: how to evolve routing protocols for large-scale loosely-coupled networking environments, how to engineer a network for efficient routing from an operational point of view, how to do efficient packet processing at routers, and how to effectively take into account the complexity of policy issues in the determination of routes. And while there have been many exciting advances over the past two decades, much work remains to be done.

In parallel, we have seen tremendous advances in traditional telephony. The underlying telecommunication system has changed from analog to digital and has incorporated the latest advances in optical technologies and, more recently, voice over IP. Throughout these revolutionary changes, routing has continued to play a critical role.

We are now at a crossroad. Various efforts are underway to determine a framework for next generation networks that allow seamless convergence of services and a platform to more easily create new services. Among other things, this requires a fresh look at routing. To be successful, it is important that we understand what has worked to date. To better understand the issues and complexities, we should look at this broadly, considering a variety of *different network architectures*, not just for the Internet. For each such network architecture, we can benefit from understanding its principles, protocols, algorithms, and functions, with a focus on routing. This will help give us perspective as we consider how to design routing for the next-generation network.

In this regard, Deepankar Medhi and Karthikeyan Ramasamy's book, *Network Routing: Algorithms, Protocols, and Architectures*, is very timely. Departing from most other works, it

is unique in providing an in-depth understanding of routing in a wide variety of types of networks. It includes extensive coverage of the evolution of routing over time. Particularly appealing is its in-depth coverage across a spectrum of algorithmic, technical, experiential, and practical issues. In addition, the detailed coverage of routers and switches is particularly valuable, as it helps the reader gain an understanding of why different approaches and components are needed to address packet processing, especially for scalability. In this regard, it is uniquely successful in drawing an important connection between routing and routers.

Medhi and Ramasamy's presentation is clear and approachable, allowing a wide audience to understand and gain an appreciation of network routing. I believe that it will become a core reference book on routing for router developers, network providers, students, and researchers for both today's practitioners and those who are interested in next-generation routing.

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Preface

In the span of a quarter-century, network routing in communication networks has evolved tremendously. Just a quarter-century ago, the public switched telephone network (PSTN) was running hierarchical routing, ARPANET routing was operational, and the telecommunication infrastructure had fixed static transport routes. In the 1980s, we saw the first tremendous growth in routing: Internet routing was deployed under the TCP/IP stack starting, first with the RIP protocol; the telephone network started deploying dynamic call routing schemes; and the telecommunication transport network deployed SONET transport mechanisms, which could reroute in a ring topology in 40 millisec in the event of a failure. In the past fifteen years, we have seen the need for policy routing because of multiprovider settings, and the need to develop fast lookup algorithms for packet processing that enables efficient routing. We have also seen interdependency between addressing and routing as first addressed through classless interdomain routing (CIDR) and more recently, because of number portability in the PSTN. More importantly, we saw how the way an addressing scheme is deployed can impact routing and lookup algorithms.

Network routing can be broadly divided into three basic fundamental categories: packet routing, circuit-switched routing, and transport routing; certainly, a combination is possible. The evolution over the past quarter-century has brought to the foreground the need to understand and examine where and how different dimensions of routing, from algorithms to protocols to architectures, can differ for different types of networks, and where they intersect. Certainly, the goal is to learn from our past experiences and prepare ourselves for next generation networks and routing.

While numerous papers have been written on the subject of network routing, and several books are now available on routing for specific networks, the field still lacks a comprehensive or systematic guide that encompasses various routing paradigms. Second, even in discussions of a single routing type (for example, either the Internet or PSTN), the focus often appears to be either on protocols or algorithms without tying them together with analysis and implementation; or, the work delves more into router command-line for router configuration; or, being informational without explaining the whys. Furthermore, how the addressing mechanism can affect routing decisions is yet another important topic that is rarely discussed. For efficient routing, how routers are architectured—and why—is yet another mystery. Finally, the relation between traffic engineering and efficient routing is also another topic. In the end, one needs to be somewhat of an "expert" in different routing paradigms to get a well-rounded view.

Last, after investigating routing in different networks for a number of years, we have come to the conclusion that network routing is like an economy. Similar to macroeconomics and microeconomics, network routing also has macro- and micro-centric issues. In addition, seemingly different and conflicting systems can and do co-exist. Not all of the issues are purely technical; business relations and regulatory issues are also important to recognize and consider. This book is an attempt to paint a broad picture that encompasses various aspects of network routing in one place.

AUDIENCE

Our goal has been to create a book that can be used by a diverse set of audiences, with varied levels of background. Specifically, we set out to create a book that can be used by professionals, as well as students and researchers. In general, this is intended as a self-study. We assume that the reader already has some basic knowledge of networking. Among professionals, the intent has been to cover two broad groups: router developers, including protocol designers and router architects, and network designers and operators, with the overall goal to bring out issues that one group might want to understand that the other group faces. For students, this book is intended to help learn about routing in depth, along with the big picture and lessons from operational and implementation experience. For researchers who want to know what has been done so far and what critical issues to address for next-generation routing, this is intended as a helpful reference. In general, this book has been intended as a one-stop treat for all interested in network routing in different networks.

ORGANIZATION AND APPROACH

The book is organized into six parts. Each part starts with a chapter-level summary. We present below a brief overview of each part:

- Part I (four chapters): We cover the basic foundations of routing from algorithms to protocols, along with network flow modeling.
- Part II (five chapters): This part is about IP network routing, from standardized protocols for both intra- and inter-domain routing, to IP traffic engineering and Internet routing architectures.
- Part III (four chapters): This part covers PSTN routing, from hierarchical routing to dynamic routing, and from addressing to traffic engineering, including the role of signaling in routing, along with the impact of number portability in routing.
- Part IV (three chapters): In this part, we cover router architectures for different scale routers for efficient packet processing, along with address lookup algorithms and packet filtering and classification mechanisms.
- Part V (four chapters): As impetuses for next generation routing, we present quality-of-service routing, multiprotocol label switching, generalized multiprotocol label switching, and routing at the intersection of IP-PSTN for voice over IP.
- Part VI (five chapters): This bonus material (available on the CD-ROM) is made up of two sub-parts: the first three chapters continue beyond Part IV by delving more into routers by

presenting efficient switching, packet queueing and scheduling, and traffic conditioning; the remaining two chapters extend Part V by covering transport network routing, optical network routing, and multi-layer routing.

At the beginning of each chapter, a reading guideline is provided. This gives a brief description on the background needed to read the chapter; it also discusses which other chapters this chapter is connected to or has dependency on. In general, it is not necessary to read the chapters in sequential order. Furthermore, the chapters are organized in a way so that the reader who has familiarity with a particular topic can move on and read other chapters of interest. Similarly, there are a few chapters on traffic engineering that require a certain level of mathematical background. They can be read independently if the reader has the background, or can be skipped for later reading, without missing the broad picture. Regardless, each chapter contains a Further Lookup section, which includes a brief discussion on additional reading; followed by a set of exercises that is meant for a wide audience. Notations, conventions, and symbols used in the book are summarized in Appendix A. Miscellaneous refresher topics that are helpful in understanding the material presented in this book are included in Appendix B.

In general, we have given special attention to being concise about describing each topic, while ensuring that the material is approachable for a wider audience. The book is still hefty in size in order to cover routing in different networks. Despite our keen interest, we needed to make the decision to leave out certain important topics instead of cutting corners on the topics presented. The topics *not* covered in the book (except for cursory remarks) are: multicast routing, routing in ATM networks, routing in cellular/wireless networks, routing in sensor networks, and security vulnerabilities in routing. The router command-line–based configuration of protocols is not included in this book, because there are many detailed books available on this aspect for various Internet routing protocols. Finally, there is a direct connection between routing and capacity design and planning. For an in-depth treatment of capacity design and planning, the reader is referred to the companion book [564].

Bonus Materials and Online Resources

The book, in its printed form, has 20 chapters. A CD-ROM is provided with the book that contains an additional five chapters labeled "Advanced Topics." Of these five chapters, three chapters are related to router architectures: switching packets (Chapter 21), packet queueing and scheduling (Chapter 22), and traffic conditioning (Chapter 23). The remaining two chapters are related to transport and next-generation routing: transport network routing (Chapter 24), and optical network routing and multilayer routing (Chapter 25).

Additional support materials (for example, instructional materials and additional exercises) will be available at http://www.mkp.com/?isbn=9780120885886 and http://www.NetworkRouting.net. The latter site will also serve as a resource site and will provide links to materials available on the web on network routing.

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The current and recent PhD students of the first author also read many chapters and provided valuable feedback. Many thanks to Amit Sinha, Balaji Krithikaivasan, Dijiang Huang, Gaurav Agrawal, Haiyang Qian, Plarent Tirana, and Shekhar Srivastava.

Several students who took the course, Network Routing, from the first author, in the fall of 2005, read the initial version of the first few chapters. When he taught it again in the fall 2006 semester, the entire manuscript was ready in its draft form; the entire class helped debug it by carefully reading various chapters and providing detailed feedback. For their help, we would like to thank Aditya Walavalkar, Ajay Karanam, Amol Rege, Dong Yoo, Francisco Jose Landeras, Hafeez Razzaq, Haiyang Qian, Hui Chang, Jignesh K. Patel, Jin-Ho Lee,

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Karthikeyan Ramasamy has 15 years of software development experience, including working with companies such as Juniper Networks, Desana Systems, and NCR. His primary areas of technical expertise are networking and database management. As a member of the technical staff at Juniper, he developed and delivered a multitude of features spanning a diverse set of technologies including protocols, platforms, databases, and high availability solutions for the JUNOS routing operating system. As a principal engineer at Desana Systems, he was instrumental in developing and delivering many fundamental components of an L7 switch for managing data centers. While pursuing his doctorate, he worked on a parallel object relational database system, which was spun off as a company and later acquired by NCR. Subsequently, he initiated a project in data warehousing which was adapted by NCR. As a consulting software engineer at NCR, he assisted in the commercialization of these technologies. Currently, he serves as an independent consultant. He received a B.E. in Computer Science and Engineering with distinction from Anna University, India, an M.S. in Computer Science from the University of Missouri–Kansas City, USA, and a Ph.D. in Computer Sciences from the University of Wisconsin–Madison, USA. He has published papers in premier conferences and holds 7 patents.

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