

SECOND EDITION

Routing in the Internet



Christian Huitema

Contents

1	Introduction to Routing in the Internet	1
1.1	The Worldwide Internet	1
1.2	How Is It Organized?	2
1.3	A Study of Routing	3
1.4	Acknowledgments	3

Part I: Architecture and Protocols

2	The Internet Architecture	7
2.1	Is There an Internet Architecture?	7
2.2	The End-to-End Argument	8
2.2.1	Datagrams and Virtual Circuits	8
2.2.2	Should We Trust Networks?	9
2.2.3	States and Fate-Sharing	10
2.2.4	A Far-Reaching Argument	12
2.3	IP over Everything	12
2.3.1	Interconnection of Networks	12
2.3.2	IP and New Technologies	13
2.3.3	Unique Addresses	13
2.3.4	What about Other Protocols?	14
2.4	Connectivity Is Its Own Reward	14
2.4.1	E-mail and the Internet	15
2.4.2	Connectivity Is More than E-mail	15
2.4.3	Cooperation between Network Providers	16
2.4.4	Be Liberal	17

2.5 Developing the Internet Architecture.....	18
2.5.1 From DARPA to the Internet Society	19
2.5.2 The IETF	20
2.5.3 Rough Consensus and Running Code.....	21
2.6 The Future of the Internet.....	22
3 The Internet Protocol	23
3.1 Model of Operation.....	23
3.2 The Internet Addresses	25
3.2.1 Address Formats.....	25
3.2.2 Addresses and Interfaces.....	26
3.2.3 Special Purpose Addresses	27
3.3 The Internet Protocol	28
3.3.1 The Internet Header	28
3.3.2 Precedence and Type of Service	30
3.3.3 Fragmentation and Reassembly.....	31
3.3.4 IP Options.....	33
3.3.5 Options and Header Processing	35
3.4 ICMP	36
3.4.1 Diagnostics	36
3.4.2 Ping	38
3.4.3 Traceroute	39
3.4.4 Time Management.....	40
3.5 Sending IP Packets.....	41
3.5.1 Sending Packets on the Network.....	41
3.5.2 Discovering the Local Router.....	43
3.5.3 Using Redirects	45
3.5.4 Black Holes.....	46
3.5.5 Some Reflections.....	47
3.6 IP and Companion Protocols.....	48
3.6.1 TCP.....	49
3.6.2 UDP	50
3.6.3 DNS	50
3.6.4 SNMP	51
3.7 Interconnecting Local Networks	52
4 From IPv4 to IPv6	55
4.1 IPv6 Address Architecture.....	55
4.1.1 Notation of IPv6 Addresses	56
4.1.2 Unicast Addresses, Prefixes and Subnets	58
4.1.3 Special Address Formats	59
4.1.4 Multicast Addresses	60
4.1.5 Anycast	62
4.2 The IPv6 Header Format	63
4.2.1 A Simpler Header	63
4.2.2 Simplifications	64

4.2.3 From Options to a Daisy Chain of Headers	65
4.2.4 Routing Header	66
4.2.5 Fragment Header	67
4.2.6 Security Headers	67
4.2.7 Destination Options Header	68
4.2.8 Hop-by-Hop Options	69
4.2.9 Extension Header Order	69
4.3 ICMP v6	70
4.4 Address Resolution	71
4.4.1 Getting Information from Routers	72
4.4.2 The Neighbor Discovery Algorithm	73
4.4.3 Redirects	74
4.4.4 The Case of Nonconnected Networks	75
4.4.5 Black Hole Detection	75
4.4.6 Random Delays	76
4.4.7 Protection Against Off-link Messages	77
4.5 Automatic Configuration	77
4.5.1 Link Local Addresses	77
4.5.2 Duplicate Detection	77
4.5.3 Stateless Autoconfiguration	78
4.5.4 Stateful Configuration	79
4.5.5 Lifetime of Addresses	80
4.5.6 Updating the Name Servers	81
4.6 When Will We Deploy IPv6?	81

Part II: Interior Routing Protocols

5 Why Is RIP So Simple?	85
5.1 Routing Information Protocol	85
5.2 An Introduction to Distance Vector Protocols	85
5.2.1 Cold Start	86
5.2.2 What If a Link Breaks?	89
5.2.3 The Bouncing Effect	92
5.2.4 Counting to Infinity	94
5.2.5 Split Horizon	95
5.2.6 Triggered Updates	97
5.2.7 Some Mathematics	97
5.3 RIP, Version 1	98
5.3.1 RIP, a Distance Vector Protocol	98
5.3.2 Message Format	99
5.3.3 Processing of RIP	100
5.3.4 Silent Nodes	102
5.3.5 Configuration and Interfaces	102

5.4 RIP, Version 2	103
5.4.1 Formats and Compatibility	103
5.4.2 Routing per Subnet	104
5.4.3 Authentication	105
5.4.4 Next Hop	108
5.4.5 Multicasting	108
5.5 Using RIPvng for IPv6	109
5.5.1 Using IPv6 Security for RIPvng	109
5.5.2 Changes in Format	110
5.6 Further Improvements	111
5.6.1 Breaking Synchronizations	111
5.6.2 Acknowledged Updates	112
5.6.3 Support of Multiple Metrics	114
5.6.4 Loop Resolution	115
5.7 The Cost of Simplicity	117
 6 Why Is OSPF So Complex?	119
6.1 Open Shortest Path First	119
6.2 What Is a Link State Routing Protocol?	120
6.2.1 The Link State Database	120
6.2.2 The Flooding Protocol	121
6.2.3 Bringing Up Adjacencies	122
6.2.4 Securing the Map Updates	124
6.2.5 Why Is It Called “Shortest Path First”?	125
6.3 Why Is a Link State Protocol Better?	126
6.3.1 Fast, Loopless Convergence	126
6.3.2 Support of Multiple Metrics	126
6.3.3 Multiple Paths	128
6.3.4 External Routes	131
6.4 The Design of OSPF	131
6.4.1 Separating Hosts and Routers	132
6.4.2 Broadcast Networks	132
6.4.3 Nonbroadcast Networks	134
6.4.4 Multiple Areas	135
6.4.5 Stub Areas	137
6.5 The Link State Database	138
6.5.1 The Link State Header	138
6.5.2 The Router Links	140
6.5.3 The Network Links	140
6.5.4 The Summary Links	141
6.5.5 The External Links	141
6.5.6 The Computation of Routes	142
6.6 The Protocols Within OSPF	144
6.6.1 The Common Header	144
6.6.2 The Hello Protocol	145
6.6.3 The Exchange Protocol	148

6.6.4 The Flooding Protocol	150
6.6.5 Aging Link State Records	151
6.7 OSPF for IPv6	152
6.7.1 Protocol Changes	152
6.7.2 New Database Formats	153
6.8 Research and Developments	154
6.8.1 Overflow	154
6.8.2 Secure Networks and Insecure Routers	156
6.8.3 Load Sharing on Multiple Paths	156
6.9 Complexity and Services	159
7 Other Routing Protocols	161
7.1 RIP and OSPF Are Not Alone	161
7.2 Routers or Intermediate Systems?	162
7.2.1 ISO, OSI, and Routing	163
7.2.2 The IS-IS Protocol	164
7.2.3 Flooding, Aging, and Exchanges	165
7.2.4 Integrated Routing	166
7.2.5 IS – IS = 0	167
7.2.6 Further Work on IS-IS	168
7.3 IGRP	169
7.3.1 Composite Metrics	170
7.3.2 Handling of Default Routes	171
7.3.3 Loop Detection	172
7.3.4 Multipath Routing	172
7.4 Enhanced IGRP	173
7.4.1 The Distance Vector School	174
7.4.2 The DUAL Algorithm	175
7.4.3 Extending IGRP	176
7.5 Choosing Routing Protocols	177

Part III: Exterior Routing Protocols

8 EGP: A First Step Toward the Global Internet	183
8.1 Splitting the Internet into Autonomous Systems	183
8.1.1 Enlarging the Internet	183
8.1.2 What Is an Autonomous System?	184
8.1.3 Exchanging Routing Information	185
8.2 Exchanging Information Through EGP	185
8.2.1 The EGP Messages	186
8.2.2 Neighbor Acquisition	187
8.2.3 Neighbor Reachability	188
8.2.4 Network Reachability	189

8.3 Routes, Distances, and Loops	192
8.3.1 Advertising Destinations	192
8.3.2 Computing EGP Distances.....	194
8.3.3 Routing Tables	195
8.3.4 An Engineered Topology	197
8.4 The Limits of EGP	197
8.4.1 Avoiding False Information.....	198
8.4.2 Policy Routing	198
8.4.3 Topology and Routing Loops.....	199
8.4.4 Message Size and Fragmentation	199
8.5 Developing BGP	200
9 With BGP and CIDR Toward the World Wide Internet	201
9.1 Exponential Growth and the Need for CIDR.....	201
9.1.1 Class B Exhaustion	202
9.1.2 Routing Table Explosion.....	202
9.1.3 Classless Addresses	203
9.2 The Concept of Path Vectors	204
9.2.1 From Distance Vectors to Path Vectors.....	204
9.2.2 Path Vectors and Loop Avoidance	205
9.2.3 Route Aggregation	206
9.2.4 Path Attributes.....	207
9.2.5 Internal and External Peers	209
9.3 The Border Gateway Protocol.....	210
9.3.1 Running over TCP.....	210
9.3.2 The BGP Header	211
9.3.3 Initial Exchange	213
9.3.4 Updates	214
9.3.5 Keep-Alive Features.....	215
9.3.6 Error Notifications.....	217
9.3.7 Securing the TCP Connection	218
9.4 Synchronizing with the IGP	219
9.4.1 Interconnection Policies	219
9.4.2 The Decision Process	220
9.4.3 Exporting Routes in the IGP	222
9.4.4 CIDR and the IGP	223
9.4.5 Exporting Routes to Neighboring ASs	225
9.4.6 What If a Neighbor Does Not Use BGP-4?	225
9.4.7 Complex Autonomous Systems.....	227
9.5 Growing Pains	227
10 Growing Pains: From CIDR to IPv6.....	229
10.1 Addresses, Networks, and Routing Tables	229
10.1.1 Routing Instabilities.....	231
10.1.2 Controlling the Rate of the Advertisements	232
10.1.3 Controlling the Source of the Advertisements	234

10.2 The Structure of Interconnections	235
10.2.1 From Public Exchanges to Private Peering.....	236
10.2.2 Managing a Large AS	238
10.2.3 Interconnection Between Large ASs	239
10.3 Routing Table Aggregation and Address Allocation	241
10.3.1 Coordinated Address Allocation.....	241
10.3.2 Provider and Clients.....	242
10.3.3 Will We Need to Renumber?	243
10.3.4 The NAT Alternative	244
10.4 Is IPv6 the Solution?	246
10.4.1 A Larger Address Space Is a Two-edged Sword.....	246
10.4.2 Extending BGP for IPv6.....	246
10.5 Waiting for the New IP	248
11 Policy Routing.....	251
11.1 The Objectives of Policy Routing.....	251
11.2 Provider Selection	252
11.2.1 The Regional Network Problem.....	252
11.2.2 BGP in a Tunnel	253
11.2.3 UNIFY, IDRP, and SDRP.....	255
11.2.4 Source Demand Routing.....	255
11.3 The IDPR Approach.....	258
11.3.1 The AS-Level Map	258
11.3.2 Shortest AS Paths	259
11.3.3 Forwarding Packets with IDPR.....	261
11.3.4 Experience with IDPR	262
11.4 Multi-Protocol Label Switching	262
11.4.1 Label Switching.....	263
11.4.2 Proposed Usage of MPLS	265
11.4.3 Establishing MPLS Paths	266
11.5 The Future of Policy Routing.....	267

Part IV: New Developments

12 IP Multicast Routing	271
12.1 Benefits of Multicast	271
12.1.1 Multicast and Resource Discovery.....	272
12.1.2 Transmitting Files	273
12.1.3 Conferencing	274
12.1.4 Streaming Audio and Video	275
12.1.5 Interactive Applications.....	275
12.1.6 Issues with Deploying Multicast.....	276
12.2 Multicast Routing.....	277
12.2.1 Flooding	277

12.2.2 Spanning Trees.....	278
12.2.3 Reverse-Path Forwarding	279
12.2.4 RPF and Prunes.....	281
12.2.5 Steiner Trees.....	282
12.2.6 Center-Based Trees.....	284
12.3 Multicast Routing Protocols for the Internet.....	285
12.3.1 Distance Vector Multicast Routing Protocol	285
12.3.2 Multicast Extensions to OSPF	286
12.3.3 Protocol-Independent Multicast, Dense Mode.....	287
12.3.4 Protocol-Independent Multicast, Sparse Mode.....	290
12.4 Internet Multicast Today.....	291
12.4.1 The Experimental Multicast Backbone	292
12.4.2 The Current Architecture	293
12.4.3 Internet Group Membership Protocol.....	294
12.4.4 Interdomain Routing.....	296
12.4.5 MSDP and MBGP	296
12.4.6 BGMP	297
12.5 IP Multicast Deployment Issues.....	298
12.5.1 Domain Independence and Management	299
12.5.2 Address Allocation and Address Control	301
12.5.3 Open Multicast Model and Commercial Imperative	303
12.5.4 Dynamic Receivers and Group Security	304
12.5.5 Is IPv6 the Solution?	305
12.6 The Future of Multicast Routing.....	306
13 Mobility.....	309
13.1 Mobile Hosts	309
13.2 The Objectives of IP Mobility	309
13.2.1 Portable Computers	310
13.2.2 Mobile Computing.....	310
13.2.3 Various Transmission Technologies.....	311
13.2.4 Moving Networks	312
13.2.5 The Requirements	312
13.3 Architecture/Terminology	313
13.3.1 The Basic Model.....	313
13.3.2 Requirements of Basic Model.....	315
13.3.3 Moving from Network to Network.....	316
13.3.4 What If There Is No Foreign Agent?	317
13.4 Protocols and Conventions	317
13.4.1 The Discovery Protocol	318
13.4.2 The Registration Procedure.....	319
13.4.3 Encapsulation Procedures	321
13.4.4 Broadcast and Multicast.....	323
13.4.5 Mobile Networks	324
13.5 Further Refinements	324
13.5.1 Multiple Home Agents	324

13.5.2 Clusters of Foreign Agents	325
13.5.3 Mobile Ad-Hoc Networks.....	326
13.5.4 Dogleg Routing Elimination	327
13.5.5 Source Address Verification	328
13.6 Mobility and IPv6.....	328
13.6.1 Discovery	329
13.6.2 Binding Updates	329
13.6.3 Encapsulation	330
13.7 The Future of Mobility	330
14 Network Service Quality and Resource Reservation.....	333
14.1 Queues and Delays	334
14.1.1 The Basic Quality of Service	334
14.1.2 Can We Solve Congestion Through Routing?	335
14.1.3 End-to-End Control	337
14.1.4 The Limits of End-to-End Control	338
14.2 Queueing and Scheduling	338
14.2.1 Fair Queueing.....	338
14.2.2 Weighted Fair Queueing.....	341
14.2.3 Shared Links	342
14.2.4 A Theorem on Queueing and Delays.....	345
14.2.5 A Definition of Integrated Services.....	345
14.3 A Reservation Protocol.....	346
14.3.1 The Principles of RSVP	347
14.3.2 Sessions, Flows, and Filters.....	348
14.3.3 Paths and Reservations	349
14.3.4 Soft States and Synchronizations	350
14.3.5 Soft-State Overhead Reduction by State Compression	351
14.3.6 A Few More Words for the Evolving Protocol	352
14.4 Do We Need Resource Reservation?.....	353
14.4.1 Real-Time Applications Are Flexible	353
14.4.2 The Economy of Reservation	355
14.5 Differentiated Services	357
14.5.1 QOS Support Seen from 10,000 Feet	358
14.5.2 Intserv.....	358
14.5.3 How and How Much Diffserv Differs from Intserv.....	359
14.5.4 Basic Mechanisms	360
14.6 Future Internet Services	361
15 Toward the New IP.....	365
15.1 The Internet Lives.....	365
15.2 Address Depletion.....	366
15.3 Preparing for IPv6.....	366
Index.....	369