Microsoft

Understanding IPv6

3 THIRD EDITION

Covers Windows® 8 and Windows Server® 2012

Joseph Davies

Understanding IPv6

THIRD EDITION

Your essential guide to IPv6—now updated for Windows 8 and Windows Server 2012

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- Determine a practical IPv6 addressing and routing plan for your network
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*For **system requirements**, see the Introduction.*

About the Author

Joseph Davies is an award-winning author and instructor with 18 years of experience in TCP/IP, networking, and security technologies. The author of *Understanding IPv6, Second Edition* and *Windows Server 2008 TCP/IP Protocols and Services*, he also wrote "The Cable Guy," a monthly column for Microsoft TechNet and *TechNet Magazine*.

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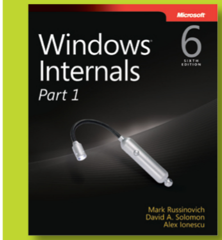

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Joseph Davies

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For Kara:
My lady, my love, my life.

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Foreword

When Joe first asked me to write a foreword for this latest edition of *Understanding IPv6*, I looked to forewords from previous editions as well as other networking books, hoping to draw some inspiration. As will become increasingly obvious, my writing skills are not as honed as Joe's.

Looking back was actually incredibly useful to me, because it clearly accentuated what has changed in the last few years. Microsoft has supported IPv6—the next generation of the Internet Protocol—since its inception. We built support into the Windows stack, rearchitected our platform to enable developers to take advantage of IPv6, and over the past 10 years have been extending support across the company.

The Internet Protocol is the routing and transit protocol for the Internet, the largest and most important assembly of computing infrastructure of our time. IPv6 is going to make the Internet better, by allowing direct connectivity between host, whether they be family members video chatting or business information zooming between data centers.

We frequently take the time to remind everyone of our commitment to the realization of the end-benefits of IPv6. We do this for multiple reasons. We take pride in our work, certainly, and it gives us great pleasure to do our part to make technology a bit better. But perhaps more important, these reminders are evangelical; they assure customers, partners, and readers that IPv6 is something worthy of attention, worthy of adoption.

For many years, this was a difficult task. People didn't want IPv6. The growth and maturation of IPv4 survival strategies, such as large-scale network address translation, threatened the inevitability of IPv6 adoption. That's the truth. Some in the networking world might try to revise the past 10 years: the broken routing equipment, the inadequate software, the legends of danger, IPv6 performance problems, IPv6 security problems, IPv6 money issues, and IPv6 zombies.

That darkness was real, but that darkness has past. In the past 24 months, we've made immense progress toward the goal of upgrading the Internet. IPv6 is no longer the next-generation Internet Protocol; it has become the now-generation Internet Protocol.

The World IPv6 Launch in June 2012 marked a key turning point in this transition. When you read this book, some of the most important web services in the world, not only from Microsoft but from across the technology community, are operational on the IPv6 Internet. Millions of users with IPv6-ready computers are using IPv6 to interact with these services and with one another. The apps, the operating systems, the routing infrastructure, the ISPs, and the services are not merely ready, they're activated.

Joe’s book, in all its editions, has always been *the* IPv6 reference; it's a fantastic medium for anyone interested in networking for understanding the Internet Protocol and its evolution. But as you read through this edition, I hope you gain not only the ability to understand and build networks by using IPv6, but also acquire a clearer perception of the changes happening all around you. The reality of how you search the Internet, play games with your friends, and access workplace resources is increasingly an IPv6 story.

When talking about the IPv6 story, we always note our commitment to ensuring that everyday users don’t notice any change, or sense that their experience has diminished as we transition. It shouldn’t matter whether your connection is over IPv4 or IPv6. You should have an Internet experience that is fast, reliable, and enjoyable, with the only evidence of the IPv6 transition being the lingering feeling that things simply got better.

After reading this book, you’ll likely be able to notice more than just that lingering feeling. The details, flags, and bits that make up IPv6 and the Internet’s evolution will become absolutely clear.

The Internet is going through an asynchronous, distributed, and transformative change at its very foundation. That change includes more than software or hardware; it involves a swath of people who work in networking, who use those systems, who architect networks, or who build apps.

By understanding IPv6 and this transformation, you contribute to its forward progress. Your journey becomes part of the greater tale of this technological evolution.

Thank you, and good luck.

Chris Palmer
IPv6 Program Manager,
Microsoft

Preface

The first edition of this book began in the spring of 1999. At that time, I developed a set of slides and presented an "Introduction to IPv6" course at Bellevue Community College in Bellevue, Washington, to four students. Although the turnout was not what I expected, the time spent learning IPv6, creating the slide presentation, and presenting IPv6 technology to these curious students proved to be an invaluable experience and prepared a firm foundation for future endeavors.

In 2000, as a technical writer for Windows, I wrote a white paper titled "Introduction to IP version 6" that is published on the Microsoft Windows IPv6 website (*www.microsoft.com/ipv6*) and generally inserted myself in any documentation task associated with IPv6. I also developed and delivered an internal course called "IPv6 Overview" with help on the topic of Windows Sockets from Tom Fout. Beginning in October 2000, this one-day course was taught to Microsoft software design engineers, software test engineers, program managers, and technical writers.

My transition to a program manager for technical content development afforded me the time, focus, and experience to turn the "IPv6 Overview" courseware and numerous other white papers and articles about IPv6 into *Understanding IPv6* (Microsoft Press, ISBN 978-0735612457), the first edition of this book. Between its first publication in November 2002 and January 2008, I continued to develop content for IPv6, supporting interim releases of IPv6 technology for Windows XP and the releases of Windows Server 2008 and Windows Vista, which have fully integrated IPv6 support for services and applications. The result of those efforts was the second edition of *Understanding IPv6*.

Between January 2008 and May 2012, I continued to follow the evolution of IPv6 in Windows, through Windows 7 and Windows Server 2008 R2 (writing detailed planning, deployment and troubleshooting information for DirectAccess) and on into the development of Windows Server 2012 and Windows 8. This third edition encapsulates all of these efforts.

It is my fervent hope that the work that I started in the spring of 1999 has culminated in a well-organized and readable text from which you can learn and understand the concepts, principles, and processes of IPv6.

Joseph Davies

Introduction

Due to the following recent events, the importance of Internet Protocol version 6 (IPv6) to the future of the Internet and organization intranets is now without question:

- On February 3, 2011, the Internet Corporation for Assigned Names and Numbers (ICANN) joined the Number Resources Organization (NRO), the Internet Architecture Board (IAB), and the Internet Society to announce that the pool of public Internet Protocol version 4 (IPv4) Internet addresses has now been completely allocated. Public IPv4 address space still exists to be assigned to organizations by regional address authorities, but there is no more public IPv4 address space in reserve.
- On June 8, 2011, Microsoft and other members of the Internet Society (ISOC) participated in World IPv6 Day to temporarily test connectivity and performance issues with dual-stack (IPv4 and IPv6) Internet properties.
- In April of 2012, the Internet Engineering Task Force (IETF) published Request for Comments (RFC) 6540, “IPv6 Support Required for All IP-Capable Nodes.” This Best Current Practice RFC advises that IPv6 support be required for all network nodes, in addition to IPv4.
- On June 6, 2012, Microsoft and other members of the ISOC participated in World IPv6 Launch to permanently enable dual stack on Internet properties.

The time has come to embrace, learn, and understand IPv6.

Pursuant to this need, this book is a straightforward discussion of the concepts, principles, and processes of IPv6 and how it is supported by the Microsoft Windows Server 2012, Windows Server 2008 R2, Windows Server 2008, Windows 8, Windows 7, and Windows Vista operating systems. Note that this book does not contain programming code–level details of the IPv6 protocol for these versions of Windows, such as structures, tables, buffers, or coding logic. These details are highly guarded Microsoft intellectual property that is of interest only to a relative handful of software developers. However, this book does contain details of how the Microsoft implementation of IPv6 in these versions of Windows works for described processes and how to modify default behaviors with Windows PowerShell and Netsh.exe tool commands, Group Policy settings, and registry values.

The purpose of this book is to provide an educational vehicle with which you can learn IPv6 to a fair level of technical depth—the terms, the addresses, the protocols, and the processes—to prepare you for planning, deployment, and operation of a native IPv6 infrastructure on your intranet.

> **Note** The contents of this book reflect the Internet standards for IPv6 and the feature set of the IPv6 protocol for Windows Server 2008 R2, Windows Server 2008, Windows 7, Windows Vista and the Release Preview versions of Windows Server 2012 and Windows 8. For information about changes in Internet standards and the IPv6 protocol for Windows Server 2012 and Windows 8 past the Release Preview version, go to the Microsoft Windows IPv6 website at *http://www.microsoft.com/ipv6*.

Who Should Read This Book

This book is intended for the following audiences:

- **Windows networking consultants and planners** This group includes anyone who will be planning for an eventual IPv6 migration with Windows.
- **Microsoft Windows network administrators** This group includes anyone who manages an IPv4-based network and wants to gain technical knowledge about IPv6 and its implementation in Windows.
- **Microsoft Certified Systems Engineers (MCSEs) and Microsoft Certified Trainers (MCTs)** Regardless of the eventual IPv6 content for Microsoft Official Curriculum (MOC) courseware for Windows Server, this book can be a standard reference for MCSEs and MCTs for IPv6 technology.
- **General technical staff** Because this book is mostly about IPv6 protocols and processes, independent of its implementation in Windows Server, general technical staff can use this book as an in-depth primer on IPv6 technologies.
- **Information technology students** This book originated as courseware for internal Microsoft software developers, testers, and program managers; thus it retains its capability as a textbook for IPv6 courses taught at an organization or educational institution, using Windows as the example IPv6 implementation.

What You Should Know Before Reading This Book

This book assumes a foundation of networking knowledge that includes basic networking concepts, widely used networking technologies, and sound knowledge of the TCP/IP suite. Wherever possible, I try to facilitate the reader's transition to IPv6 by comparing it with the corresponding feature, behavior, or component of IPv4.

For a firm foundation of knowledge of the TCP/IP protocol suite, let me recommend as a prerequisite that you read my other book, *Windows Server 2008 TCP/IP Protocols and Services* (Microsoft Press, 2008). Like this book, this resource is mostly about implementation-independent protocols and processes. As the author of this resource, I might be a bit biased; however, this book was written with *Windows Server 2008 TCP/IP Protocols and Services* in mind and builds upon it.

Organization of This Book

In this edition, I have organized the chapters into sections and the chapters within each section build upon each other in a logical fashion. For example, it is difficult to understand Neighbor Discovery processes without first understanding IPv6 addressing, the IPv6 header, and Internet Control Message Protocol for IPv6 (ICMPv6). Likewise, it's almost impossible to understand IPv6 transition technologies without first understanding IPv6 addressing, Neighbor Discovery processes, name resolution, and routing. The chapters lead to a discussion of planning for deployment, which requires an understanding of many elements of the preceding chapters.

Appendices of This Book

This book contains the following appendices:

- **Appendix A: IPv6 RFC Index** A listing of the RFCs and Internet drafts for IPv6 that are the most relevant to the IPv6 implementation in Windows at the time of this book's publication. This appendix is not designed to be an exhaustive list and will certainly be obsolete at some level after this book is printed.
- **Appendix B: Testing for Understanding Answers** Provides answers to the questions in the "Testing for Understanding" section for each chapter, which contain a series of review questions pertaining to the material in the chapter.

- **Appendix C: Setting Up an IPv6 Test Lab** This appendix answers the question, "How do I get it going so that I can play with it?" By using the instructions in this appendix, you can take five computers and create an IPv6 test lab to test address autoconfiguration, routing, and name resolution. At the end, you are left with a working IPv4 and IPv6 or IPv6-only test network with which you can experiment on your own.
- **Appendix D: IPv6 Reference Tables** A reprinting of the most relevant IPv6 tables of IPv6 protocol field values and other parameters.
- **Appendix E: Link-Layer Support for IPv6** A discussion of link-layer encapsulation of IPv6 packets for typical local area network (LAN) and wide area network (WAN) technologies.
- **Appendix F: Windows Sockets Changes for IPv6** A description of the enhancements to Windows Sockets to support both IPv6 and IPv4 at the same time.
- **Appendix G: Mobile IPv6** An in-depth discussion of Mobile IPv6, a protocol by which an IPv6 host can change locations and addresses while maintaining existing transport layer connections.
- **Appendix H: Teredo Protocol Processes** An in-depth discussion of the processes that a Teredo client uses to perform address autoconfiguration and initiate communication with other IPv6-capable hosts.

About the Companion Content

The companion content for this book, available at *http://www.microsoftpressstore.com/title/9780735659148*, includes the following:

- **Network Monitor captures** Throughout the book, packet structure and protocol processes are illustrated with actual IPv6 packets displayed by using Microsoft Network Monitor 3.4, a frame capturing and viewing program (also known as a network sniffer) that is provided free of charge by Microsoft. The display of the frames within the capture files depends on the version of Network Monitor that you are using. To install Network Monitor 3.4, see the Network Monitor blog at *http://blogs.technet.com/netmon/*.

- **Training slides** This is a set of Microsoft Office PowerPoint 2007 files that can be used along with this book to teach IPv6. For more information, see "A Special Note to Teachers and Instructors." To view the training slides, you need PowerPoint 2007 or later or the PowerPoint Viewer 2007. You can install PowerPoint Viewer 2007 from *Replace with http://www.microsoft.com/en-us/download/details.aspx?id=6*.

System Requirements

To view the book's capture files (*.cap), you must have Microsoft Network Monitor 3.4 or later. You can install Microsoft Network Monitor 3.4 from *http://blogs.technet.com/b/netmon/*.

IPv6 Protocol and Windows Product Versions

There are different versions of the Microsoft IPv6 protocol for Windows. In this book, I have chosen to confine the discussion to the IPv6 implementation in Windows Server 2012, Windows Server 2008 R2, Windows Server 2008, Windows 8, Windows 7, and Windows Vista. IPv6 in previous versions of Windows is typically not described, except as a point of contrast to IPv6 in these more recent versions of Windows.

A Special Note to Teachers and Instructors

This book originated from courseware and retains many of the inherent attributes, including objectives at the beginning of each chapter and review questions at the end of each chapter. If you are a teacher or instructor tasked with inculcating an understanding of IPv6 protocols and processes in others, I strongly urge you to consider using this book, the training slides found in the companion content for this book, and the IPv6 test lab instructions in Appendix C as a basis for your own IPv6 course.

The training slides are included to provide a foundation for your own slide presentation. The included slides contain either bulleted text or my original PowerPoint diagrams, which are synchronized with their chapter content. Because the slides were completed after the final book pages were done, there might be minor differences between the slides and the chapter content. These changes were made to enhance the ability to teach an IPv6 course based on the book.

The template I have chosen for the included slides is intentionally simple so that there are minimal issues with text and drawing color translations when you switch to a different template. Please feel free to customize the slides as you see fit.

If you are designing an implementation-independent IPv6 technology course, I suggest that you skip Chapter 2, "IPv6 Protocol for Windows," and cover Appendix E, "Link-Layer Support for IPv6," after Chapter 4, "The IPv6 Header."

For hands-on exercises, I encourage you to have your students build out the IPv6 test lab that is described in Appendix C, "Setting Up an IPv6 Test Lab." This can be done by each student on a server computer that can host five computers in a virtualized environment. The resulting test lab can be used for hands-on configuration exercises; analysis of IPv6 network traffic with Network Monitor (based on the captures provided with the companion content for this book or traffic captured on the test lab subnets); experimentation with IPv6 transition technologies and migration from an IPv4-only network to an IPv6-only network; and for application development and testing.

As a fellow instructor, I wish you success in your efforts to teach this interesting and important new technology to others.

Disclaimers and Support

This book represents a best-effort snapshot of information available at the time of its publication for IPv6 standards and the implementation of IPv6 and related protocols in Windows Server 2008 R2, Windows Server 2008, Windows 7, Windows Vista, and the Release Preview versions of Windows Server 2012 and Windows 8. Changes made to Windows Server 2012 and Windows 8 that were made after the Release Preview version or to IETF standards after May 30, 2012 are not reflected in this book.

To obtain the latest information about IETF standards for IPv6, go to the IETF website at *http://www.ietf.org*.

Acknowledgments

I would like to the thank the following people at Microsoft for participating in the technical reviews and for contributing content to the chapters and appendixes of the third edition of this book: Vivek Bhanu, Onur Filiz, Firat Kiyak, Darene Lewis, Bill Murray, Chidambaram Muthu, Tim Quinn, Pat Telford, Ben Schultz, Sean Siler, and Jeromy Statia. I would like to give special thanks to IPv6 Program Manager, Christopher Palmer, for the

Foreword. I would also like to give honorable mention to Dmitry Anipko, a senior software development engineer on the Windows Networking Core development team, who gave me very detailed feedback on both standards-based IPv6 and the implementation details of IPv6 in Windows Server 2012 and Windows 8.

To make this book a published reality, I would like to thank Ken Jones (Senior Editor at O'Reilly Media), my long-time professional colleague and IPv6 enthusiast Ed Horley for his great suggestions about current IPv6 industry trends and considerations (Technical Editor), Holly Bauer (O'Reilly Production Editor), and Richard Carey (Copyeditor).

And last, I would like to express my thanks and appreciation to my wife, Kara, and daughter, Katie, for their patience and tolerance for my time away during the last weeks of writing.

Support & Feedback

The following sections provide information on errata, book support, feedback, and contact information.

Errata

We've made every effort to ensure the accuracy of this book and its companion content. Any errors that have been reported since this book was published are listed on our Microsoft Press site:

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CHAPTER 1

Introduction to IPv6

At the end of this chapter, you should be able to do the following:

- Describe the shortcomings of Internet Protocol version 4 (IPv4) and the modern-day Internet, and describe how Internet Protocol version 6 (IPv6) addresses these shortcomings.
- Describe how the address depletion problem of IPv4 leads to the use of Network Address Translators (NATs) and problems with end-to-end communication.
- List and describe the features of IPv6.
- List and describe the key differences between IPv4 and IPv6.
- State the reasons for and business value of deploying IPv6.

Limitations of IPv4

The current version of IP (known as version 4 or IPv4) has not changed substantially since Request for Comments (RFC) 791, which was published in 1981. IPv4 has proven to be robust, easily implemented, and interoperable. It has stood up to the test of scaling an internetwork to a global utility the size of today's Internet. This is a tribute to its initial design.

However, the initial design of IPv4 did not anticipate the following:

- **The recent exponential growth of the Internet and the impending exhaustion of the IPv4 address space** Although the 32-bit address space of IPv4 allows for 4,294,967,296 addresses, previous and current allocation practices limit the number of public IPv4 addresses to a few hundred million. As a result, public IPv4 addresses have become relatively scarce, forcing many users and some organizations to use a NAT to map a small number of public IPv4 addresses to multiple private IPv4 addresses. Although NATs promote reuse of the private address space, they violate the fundamental design principle of the original Internet that all nodes have a unique, globally reachable address, thus preventing true end-to-end connectivity for all types of networking applications.

  Additionally, the rising prominence of Internet-connected devices and appliances ensures that the public IPv4 address space will eventually be depleted.

- **The need for simpler configuration** Most current IPv4 implementations must either be manually configured or use a stateful address configuration protocol such as Dynamic Host Configuration Protocol (DHCP). With more computers and devices using IP, there is a need for a simpler and more automatic configuration of addresses and routing configuration that does not rely on the administration of a DHCP infrastructure.

- **The requirement for security at the Internet layer** Private communication over a public medium such as the Internet requires cryptographic services that protect the data being sent from being viewed or modified in transit. Although a standard now exists for providing security for IPv4 packets (known as Internet Protocol security, or IPsec), this standard is optional for IPv4, and additional security solutions, some of which are proprietary, are prevalent.

- **The need for better support for prioritized and real-time delivery of data** Although standards for prioritized and real-time delivery of data—sometimes referred to as Quality of Service (QoS)—exist for IPv4, real-time traffic support relies on the 8 bits of the historical IPv4 Type of Service (TOS) field and the identification of the payload, typically using a User Datagram Protocol (UDP) or Transmission Control Protocol (TCP) port. Unfortunately, the IPv4 TOS field has limited functionality and, over time, has been redefined and has different local interpretations. The current standards for IPv4 use the TOS field to indicate a Differentiated Services Code Point (DSCP), a value set by the originating node and used by intermediate routers for prioritized delivery and handling. Additionally, payload identification that uses a TCP or UDP port is not possible when the IPv4 packet payload is encrypted.

To address these and other concerns, the Internet Engineering Task Force (IETF) has developed a suite of protocols and standards known as IP version 6 (IPv6). This new version, previously called IP-The Next Generation (IPng), incorporates the concepts of many proposed methods for updating the IPv4 protocol. IPv6 is designed to have minimal impact on upper-layer and lower-layer protocols and to avoid the random addition of new features.

Consequences of the Limited IPv4 Address Space

Because of the relative scarcity of public IPv4 addresses, NATs are being deployed to reuse the IPv4 private address space. In some configurations, there might be multiple levels of NATs between the client computer and the Internet. Although NATs do allow more clients to connect to the Internet, they also act as traffic bottlenecks and barriers to some types of communications.

Let’s examine the operation of a NAT to illustrate why network address translation is a nonscalable, stopgap solution that impairs end-to-end communication.

For example, say that a small business uses the 192.168.0.0/24 private IPv4 address prefix for its intranet and has been assigned the public IPv4 address of 131.107.47.119 by its Internet service provider (ISP). The NAT deployed at the edge of this network maps all private addresses on 192.168.0.0/24 to the public address of 131.107.47.119. The NAT uses dynamically chosen TCP and UDP ports to map internal (intranet) data streams to external (Internet) data streams. Figure 1-1 shows this example configuration.

If a private host assigned the private IPv4 address 192.168.0.10 uses a web browser to connect to the web server at 157.60.13.9, the private host creates an IPv4 packet with the following:

- Destination address: 157.60.13.9
- Source address: 192.168.0.10
- Destination TCP port: 80
- Source TCP port: 1025

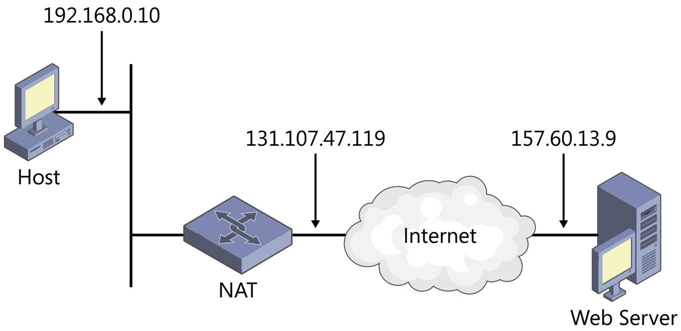

FIGURE 1-1 A NAT example.

This IPv4 packet is then forwarded to the NAT, which typically translates the source address and source TCP port of the outgoing packet to the following:

- Destination address: 157.60.13.9
- **Source address: 131.107.47.119**
- Destination TCP port: 80
- **Source TCP port: 5000**

The NAT keeps the mapping of {192.168.0.10, TCP 1025} to {131.107.47.119, TCP 5000} in a local translation table for future reference.

The translated IPv4 packet is sent over the Internet. The response is sent back by the web server and received by the NAT. When received, the packet contains the following:

- Destination address: 131.107.47.119
- Source address: 157.60.13.9
- Destination TCP port: 5000
- Source TCP port: 80

The NAT checks its translation table, locates the entry that was created when the initial packet was sent, translates the destination address and destination TCP port, and forwards the packet to the host at 192.168.0.10. The forwarded packet contains the following:

- **Destination address: 192.168.0.10**
- Source address: 157.60.13.9
- **Destination TCP port: 1025**
- Source TCP port: 80

For outgoing packets from the NAT, the source IPv4 address (a private address) is mapped to the ISP-assigned address (a public address), and the source TCP/UDP port numbers are mapped to different TCP/UDP port numbers. For incoming packets to the NAT, the destination IPv4 address (a public address) is mapped to the original intranet address (a private address), and the destination TCP/UDP port numbers are mapped back to their original TCP/UDP port numbers.

Normal network address translation relies on the following:

- **Address translation** Translation of the IPv4 addresses in the IPv4 header
- **Port translation** Translation of the TCP port numbers in the TCP header or of the UDP port numbers in the UDP header

Address and port translation lowers the forwarding performance of the NAT because of the additional operations that must be performed on each packet. As a result, NATs are typically not deployed in large-scale environments. However, recent development of standards such as carrier-grade NATs (CGNs) promise to scale NAT to enterprises and large ISPs.

To make modifications to the IPv4 packet beyond address or port translation requires additional processing and software components on the NAT called *NAT editors*. HyperText Transfer Protocol (HTTP) traffic on the World Wide Web does not require a NAT editor because all HTTP traffic requires only address and TCP port translation. However, NAT editors are required in the following situations:

- **An IPv4 address, TCP port, or UDP port is stored elsewhere in the payload.** For example, File Transfer Protocol (FTP) stores the dotted decimal representation of IPv4 addresses in the FTP header for the FTP PORT command. If the NAT does not properly translate the IPv4 address within the FTP header for the FTP PORT command and adjust the TCP sequence numbers in the data stream, connectivity and data transfer problems will occur.
- **TCP or UDP is not used to identify the data stream.** For example, Point-to-Point Tunneling Protocol (PPTP) tunneled data does not use a TCP or UDP header. Instead, PPTP uses a Generic Routing Encapsulation (GRE) header and the Call ID field of the GRE header to identify the data stream. If the NAT does not properly translate the Call ID field within the GRE header, connectivity problems will occur.

Most traffic can traverse a NAT because either the packets require only address or port translation or a NAT editor is present to modify the payload appropriately. However, some traffic cannot traverse a NAT. If the data requiring translation is in an encrypted part of the packet, translation is not possible. For IPsec-protected packets, address and port translation can invalidate the packet's integrity. IPsec NAT-Traversal (NAT-T) is a recent Internet standard that allows some types of IPsec-protected packets to be translated by a NAT.

An additional problem with NATs is their effect on peer-to-peer applications. In the peer-to-peer communication model, peers can act as either the client or the server and initiate communications to each other. If a peer is behind a NAT, two addresses are associated with it, one that is known to the peer behind the NAT (the private address) and one that is known in front of the NAT (the public address).

Let's examine a simple configuration in which NATs can cause problems for peer-to-peer applications. Figure 1-2 shows an intranet with a NAT at its edge.

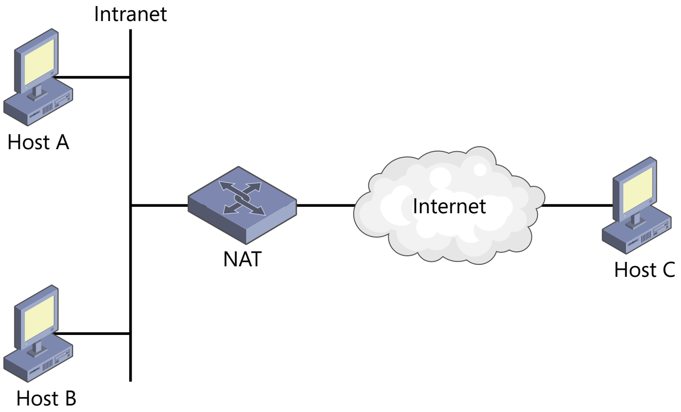

FIGURE 1-2 NAT and peer-to-peer applications.

For a peer-to-peer application running on all hosts, Host A can initiate a session with Host B (directly reachable on its link) and with Host C. However, Host A cannot inform Host C of the public address and port number of Host B because Host A does not know it. Also, Host C cannot initiate a session with either Host A or Host B without an existing translation table entry to translate the inbound connection-request packets to Host A's private address and port. Even with the table entry, Host C might not be able to initiate a session with both Host A and Host B because both hosts are known by the same public IPv4 address.

To make matters worse, it is a more common situation to have each Internet peer behind a NAT. To solve these problems, the peer-to-peer or multiple-party applications must be modified to be NAT-aware or use a NAT traversal technology, resulting in additional complexity. Also, some NAT-aware applications use an echo server to automatically discover their public address and port number, which adds costs for independent software vendors (ISVs) to deploy and maintain echo servers on the Internet.

NATs are a makeshift measure to extend the life of the IPv4 public address space, and they are not a solution to the IPv4 public address space problem. NATs work best for reusing the private address space for client computers and client/server-based communication when the client behind the NAT initiates the communication. Most server computers still need unambiguous public addresses. Although a server can be placed behind a NAT, the NAT must be configured manually with a static translation table entry to translate the inbound packets to the server's private address and port. In peer-to-peer communications, each end acts as both client and server and, therefore, peers separated by NATs might not operate correctly and must be modified for NAT awareness.

Features of IPv6

The following list summarizes the features of the IPv6 protocol:

- New header format
- Large address space
- Stateless and stateful address configuration
- IPsec header support required
- Better support for prioritized delivery
- New protocol for neighboring node interaction
- Extensibility

New Header Format

The IPv6 header has a new format that is designed to minimize header processing. This is achieved by moving both nonessential and optional fields to extension headers that are placed after the IPv6 header. The streamlined IPv6 header is more efficiently processed at intermediate routers.

IPv4 headers and IPv6 headers are not interoperable. IPv6 is not a superset of functionality that is backward compatible with IPv4. A host or router must use an implementation of both IPv4 and IPv6 to recognize and process both header formats. The new default IPv6 header is only twice the size of the default IPv4 header, even though the number of bits in IPv6 addresses is four times larger than in IPv4 addresses.

Large Address Space

IPv6 has 128-bit (16-byte) source and destination addresses. Although 128 bits can express over 3.4×10^{38} possible combinations, the large address space of IPv6 has been designed to allow for multiple levels of subnetting and address allocation, from the Internet backbone to the individual subnets within an organization.

Even with all of the addresses currently assigned for use by hosts, plenty of addresses are available for future use. With a much larger number of available addresses, address-conservation techniques, such as the deployment of NATs, are no longer necessary.

Stateless and Stateful Address Configuration

To simplify host configuration, IPv6 supports both stateful address configuration (such as address configuration in the presence of a DHCP for IPv6, or DHCPv6, server) and stateless address configuration (such as address and routing configuration in the absence of a DHCPv6 server). With stateless address configuration, hosts on a link automatically configure themselves with IPv6 addresses for the link (called *link-local addresses*), with IPv6 transition addresses, with addresses derived from prefixes advertised by local routers, and local subnet and default routes.

Both stateless and stateful addressing can be used at the same time. Even in the absence of a router, hosts on the same link can automatically configure themselves with link-local addresses and communicate without manual configuration. Link-local addresses are autoconfigured within seconds, and communication with neighboring nodes on the link is possible immediately. In comparison, some IPv4 hosts using DHCP must wait a full minute before abandoning DHCP configuration and self-configuring an IPv4 address.

IPsec Header Support Required

Support for the IPsec headers is an IPv6 protocol suite requirement. This requirement provides a standards-based solution for network protection needs and promotes interoperability between different IPv6 implementations. IPsec consists of two types of extension headers and a protocol to negotiate security settings. The Authentication header (AH) provides data integrity, data authentication, and replay protection for the entire IPv6 packet (excluding fields in the IPv6 header that must change in transit). The Encapsulating Security Payload (ESP) header and trailer provide data integrity, data authentication, data confidentiality, and replay protection for the ESP-encapsulated payload. The protocol typically used to negotiate IPsec security settings for unicast communication is the Internet Key Exchange (IKE) protocol.

The requirement to process IPsec headers does not make IPv6 inherently more secure. IPv6 packets are not required to be protected with IPsec, and IPsec is not a requirement of an IPv6 deployment. Additionally, the IPv6 standards do not require an implementation to support any specific encryption methods, hashing methods, or negotiation protocol (such as IKE).

Better Support for Prioritized Delivery

New fields in the IPv6 header define how traffic is handled and identified. Traffic is prioritized by using a Traffic Class field, which specifies a DSCP value just like IPv4. A Flow Label field in the IPv6 header allows routers to identify and provide special handling for packets that belong to a flow (a series of packets between a source and destination). Because the traffic is identified in the IPv6 header, support for prioritized delivery can be achieved even when the packet payload is encrypted with IPsec and ESP.

New Protocol for Neighboring Node Interaction

The Neighbor Discovery protocol for IPv6 is a series of Internet Control Message Protocol for IPv6 (ICMPv6) messages that manages the interaction of neighboring nodes (nodes on the same link). Neighbor Discovery replaces and extends the combination of the Address Resolution Protocol (ARP) (broadcast-based), ICMPv4 Router Discovery, and ICMPv4 Redirect messages with efficient multicast and unicast Neighbor Discovery messages.

Extensibility

IPv6 can easily be extended for new features by adding extension headers after the IPv6 header. Unlike options in the IPv4 header, which can support only 40 bytes of options, the size of IPv6 extension headers is constrained only by the size of the IPv6 packet.

Comparison of IPv4 and IPv6

Table 1-1 highlights some of the key differences between IPv4 and IPv6.

TABLE 1-1 Differences Between IPv4 and IPv6

IPv4	IPv6
Source and destination addresses are 32 bits (4 bytes) in length.	Source and destination addresses are 128 bits (16 bytes) in length. For more information, see Chapter 3, “IPv6 Addressing.”
IPsec header support is optional.	IPsec header support is required. For more information, see Chapter 4, “The IPv6 Header.”
No identification of packet flow for prioritized delivery handling by routers is present within the IPv4 header.	Packet flow identification for prioritized delivery handling by routers is present within the IPv6 header using the Flow Label field. For more information, see Chapter 4.
Fragmentation is performed by the sending host and at routers, slowing router performance.	Fragmentation is performed only by the sending host. For more information, see Chapter 4.
Has no link-layer packet-size requirements and must be able to reassemble a 576-byte packet.	Link layer must support a 1,280-byte packet and be able to reassemble a 1,500-byte packet. For more information, see Chapter 4.
Header includes a checksum.	Header does not include a checksum. For more information, see Chapter 4.
Header includes options.	All optional data is moved to IPv6 extension headers. For more information, see Chapter 4.
ARP uses broadcast ARP Request frames to resolve an IPv4 address to a link-layer address.	ARP Request frames are replaced with multicast Neighbor Solicitation messages. For more information, see Chapter 6, “Neighbor Discovery.”
Internet Group Management Protocol (IGMP) is used to manage local subnet group membership.	IGMP is replaced with Multicast Listener Discovery (MLD) messages. For more information, see Chapter 7, “Multicast Listener Discovery and MLD Version 2.”

IPv4	IPv6
ICMP Router Discovery is used to determine the IPv4 address of the best default gateway and is optional.	ICMPv4 Router Discovery is replaced with ICMPv6 Router Solicitation and Router Advertisement messages, and it is required. For more information, see Chapter 6.
Broadcast addresses are used to send traffic to all nodes on a subnet.	There are no IPv6 broadcast addresses. Instead, a link-local scope all-nodes multicast address is used. For more information, see "Multicast IPv6 Addresses" in Chapter 3.
Must be configured either manually or through DHCP for IPv4.	Does not require manual configuration or DHCP for IPv6. For more information, see Chapter 8, "Address Autoconfiguration."
Uses host address (A) resource records in the Domain Name System (DNS) to map host names to IPv4 addresses.	Uses AAAA records in the DNS to map host names to IPv6 addresses. For more information, see Chapter 9, "IPv6 and Name Resolution."
Uses pointer (PTR) resource records in the IN-ADDR.ARPA DNS domain to map IPv4 addresses to host names.	Uses pointer (PTR) resource records in the IP6.ARPA DNS domain to map IPv6 addresses to host names. For more information, see Chapter 9.

IPv6 Terminology

The following list of common terms for network elements and concepts provides a foundation for subsequent chapters. Figure 1-3 shows an IPv6 network.

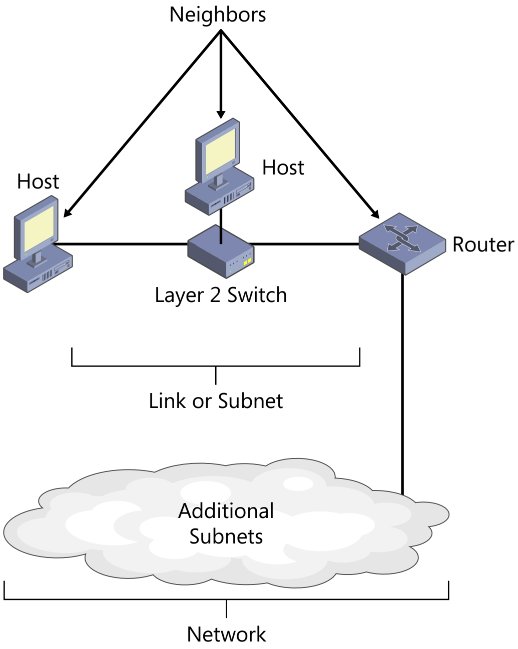

FIGURE 1-3 Elements of an IPv6 network.

IPv6 common terms and concepts are defined as follows:

- **Node** Any device that runs an implementation of IPv6. This includes routers and hosts.
- **Router** A node that can forward IPv6 packets not explicitly addressed to itself. On an IPv6 network, a router also typically advertises its presence and host configuration information.
- **Host** A node that cannot forward IPv6 packets not explicitly addressed to itself (a non-router). A host is typically the source and a destination of IPv6 traffic, and it silently discards traffic received that is not explicitly addressed to itself.
- **Upper-layer protocol** A protocol that uses IPv6 as its transport. Examples include Internet layer protocols such as ICMPv6 and Transport layer protocols such as TCP and UDP (but not Application layer protocols such as FTP and DNS, which use TCP and UDP as their transport).
- **Link** The set of network interfaces that are bounded by routers (or contains no routers) and that use the same 64-bit IPv6 unicast address prefix. Other terms for "link" are *subnet* and *network segment*. Many link-layer technologies are already defined for IPv6, including typical LAN technologies (such as Ethernet and Institute of Electrical and Electronics Engineers [IEEE] 802.11 wireless) and wide area network (WAN) technologies (such as the Point-to-Point Protocol [PPP] and Frame Relay). Additionally, IPv6 packets can be sent over logical links representing an IPv4 or IPv6 network, by encapsulating the IPv6 packet within an IPv4 or IPv6 header. For more information about LAN and WAN media support for IPv6, see Appendix E, "Link-Layer Support for IPv6."
- **Network** Two or more subnets connected by routers. Another term for network is *internetwork*.
- **Neighbors** Nodes connected to the same link. Neighbors in IPv6 have special significance because of IPv6 Neighbor Discovery, which can resolve neighbor link-layer addresses and detect and monitor neighbor reachability.
- **Interface** The representation of an attachment to a physical or logical link. An example of a physical interface is a network adapter. An example of a logical interface is a "tunnel" interface that is used to send IPv6 packets across an IPv4 network by encapsulating the IPv6 packet inside an IPv4 header.
- **Address** An identifier that can be used as the source or destination of IPv6 packets that is assigned at the IPv6 layer to an interface or set of interfaces.
- **Packet** The protocol data unit (PDU) that exists at the IPv6 layer and is composed of an IPv6 header and payload.
- **Link MTU** The maximum transmission unit (MTU)—the number of bytes in the largest IPv6 packet—that can be sent on a link. Because the maximum frame size includes the link-layer medium headers and trailers, the link MTU is not the same as the maximum frame size of the link. The link MTU is the same as the maximum payload size of the link-layer technology. For

example, for Ethernet using Ethernet II encapsulation, the maximum Ethernet frame payload size is 1,500 bytes. Therefore, the link MTU is 1500. For a link with multiple link-layer technologies (for example, a bridged link), the link MTU is the smallest link MTU of all the link-layer technologies present on the link.

- **Path MTU** The maximum-sized IPv6 packet that can be sent without performing host fragmentation between a source and destination over a path in an IPv6 network. The path MTU is typically the smallest link MTU of all the links in the path.

Figure 1-4 shows an IPv6-capable organization network and its relation to the IPv4 and IPv6 Internets.

A *site* is an autonomously operating IP-based network that is connected to the IPv6 Internet. Network architects and administrators within the site determine the addressing plan and routing policy for the organization network. An organization can have multiple sites. The actual connection to the IPv6 Internet can be either of the following types:

- **Direct** The connection to the IPv6 Internet uses a wide area network link (such as Frame Relay or T-Carrier) and connects to an IPv6-capable ISP (shown in Figure 1-4).
- **Tunneled** The connection to the IPv6 Internet uses an IPv6-over-IPv4 tunnel and connects to an IPv6 tunneling router.

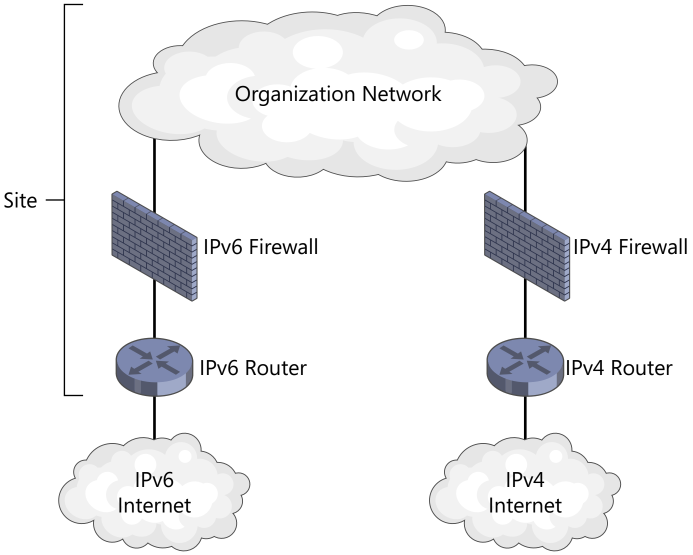

FIGURE 1-4 An IPv6-capable organization network and the IPv4 and IPv6 Internets.

For more information about how sites use IPv6 address prefixes, see Chapter 3.

The Case for IPv6 Deployment

Although the IPv6 protocol offers a host of technological advances and innovations, its use must still be justified from a business perspective and deployed by information technology (IT) staff in end-user organizations and ISPs. The deployment of native IPv6 support in the network infrastructure involves the planning and design of coexistence and migration strategies and the installation and maintenance of hardware and software. The resulting combination of IT staff, hardware and software resources, and time required for the transition makes the decision to deploy native IPv6 support a significant one, especially in light of other technology initiatives that might have higher visibility or better short-term benefits.

One must consider, however, that the Internet, once a pseudo-private network connecting educational institutions and United States government agencies, has become an indispensable worldwide communications medium that is an integral part of increased efficiency and productivity for commercial organizations and individuals, and it is now a major component of the world's economic engine. *Its growth must continue*.

To continue the growth of the Internet and private intranets, IPv4 must eventually be replaced. The sooner IPv4 is replaced, the sooner the benefits of its replacement protocol are realized. The following sections present the key technological and business benefits in the case to deploy IPv6.

IPv6 Solves the Address Depletion Problem

With the explosion in the popularity of the Internet has come the introduction of commerce-related activities that can now be done over the Internet by an ever-increasing number of devices. With IPv4, the number of public addresses available to new devices is limited and shrinking. IPv4 cannot continue to scale and provide global connectivity to all of the planned Internet-capable devices to be produced and connected in the next 10 years. Although these devices can be assigned private addresses, address and port translation introduces complexity to the devices that need to perform server, listening, or peer functionality. IPv6 solves the IPv4 public address depletion problem by providing an address space to last well into the twenty-first century.

The business benefit of moving to IPv6 is that mobile cell phones, personal data assistants (PDAs), automobiles, appliances, and even people can be assigned multiple globally reachable addresses. The growth of the devices connected to the Internet and the software that these devices run can proceed without restraint and without the complexity and cost of having to operate behind NATs.

IPv6 Solves the Disjoint Address Space Problem

With IPv4, there are typically two different addressing schemes for the home and the enterprise network. In the home, an Internet gateway device (IGD) is assigned a single public IPv4 address and the IGD assigns private IPv4 addresses to the hosts on the home network. An enterprise might have multiple public IPv4 addresses or a public address range and either assign public, private, or both types of addresses within the enterprise's intranet.

However, the public and private IPv4 address spaces are disjoint; that is, they do not provide symmetric reachability at the Network layer. Symmetric reachability exists when packets can be sent to and received from an arbitrary destination. With IPv4, there is no single addressing scheme that is applied to both networks that allows seamless connectivity. Connectivity between disjoint networks requires intermediate devices such as NATs or proxy servers. With IPv6, both homes and enterprises will be assigned global address prefixes and can seamlessly connect, subject to security restrictions such as firewall filtering and authenticated communication.

IPv6 Solves the International Address Allocation Problem

The Internet was principally a creation of educational institutions and government agencies of the United States of America. In the early days of the Internet, connected sites in the United States received IPv4 address prefixes without regard to summarizability or need. The historical result of this address allocation practice is that the United States has a disproportionate number of public IPv4 addresses.

With IPv6, public address prefixes are assigned to regional Internet registries, which, in turn, assign address prefixes to other ISPs and organizations based on justified need. This new address allocation practice ensures that address prefixes will be distributed globally based on regional connectivity needs rather than by historical origin. This makes the Internet more of a truly global resource rather than a United States–centric one. The business benefit to organizations across the globe is that they can rely on having available public IPv6 address space, without the current cost of obtaining IPv4 public address prefixes from their ISP or other source.

IPv6 Restores End-to-End Communication

With IPv4 NATs, there is a technical barrier for applications that rely on listening or peer-based connectivity because of the need for the communicating peers to discover and advertise their public IPv4 addresses and ports. The workarounds for the translation barrier might also require the deployment of echo or rendezvous servers on the Internet to provide public address and port configuration information.

With IPv6, NATs are no longer necessary to conserve public address space, and the problems associated with mapping addresses and ports disappear for developers of applications and gateways. More importantly, end-to-end communication is restored between hosts on the Internet by using addresses in packets that do not change in transit. This functional restoration has immense value when one considers the emergence of peer-to-peer telephony, video, and other real-time collaboration technologies for personal communications, and that the next wave of devices that are connected to the Internet include many types of peer-to-peer devices, such as mobile phones and gaming consoles.

By restoring global addressing and end-to-end connectivity, IPv6 has no barrier to new applications that are based on ad hoc connectivity and peer-based communication. Additionally, there is no need to deploy echo servers on the Internet. The business benefit for software developers is easier development of peer-based applications to share information, music, and media or to collaborate without having to work around the NAT translation barrier. An additional benefit to global addressing and end-to-end connectivity is that users can remotely access computers on their home networks rather than having to use intermediate hosts on the Internet.

IPv6 Uses Scoped Addresses and Address Selection

Unlike IPv4 addresses, IPv6 addresses have a *scope*, or a defined area of the network over which they are unique and relevant. For example, IPv6 has a global address that is equivalent to the IPv4 public address and a unique local address that is roughly equivalent to the IPv4 private address. Typical IPv4 routers do not distinguish a public address from a private address and will forward a privately addressed packet on the Internet. An IPv6 router, on the other hand, is aware of the scope of IPv6 addresses and will never forward a packet over an interface that does not have the correct scope.

There are different types of IPv6 addresses with different scopes. When multiple IPv6 addresses are returned in a DNS name query, the sending node must be able to distinguish their types and, when initiating communication, use a pair (source address and destination address) that is matched in scope and that is the most appropriate pair to use. For example, for a source and a destination that have been assigned both global (public) and link-local addresses, a sending IPv6 host would never use a global destination with a link-local source. IPv6 sending hosts include the address selection logic that is needed to decide which pair of addresses to use in communication. Moreover, the address selection rules are configurable. This allows you to configure multiple addressing infrastructures within an organization. Regardless of how many types of addressing infrastructures are in place, the sending host always chooses the "best" set of addresses. In comparison, IPv4 nodes have no awareness of address types and can send traffic to a public address from a private address.

The benefit of scoped addresses is that by using the set of addresses of the smallest scope, your traffic does not travel beyond the scope for the address, exposing your network traffic to fewer possible malicious hosts. The benefit of standardized and built-in address selection algorithms for ISVs is that they do not have to develop and test their own address selection schemes and can rely on the sorted list of addresses, resulting in lower software development costs.

IPv6 Has More Efficient Forwarding

IPv6 is a streamlined version of IPv4. Excluding prioritized delivery traffic, IPv6 has fewer fields to process and fewer decisions to make in forwarding an IPv6 packet. Unlike IPv4, the IPv6 header is a fixed size (40 bytes), which allows routers to process IPv6 packets faster. Additionally, the hierarchical and summarizable addressing structure of IPv6 global addresses means that there are fewer routes to analyze in the routing tables of organization and Internet backbone routers. The consequence is traffic that can be forwarded at higher data rates, resulting in higher performance for tomorrow's high-bandwidth applications that use multiple data types.

IPv6 Has Support for Security and Mobility

IPv6 has been designed to support security (IPsec, with AH and ESP header support required) and mobility (optionally, Mobile IPv6). Although one could argue that these features are available for IPv4, they are available on IPv4 as extensions and therefore have architectural or connectivity limitations that might not have been present if they had been part of the original IPv4 design. It is always better to design features in rather than bolt them on. Designing IPv6 with security and mobility in mind has resulted in an implementation that is a defined standard, has fewer limitations, and is more robust and scalable to handle the current and future communication needs of the users of the Internet.

The business benefit of requiring support for IPsec and using a single, global address space is that IPv6 can protect packets from end to end across the entire IPv6 Internet. Unlike IPsec on the IPv4 Internet, which must be modified and has limited functionality when the endpoints are behind NATs, IPsec on the IPv6 Internet is fully functional between any two endpoints.

Testing for Understanding

To test your understanding of IPv6, answer the following questions. See Appendix B, “Testing for Understanding Answers,” to check your answers.

1. What are the problems with IPv4 on today’s Internet?
2. How does IPv6 solve these problems?
3. How does IPv6 provide better prioritized delivery support?
4. Describe at least three ways in which IPv6 is more efficient than IPv4.
5. Explain how NATs prevent peer-to-peer applications from working properly.
6. What are the key technical benefits of deploying IPv6 now?
7. What are the key business benefits of deploying IPv6 now?

CHAPTER 4

The IPv6 Header

At the end of this chapter, you should be able to do the following:

- Describe the structure of an IPv6 packet.
- List and describe the fields in the IPv4 header.
- List and describe the fields in the IPv6 header.
- Compare and contrast the fields in the IPv4 header with the fields in the IPv6 header.
- List and describe each IPv6 extension header.
- Describe the IPv6 maximum transmission unit (MTU).
- Describe the new pseudo-header used for upper-layer checksums.

Structure of an IPv6 Packet

An Internet Protocol version 6 (IPv6) packet consists of an IPv6 header, extension headers, and an upper-layer protocol data unit. Figure 4-1 shows the structure of an IPv6 packet.

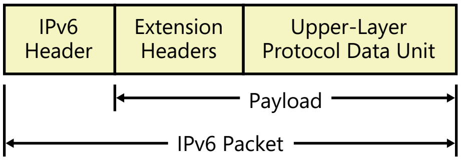

FIGURE 4-1 The structure of an IPv6 packet.

The components of an IPv6 packet are the following:

- **IPv6 Header** The IPv6 header is always present and is a fixed size of 40 bytes. The fields in the IPv6 header are described in the "IPv6 Header" section in this chapter.
- **Extension Headers** Zero or more extension headers can be present and are of varying lengths. If extension headers are present, a Next Header field in the IPv6 header indicates the first extension header. Within each extension header is another Next Header field, indicating the next extension header. The last extension header indicates the header for the upper-layer protocol—such as Transmission Control Protocol (TCP), User Datagram Protocol (UDP), or

Internet Control Message Protocol for version 6 (ICMPv6)—contained within the upper-layer protocol data unit.

The IPv6 header and extension headers replace the existing IPv4 header and its options. The new extension header format allows IPv6 to be enhanced to support future needs and capabilities. Unlike options in the IPv4 header, IPv6 extension headers have no maximum size and can expand to accommodate all the extension data needed for IPv6 communication. IPv6 extension headers are described in the "IPv6 Extension Headers" section in this chapter.

- **Upper-Layer Protocol Data Unit** The upper-layer protocol data unit (PDU) typically consists of an upper-layer protocol header and its payload (for example, an ICMPv6 message, a TCP segment, or a UDP message).

  The IPv6 packet payload is the combination of the IPv6 extension headers and the upper-layer PDU. Normally, it can be up to 65,535 bytes long. IPv6 packets with payloads larger than 65,535 bytes in length, known as *jumbograms*, can also be sent.

IPv4 Header

Before examining the IPv6 header, you might find it helpful, for contrasting purposes, to review the IPv4 header shown in Figure 4-2.

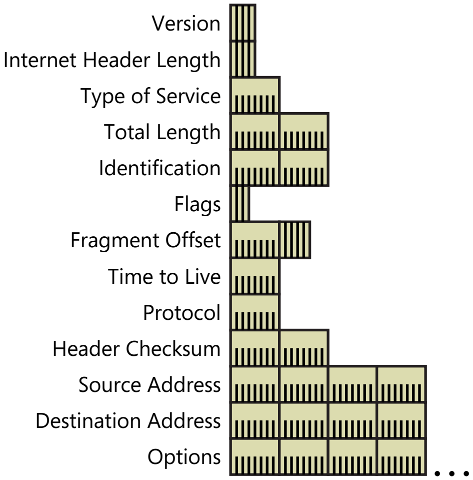

FIGURE 4-2 The structure of the IPv4 header.

Following is a list of the fields in the IPv4 header:

- **Version** The Version field indicates the version of IP and is set to 4. The size of this field is 4 bits.

- **Internet Header Length** The Internet Header Length (IHL) field indicates the number of 4-byte blocks in the IPv4 header. The size of this field is 4 bits. Because an IPv4 header is a minimum of 20 bytes in size, the smallest value of the IHL field is 5. IPv4 options can extend the minimum IPv4 header size in increments of 4 bytes. If an IPv4 option is not an integral multiple of 4 bytes in length, the remaining bytes are padded with padding options, making the entire IPv4 header an integral multiple of 4 bytes. With a maximum IHL value of 0xF, the maximum size of the IPv4 header, including options, is 60 bytes (15 × 4).

- **Type of Service** The Type of Service field indicates the desired service expected by this packet for delivery through routers across the IPv4 internetwork. The size of this field is 8 bits, including bits originally defined in RFC 791 for precedence, delay, throughput, reliability, and cost characteristics. RFC 2474 provides the modern definition as the Differentiated Services (DS) field. The high-order 6 bits of the DS field comprise the DS Code Point (DSCP) field. The DSCP field allows devices in a network to mark, unmark, and classify packets for forwarding. This is usually done based on the needs of an application. For example, Voice over IP and other real-time packets take precedence over e-mail in congested areas of the network. This is commonly referred to as Quality of Service (QoS). The low-order 2 bits of the Type of Service field are used for Explicit Congestion Notification (ECN), as defined in RFC 3168.

- **Total Length** The Total Length field indicates the total length of the IPv4 packet (IPv4 header + IPv4 payload) and does not include link-layer framing. The size of this field is 16 bits, which can indicate an IPv4 packet that is up to 65,535 bytes long.

- **Identification** The Identification field identifies this specific IPv4 packet. The size of this field is 16 bits. The Identification field is selected by the source node of the IPv4 packet. If the IPv4 packet is fragmented, all the fragments retain the Identification field value so that the destination node can group the fragments for reassembly.

- **Flags** The Flags field identifies flags for the fragmentation process. The size of this field is 3 bits; however, only 2 bits are defined for current use. There are two flags—one to indicate whether the IPv4 packet can be fragmented and another to indicate whether more fragments follow the current fragment.

- **Fragment Offset** The Fragment Offset field indicates the position of the fragment relative to the beginning of the original IPv4 payload. The size of this field is 13 bits.

- **Time-to-Live** The Time-to-Live (TTL) field indicates the maximum number of links on which an IPv4 packet can travel before being discarded. The size of this field is 8 bits. The TTL field was originally defined as a time count for the number of seconds the packet could exist on the network. An IPv4 router determined the length of time required (in seconds) to forward the IPv4 packet and decremented the TTL accordingly. Modern routers almost always forward an IPv4 packet in less than a second, and they are required by RFC 791 to decrement the TTL by at least one. Therefore, the TTL becomes a maximum link count with the value set by the sending node. When the TTL equals 0, an ICMPv4 Time Exceeded-Time to Live Exceeded in Transit message is sent to the source of the packet and the packet is discarded.

- **Protocol** The Protocol field identifies the upper-layer protocol. The size of this field is 8 bits. For example, a value of 6 in this field identifies TCP as the upper-layer protocol, a decimal value of 17 identifies UDP, and a value of 1 identifies ICMPv4. The Protocol field is used to identify the upper-layer protocol that is to receive the IPv4 packet payload.
- **Header Checksum** The Header Checksum field provides a checksum on the IPv4 header only. The size of this field is 16 bits. The IPv4 payload is not included in the checksum calculation because the IPv4 payload usually contains its own checksum. Each IPv4 node that receives IPv4 packets verifies the IPv4 header checksum and silently discards the IPv4 packet if checksum verification fails. When a router forwards an IPv4 packet, it must decrement the TTL. Therefore, the Header Checksum value is recomputed at each hop between source and destination.
- **Source Address** The Source Address field stores the IPv4 address of the originating host. The size of this field is 32 bits.
- **Destination Address** The Destination Address field stores the IPv4 address of an intermediate destination (in the case of source routing) or the destination host. The size of this field is 32 bits.
- **Options** The Options field stores one or more IPv4 options. The size of this field is a multiple of 32 bits (4 bytes). If an IPv4 option does not use all 32 bits, padding options must be added so that the IPv4 header is an integral number of 4-byte blocks that can be indicated by the IHL field.

IPv6 Header

The IPv6 header is a streamlined version of the IPv4 header. It eliminates fields that are either unneeded or rarely used, and it adds a field that provides better support for real-time traffic. Figure 4-3 shows the structure of the IPv6 header as described in RFC 2460.

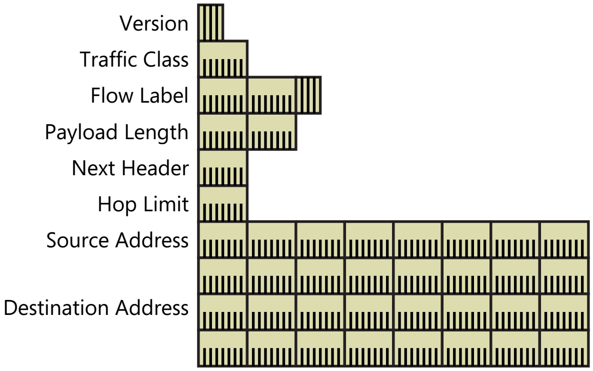

FIGURE 4-3 The structure of the IPv6 header.

Following is a list of the fields in the IPv6 header:

- **Version** The Version field indicates the version of IP and is set to 6. The size of this field is 4 bits. While the purpose of the Version field is defined in the same way for both IPv4 and IPv6, its value is not used to pass the packet to an IPv4 or IPv6 protocol layer. This identification is done through a protocol identification field in the link-layer header. For example, a common link-layer encapsulation for Ethernet, called Ethernet II, uses a 16-bit EtherType field to identify the Ethernet frame payload. For IPv4 packets, the EtherType field is set to 0x800. For IPv6 packets, the EtherType field is set to 0x86DD. Thus, the determination of the protocol of the Ethernet payload occurs before the packet is passed to the appropriate protocol layer.
- **Traffic Class** The Traffic Class field indicates the IPv6 packet's class or priority. The size of this field is 8 bits. This field provides functionality similar to the IPv4 Type of Service field. Like the Type of Service field in the IPv4 header, the first 6 bits of the Traffic Class field represent the DSCP field as defined in RFC 2474, and the last 2 bits are used for ECN as defined in RFC 3168.
- **Flow Label** The Flow Label field indicates that this packet belongs to a specific sequence of packets between a source and destination, requiring special handling by intermediate IPv6 routers. The size of this field is 20 bits. The flow label is used for prioritized delivery, such as delivery needed by real-time data (voice and video). For default router handling, the Flow Label field is set to 0. To distinguish a given flow, an intermediate router can use the packet's source address, destination address, and flow label. Therefore, there can be multiple flows between a source and destination, as distinguished by separate non-zero flow labels. The details of the use of the Flow Label field are described in RFC 3697.
- **Payload Length** The Payload Length field indicates the length of the IPv6 payload. The size of this field is 16 bits. The Payload Length field includes the extension headers and the upper-layer PDU. With 16 bits, an IPv6 payload of up to 65,535 bytes can be indicated. For payload lengths greater than 65,535 bytes, the Payload Length field is set to 0 and the Jumbo Payload option is used in the Hop-by-Hop Options extension header, which is described in the "Hop-by-Hop Options Header" section in this chapter.
- **Next Header** The Next Header field indicates either the type of the first extension header (if present) or the protocol in the upper-layer PDU (such as TCP, UDP, or ICMPv6). The size of this field is 8 bits. When indicating an upper-layer protocol, the Next Header field uses the same values that are used in the IPv4 Protocol field.
- **Hop Limit** The Hop Limit field indicates the maximum number of links over which the IPv6 packet can travel before being discarded. The size of this field is 8 bits. The Hop Limit field is similar to the IPv4 TTL field except that there is no historical relation to the amount of time (in seconds) that the packet is queued at the router. When Hop Limit equals 0 at a router, the router sends an ICMPv6 Time Exceeded-Hop Limit Exceeded in Transit message to the source and discards the packet.
- **Source Address** The Source Address field indicates the IPv6 address of the originating host. The size of this field is 128 bits.

- **Destination Address** The Destination Address field indicates the IPv6 address of the current destination node. The size of this field is 128 bits. In most cases, the Destination Address field is set to the final destination address. However, if a Routing extension header is present, the Destination Address field might be set to the address of the next intermediate destination.

Network Monitor Capture

Here is an example of an IPv6 header, as displayed by Network Monitor 3.4 (capture 04_01 in the companion content for this book):

```
 Frame:
+ Ethernet: Etype = IPv6
- Ipv6: Next Protocol = ICMPv6, Payload Length = 40
  - Versions: IPv6, Internet Protocol, DSCP 0
     Version:  (0110............................) IPv6, Internet Protocol, 6(0x6)
     DSCP:     (....000000......................) Differentiated services codepoint 0
     ECT:      (..........0.....................) ECN-Capable Transport not set
     CE:       (...........0....................) ECN-CE not set
     FlowLabel: (............00000000000000000000) 0
    PayloadLength: 40 (0x28)
    NextProtocol: ICMPv6, 58(0x3a)
    HopLimit: 128 (0x80)
    SourceAddress: FE80:0:0:0:260:97FF:FE02:6E8F
    DestinationAddress: FE80:0:0:0:260:97FF:FE02:6D3D
+ Icmpv6: Echo request, ID = 0x0, Seq = 0x18
```

This ICMPv6 Echo Request packet uses the default Traffic Class and Flow Label and a Hop Limit of 128, and it is sent between two hosts using link-local addresses.

Values of the Next Header Field

Table 4-1 lists typical values of the Next Header field for an IPv6 header or an IPv6 extension header. Each of the IPv6 extension headers is covered later in the chapter.

TABLE 4-1 Typical Values of the Next Header Field

Value (Decimal)	Header
0	Hop-by-Hop Options header
6	TCP
17	UDP
41	Encapsulated IPv6 header
43	Routing header
44	Fragment header
50	Encapsulating Security Payload header
51	Authentication header
58	ICMPv6
59	No next header
60	Destination Options header

For the most current list of the reserved values for the IPv4 Protocol and IPv6 Next Header fields, see *http://www.iana.org/assignments/protocol-numbers*.

In looking at the value of the Next Header field to indicate no next header, it would seem to make more sense to set its value to 0, rather than 59. However, the designers of IPv6 wanted to optimize the processing of IPv6 packets at intermediate routers. The only extension header that must be processed at every intermediate router is the Hop-by-Hop Options header. To optimize the test of whether the Hop-by-Hop Options header is present, its Next Header value is set to 0. In router hardware, it is easier to test for a value of 0 than to test for a value of 59.

Comparing the IPv4 and IPv6 Headers

In comparing the IPv4 and IPv6 headers, you can see the following:

- The number of fields has dropped from 12 (including options) in the IPv4 header to 8 in the IPv6 header.
- The number of fields that must be processed by an intermediate router has dropped from 6 to 4, making the forwarding of normal IPv6 packets more efficient.
- Seldom-used fields, such as fields supporting fragmentation and options in the IPv4 header, have been moved to extension headers in the IPv6 header.
- The size of the IPv6 header has doubled from 20 bytes for a minimum-sized IPv4 header to 40 bytes. However, the new IPv6 header contains source and destination addresses that are four times longer than IPv4 source and destination addresses.

Table 4-2 lists the individual differences between the IPv4 and IPv6 header fields.

TABLE 4-2 IPv4 Header Fields and Corresponding IPv6 Equivalents

IPv4 Header Field	IPv6 Header Field
Version	Same field but with a different version number.
Internet Header Length	Removed in IPv6. IPv6 does not include a Header Length field because the IPv6 header is always a fixed length of 40 bytes. Each extension header is either a fixed length or indicates its own length.
Type of Service	Replaced by the IPv6 Traffic Class field.
Total Length	Replaced by the IPv6 Payload Length field, which indicates only the size of the payload.
Identification Flags Fragment Offset	Removed in IPv6. Fragmentation information is not included in the IPv6 header. It is contained in a Fragment extension header.
Time-to-Live	Replaced by the IPv6 Hop Limit field.
Protocol	Replaced by the IPv6 Next Header field.
Header Checksum	Removed in IPv6. The link layer has a checksum that performs bit-level error detection for the entire IPv6 packet.
Source Address	The field is the same except that IPv6 addresses are 128 bits in length.
Destination Address	The field is the same except that IPv6 addresses are 128 bits in length.
Options	Removed in IPv6. IPv6 extension headers replace IPv4 options.

The one new field in the IPv6 header that is not included in the IPv4 header is the Flow Label field.

The result of the new IPv6 header is a reduction in the critical router loop, which is the set of instructions that must be executed to determine how to forward a packet. To forward a normal IPv4 packet, a router typically performs the following in its critical router loop:

1. Verify the Header Checksum field by performing its own checksum calculation and comparing its result with the result stored in the IPv4 header. Although this step is required by RFC 1812, modern high-speed routers commonly skip it.
2. Verify the value of the Version field. Although this step is not required by RFC 791 or 1812, performing this step saves network bandwidth because a packet containing an invalid version number is not propagated across the IPv4 internetwork only to be discarded by the destination node.
3. Decrement the value of the TTL field. If its new value is less than 1, send an ICMPv4 Time Exceeded-Time to Live Exceeded in Transit message to the source of the packet and then discard the packet. If not, place the new value in the TTL field.
4. Check for the presence of IPv4 header options. If present, process them.
5. Use the value of the Destination Address field and the contents of the local routing table to determine a forwarding interface and a next-hop IPv4 address. If a route is not found, send an ICMPv4 Destination Unreachable-Host Unreachable message to the source of the packet and discard the packet.
6. If the IPv4 MTU of the forwarding interface is less than the value of the Total Length field and the Don't Fragment (DF) flag is set to 0, perform IPv4 fragmentation. If the MTU of the forwarding interface is less than the value of the Total Length field and the DF flag is set to 1, send an ICMPv4 Destination Unreachable-Fragmentation Needed and DF Set message to the source of the packet and discard the packet.
7. Recalculate the new header checksum, and place its new value in the Header Checksum field.
8. Forward the packet by using the appropriate forwarding interface.

Note This critical router loop for IPv4 routers is a simplified list of items that an IPv4 router typically performs when forwarding. This list is not meant to imply any specific implementation nor an optimized order in which to process IPv4 packets for forwarding.

To forward a normal IPv6 packet, a router typically performs the following steps in its critical router loop:

1. Verify the value of the Version field. Although this step is not required by RFC 2460, performing it saves network bandwidth because a packet containing an invalid version number is not propagated across the IPv6 internetwork only to be discarded by the destination node.

2. Decrement the value of the Hop Limit field. If its new value is less than 1, send an ICMPv6 Time Exceeded-Hop Limit Exceeded in Transit message to the source of the packet and discard the packet. If not, place the new value in the Hop Limit field.
3. Check the Next Header field for a value of 0. If it is 0, process the Hop-by-Hop Options header.
4. Use the value of the Destination Address field and the contents of the local routing table to determine a forwarding interface and a next-hop IPv6 address. If a route is not found, send an ICMPv6 Destination Unreachable-No Route To Destination message to the source of the packet and then discard the packet.
5. If the link MTU of the forwarding interface is less than 40 plus the value of the Payload Length field, send an ICMPv6 Packet Too Big message to the source of the packet and discard the packet.
6. Forward the packet by using the appropriate forwarding interface.

> **Note** This critical router loop for IPv6 routers is a simplified list of items that an IPv6 router typically performs when forwarding. This list is not meant to imply any specific implementation nor an optimized order in which to process packets for forwarding.

As you can see, the process to forward an IPv6 packet is much simpler than for an IPv4 packet because it does not have to verify and recalculate a header checksum, perform fragmentation, or process options not intended for the router.

IPv6 Extension Headers

The IPv4 header includes all options. Therefore, each intermediate router must check for their existence and process them when present. This can cause performance degradation in the forwarding of IPv4 packets. With IPv6, delivery and forwarding options are moved to extension headers. The only extension header that must be processed at each intermediate router is the Hop-by-Hop Options extension header. This increases IPv6 header processing speed and improves the performance of forwarding IPv6 packets.

RFC 2460 specifies that the following IPv6 extension headers must be supported by all IPv6 nodes:

- Hop-by-Hop Options header
- Destination Options header
- Routing header
- Fragment header
- Authentication header
- Encapsulating Security Payload header

With the exception of the Authentication header and Encapsulating Security Payload header, all the IPv6 extension headers in the preceding list are defined in RFC 2460.

In a typical IPv6 packet, no extension headers are present. If special handling is required by either intermediate routers or the destination, the sending host adds one or more extension headers.

Each extension header must fall on a 64-bit (8-byte) boundary. Extension headers of a fixed size must be an integral multiple of 8 bytes. Extension headers of variable size contain a Header Extension Length field and must use padding as needed to ensure that their size is an integral multiple of 8 bytes.

The Next Header field in the IPv6 header and zero or more extension headers form a chain of pointers. Each pointer indicates the type of header that comes after the immediate header until the upper-layer protocol is ultimately identified. Figure 4-4 shows the chain of pointers formed by the Next Header field for various IPv6 packets.

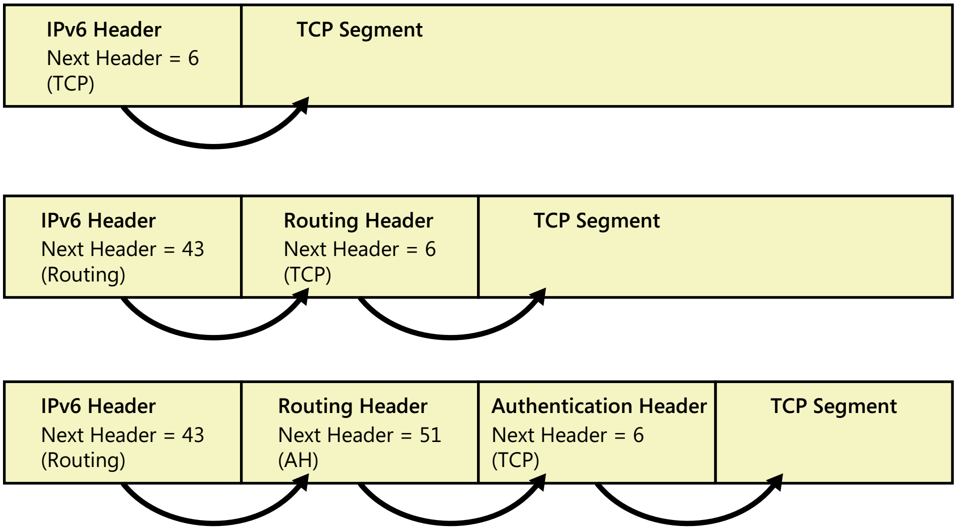

FIGURE 4-4 The chain of pointers formed by the Next Header field.

If an extension header contains an unrecognized or improper value of the Next Header field, the node discards the packet and sends an ICMP Parameter Problem-Unrecognized Next Header Type Encountered message to the packet source. An example of an improper value for any extension header is 0, because the Hop-by-Hop Options header must always be immediately after the IPv6 header.

Extension Headers Order

Extension headers are processed in the order in which they are present. Because the only extension header that is processed by every node on the path is the Hop-by-Hop Options header, it must be first. Similar rules apply for other extension headers. In RFC 2460, it is recommended that extension headers be placed after the IPv6 header in the following order:

1. Hop-by-Hop Options header
2. Destination Options header (for intermediate destinations when the Routing header is present)
3. Routing header
4. Fragment header
5. Authentication header
6. Encapsulating Security Payload header
7. Destination Options header (for the final destination)

Hop-by-Hop Options Header

The Hop-by-Hop Options header is used to specify delivery parameters at each hop on the path to the destination. It is identified by the value of 0 in the IPv6 header's Next Header field. Figure 4-5 shows the structure of the Hop-by-Hop Options header.

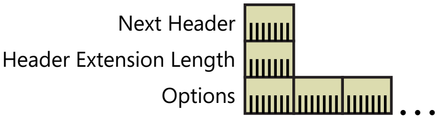

FIGURE 4-5 The structure of the Hop-by-Hop Options header.

The Hop-by-Hop Options header consists of a Next Header field, a Header Extension Length field, and an Options field that contains one or more options. The value of the Header Extension Length field is the number of 8-byte blocks in the Hop-by-Hop Options extension header, not including the first 8 bytes. Therefore, for an 8-byte Hop-by-Hop Options header, the value of the Header Extension Length field is 0. Padding options are used to ensure 8-byte boundaries.

An IPv6 Router Optimization

The interpretation of the Header Extension Length field in the Hop-by-Hop Options header is another example of how the designers of IPv6 wanted to optimize processing of IPv6 packets at intermediate routers. For packets with a Hop-by-Hop Options header, one of the first operations is to determine the size of the header. If the Header Extension Length field were defined to be the number of 8-byte blocks in the header, its minimum value would be 1 (the minimum-sized Hop-by-Hop Options header is 8 bytes long). To ensure robustness in an IPv6 forwarding implementation, a field whose valid values begin at 1 has to be checked for the invalid value of 0 before additional processing can be done.

With the current definition of the Header Extension Length field, 0 is a valid value and no testing of invalid values needs to be done. The number of bytes in the Hop-by-Hop Options header is calculated from the following formula: (header extension length + 1) × 8.

An option is a set of fields that either describes a specific characteristic of the packet delivery or provides padding. Options are sent in the Hop-by-Hop Options header and Destination Options header (described later in this chapter). Each option is encoded in the type-length-value (TLV) format that is commonly used in TCP/IP protocols. Figure 4-6 shows the structure of an option.

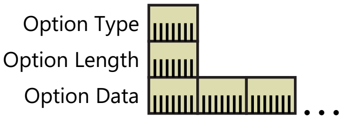

FIGURE 4-6 The structure of an option.

The Option Type field both identifies the option and determines the way it is handled by the processing node. The Option Length field indicates the number of bytes in the option, not including the Option Type and Option Length fields. The option data is the specific data associated with the option.

An option might have an alignment requirement to ensure that specific fields within the option fall on desired boundaries. For example, it is easier to process an IPv6 address if it falls on an 8-byte boundary. Alignment requirements are expressed by using the notation xn + y, indicating that the option must begin at a byte boundary equal to an integral multiple of x bytes plus y bytes from the start of the header. For example, the alignment requirement 4n + 2 indicates that the option must begin at a byte boundary of (an integral multiple of 4 bytes) + 2 bytes. In other words, the option must begin at the byte boundary of 6, 10, 14, and so on, relative to the start of the Hop-by-Hop Options or Destination Options headers. To accommodate alignment requirements, padding typically appears before an option and between each option when multiple options are present.

Option Type Field

Within the Option Type field, the two high-order bits indicate how the option is handled when the node processing the option does not recognize the option type. Table 4-3 lists the defined values of these two bits and their purpose.

TABLE 4-3 Values of the Two High-Order Bits in the Option Type Field

Value (Binary)	Action Taken
00	Skip the option.
01	Silently discard the packet.
10	Discard the packet, and send an ICMPv6 Parameter Problem message to the sender if the Destination Address field in the IPv6 header is a unicast or multicast address.
11	Discard the packet, and send an ICMPv6 Parameter Problem message to the sender if the Destination Address field in the IPv6 header is not a multicast address.

The third-highest-order bit of the Option Type indicates whether the option data can change (= 1) or not change (= 0) in the path to the destination.

Pad1 Option

The Pad1 option is defined in RFC 2460. It is used to insert a single byte of padding so that the Hop-by-Hop Options or Destination Options headers fall on 8-byte boundaries and to accommodate the alignment requirements of options. The Pad1 option has no alignment requirements. Figure 4-7 shows the Pad1 option.

Option Type
= 0

FIGURE 4-7 The structure of the Pad1 option.

The Pad1 option consists of a single byte; Option Type is set to 0, and it has no length or value fields. With Option Type set to 0, the option is skipped if not recognized, and it is not allowed to change in transit.

PadN Option

The PadN option is defined in RFC 2460. It is used to insert two or more bytes of padding so that the Hop-by-Hop Options or Destination Options headers fall on 8-byte boundaries and to accommodate the alignment requirements of options. The PadN option has no alignment requirements. Figure 4-8 shows the PadN option.

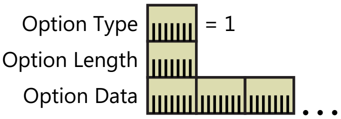

FIGURE 4-8 The structure of the PadN option.

The PadN option consists of the Option Type field (set to 1), the Length field (set to the number of padding bytes present), and 0 or more bytes of padding. With the Option Type field set to 1, the option is skipped if not recognized, and it is not allowed to change in transit.

Jumbo Payload Option

The Jumbo Payload option is defined in RFC 2675. It is used to indicate a payload size that is greater than 65,535 bytes. The Jumbo Payload option has the alignment requirement of 4n + 2. Figure 4-9 shows the Jumbo Payload option.

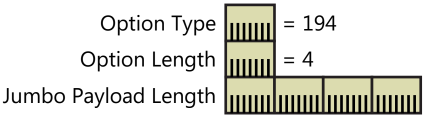

FIGURE 4-9 The structure of the Jumbo Payload option.

With the Jumbo Payload option, the Payload Length field in the IPv6 header no longer indicates the size of the IPv6 packet payload. Instead, the Jumbo Payload Length field in the Jumbo Payload option indicates the size, in bytes, of the IPv6 packet payload. With a 32-bit Jumbo Payload Length field, payload sizes of up to 4,294,967,295 bytes can be indicated. An IPv6 packet with a payload size greater than 65,535 bytes is known as a *jumbogram*. With the Option Type field set to 194 (0xC2 hexadecimal, binary 11000010), the packet is discarded and an ICMPv6 Parameter Problem message is sent if the option is not recognized and the destination address is not a multicast address; and the option is not allowed to change in transit.

The IPv6 protocol in Windows Server 2012, Windows Server 2008 R2, Windows Server 2008, Windows 8, Windows 7, and Windows Vista supports incoming jumbograms at the IPv6 layer. However, there is no support in UDP or TCP for sending or receiving jumbograms.

Router Alert Option

The Router Alert option (Option Type 5) is defined in RFC 2711 and is used to indicate to a router that the contents of the packet require additional processing. The Router Alert option has the alignment requirement of 2n + 0. Figure 4-10 shows the structure of the Router Alert option.

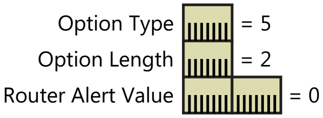

FIGURE 4-10 The structure of the Router Alert option.

The Router Alert option is used for Multicast Listener Discovery (MLD) and the Resource ReSerVation Protocol (RSVP). With the Option Type field set to 5, the option is skipped if not recognized, and it is not allowed to change in transit.

Network Monitor Capture

Here is an example of a Hop-by-Hop Options header as displayed by Network Monitor 3.4 (capture 04_02 in the companion content for this book):

```
 Frame:
+ Ethernet: Etype = IPv6
- Ipv6: Next Protocol = ICMPv6, Payload Length = 32
  + Versions: IPv6, Internet Protocol, DSCP 0
    PayloadLength: 32 (0x20)
    NextProtocol: HOPOPT, IPv6 Hop-by-Hop Option, 0(0)
    HopLimit: 1 (0x1)
    SourceAddress: FE80:0:0:0:2B0:D0FF:FEE9:4143
    DestinationAddress: FF02:0:0:0:0:1:FFE9:4143
  - HopbyHopHeader:
     NextHeader: ICMPv6
     ExtHdrLen: 0(8 bytes)
   - OptionRouterAlert:
    - OptionType: Router Alert
       Action:     (00......) Skip over this option
       C:          (..0.....) Option Data does not change en-route
       OptionType: (...00101) Router Alert
      OptDataLen: 2 bytes
      Value: Datagram contains a Multicast Listener Discovery message, 0 (0x0)
   - OptionPadN:
    - OptionType: PadN
       Action:     (00......) Skip over this option
       C:          (..0.....) Option Data does not change en-route
       OptionType: (...00001) PadN
      OptDataLen: 0 bytes
      OptionData: 0 bytes
+ Icmpv6: Multicast Listener Report
```

Notice the use of the Router Alert option (option type 5) and the PadN option (option type 1) to pad the entire Hop-by-Hop Options header to 8 bytes (1-byte Next Header field + 1-byte Option Length field + 4-byte Router Alert option + 2-byte PadN option).

Destination Options Header

The Destination Options header is used to specify packet delivery parameters for either intermediate destinations or the final destination. This header is identified by the value of 60 in the previous header's Next Header field. The Destination Options header has the same structure as the Hop-by-Hop Options header, as shown in Figure 4-11.

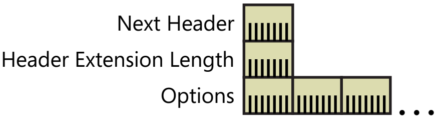

FIGURE 4-11 The structure of the Destination Options header.

The Destination Options header is used in two ways:

1. If a Routing header is present, it specifies delivery or processing options at each intermediate destination. In this case, the Destination Options header occurs before the Routing header.
2. If no Routing header is present or if this header occurs after the Routing header, this header specifies delivery or processing options at the final destination.

An example of a destination option is the Home Address destination option for Mobile IPv6.

Note The discussion of the Home Address destination option is here for example purposes only. Computers running Windows Server 2012, Windows Server 2008 R2, Windows Server 2008, Windows 8, Windows 7, or Windows Vista do not support Mobile IPv6 and act as correspondent nodes that are not Mobile IPv6–capable.

Home Address Option

The Home Address destination option (Option Type 201) is defined in RFC 6275 and is used to indicate the home address of the mobile node. The home address is an address assigned to the mobile node when it is attached to the home link and through which the mobile node is always reachable, regardless of its location on an IPv6 network. For information about when the Home Address option is sent, see Appendix G, "Mobile IPv6." The Home Address option has the alignment requirement of 8n + 6. Figure 4-12 shows the structure of the Home Address option.

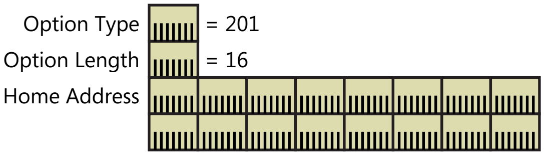

FIGURE 4-12 The structure of the Home Address option.

Following is a description of the fields in the Home Address option:

- **Option Type** With the Option Type field set to 201 (0xC9 hexadecimal, 11001001 binary), the packet is discarded and an ICMPv6 Parameter Problem message is sent if the option is not recognized and the destination address is not a multicast address; and the option is not allowed to change in transit.
- **Option Length** The Option Length field indicates the length of the option in bytes, not including the Option Type and Option Length fields. Because the only field past the Option Length field is the Home Address field to store an IPv6 address, the Option Length field is set to 16.
- **Home Address** The Home Address field indicates the home address of the mobile node. The size of this field is 128 bits.

For an example of the Home Address option in the Destination Options header, see the Network Monitor Capture 04_03 in the companion content for this book.

Summary of Option Types

Table 4-4 lists the different option types for options in Hop-by-Hop Options and Destination Options headers.

TABLE 4-4 Option Types

Option Type	Option and Where It Is Used	Alignment Requirement
0	Pad1 option: Hop-by-Hop and Destination Options headers	None
1	PadN option: Hop-by-Hop and Destination Options headers	None
194 (0xC2)	Jumbo Payload option: Hop-by-Hop Options header	4n + 2
5	Router Alert option: Hop-by-Hop Options header	2n + 0
201 (0xC9)	Home Address option: Destination Options header	8n + 6

Routing Header

IPv4 defines strict source routing, in which each intermediate destination must be only one hop away, and loose source routing, in which each intermediate destination can be one or more hops away. IPv6 source nodes can use the Routing header to specify a source route, which is a list of intermediate destinations for the packet to travel to on its path to the final destination. The Routing header is identified by the value of 43 in the previous header's Next Header field. Figure 4-13 shows the structure of the Routing header.

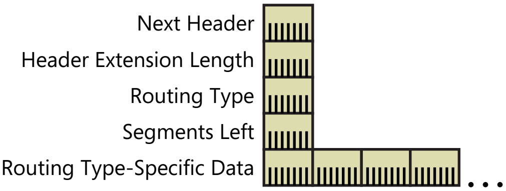

FIGURE 4-13 The structure of the Routing header.

The Routing header consists of a Next Header field, a Header Extension Length field (defined in the same way as the Hop-by-Hop Options extension header), a Routing Type field, a Segments Left field that indicates the number of intermediate destinations that are still to be visited, and routing type-specific data.

Note RFC 2460 also defines Routing Type 0, used for loose source routing. Because of security concerns, the Internet Engineering Task Force (IETF) has deprecated support for the Routing Type 0 header in RFC 5095. By default, IPv6 in Windows Server 2012, Windows Server 2008 R2, Windows 8, and Windows 7 will accept the packet if it has a complete routing header. If not, Windows drops the packet and sends an ICMP Parameter Problem-Erroneous Header Field Encountered message. This behavior is configurable with the *Set-NetIPv6Protocol –SourceRoutingBehavior* Windows PowerShell command (for Windows Server 2012 and Windows 8) and the *netsh interface ipv6 set global sourceroutingbehavior* command. Mobile IPv6 uses a Type 2 Routing header. For more information, see Appendix G.

Fragment Header

The Fragment header is used for IPv6 fragmentation and reassembly services. This header is identified by the value of 44 in the previous header's Next Header field. Figure 4-14 shows the structure of the Fragment header.

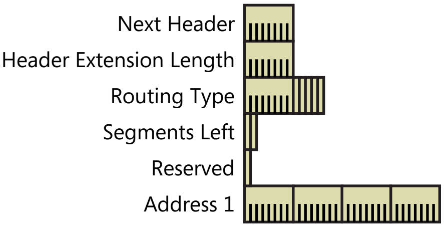

FIGURE 4-14 The structure of the Fragment header.

The Fragment header includes a Next Header field, a 13-bit Fragment Offset field, a More Fragments flag, and a 32-bit Identification field. The Fragment Offset, More Fragments flag, and Identification fields are used in the same way as the corresponding fields in the IPv4 header. Because the use of the Fragment Offset field is defined for 8-byte fragment blocks, the Fragment header cannot be used for jumbograms. The maximum number that can be expressed with the 13-bit Fragment Offset field is 8191. Therefore, Fragment Offset can be used to indicate only a fragment data starting position of up to 8191 × 8, or 65,528.

In IPv6, only source nodes can fragment payloads. If the payload submitted by the upper-layer protocol is larger than the link or path MTU, IPv6 fragments the payload at the source and uses the Fragment header to provide reassembly information. An IPv6 router will never fragment an IPv6 packet being forwarded.

Because the IPv6 internetwork does not transparently fragment payloads, data sent from applications that do not have an awareness of the destination path MTU cannot sense when data needing fragmentation by the source is discarded by IPv6 routers. This can be a problem for unicast or multicast traffic sent as a UDP message or other types of message streams that do not use TCP.

Differences in Fragmentation Fields

There are some subtle differences between the fragmentation fields in IPv4 and IPv6. In IPv4, the fragmentation flags are the three high-order bits of the 16-bit quantity composed of the combination of the fragmentation flags and the Fragment Offset field. In IPv6, the bits used for fragmentation flags are the three low-order bits of the 16-bit quantity composed of the combination of the fragmentation flags and the Fragment Offset field. In IPv4, the Identification field is 16 bits rather than 32 bits, as in IPv6, and in IPv6 there is no Don't Fragment flag. Because IPv6 routers never perform fragmentation, the Don't Fragment flag is always set to 1 for all IPv6 packets and therefore does not need to be included.

IPv6 Fragmentation Process

When an IPv6 packet is fragmented, it is initially divided into unfragmentable and fragmentable parts:

- The unfragmentable part of the original IPv6 packet must be processed by intermediate nodes between the fragmenting node and the destination. This part consists of the IPv6 header, the Hop-by-Hop Options header, the Destination Options header for intermediate destinations, and the Routing header.
- The fragmentable part of the original IPv6 packet must be processed only at the final destination node. This part consists of the Authentication header, the Encapsulating Security Payload header, the Destination Options header for the final destination, and the upper-layer PDU.

Next, the IPv6 fragment packets are formed. Each fragment packet consists of the unfragmentable part, a fragment header, and a portion of the fragmentable part. Figure 4-15 shows the IPv6 fragmentation process for a packet divided into three fragments.

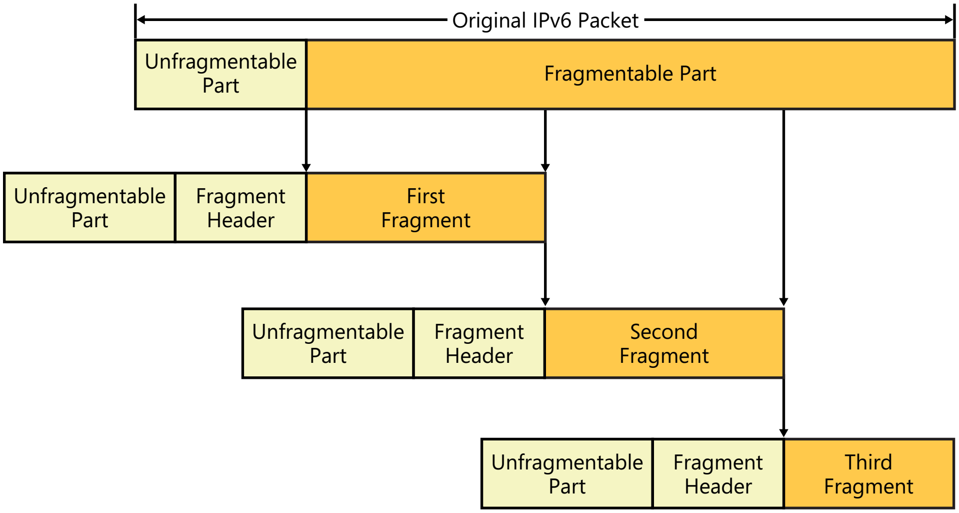

FIGURE 4-15 The IPv6 fragmentation process.

In each fragment, the Next Header field in the Fragment header indicates the first header or the upper-layer protocol in the original fragmentable part. The Fragment Offset field in the Fragment header indicates the offset, in 8-byte units known as *fragment blocks*, of this fragment relative to the original payload. The More Fragments flag is set on all fragment packets except the last fragment packet. All fragment packets created from the same IPv6 packet must contain the same Identification field value.

Fragmentation of IPv6 packets can occur when the upper-layer protocol of the sending host submits a packet to IPv6 that is larger than the path MTU to the destination. An example of IPv6 fragmentation is when a UDP application that is not aware of a path MTU sends large packets to a destination.

IPv6 packets sent to IPv4 destinations that undergo IPv6-to-IPv4 header translation might receive a path MTU update of less than 1280. In this case, the sending host sends IPv6 packets with a Fragment header in which the Fragment Offset field is set to 0 and the More Fragments flag is not set, and with a smaller payload size of 1272 bytes. The Fragment header is included so that the IPv6-to-IPv4 translator can use the Identification field in the Fragment header to perform IPv4 fragmentation to reach the IPv4 destination.

Network Monitor Capture

Here is an example of a Fragment header as displayed by Network Monitor 3.4 (frame 3 of capture 04_04 in the companion content for this book):

```
 Frame:
+ Ethernet: Etype = IPv6
- Ipv6: Next Protocol = ICMPv6, Payload Length = 1456
  + Versions: IPv6, Internet Protocol, DSCP 0
    PayloadLength: 1456 (0x5B0)
    NextProtocol: IPv6 Fragment header, 44(0x2c)
    HopLimit: 128 (0x80)
    SourceAddress: FE80:0:0:0:210:5AFF:FEAA:20A2
    DestinationAddress: FE80:0:0:0:250:DAFF:FED8:C153
  - FragmentHeader:
     NextHeader: ICMPv6
     Reserved: 0 (0x0)
   - FragmentInfor:
      FragmentOffset: 2896(0XB50)
      Reserved: (.............00.)
      M:        (...............1) More fragments
      Identification: 5 (0x5)
     FragmentData: Binary Large Object (1448 Bytes)
```

This is a fragment of a payload that uses the identification number of 5 and starts in byte position 2896 relative to the fragmentable portion of the original IPv6 payload.

Note You can create your own fragmented IPv6 traffic with the Ping.exe tool and the "–l" option by setting the buffer size so that IPv6 must fragment the ICMPv6-Echo Request message. Try this in the IPv6 test lab, as described in Appendix C, "Setting Up an IPv6 Test Lab," using Network Monitor 3.4 to capture the traffic.

IPv6 Reassembly Process

The fragment packets are forwarded by the intermediate IPv6 router or routers to the destination IPv6 address. The fragment packets can take different paths to the destination and arrive in a different order from which they were sent. To reassemble the fragment packets into the original payload, IPv6 uses the Source Address and Destination Address fields in the IPv6 header and the Identification field in the Fragment header to group the fragments. Figure 4-16 shows the IPv6 reassembly process.

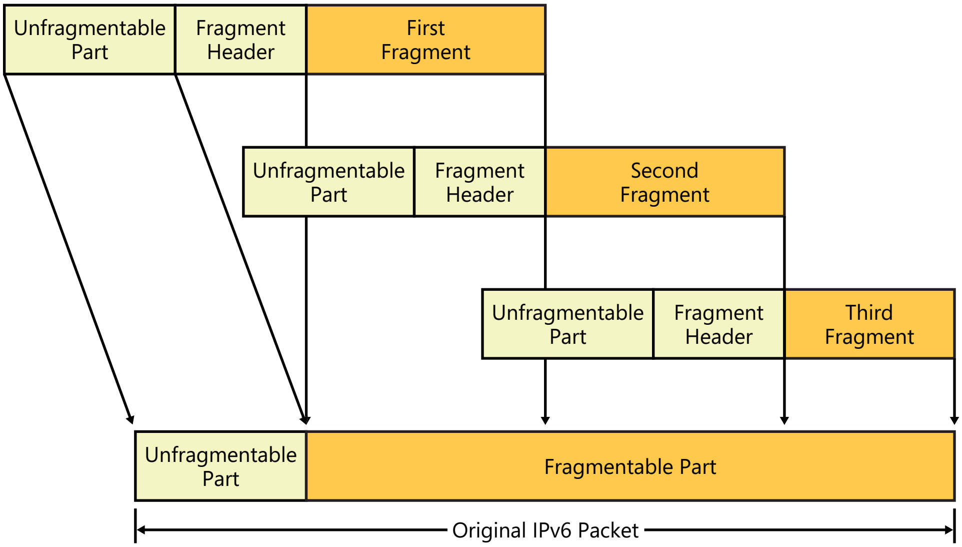

FIGURE 4-16 The IPv6 reassembly process.

After all the fragments arrive, the original payload length is calculated and the Payload Length field in the IPv6 header for the reassembled packet is updated. Additionally, the Next Header field of the last header of the unfragmentable part is set to the Next Header field of the Fragment header of the first fragment.

RFC 2460 recommends a reassembly time of 60 seconds before abandoning reassembly and discarding the partially reassembled packet. If the first fragment has arrived and reassembly has not completed, the reassembling host sends an ICMPv6 Time Exceeded-Fragment Reassembly Time Exceeded message to the source of the fragment.

Authentication Header

The Authentication header provides data authentication (verification of the node that sent the packet), data integrity (verification that the data was not modified in transit), and anti-replay protection (assurance that captured packets cannot be retransmitted and accepted as valid data) for the IPv6 packet, including the fields in the IPv6 header that do not change in transit across an IPv6 internetwork. The Authentication header, described in RFC 4302, is part of the security architecture for IP, as defined in RFC 4301. The Authentication header is identified by the value of 51 in the previous header's Next Header field. Figure 4-17 shows the structure of the Authentication header.

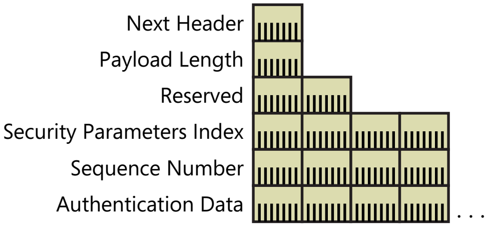

FIGURE 4-17 The structure of the Authentication header.

The Authentication header contains a Next Header field, a Payload Length field (the number of 4-byte blocks in the Authentication header, not counting the first two), a Reserved field, a Security Parameters Index (SPI) field that helps identify a specific IP Security (IPsec) security association (SA), a Sequence Number field that provides anti-replay protection, and an Authentication Data field that contains an integrity value check (ICV). The ICV provides data authentication and data integrity.

The Authentication header does not provide data confidentiality services for the upper-layer PDU by encrypting the data so that it cannot be viewed without the encryption key. To obtain data authentication and data integrity for the entire IPv6 packet and data confidentiality for the upper-layer PDU, you can use both the Authentication header and the Encapsulating Security Payload header and trailer.

Encapsulating Security Payload Header and Trailer

The Encapsulating Security Payload (ESP) header and trailer, described in RFC 4303, provide data confidentiality, data authentication, data integrity, and replay protection services to the encapsulated payload. The ESP header provides no security services for the IPv6 header or extension headers that occur before the ESP header. The ESP header and trailer are identified by the value of 50 in the previous header's Next Header field. Figure 4-18 shows the structure of the ESP header and trailer.

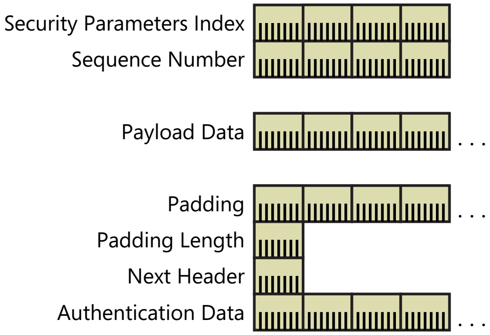

FIGURE 4-18 The structure of the ESP header and trailer.

The ESP header contains an SPI field that helps identify the IPsec SA, and a Sequence Number field that provides anti-replay protection. The ESP trailer contains the Padding, Padding Length, Next Header, and Authentication Data fields. The Padding field is used to ensure 4-byte boundaries for the ESP payload and appropriate data-block boundaries for encryption algorithms. The Padding Length field indicates the size of the Padding field in bytes. The Authentication Data field contains the ICV.

Details about how the ESP header and trailer provide data confidentiality, authentication, and integrity through cryptographic techniques are beyond the scope of this book.

IPv6 MTU

IPv6 requires that the link layer support a minimum MTU size of 1280 bytes. Link layers that do not support this MTU size must provide a link-layer fragmentation and reassembly scheme that is transparent to IPv6. For link layers that can support a configurable MTU size, RFC 2460 recommends that they be configured with an MTU size of at least 1500 bytes (the IPv6 MTU for Ethernet II encapsulation). An example of a configurable MTU is the Maximum Receive Unit (MRU) of a Point-to-Point Protocol (PPP) link.

Like IPv4, IPv6 provides a Path MTU Discovery process that uses the ICMPv6 Packet Too Big message described in the "Path MTU Discovery" section of Chapter 5, "ICMPv6." Path MTU Discovery allows the transmission of IPv6 packets that are larger than 1280 bytes.

IPv6 source hosts can fragment payloads of upper-layer protocols that are larger than the path MTU by using the process and Fragment header previously described. However, the use of IPv6 fragmentation is highly discouraged. An IPv6 node must be able to reassemble a fragmented packet that is at least 1500 bytes in size.

Table 4-5 lists commonly used local area network (LAN) and wide area network (WAN) technologies and their defined IPv6 MTUs.

TABLE 4-5 IPv6 MTUs for Common LAN and WAN Technologies

LAN or WAN Technology	IPv6 MTU
Ethernet (Ethernet II encapsulation)	1500, up to 9000 for jumbo frames
Ethernet (IEEE 802.3 SubNetwork Access Protocol [SNAP] encapsulation)	1492
IEEE 802.11	2312
Token Ring	Varies
Fiber Distributed Data Interface (FDDI)	4352
Attached Resource Computer Network (ARCNet)	9072
PPP	1500
X.25	1280
Frame Relay	1592
Asynchronous Transfer Mode (ATM) (Null or SNAP encapsulation)	9180

For more information about LAN and WAN encapsulations for IPv6 packets, see Appendix E, "Link-Layer Support for IPv6."

Upper-Layer Checksums

The current implementation of TCP, UDP, and ICMP for IPv4 incorporates into their checksum calculation a pseudo-header that includes both the IPv4 Source Address and Destination Address fields. This checksum calculation must be modified for TCP, UDP, and ICMPv6 traffic sent over IPv6 to include IPv6 addresses. Figure 4-19 shows the structure of the new IPv6 pseudo-header that must be used by TCP, UDP, and ICMPv6 checksum calculations. IPv6 uses the same algorithm as IPv4 for computing the checksum value.

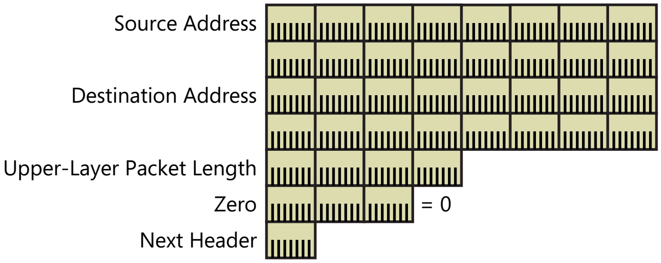

FIGURE 4-19 The structure of the new IPv6 pseudo-header.

The IPv6 pseudo-header includes the Source Address field, the Destination Address field, an Upper Layer Packet Length field that indicates the length of the upper-layer PDU, and a Next Header field that indicates the upper-layer protocol for which the checksum is being calculated.

References

The following references were cited in this chapter:

- **RFC 791** “Internet Protocol”
- **RFC 1812** “Requirements for IP Version 4 Routers”
- **RFC 2460** “Internet Protocol, Version 6 (IPv6)”
- **RFC 2474** “Definition of the Differentiated Services Field (DS Field)”
- **RFC 2675** “IPv6 Jumbograms”
- **RFC 2711** “IPv6 Router Alert Option”
- **RFC 3168** “The Addition of Explicit Congestion Notification (ECN) to IP”
- **RFC 3697** “IPv6 Flow Label Specification”
- **RFC 4301** “Security Architecture for the Internet Protocol”
- **RFC 4302** “IP Authentication Header”
- **RFC 4303** “IP Encapsulating Security Payload (ESP)”
- **RFC 5095** “Deprecation of Type 0 Routing Headers in IPv6”
- **RFC 6275** “Mobility Support in IPv6”

You can obtain these RFCs from *http://www.ietf.org/rfc.html*.

Testing for Understanding

To test your understanding of the IPv6 header, answer the following questions. See Appendix B, “Testing for Understanding Answers,” to check your answers.

1. Why does the IPv6 header not include a checksum?
2. What is the IPv6 equivalent to the IHL field in the IPv4 header?
3. How does the combination of the Traffic Class and Flow Label fields provide better support for prioritized traffic delivery?
4. Which extension headers are fragmentable and why? Which extension headers are not fragmentable and why?

5. Describe a situation that results in an IPv6 packet that contains a Fragment Header in which the Fragment Offset field is set to 0 and the More Fragments flag is not set to 1.

6. Describe how the new upper-layer checksum calculation affects transport layer protocols such as TCP and UDP.

7. If the minimum MTU for IPv6 packets is 1280 bytes, how are 1280-byte packets sent on a link that supports only 512-byte frames?

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