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Security Architecture for the Internet Protocol

Status of This Memo

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Abstract

This document describes an updated version of the "Security Architecture for IP", which is designed to provide security services for traffic at the IP layer. This document obsoletes RFC 2401 (November 1998).

Dedication

This document is dedicated to the memory of Charlie Lynn, a long-time senior colleague at BBN, who made very significant contributions to the IPsec documents.

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1. Introduction

1.1. Summary of Contents of Document

This document specifies the base architecture for IPsec-compliant systems. It describes how to provide a set of security services for traffic at the IP layer, in both the IPv4 [Pos81a] and IPv6 [DH98] environments. This document describes the requirements for systems that implement IPsec, the fundamental elements of such systems, and how the elements fit together and fit into the IP environment. It also describes the security services offered by the IPsec protocols,

and how these services can be employed in the IP environment. This document does not address all aspects of the IPsec architecture. Other documents address additional architectural details in specialized environments, e.g., use of IPsec in Network Address Translation (NAT) environments and more comprehensive support for IP multicast. The fundamental components of the IPsec security architecture are discussed in terms of their underlying, required functionality. Additional RFCs (see Section 1.3 for pointers to other documents) define the protocols in (a), (c), and (d).

a. Security Protocol -- Encapsulating Security Payload (ESP)
b. Security Associations -- what they are and how they work, how they are managed, associated processing
c. Key Management -- manual and automated (The Internet Key Exchange (IKE))
d. Cryptographic algorithms for authentication and encryption

This document is not a Security Architecture for the Internet; it addresses security only at the IP layer, provided through the use of a combination of cryptographic and protocol security mechanisms.

The spelling "IPsec" is preferred and used throughout this and all related IPsec standards. All other capitalizations of IPsec (e.g., IPSEC, IPSec, ipsec) are deprecated. However, any capitalization of the sequence of letters "IPsec" should be understood to refer to the IPsec protocols.

The keywords MUST, MUST NOT, REQUIRED, SHALL, SHALL NOT, SHOULD, SHOULD NOT, RECOMMENDED, MAY, and OPTIONAL, when they appear in this document, are to be interpreted as described in RFC 2119 [Bra97].

1.2. Audience

The target audience for this document is primarily individuals who implement this IP security technology or who architect systems that will use this technology. Technically adept users of this technology (end users or system administrators) also are part of the target audience. A glossary is provided in Appendix A to help fill in gaps in background/vocabulary. This document assumes that the reader is familiar with the Internet Protocol (IP), related networking technology, and general information system security terms and concepts.

1.3. Related Documents

As mentioned above, other documents provide detailed definitions of some of the components of IPsec and of their interrelationship. They include RFCs on the following topics:

a. security protocol -- RFCs describing Encapsulating Security Payload (ESP) [Ken05a].
b. cryptographic algorithms for integrity and encryption -- one RFC that defines the mandatory, default algorithms for use with ESP [Eas05], a similar RFC that defines the mandatory

algorithms for use with IKEv2 [Sch05] plus a separate RFC for each cryptographic algorithm.

c. automatic key management -- RFCs on "The Internet Key Exchange (IKEv2) Protocol" [Kau05] and "Cryptographic Algorithms for Use in the Internet Key Exchange Version 2 (IKEv2)" [Sch05].

2. Design Objectives

2.1. Goals/Objectives/Requirements/Problem Description

IPsec is designed to provide interoperable, high quality, cryptographically-based security for IPv4 and IPv6. The set of security services offered includes access control, connectionless integrity, data origin authentication, detection and rejection of replays (a form of partial sequence integrity), confidentiality (via encryption), and limited traffic flow confidentiality. These services are provided at the IP layer, offering protection in a standard fashion for all protocols that may be carried over IP (including IP itself).

IPsec includes a specification for minimal firewall functionality, since that is an essential aspect of access control at the IP layer. Implementations are free to provide more sophisticated firewall mechanisms, and to implement the IPsec-mandated functionality using those more sophisticated mechanisms. (Note that interoperability may suffer if additional firewall constraints on traffic flows are imposed by an IPsec implementation but cannot be negotiated based on the traffic selector features defined in this document and negotiated via IKEv2.) The IPsec firewall function makes use of the cryptographically-enforced authentication and integrity provided for all IPsec traffic to offer better access control than could be obtained through use of a firewall (one not privy to IPsec internal parameters) plus separate cryptographic protection.

Most of the security services are provided through use of the Encapsulating Security Payload (ESP), and through the use of cryptographic key management procedures and protocols. The set of IPsec protocols employed in a context, and the ways in which they are employed, will be determined by the users/administrators in that context. It is the goal of the IPsec architecture to ensure that compliant implementations include the services and management interfaces needed to meet the security requirements of a broad user population.

When IPsec is correctly implemented and deployed, it ought not adversely affect users, hosts, and other Internet components that do not employ IPsec for traffic protection. IPsec security protocols (ESP, and to a lesser extent, IKE) are designed to be cryptographic algorithm independent. This modularity permits selection of different sets of cryptographic algorithms as appropriate, without affecting the other parts of the implementation. For example, different user communities may select different sets of cryptographic algorithms (creating cryptographically-enforced cliques) if required.

To facilitate interoperability in the global Internet, a set of default cryptographic algorithms for use ESP is specified in [Eas05] and a set of mandatory-to-implement algorithms for IKEv2 is specified in [Sch05]. [Eas05] and [Sch05] will be periodically updated to keep pace with computational and cryptologic advances. By specifying these algorithms in documents that are separate from the ESP, and IKEv2 specifications, these algorithms can be updated or replaced without affecting the standardization progress of the rest of the IPsec document suite. The use of these cryptographic algorithms, in conjunction with IPsec traffic protection and key management protocols, is intended to permit system and application developers to deploy high quality, Internet-layer, cryptographic security technology.

2.2. Caveats and Assumptions

The suite of IPsec protocols and associated default cryptographic algorithms are designed to provide high quality security for Internet traffic. However, the security offered by use of these protocols ultimately depends on the quality of their implementation, which is outside the scope of this set of standards. Moreover, the security of a computer system or network is a function of many factors, including personnel, physical, procedural, compromising emanations, and computer security practices. Thus, IPsec is only one part of an overall system security architecture.

Finally, the security afforded by the use of IPsec is critically dependent on many aspects of the operating environment in which the IPsec implementation executes. For example, defects in OS security, poor quality of random number sources, sloppy system management protocols and practices, etc., can all degrade the security provided by IPsec. As above, none of these environmental attributes are within the scope of this or other IPsec standards.

3. System Overview

This section provides a high level description of how IPsec works, the components of the system, and how they fit together to provide the security services noted above. The goal of this description is to enable the reader to "picture" the overall process/system, see how it fits into the IP environment, and to provide context for later sections of this document, which describe each of the components in more detail.

An IPsec implementation operates in a host, as a security gateway (SG), or as an independent device, affording protection to IP traffic. (A security gateway is an intermediate system implementing IPsec, e.g., a firewall or router that has been IPsec-enabled.) More detail on these classes of implementations is provided later, in Section 3.3. The protection offered by IPsec is based on requirements defined by a Security Policy Database (SPD) established and maintained by a user or system administrator, or by an application operating within constraints established by either of the above. In

general, packets are selected for one of three processing actions based on IP and next layer header information ("Selectors", Section 4.4.1.1) matched against entries in the SPD. Each packet is either PROTECTed using IPsec security services, DISCARDed, or allowed to BYPASS IPsec protection, based on the applicable SPD policies identified by the Selectors.

3.1. What IPsec Does

IPsec creates a boundary between unprotected and protected interfaces, for a host or a network (see Figure 1 below). Traffic traversing the boundary is subject to the access controls specified by the user or administrator responsible for the IPsec configuration. These controls indicate whether packets cross the boundary unimpeded, are afforded security services via ESP, or are discarded.

IPsec security services are offered at the IP layer through selection of appropriate security protocols, cryptographic algorithms, and cryptographic keys. IPsec can be used to protect one or more "paths" between a pair of security gateways.

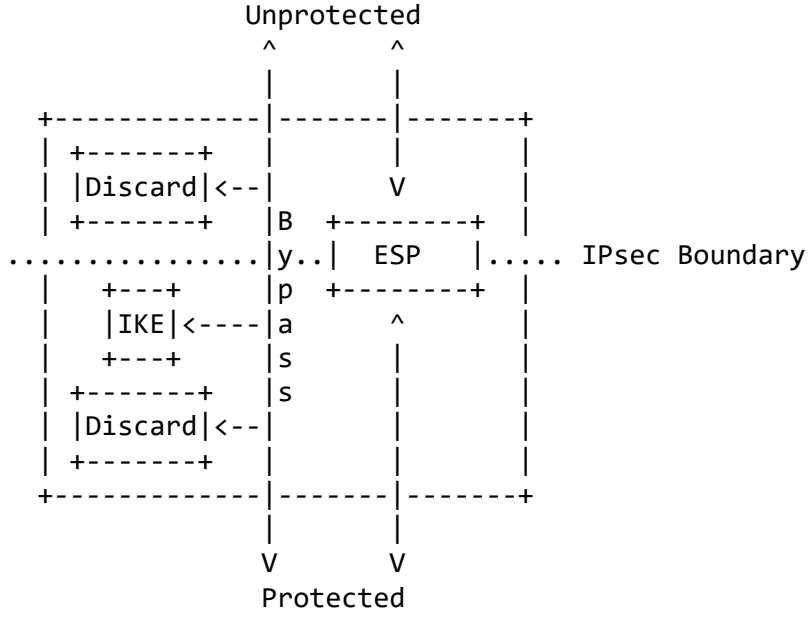


Figure 1. Top Level IPsec Processing Model

In this diagram, "unprotected" refers to an interface that might also be described as "black" or "ciphertext". Here, "protected" refers to an interface that might also be described as "red" or "plaintext". The protected interface noted above may be internal, e.g., in a host implementation of IPsec, the protected interface may link to a socket layer interface presented by the OS. In this document, the term "inbound" refers to traffic entering an IPsec implementation via the unprotected interface or emitted by the implementation on the unprotected side of the boundary and directed towards the protected interface. The term "outbound" refers to traffic entering the implementation via the protected interface, or emitted by the implementation on the protected side of the boundary and directed

toward the unprotected interface. An IPsec implementation may support more than one interface on either or both sides of the boundary.

Note the facilities for discarding traffic on either side of the IPsec boundary, the BYPASS facility that allows traffic to transit the boundary without cryptographic protection, and the reference to IKE as a protected-side key and security management function.

A conforming implementation MUST NOT support negotiation of IP compression (IPComp).

3.2. How IPsec Works

IPsec uses Encapsulating Security Payload (ESP) to provide traffic security services. This protocol is described in detail in [Ken05a] IPsec implementations MUST support ESP. It offers integrity, confidentiality and anti-replay features. ESP MUST NOT be used to provide confidentiality without integrity. When ESP is used with confidentiality enabled, there are provisions for limited traffic flow confidentiality, i.e., provisions for concealing packet length, and for facilitating efficient generation and discard of dummy packets. This capability is likely to be effective primarily in virtual private network (VPN) and overlay network contexts.

ESP also offers access control, enforced through the distribution of cryptographic keys and the management of traffic flows as dictated by the Security Policy Database (SPD, Section 4.4.1).

The tunnel mode MUST be the only supported mode. Transport mode MUST NOT be implemented.

IPsec allows the user (or system administrator) to control the granularity at which a security service is offered. For example, one can create a single encrypted tunnel to carry all the traffic between two security gateways, or a separate encrypted tunnel can be created for each TCP connection between each pair of hosts communicating across these gateways. IPsec, through the SPD management paradigm, incorporates facilities for specifying:

- which security service options to employ, what cryptographic algorithms to use

- the granularity at which protection should be applied.

Because most of the security services provided by IPsec require the use of cryptographic keys, IPsec relies on a separate set of mechanisms for putting these keys in place. This document requires support for both manual and automated distribution of keys. It specifies a specific public-key based approach (IKEv2 [Kau05]) for automated key management. Other automated key distribution techniques MUST NOT be used.

Note: This document mandates support for several features for which

support is available in IKEv2 but not in IKEv1, e.g., negotiation of an SA representing ranges of local and remote ports or negotiation of multiple SAs with the same selectors. Therefore, this document assumes use of IKEv2 or a key and security association management system with comparable features.

3.3. Where IPsec Can Be Implemented

There are many ways in which IPsec may be implemented in a host, or in conjunction with a router or firewall to create a security gateway, or as an independent security device.

a. IPsec may be integrated into the native IP stack. This requires access to the IP source code and is applicable to both hosts and security gateways, although native host implementations benefit the most from this strategy, as explained later (Section 4.4.1, paragraph 6; Section 4.4.1.1, last paragraph).

b. In a "bump-in-the-stack" (BITS) implementation, IPsec is implemented "underneath" an existing implementation of an IP protocol stack, between the native IP and the local network drivers. Source code access for the IP stack is not required in this context, making this implementation approach appropriate for use with legacy systems. This approach, when it is adopted, is usually employed in hosts.

c. The use of a dedicated, inline security protocol processor is a common design feature of systems used by the military, and of some commercial systems as well. It is sometimes referred to as a "bump-in-the-wire" (BITW) implementation. Such implementations may be designed to serve either a host or a gateway. Usually, the BITW device is itself IP addressable. When supporting a single host, it may be quite analogous to a BITS implementation, but in supporting a router or firewall, it must operate like a security gateway.

This document often talks in terms of use of IPsec by a host or a security gateway, without regard to whether the implementation is native, BITS, or BITW. When the distinctions among these implementation options are significant, the document makes reference to specific implementation approaches.

A security gateway might employ separate IPsec implementations to protect its management traffic and subscriber traffic. The architecture described in this document is very flexible. For example, a computer with a full-featured, compliant, native OS IPsec implementation should be capable of being configured to protect resident (host) applications and to provide security gateway protection for traffic traversing the computer. Such configuration would make use of the forwarding tables and the SPD selection function described in Sections 5.1 and 5.2.

4. Security Associations

This section defines Security Association management requirements for all IPv6 implementations and for those IPv4 implementations that implement ESP. The concept of a "Security Association" (SA) is fundamental to IPsec. ESP makes use of SAs, and a major function of IKE is the establishment and maintenance of SAs. All implementations of ESP MUST support the concept of an SA as described below. The remainder of this section describes various aspects of SA management, defining required characteristics for SA policy management and SA management techniques.

4.1. Definition and Scope

An SA is a simplex "connection" that affords security services to the traffic carried by it. Security services are afforded to an SA by the use of ESP. To secure typical, bi-directional communication between two IPsec-enabled systems, a pair of SAs (one in each direction) is required. IKE explicitly creates SA pairs in recognition of this common usage requirement.

For an SA used to carry unicast traffic, the Security Parameters Index (SPI) by itself suffices to specify an SA. (For information on the SPI, see Appendix A and the ESP specification [Ken05a].) If an IPsec implementation supports multicast, then it MUST support multicast SAs using the algorithm below for mapping inbound IPsec datagrams to SAs. Implementations that support only unicast traffic need not implement this demultiplexing algorithm.

In many secure multicast architectures, e.g., [RFC3740], a central Group Controller/Key Server unilaterally assigns the Group Security Association's (GSA's) SPI. This SPI assignment is not negotiated or coordinated with the key management (e.g., IKE) subsystems that reside in the individual end systems that constitute the group. Consequently, it is possible that a GSA and a unicast SA can simultaneously use the same SPI. A multicast-capable IPsec implementation MUST correctly de-multiplex inbound traffic even in the context of SPI collisions.

Each entry in the SA Database (SAD) (Section 4.4.2) must indicate whether the SA lookup makes use of the destination IP address, or the destination and source IP addresses, in addition to the SPI. For multicast SAs, the protocol field is not employed for SA lookups. For each inbound, IPsec-protected packet, an implementation must conduct its search of the SAD such that it finds the entry that matches the "longest" SA identifier. In this context, if two or more SAD entries match based on the SPI value, then the entry that also matches based on destination address, or destination and source address (as indicated in the SAD entry) is the "longest" match. This implies a logical ordering of the SAD search as follows:

1. Search the SAD for a match on the combination of SPI, destination address, and source address. If an SAD entry matches, then process the inbound packet with that matching SAD entry. Otherwise, proceed to step 2.

2. Search the SAD for a match on both SPI and destination address. If the SAD entry matches, then process the inbound packet with that matching SAD entry. Otherwise, proceed to step 3.

3. Search the SAD for a match on only SPI. If an SAD entry matches, then process the inbound packet with that matching SAD entry. Otherwise, discard the packet and log an auditable event.

In practice, an implementation may choose any method (or none at all) to accelerate this search, although its externally visible behavior MUST be functionally equivalent to having searched the SAD in the above order. For example, a software-based implementation could index into a hash table by the SPI. The SAD entries in each hash table bucket's linked list could be kept sorted to have those SAD entries with the longest SA identifiers first in that linked list. Those SAD entries having the shortest SA identifiers could be sorted so that they are the last entries in the linked list. A hardware-based implementation may be able to effect the longest match search intrinsically, using commonly available Ternary Content-Addressable Memory (TCAM) features.

The indication of whether source and destination address matching is required to map inbound IPsec traffic to SAs MUST be set either as a side effect of manual SA configuration or via negotiation using an SA management protocol, e.g., IKE or Group Domain of Interpretation (GDOI) [RFC3547]. Typically, Source-Specific Multicast (SSM) [HC03] groups use a 3-tuple SA identifier composed of an SPI, a destination multicast address, and source address. An Any-Source Multicast group SA requires only an SPI and a destination multicast address as an identifier.

If different classes of traffic (distinguished by Differentiated Services Code Point (DSCP) bits [NiBlBaBL98], [Gro02]) are sent on the same SA, this could result in inappropriate discarding of lower priority packets due to the windowing mechanism used by the anti-replay feature. Therefore, a sender SHOULD put traffic of different classes, but with the same selector values, on different SAs to support Quality of Service (QoS) appropriately. To permit this, the IPsec implementation MUST permit establishment and maintenance of multiple SAs between a given sender and receiver, with the same selectors. Distribution of traffic among these parallel SAs to support QoS is locally determined by the sender and is not negotiated by IKE. The receiver MUST process the packets from the different SAs without prejudice.

DISCUSSION: Although the DSCP [NiBlBaBL98, Gro02] and Explicit Congestion Notification (ECN) [RaFlBl01] fields are not "selectors", as that term in used in this architecture, the sender will need a mechanism to direct packets with a given (set of) DSCP values to the appropriate SA. This mechanism might be termed a "classifier".

A tunnel mode SA is essentially an SA applied to an IP tunnel, with the access controls applied to the headers of the traffic inside the tunnel. Two hosts MAY establish a tunnel mode SA between themselves.

Aside from the two exceptions below, whenever either end of a security association is a security gateway, the SA MUST be tunnel mode. Thus, an SA between two security gateways is typically a tunnel mode SA, as is an SA between a host and a security gateway.

Several concerns motivate the use of tunnel mode for an SA involving a security gateway. For example, if there are multiple paths (e.g., via different security gateways) to the same destination behind a security gateway, it is important that an IPsec packet be sent to the security gateway with which the SA was negotiated. Similarly, a packet that might be fragmented en route must have all the fragments delivered to the same IPsec instance for reassembly prior to cryptographic processing. Also, when a fragment is processed by IPsec and transmitted, then fragmented en route, it is critical that there be inner and outer headers to retain the fragmentation state data for the pre- and post-IPsec packet formats. Hence there are several reasons for employing tunnel mode when either end of an SA is a security gateway.

For a tunnel mode SA, there is an "outer" IP header that specifies the IPsec processing source and destination, plus an "inner" IP header that specifies the (apparently) ultimate source and destination for the packet. The security protocol header appears after the outer IP header, and before the inner IP header. The protection is afforded only to the tunneled packet, not to the outer header.

A conforming implementation MUST NOT implement transport mode SA.

4.2. SA Functionality

The set of security services offered by an SA depends on the security mode, the endpoints of the SA, and the election of optional services within the protocol.

ESP offers integrity and authentication services, but the coverage differs depending on the mode. If the integrity of an IPv4 option or IPv6 extension header must be protected en route between sender and receiver, then ESP MUST be used in the tunnel mode.

The granularity of access control provided is determined by the choice of the selectors that define each SA. Moreover, the authentication means employed by IPsec peers, e.g., during creation of an IKE (vs. child) SA also affects the granularity of the access control afforded.

ESP (tunnel mode) SA between two security gateways can offer partial traffic flow confidentiality. The use of tunnel mode allows the inner IP headers to be encrypted, concealing the identities of the (ultimate) traffic source and destination. Moreover, ESP payload padding also can be invoked to hide the size of the packets, further concealing the external characteristics of the traffic. Similar traffic flow confidentiality services may be offered when a mobile user is assigned a dynamic IP address in a dialup context, and

establishes a (tunnel mode) ESP SA to a corporate firewall (acting as a security gateway). Note that fine-granularity SAs generally are more vulnerable to traffic analysis than coarse-granularity ones that are carrying traffic from many subscribers.

Note: A compliant implementation MUST NOT allow instantiation of an ESP SA that employs NULL encryption or no integrity algorithm. An attempt to negotiate such an SA is an auditable event by both initiator and responder. The audit log entry for this event SHOULD include the current date/time, local IKE IP address, and remote IKE IP address. The initiator SHOULD record the relevant SPD entry.

4.3. Combining SAs

An implementation MUST NOT provide support for nested SAs.

4.4. Major IPsec Databases

Many of the details associated with processing IP traffic in an IPsec implementation are largely a local matter, not subject to standardization. However, some external aspects of the processing must be standardized to ensure interoperability and to provide a minimum management capability that is essential for productive use of IPsec. This section describes a general model for processing IP traffic relative to IPsec functionality, in support of these interoperability and functionality goals. The model described below is nominal; implementations need not match details of this model as presented, but the external behavior of implementations MUST correspond to the externally observable characteristics of this model in order to be compliant.

There are three nominal databases in this model: the Security Policy Database (SPD), the Security Association Database (SAD), and the Peer Authorization Database (PAD). The first specifies the policies that determine the disposition of all IP traffic inbound or outbound from a host or security gateway (Section 4.4.1). The second database contains parameters that are associated with each established (keyed) SA (Section 4.4.2). The third database, the PAD, provides a link between an SA management protocol (such as IKE) and the SPD (Section 4.4.3).

Multiple Separate IPsec Contexts

If an IPsec implementation acts as a security gateway for multiple subscribers, it MAY implement multiple separate IPsec contexts. Each context MAY have and MAY use completely independent identities, policies, key management SAs, and/or IPsec SAs. This is for the most part a local implementation matter. However, a means for associating inbound (SA) proposals with local contexts is required. To this end, if supported by the key management protocol in use, context identifiers MAY be conveyed from initiator to responder in the signaling messages, with the result that IPsec SAs are created with a binding to a particular context. For example, a security gateway that provides VPN service to

multiple customers will be able to associate each customer's traffic with the correct VPN.

Forwarding vs Security Decisions

The IPsec model described here embodies a clear separation between forwarding (routing) and security decisions, to accommodate a wide range of contexts where IPsec may be employed. Forwarding may be trivial, in the case where there are only two interfaces, or it may be complex, e.g., if the context in which IPsec is implemented employs a sophisticated forwarding function. IPsec assumes only that outbound and inbound traffic that has passed through IPsec processing is forwarded in a fashion consistent with the context in which IPsec is implemented. Support for nested SAs is optional; if required, it requires coordination between forwarding tables and SPD entries to cause a packet to traverse the IPsec boundary more than once.

"Local" vs "Remote"

In this document, with respect to IP addresses and ports, the terms "Local" and "Remote" are used for policy rules. "Local" refers to the entity being protected by an IPsec implementation, i.e., the "source" address/port of outbound packets or the "destination" address/port of inbound packets. "Remote" refers to a peer entity or peer entities. The terms "source" and "destination" are used for packet header fields.

"Non-initial" vs "Initial" Fragments

Throughout this document, the phrase "non-initial fragments" is used to mean fragments that do not contain all of the selector values that may be needed for access control (e.g., they might not contain Next Layer Protocol, source and destination ports, ICMP message type/code, Mobility Header type). And the phrase "initial fragment" is used to mean a fragment that contains all the selector values needed for access control. However, it should be noted that for IPv6, which fragment contains the Next Layer Protocol and ports (or ICMP message type/code or Mobility Header type [Mobip]) will depend on the kind and number of extension headers present. The "initial fragment" might not be the first fragment, in this context.

4.4.1. The Security Policy Database (SPD)

An SA is a management construct used to enforce security policy for traffic crossing the IPsec boundary. Thus, an essential element of SA processing is an underlying Security Policy Database (SPD) that specifies what services are to be offered to IP datagrams and in what fashion. The form of the database and its interface are outside the scope of this specification. However, this section specifies minimum management functionality that must be provided, to allow a user or system administrator to control whether and how IPsec is applied to traffic transmitted or received by a host or transiting a security

gateway. The SPD, or relevant caches, must be consulted during the processing of all traffic (inbound and outbound), including traffic not protected by IPsec, that traverses the IPsec boundary. This includes IPsec management traffic such as IKE. An IPsec implementation MUST have at least one SPD, and it MAY support multiple SPDs, if appropriate for the context in which the IPsec implementation operates. There is no requirement to maintain SPDs on a per-interface basis, as was specified in RFC 2401 [RFC2401]. However, if an implementation supports multiple SPDs, then it MUST include an explicit SPD selection function that is invoked to select the appropriate SPD for outbound traffic processing. The inputs to this function are the outbound packet and any local metadata (e.g., the interface via which the packet arrived) required to effect the SPD selection function. The output of the function is an SPD identifier (SPD-ID).

The SPD is an ordered database, consistent with the use of Access Control Lists (ACLs) or packet filters in firewalls, routers, etc. The ordering requirement arises because entries often will overlap due to the presence of (non-trivial) ranges as values for selectors. Thus, a user or administrator MUST be able to order the entries to express a desired access control policy. There is no way to impose a general, canonical order on SPD entries, because of the allowed use of wildcards for selector values and because the different types of selectors are not hierarchically related.

Processing Choices: DISCARD, BYPASS, PROTECT

> An SPD must discriminate among traffic that is afforded IPsec protection and traffic that is allowed to bypass IPsec. This applies to the IPsec protection to be applied by a sender and to the IPsec protection that must be present at the receiver. For any outbound or inbound datagram, three processing choices are possible: DISCARD, BYPASS IPsec, or PROTECT using IPsec. The first choice refers to traffic that is not allowed to traverse the IPsec boundary (in the specified direction). The second choice refers to traffic that is allowed to cross the IPsec boundary without IPsec protection. The third choice refers to traffic that is afforded IPsec protection, and for such traffic the SPD must specify the security service options to be employed, and the cryptographic algorithms to be used.

SPD-S, SPD-I, SPD-O

> An SPD is logically divided into three pieces. The SPD-S (secure traffic) contains entries for all traffic subject to IPsec protection. SPD-O (outbound) contains entries for all outbound traffic that is to be bypassed or discarded. SPD-I (inbound) is applied to inbound traffic that will be bypassed or discarded. All three of these can be decorrelated (with the exception noted above for native host implementations) to facilitate caching. If an IPsec implementation supports only one SPD, then the SPD consists of all three parts. If multiple SPDs are supported, some of them may be partial, e.g., some SPDs might contain only SPD-I

entries, to control inbound bypassed traffic on a per-interface basis. The split allows SPD-I to be consulted without having to consult SPD-S, for such traffic. Since the SPD-I is just a part of the SPD, if a packet that is looked up in the SPD-I cannot be matched to an entry there, then the packet MUST be discarded. Note that for outbound traffic, if a match is not found in SPD-S, then SPD-O must be checked to see if the traffic should be bypassed. The SPD-S MUST be checked before the SPD-O. In an ordered, non-decorrelated SPD, the entries for the SPD-S, SPD-I, and SPD-O are interleaved. So there is one lookup in the SPD.

SPD Entries

Each SPD entry specifies packet disposition as BYPASS, DISCARD, or PROTECT. The entry is keyed by a list of one or more selectors. The SPD contains an ordered list of these entries. The required selector types are defined in Section 4.4.1.1. These selectors are used to define the granularity of the SAs that are created in response to an outbound packet or in response to a proposal from a peer. The detailed structure of an SPD entry is described in Section 4.4.1.2. Every SPD SHOULD have a nominal, final entry that matches anything that is otherwise unmatched, and discards it.

The SPD MUST permit a user or administrator to specify policy entries as follows:

- SPD-I: For inbound traffic that is to be bypassed or discarded, the entry consists of the values of the selectors that apply to the traffic to be bypassed or discarded.

- SPD-O: For outbound traffic that is to be bypassed or discarded, the entry consists of the values of the selectors that apply to the traffic to be bypassed or discarded.

- SPD-S: For traffic that is to be protected using IPsec, the entry consists of the values of the selectors that apply to the traffic to be protected via ESP, controls on how to create SAs based on these selectors, and the parameters needed to effect this protection (e.g., algorithms, etc.). Note that an SPD-S entry also contains information such as "populate from packet" (PFP) flag (see paragraphs below on "How To Derive the Values for an SAD entry") and bits indicating whether the SA lookup makes use of the local and remote IP addresses in addition to the SPI (see ESP [Ken05a] specifications).

Representing Directionality in an SPD Entry

For traffic protected by IPsec, the Local and Remote address and ports in an SPD entry are swapped to represent directionality, consistent with IKE conventions. In general, the protocols that IPsec deals with have the property of requiring symmetric SAs with flipped Local/Remote IP addresses. However, for ICMP, there is often no such bi-directional authorization requirement. Nonetheless, for the sake of uniformity and simplicity, SPD

entries for ICMP are specified in the same way as for other protocols. Note also that for ICMP, Mobility Header, and non-initial fragments, there are no port fields in these packets. ICMP has message type and code and Mobility Header has mobility header type. Thus, SPD entries have provisions for expressing access controls appropriate for these protocols, in lieu of the normal port field controls. For bypassed or discarded traffic, separate inbound and outbound entries are supported, e.g., to permit unidirectional flows if required.

OPAQUE and ANY

For each selector in an SPD entry, in addition to the literal values that define a match, there are two special values: ANY and OPAQUE. ANY is a wildcard that matches any value in the corresponding field of the packet, or that matches packets where that field is not present or is obscured. OPAQUE indicates that the corresponding selector field is not available for examination because it may not be present in a fragment, it does not exist for the given Next Layer Protocol, or prior application of IPsec may have encrypted the value. The ANY value encompasses the OPAQUE value. Thus, OPAQUE need be used only when it is necessary to distinguish between the case of any allowed value for a field, vs. the absence or unavailability (e.g., due to encryption) of the field.

How to Derive the Values for an SAD Entry

For each selector in an SPD entry, the entry specifies how to derive the corresponding values for a new SA Database (SAD, see Section 4.4.2) entry from those in the SPD and the packet. The goal is to allow an SAD entry and an SPD cache entry to be created based on specific selector values from the packet, or from the matching SPD entry. For outbound traffic, there are SPD-S cache entries and SPD-O cache entries. For inbound traffic not protected by IPsec, there are SPD-I cache entries and there is the SAD, which represents the cache for inbound IPsec-protected traffic (see Section 4.4.2). If IPsec processing is specified for an entry, a "populate from packet" (PFP) flag may be asserted for one or more of the selectors in the SPD entry (Local IP address; Remote IP address; Next Layer Protocol; and, depending on Next Layer Protocol, Local port and Remote port, or ICMP type/code, or Mobility Header type). If asserted for a given selector X, the flag indicates that the SA to be created should take its value for X from the value in the packet. Otherwise, the SA should take its value(s) for X from the value(s) in the SPD entry. Note: In the non-PFP case, the selector values negotiated by the SA management protocol (e.g., IKEv2) may be a subset of those in the SPD entry, depending on the SPD policy of the peer. Also, whether a single flag is used for, e.g., source port, ICMP type/code, and Mobility Header (MH) type, or a separate flag is used for each, is a local matter.

The following example illustrates the use of the PFP flag in the

context of a security gateway or a BITS/BITW implementation. Consider an SPD entry where the allowed value for Remote address is a range of IPv4 addresses: 192.0.2.1 to 192.0.2.10. Suppose an outbound packet arrives with a destination address of 192.0.2.3, and there is no extant SA to carry this packet. The value used for the SA created to transmit this packet could be either of the two values shown below, depending on what the SPD entry for this selector says is the source of the selector value:

PFP flag value for the Remote addr. selector	example of new SAD dest. address selector value
a. PFP TRUE	192.0.2.3 (one host)
b. PFP FALSE	192.0.2.1 to 192.0.2.10 (range of hosts)

Note that if the SPD entry above had a value of ANY for the Remote address, then the SAD selector value would have to be ANY for case (b), but would still be as illustrated for case (a). Thus, the PFP flag can be used to prohibit sharing of an SA, even among packets that match the same SPD entry.

Management Interface

For every IPsec implementation, there MUST be a management interface that allows a user or system administrator to manage the SPD. The interface must allow the user (or administrator) to specify the security processing to be applied to every packet that traverses the IPsec boundary. (In a native host IPsec implementation making use of a socket interface, the SPD may not need to be consulted on a per-packet basis, as noted at the end of Section 4.4.1.1 and in Section 5.) The management interface for the SPD MUST allow creation of entries consistent with the selectors defined in Section 4.4.1.1, and MUST support (total) ordering of these entries, as seen via this interface. The SPD entries' selectors are analogous to the ACL or packet filters commonly found in a stateless firewall or packet filtering router and which are currently managed this way.

In host systems, applications MAY be allowed to create SPD entries. (The means of signaling such requests to the IPsec implementation are outside the scope of this standard.) However, the system administrator MUST be able to specify whether or not a user or application can override (default) system policies. The form of the management interface is not specified by this document and may differ for hosts vs. security gateways, and within hosts the interface may differ for socket-based vs. BITS implementations. However, this document does specify a standard set of SPD elements that all IPsec implementations MUST support.

Decorrelation

The processing model described in this document assumes the ability to decorrelate overlapping SPD entries to permit caching,

which enables more efficient processing of outbound traffic in security gateways and BITS/BITW implementations. Decorrelation [CoSa04] is only a means of improving performance and simplifying the processing description. This RFC does not require a compliant implementation to make use of decorrelation. For example, native host implementations typically make use of caching implicitly because they bind SAs to socket interfaces, and thus there is no requirement to be able to decorrelate SPD entries in these implementations.

Note: Unless otherwise qualified, the use of "SPD" refers to the body of policy information in both ordered or decorrelated (unordered) state. Appendix B provides an algorithm that can be used to decorrelate SPD entries, but any algorithm that produces equivalent output may be used. Note that when an SPD entry is decorrelated all the resulting entries MUST be linked together, so that all members of the group derived from an individual, SPD entry (prior to decorrelation) can all be placed into caches and into the SAD at the same time. For example, suppose one starts with an entry A (from an ordered SPD) that when decorrelated, yields entries A1, A2, and A3. When a packet comes along that matches, say A2, and triggers the creation of an SA, the SA management protocol (e.g., IKEv2) negotiates A. And all 3 decorrelated entries, A1, A2, and A3, are placed in the appropriate SPD-S cache and linked to the SA. The intent is that use of a decorrelated SPD ought not to create more SAs than would have resulted from use of a not-decorrelated SPD.

If a decorrelated SPD is employed, there are three options for what an initiator sends to a peer via an SA management protocol (e.g., IKE). By sending the complete set of linked, decorrelated entries that were selected from the SPD, a peer is given the best possible information to enable selection of the appropriate SPD entry at its end, especially if the peer has also decorrelated its SPD. However, if a large number of decorrelated entries are linked, this may create large packets for SA negotiation, and hence fragmentation problems for the SA management protocol.

Alternatively, the original entry from the (correlated) SPD may be retained and passed to the SA management protocol. Passing the correlated SPD entry keeps the use of a decorrelated SPD a local matter, not visible to peers, and avoids possible fragmentation concerns, although it provides less precise information to a responder for matching against the responder's SPD.

An intermediate approach is to send a subset of the complete set of linked, decorrelated SPD entries. This approach can avoid the fragmentation problems cited above yet provide better information than the original, correlated entry. The major shortcoming of this approach is that it may cause additional SAs to be created later, since only a subset of the linked, decorrelated entries are sent to a peer. Implementers are free to employ any of the approaches cited above.

A responder uses the traffic selector proposals it receives via an SA management protocol to select an appropriate entry in its SPD. The intent of the matching is to select an SPD entry and create an SA that most closely matches the intent of the initiator, so that traffic traversing the resulting SA will be accepted at both ends. If the responder employs a decorrelated SPD, it SHOULD use the decorrelated SPD entries for matching, as this will generally result in creation of SAs that are more likely to match the intent of both peers. If the responder has a correlated SPD, then it SHOULD match the proposals against the correlated entries. For IKEv2, use of a decorrelated SPD offers the best opportunity for a responder to generate a "narrowed" response.

In all cases, when a decorrelated SPD is available, the decorrelated entries are used to populate the SPD-S cache. If the SPD is not decorrelated, caching is not allowed and an ordered search of SPD MUST be performed to verify that inbound traffic arriving on an SA is consistent with the access control policy expressed in the SPD.

Handling Changes to the SPD While the System Is Running

If a change is made to the SPD while the system is running, a check SHOULD be made of the effect of this change on extant SAs. An implementation SHOULD check the impact of an SPD change on extant SAs and SHOULD provide a user/administrator with a mechanism for configuring what actions to take, e.g., delete an affected SA, allow an affected SA to continue unchanged, etc.

4.4.1.1. Selectors

An SA may be fine-grained or coarse-grained, depending on the selectors used to define the set of traffic for the SA. For example, all traffic between two hosts may be carried via a single SA, and afforded a uniform set of security services. Alternatively, traffic between a pair of hosts might be spread over multiple SAs, depending on the applications being used (as defined by the Next Layer Protocol and related fields, e.g., ports), with different security services offered by different SAs. Similarly, all traffic between a pair of security gateways could be carried on a single SA, or one SA could be assigned for each communicating host pair. The following selector parameters MUST be supported by all IPsec implementations to facilitate control of SA granularity. Note that both Local and Remote addresses should either be IPv4 or IPv6, but not a mix of address types. Also, note that the Local/Remote port selectors (and ICMP message type and code, and Mobility Header type) may be labeled as OPAQUE to accommodate situations where these fields are inaccessible due to packet fragmentation.

- Remote IP Address(es) (IPv4 or IPv6): This is a list of ranges of IP addresses (unicast, broadcast (IPv4 only)). This structure allows expression of a single IP address (via a trivial range), or a list of addresses (each a trivial range), or a range of addresses (low and high values, inclusive), as

well as the most generic form of a list of ranges. Address ranges are used to support more than one remote system sharing the same SA, e.g., behind a security gateway.

- Local IP Address(es) (IPv4 or IPv6): This is a list of ranges of IP addresses (unicast, broadcast (IPv4 only)). This structure allows expression of a single IP address (via a trivial range), or a list of addresses (each a trivial range), or a range of addresses (low and high values, inclusive), as well as the most generic form of a list of ranges. Address ranges are used to support more than one source system sharing the same SA, e.g., behind a security gateway. Local refers to the address(es) being protected by this implementation (or policy entry).

  Note: The SPD does not include support for multicast address entries. To support multicast SAs, an implementation should make use of a Group SPD (GSPD) as defined in [RFC3740]. GSPD entries require a different structure, i.e., one cannot use the symmetric relationship associated with local and remote address values for unicast SAs in a multicast context. Specifically, outbound traffic directed to a multicast address on an SA would not be received on a companion, inbound SA with the multicast address as the source.

- Next Layer Protocol: Obtained from the IPv4 "Protocol" or the IPv6 "Next Header" fields. This is an individual protocol number, ANY, or for IPv6 only, OPAQUE. The Next Layer Protocol is whatever comes after any IP extension headers that are present. To simplify locating the Next Layer Protocol, there SHOULD be a mechanism for configuring which IPv6 extension headers to skip. The default configuration for which protocols to skip SHOULD include the following protocols: 0 (Hop-by-hop options), 43 (Routing Header), 44 (Fragmentation Header), and 60 (Destination Options). Note: The default list does NOT include 50 (ESP). From a selector lookup point of view, IPsec treats ESP as Next Layer Protocols.

  Several additional selectors depend on the Next Layer Protocol value:

  * If the Next Layer Protocol uses two ports (as do TCP, UDP, SCTP, and others), then there are selectors for Local and Remote Ports. Each of these selectors has a list of ranges of values. Note that the Local and Remote ports may not be available in the case of receipt of a fragmented packet or if the port fields have been protected by IPsec (encrypted); thus, a value of OPAQUE also MUST be supported. Note: In a non-initial fragment, port values will not be available. If a port selector specifies a value other than ANY or OPAQUE, it cannot match packets that are non-initial fragments. If the SA requires a port value other than ANY or OPAQUE, an arriving fragment without ports MUST be discarded. (See Section 7, "Handling Fragments".)

* If the Next Layer Protocol is a Mobility Header, then there is a selector for IPv6 Mobility Header message type (MH type) [Mobip]. This is an 8-bit value that identifies a particular mobility message. Note that the MH type may not be available in the case of receipt of a fragmented packet. (See Section 7, "Handling Fragments".) For IKE, the IPv6 Mobility Header message type (MH type) is placed in the most significant eight bits of the 16-bit local "port" selector.

* If the Next Layer Protocol value is ICMP, then there is a 16-bit selector for the ICMP message type and code. The message type is a single 8-bit value, which defines the type of an ICMP message, or ANY. The ICMP code is a single 8-bit value that defines a specific subtype for an ICMP message. For IKE, the message type is placed in the most significant 8 bits of the 16-bit selector and the code is placed in the least significant 8 bits. This 16-bit selector can contain a single type and a range of codes, a single type and ANY code, and ANY type and ANY code. Given a policy entry with a range of Types (T-start to T-end) and a range of Codes (C-start to C-end), and an ICMP packet with Type t and Code c, an implementation MUST test for a match using

    (T-start*256) + C-start <= (t*256) + c <= (T-end*256) + C-end

  Note that the ICMP message type and code may not be available in the case of receipt of a fragmented packet. (See Section 7, "Handling Fragments".)

- Name: This is not a selector like the others above. It is not acquired from a packet. A name may be used as a symbolic identifier for an IPsec Local or Remote address. Named SPD entries are used in two ways:

  1. A named SPD entry is used by a responder (not an initiator) in support of access control when an IP address would not be appropriate for the Remote IP address selector, e.g., for "road warriors". The name used to match this field is communicated during the IKE negotiation in the ID payload. In this context, the initiator's Source IP address (inner IP header in tunnel mode) is bound to the Remote IP address in the SAD entry created by the IKE negotiation. This address overrides the Remote IP address value in the SPD, when the SPD entry is selected in this fashion. All IPsec implementations MUST support this use of names.

  2. A named SPD entry may be used by an initiator to identify a user for whom an IPsec SA will be created (or for whom traffic may be bypassed). The initiator's IP source address (from inner IP header in tunnel mode) is used to replace the following if and when they are created:

     - local address in the SPD cache entry

- local address in the outbound SAD entry
- remote address in the inbound SAD entry

Support for this use is optional for multi-user, native host implementations and not applicable to other implementations. Note that this name is used only locally; it is not communicated by the key management protocol. Also, name forms other than those used for case 1 above (responder) are applicable in the initiator context (see below).

An SPD entry can contain both a name (or a list of names) and also values for the Local or Remote IP address.

For case 1, responder, the identifiers employed in named SPD entries are one of the following four types:

a. a fully qualified user name string (email), e.g., mozart@foo.example.com
(this corresponds to ID_RFC822_ADDR in IKEv2)

b. a fully qualified DNS name, e.g., foo.example.com
(this corresponds to ID_FQDN in IKEv2)

c. X.500 distinguished name, e.g., [WaKiHo97], CN = Stephen T. Kent, O = BBN Technologies, SP = MA, C = US
(this corresponds to ID_DER_ASN1_DN in IKEv2, after decoding)

d. a byte string
(this corresponds to Key_ID in IKEv2)

For case 2, initiator, the identifiers employed in named SPD entries are of type byte string. They are likely to be Unix UIDs, Windows security IDs, or something similar, but could also be a user name or account name. In all cases, this identifier is only of local concern and is not transmitted.

The IPsec implementation context determines how selectors are used. For example, a native host implementation typically makes use of a socket interface. When a new connection is established, the SPD can be consulted and an SA bound to the socket. Thus, traffic sent via that socket need not result in additional lookups to the SPD (SPD-O and SPD-S) cache. In contrast, a BITS, BITW, or security gateway implementation needs to look at each packet and perform an SPD-O/SPD-S cache lookup based on the selectors.

4.4.1.2. Structure of an SPD Entry

This section contains a prose description of an SPD entry. Also, Appendix C provides an example of an ASN.1 definition of an SPD entry.

This text describes the SPD in a fashion that is intended to map directly into IKE payloads to ensure that the policy required by SPD entries can be negotiated through IKE. Unfortunately, the semantics of the version of IKEv2 published concurrently with this document [Kau05] do not align precisely with those defined for the SPD. Specifically, IKEv2 does not enable negotiation of a single SA that binds multiple pairs of local and remote addresses and ports to a single SA. Instead, when multiple local and remote addresses and ports are negotiated for an SA, IKEv2 treats these not as pairs, but as (unordered) sets of local and remote values that can be arbitrarily paired. Until IKE provides a facility that conveys the semantics that are expressed in the SPD via selector sets (as described below), users MUST NOT include multiple selector sets in a single SPD entry unless the access control intent aligns with the IKE "mix and match" semantics. An implementation MAY warn users, to alert them to this problem if users create SPD entries with multiple selector sets, the syntax of which indicates possible conflicts with current IKE semantics.

The management GUI can offer the user other forms of data entry and display, e.g., the option of using address prefixes as well as ranges, and symbolic names for protocols, ports, etc. (Do not confuse the use of symbolic names in a management interface with the SPD selector "Name".) Note that Remote/Local apply only to IP addresses and ports, not to ICMP message type/code or Mobility Header type. Also, if the reserved, symbolic selector value OPAQUE or ANY is employed for a given selector type, only that value may appear in the list for that selector, and it must appear only once in the list for that selector. Note that ANY and OPAQUE are local syntax conventions -- IKEv2 negotiates these values via the ranges indicated below:

```
ANY:     start = 0        end = <max>
OPAQUE:  start = <max>    end = 0
```

An SPD is an ordered list of entries each of which contains the following fields.

- Name -- a list of IDs. This quasi-selector is optional. The forms that MUST be supported are described above in Section 4.4.1.1 under "Name".

- PFP flags -- one per traffic selector. A given flag, e.g., for Next Layer Protocol, applies to the relevant selector across all "selector sets" (see below) contained in an SPD entry. When creating an SA, each flag specifies for the corresponding traffic selector whether to instantiate the selector from the corresponding field in the packet that triggered the creation of the SA or from the value(s) in the corresponding SPD entry (see Section 4.4.1, "How to Derive the Values for an SAD Entry"). Whether a single flag is used for, e.g., source port, ICMP type/code, and MH type, or a separate flag is used for each, is a local matter. There are PFP flags for:
  - Local Address

- Remote Address
- Next Layer Protocol
- Local Port, or ICMP message type/code or Mobility Header type (depending on the next layer protocol)
- Remote Port, or ICMP message type/code or Mobility Header type (depending on the next layer protocol)

o One to N selector sets that correspond to the "condition" for applying a particular IPsec action. Each selector set contains:
  - Local Address
  - Remote Address
  - Next Layer Protocol
  - Local Port, or ICMP message type/code or Mobility Header type (depending on the next layer protocol)
  - Remote Port, or ICMP message type/code or Mobility Header type (depending on the next layer protocol)

  Note: The "next protocol" selector is an individual value (unlike the local and remote IP addresses) in a selector set entry. This is consistent with how IKEv2 negotiates the Traffic Selector (TS) values for an SA. It also makes sense because one may need to associate different port fields with different protocols. It is possible to associate multiple protocols (and ports) with a single SA by specifying multiple selector sets for that SA.

o Processing info -- which action is required -- PROTECT, BYPASS, or DISCARD. There is just one action that goes with all the selector sets, not a separate action for each set. If the required processing is PROTECT, the entry contains the following information.
  - IPsec mode -- tunnel
  - local tunnel address -- For a non-mobile host, if there is just one interface, this is straightforward; if there are multiple interfaces, this must be statically configured. For a mobile host, the specification of the local address is handled externally to IPsec.
  - remote tunnel address -- There is no standard way to determine this. See 4.5.3, "Locating a Security Gateway".
  - Extended Sequence Number -- Is this SA using extended sequence numbers?
  - stateful fragment checking -- Is this SA using stateful fragment checking? (See Section 7 for more details.)
  - Bypass DF bit (T/F) -- applicable to tunnel mode SAs
  - Bypass DSCP (T/F) or map to unprotected DSCP values (array) if needed to restrict bypass of DSCP values -- applicable to tunnel mode SAs
  - IPsec protocol -- ESP
  - algorithms -- which ones to use for ESP, which ones to use for combined mode, ordered by decreasing priority

It is a local matter as to what information is kept with regard to handling extant SAs when the SPD is changed.

4.4.1.3. More Regarding Fields Associated with Next Layer Protocols

Additional selectors are often associated with fields in the Next Layer Protocol header. A particular Next Layer Protocol can have zero, one, or two selectors. There may be situations where there aren't both local and remote selectors for the fields that are dependent on the Next Layer Protocol. The IPv6 Mobility Header has only a Mobility Header message type. ESP have no further selector fields. A system may be willing to send an ICMP message type and code that it does not want to receive. In the descriptions below, "port" is used to mean a field that is dependent on the Next Layer Protocol.

A. If a Next Layer Protocol has no "port" selectors, then the Local and Remote "port" selectors are set to OPAQUE in the relevant SPD entry, e.g.,

```
Local's
  next layer protocol = ESP
  "port" selector     = OPAQUE

Remote's
  next layer protocol = ESP
  "port" selector     = OPAQUE
```

B. Even if a Next Layer Protocol has only one selector, e.g., Mobility Header type, then the Local and Remote "port" selectors are used to indicate whether a system is willing to send and/or receive traffic with the specified "port" values. For example, if Mobility Headers of a specified type are allowed to be sent and received via an SA, then the relevant SPD entry would be set as follows:

```
Local's
  next layer protocol = Mobility Header
  "port" selector     = Mobility Header message type

Remote's
  next layer protocol = Mobility Header
  "port" selector     = Mobility Header message type
```

If Mobility Headers of a specified type are allowed to be sent but NOT received via an SA, then the relevant SPD entry would be set as follows:

```
Local's
  next layer protocol = Mobility Header
  "port" selector     = Mobility Header message type

Remote's
  next layer protocol = Mobility Header
```

```
  "port" selector     = OPAQUE
```

If Mobility Headers of a specified type are allowed to be received but NOT sent via an SA, then the relevant SPD entry would be set as follows:

```
Local's
  next layer protocol = Mobility Header
  "port" selector     = OPAQUE

Remote's
  next layer protocol = Mobility Header
  "port" selector     = Mobility Header message type
```

C. If a system is willing to send traffic with a particular "port" value but NOT receive traffic with that kind of port value, the system's traffic selectors are set as follows in the relevant SPD entry:

```
Local's
  next layer protocol = ICMP
  "port" selector     = <specific ICMP type & code>

Remote's
  next layer protocol = ICMP
  "port" selector     = OPAQUE
```

D. To indicate that a system is willing to receive traffic with a particular "port" value but NOT send that kind of traffic, the system's traffic selectors are set as follows in the relevant SPD entry:

```
Local's
  next layer protocol = ICMP
  "port" selector     = OPAQUE

Remote's
  next layer protocol = ICMP
  "port" selector     = <specific ICMP type & code>
```

For example, if a security gateway is willing to allow systems behind it to send ICMP traceroutes, but is not willing to let outside systems run ICMP traceroutes to systems behind it, then the security gateway's traffic selectors are set as follows in the relevant SPD entry:

```
Local's
  next layer protocol = 1 (ICMPv4)
  "port" selector     = 30 (traceroute)

Remote's
  next layer protocol = 1 (ICMPv4)
  "port" selector     = OPAQUE
```

4.4.2. Security Association Database (SAD)

In each IPsec implementation, there is a nominal Security Association Database (SAD), in which each entry defines the parameters associated with one SA. Each SA has an entry in the SAD. For outbound processing, each SAD entry is pointed to by entries in the SPD-S part of the SPD cache. For inbound processing, for unicast SAs, the SPI is used alone to look up an SA. If an IPsec implementation supports multicast, the SPI plus destination address, or SPI plus destination and source addresses are used to look up the SA. (See Section 4.1 for details on the algorithm that MUST be used for mapping inbound IPsec datagrams to SAs.) The following parameters are associated with each entry in the SAD. They should all be present except where otherwise noted. This description does not purport to be a MIB, only a specification of the minimal data items required to support an SA in an IPsec implementation.

For each of the selectors defined in Section 4.4.1.1, the entry for an inbound SA in the SAD MUST be initially populated with the value or values negotiated at the time the SA was created. (See the paragraph in Section 4.4.1 under "Handling Changes to the SPD while the System is Running" for guidance on the effect of SPD changes on extant SAs.) For a receiver, these values are used to check that the header fields of an inbound packet (after IPsec processing) match the selector values negotiated for the SA. Thus, the SAD acts as a cache for checking the selectors of inbound traffic arriving on SAs. For the receiver, this is part of verifying that a packet arriving on an SA is consistent with the policy for the SA. (See Section 6 for rules for ICMP messages.) These fields can have the form of specific values, ranges, ANY, or OPAQUE, as described in Section 4.4.1.1, "Selectors". Note also that there are a couple of situations in which the SAD can have entries for SAs that do not have corresponding entries in the SPD. Since this document does not mandate that the SAD be selectively cleared when the SPD is changed, SAD entries can remain when the SPD entries that created them are changed or deleted. Also, if a manually keyed SA is created, there could be an SAD entry for this SA that does not correspond to any SPD entry.

Note: The SAD can support multicast SAs, if manually configured. An outbound multicast SA has the same structure as a unicast SA. The source address is that of the sender, and the destination address is the multicast group address. An inbound, multicast SA must be configured with the source addresses of each peer authorized to transmit to the multicast SA in question. The SPI value for a multicast SA is provided by a multicast group controller, not by the receiver, as for a unicast SA. Because an SAD entry may be required to accommodate multiple, individual IP source addresses that were part of an SPD entry (for unicast SAs), the required facility for inbound, multicast SAs is a feature already present in an IPsec implementation. However, because the SPD has no provisions for accommodating multicast entries, this document does not specify an automated way to create an SAD entry for a multicast, inbound SA. Only manually configured SAD entries can be created to accommodate inbound, multicast traffic.

Implementation Guidance: This document does not specify how an SPD-S entry refers to the corresponding SAD entry, as this is an implementation-specific detail. However, some implementations (based on experience from RFC 2401) are known to have problems in this regard. In particular, simply storing the (remote tunnel header IP address, remote SPI) pair in the SPD cache is not sufficient, since the pair does not always uniquely identify a single SAD entry. For instance, two hosts behind the same NAT could choose the same SPI value. The situation also may arise if a host is assigned an IP address (e.g., via DHCP) previously used by some other host, and the SAs associated with the old host have not yet been deleted via dead peer detection mechanisms. This may lead to packets being sent over the wrong SA or, if key management ensures the pair is unique, denying the creation of otherwise valid SAs. Thus, implementors should implement links between the SPD cache and the SAD in a way that does not engender such problems.

4.4.2.1. Data Items in the SAD

The following data items MUST be in the SAD:

- Security Parameter Index (SPI): a 32-bit value selected by the receiving end of an SA to uniquely identify the SA. In an SAD entry for an outbound SA, the SPI is used to construct the packet's ESP header. In an SAD entry for an inbound SA, the SPI is used to map traffic to the appropriate SA (see text on unicast/multicast in Section 4.1).

- Sequence Number Counter: a 64-bit counter used to generate the Sequence Number field in ESP header. 32-bit sequence numbers MUST NOT be supported.

- Sequence Counter Overflow: a flag indicating whether overflow of the sequence number counter should generate an auditable event and prevent transmission of additional packets on the SA, or whether rollover is permitted. The audit log entry for this event SHOULD include the SPI value, current date/time, Local Address, Remote Address, and the selectors from the relevant SAD entry.

- Anti-Replay Window: a 64-bit counter and a bit-map (or equivalent) used to determine whether an inbound ESP packet is a replay.

  Note: If anti-replay has been disabled by the receiver for an SA, e.g., in the case of a manually keyed SA, then the Anti-Replay Window is ignored for the SA in question. 64-bit sequence numbers are the default, but this counter size accommodates 32-bit sequence numbers as well.

- ESP Encryption algorithm, key, mode, IV, etc. If a combined mode algorithm is used, these fields will not be applicable.

- ESP integrity algorithm, keys, etc. If a combined mode algorithm is used, these fields will not be applicable.

- ESP combined mode algorithms, key(s), etc. This data is used when a combined mode (encryption and integrity) algorithm is used with ESP. If a combined mode algorithm is not used, these fields are not applicable.

- Lifetime of this SA: a time interval after which an SA must be replaced with a new SA (and new SPI) or terminated, plus an indication of which of these actions should occur. This may be expressed as a time or byte count, or a simultaneous use of both with the first lifetime to expire taking precedence. A compliant implementation MUST support both types of lifetimes, and MUST support a simultaneous use of both. If time is employed, and if IKE employs X.509 certificates for SA establishment, the SA lifetime must be constrained by the validity intervals of the certificates, and the NextIssueDate of the Certificate Revocation Lists (CRLs) used in the IKE exchange for the SA. Both initiator and responder are responsible for constraining the SA lifetime in this fashion. Note: The details of how to handle the refreshing of keys when SAs expire is a local matter. However, one reasonable approach is:

  (a) If byte count is used, then the implementation SHOULD count the number of bytes to which the IPsec cryptographic algorithm is applied. For ESP, this is the encryption algorithm. This includes pad bytes, etc. Note that implementations MUST be able to handle having the counters at the ends of an SA get out of synch, e.g., because of packet loss or because the implementations at each end of the SA aren't doing things the same way.

  (b) There SHOULD be two kinds of lifetime -- a soft lifetime that warns the implementation to initiate action such as setting up a replacement SA, and a hard lifetime when the current SA ends and is destroyed.

  (c) If the entire packet does not get delivered during the SA's lifetime, the packet SHOULD be discarded.

- IPsec protocol mode: tunnel only. Transport mode is not allowed.

- Stateful fragment checking flag. Indicates whether or not stateful fragment checking applies to this SA.

- Bypass DF bit (T/F) -- applicable to tunnel mode SAs where both inner and outer headers are IPv4.

- DSCP values -- the set of DSCP values allowed for packets carried over this SA. If no values are specified, no DSCP-specific filtering is applied. If one or more values are specified, these are used to select one SA among several that match the traffic selectors for an outbound packet. Note that these values are NOT checked against inbound traffic arriving on the SA.

- o Bypass DSCP (T/F) or map to unprotected DSCP values (array) if needed to restrict bypass of DSCP values -- applicable to tunnel mode SAs. This feature maps DSCP values from an inner header to values in an outer header, e.g., to address covert channel signaling concerns.

- o Path MTU: any observed path MTU and aging variables.

- o Tunnel header IP source and destination address -- both addresses must be either IPv4 or IPv6 addresses. The version implies the type of IP header to be used.

4.4.2.2. Relationship between SPD, PFP flag, packet, and SAD

For each selector, the following tables show the relationship between the value in the SPD, the PFP flag, the value in the triggering packet, and the resulting value in the SAD. Note that the administrative interface for IPsec can use various syntactic options to make it easier for the administrator to enter rules. For example, although a list of ranges is what IKEv2 sends, it might be clearer and less error prone for the user to enter a single IP address or IP address prefix.

Selector	SPD Entry	PFP	Value in Triggering Packet	Resulting SAD Entry
loc addr	list of ranges	0	IP addr "S"	list of ranges
	ANY	0	IP addr "S"	ANY
	list of ranges	1	IP addr "S"	"S"
	ANY	1	IP addr "S"	"S"
rem addr	list of ranges	0	IP addr "D"	list of ranges
	ANY	0	IP addr "D"	ANY
	list of ranges	1	IP addr "D"	"D"
	ANY	1	IP addr "D"	"D"
protocol	list of prot's*	0	prot. "P"	list of prot's*
	ANY**	0	prot. "P"	ANY
	OPAQUE****	0	prot. "P"	OPAQUE
	list of prot's*	0	not avail.	discard packet
	ANY**	0	not avail.	ANY
	OPAQUE****	0	not avail.	OPAQUE
	list of prot's*	1	prot. "P"	"P"
	ANY**	1	prot. "P"	"P"
	OPAQUE****	1	prot. "P"	***
	list of prot's*	1	not avail.	discard packet
	ANY**	1	not avail.	discard packet
	OPAQUE****	1	not avail.	***

If the protocol is one that has two ports, then there will be

selectors for both Local and Remote ports.

Selector	SPD Entry	PFP	Value in Triggering Packet	Resulting SAD Entry
loc port	list of ranges	0	src port "s"	list of ranges
	ANY	0	src port "s"	ANY
	OPAQUE	0	src port "s"	OPAQUE
	list of ranges	0	not avail.	discard packet
	ANY	0	not avail.	ANY
	OPAQUE	0	not avail.	OPAQUE
	list of ranges	1	src port "s"	"s"
	ANY	1	src port "s"	"s"
	OPAQUE	1	src port "s"	***
	list of ranges	1	not avail.	discard packet
	ANY	1	not avail.	discard packet
	OPAQUE	1	not avail.	***
rem port	list of ranges	0	dst port "d"	list of ranges
	ANY	0	dst port "d"	ANY
	OPAQUE	0	dst port "d"	OPAQUE
	list of ranges	0	not avail.	discard packet
	ANY	0	not avail.	ANY
	OPAQUE	0	not avail.	OPAQUE
	list of ranges	1	dst port "d"	"d"
	ANY	1	dst port "d"	"d"
	OPAQUE	1	dst port "d"	***
	list of ranges	1	not avail.	discard packet
	ANY	1	not avail.	discard packet
	OPAQUE	1	not avail.	***

If the protocol is mobility header, then there will be a selector for mh type.

Selector	SPD Entry	PFP	Value in Triggering Packet	Resulting SAD Entry
mh type	list of ranges	0	mh type "T"	list of ranges
	ANY	0	mh type "T"	ANY
	OPAQUE	0	mh type "T"	OPAQUE
	list of ranges	0	not avail.	discard packet
	ANY	0	not avail.	ANY
	OPAQUE	0	not avail.	OPAQUE
	list of ranges	1	mh type "T"	"T"

	ANY	1	mh type "T"	"T"
	OPAQUE	1	mh type "T"	***
	list of ranges	1	not avail.	discard packet
	ANY	1	not avail.	discard packet
	OPAQUE	1	not avail.	***

If the protocol is ICMP, then there will be a 16-bit selector for ICMP type and ICMP code. Note that the type and code are bound to each other, i.e., the codes apply to the particular type. This 16-bit selector can contain a single type and a range of codes, a single type and ANY code, and ANY type and ANY code.

Selector	SPD Entry	PFP	Value in Triggering Packet	Resulting SAD Entry
ICMP type and code	a single type & range of codes	0	type "t" & code "c"	single type & range of codes
	a single type & ANY code	0	type "t" & code "c"	single type & ANY code
	ANY type & ANY code	0	type "t" & code "c"	ANY type & ANY code
	OPAQUE	0	type "t" & code "c"	OPAQUE
	a single type & range of codes	0	not avail.	discard packet
	a single type & ANY code	0	not avail.	discard packet
	ANY type & ANY code	0	not avail.	ANY type & ANY code
	OPAQUE	0	not avail.	OPAQUE
	a single type & range of codes	1	type "t" & code "c"	"t" and "c"
	a single type & ANY code	1	type "t" & code "c"	"t" and "c"
	ANY type & ANY code	1	type "t" & code "c"	"t" and "c"
	OPAQUE	1	type "t" & code "c"	***
	a single type & range of codes	1	not avail.	discard packet
	a single type & ANY code	1	not avail.	discard packet
	ANY type & ANY code	1	not avail.	discard packet
	OPAQUE	1	not avail.	***

If the name selector is used:

			Value in	

Selector	SPD Entry	PFP	Triggering Packet	Resulting SAD Entry
name	list of user or system names	N/A	N/A	N/A

* "List of protocols" is the information, not the way that the SPD or SAD or IKEv2 have to represent this information.

** 0 (zero) is used by IKE to indicate ANY for protocol.

*** Use of PFP=1 with an OPAQUE value is an error and SHOULD be prohibited by an IPsec implementation.

**** The protocol field cannot be OPAQUE in IPv4. This table entry applies only to IPv6.

4.4.3. Peer Authorization Database (PAD)

The Peer Authorization Database (PAD) provides the link between the SPD and a security association management protocol such as IKE. It embodies several critical functions:

- identifies the peers or groups of peers that are authorized to communicate with this IPsec entity
- specifies the protocol and method used to authenticate each peer
- provides the authentication data for each peer
- constrains the types and values of IDs that can be asserted by a peer with regard to child SA creation, to ensure that the peer does not assert identities for lookup in the SPD that it is not authorized to represent, when child SAs are created
- peer gateway location info, e.g., IP address(es) or DNS names, MAY be included for peers that are known to be "behind" a security gateway

The PAD provides these functions for an IKE peer when the peer acts as either the initiator or the responder.

To perform these functions, the PAD contains an entry for each peer or group of peers with which the IPsec entity will communicate. An entry names an individual peer (a user, end system or security gateway) or specifies a group of peers (using ID matching rules defined below). The entry specifies the authentication protocol (e.g., IKEv1, IKEv2, KINK) method used (e.g., certificates or pre-shared secrets) and the authentication data (e.g., the pre-shared secret or the trust anchor relative to which the peer's certificate will be validated). For certificate-based authentication, the entry also may provide information to assist in verifying the revocation status of the peer, e.g., a pointer to a CRL repository or the name of an Online Certificate Status Protocol (OCSP) server associated with the peer or with the trust anchor associated with the peer.

Each entry also specifies whether the IKE ID payload will be used as a symbolic name for SPD lookup, or whether the remote IP address

provided in traffic selector payloads will be used for SPD lookups when child SAs are created.

Note that the PAD information MAY be used to support creation of more than one tunnel mode SA at a time between two peers, e.g., two tunnels to protect the same addresses/hosts, but with different tunnel endpoints.

4.4.3.1. PAD Entry IDs and Matching Rules

The PAD is an ordered database, where the order is defined by an administrator (or a user in the case of a single-user end system). Usually, the same administrator will be responsible for both the PAD and SPD, since the two databases must be coordinated. The ordering requirement for the PAD arises for the same reason as for the SPD, i.e., because use of "star name" entries allows for overlaps in the set of IKE IDs that could match a specific entry.

Six types of IDs are supported for entries in the PAD, consistent with the symbolic name types and IP addresses used to identify SPD entries. The ID for each entry acts as the index for the PAD, i.e., it is the value used to select an entry. All of these ID types can be used to match IKE ID payload types. The six types are:

- DNS name (specific or partial)
- Distinguished Name (complete or sub-tree constrained)
- RFC 822 email address (complete or partially qualified)
- IPv4 address (range)
- IPv6 address (range)
- Key ID (exact match only)

The first three name types can accommodate sub-tree matching as well as exact matches. A DNS name may be fully qualified and thus match exactly one name, e.g., foo.example.com. Alternatively, the name may encompass a group of peers by being partially specified, e.g., the string ".example.com" could be used to match any DNS name ending in these two domain name components.

Similarly, a Distinguished Name may specify a complete Distinguished Name to match exactly one entry, e.g., CN = Stephen, O = BBN Technologies, SP = MA, C = US. Alternatively, an entry may encompass a group of peers by specifying a sub-tree, e.g., an entry of the form "C = US, SP = MA" might be used to match all DNs that contain these two attributes as the top two Relative Distinguished Names (RDNs).

For an RFC 822 e-mail addresses, the same options exist. A complete address such as foo@example.com matches one entity, but a sub-tree name such as "@example.com" could be used to match all the entities with names ending in those two domain names to the right of the @.

The specific syntax used by an implementation to accommodate sub-tree matching for distinguished names, domain names or RFC 822 e-mail addresses is a local matter. But, at a minimum, sub-tree matching of the sort described above MUST be supported. (Substring matching

within a DN, DNS name, or RFC 822 address MAY be supported, but is not required.)

For IPv4 and IPv6 addresses, the same address range syntax used for SPD entries MUST be supported. This allows specification of an individual address (via a trivial range), an address prefix (by choosing a range that adheres to Classless Inter-Domain Routing (CIDR)-style prefixes), or an arbitrary address range.

The Key ID field is defined as an OCTET string in IKE. For this name type, only exact-match syntax MUST be supported (since there is no explicit structure for this ID type). Additional matching functions MAY be supported for this ID type.

4.4.3.2. IKE Peer Authentication Data

Once an entry is located based on an ordered search of the PAD based on ID field matching, it is necessary to verify the asserted identity, i.e., to authenticate the asserted ID. For each PAD entry, there is an indication of the type of authentication to be performed. This document requires support for two required authentication data types:

- X.509 certificate
- pre-shared secret

For authentication based on an X.509 certificate, the PAD entry contains a trust anchor via which the end entity (EE) certificate for the peer must be verifiable, either directly or via a certificate path. See RFC 3280 for the definition of a trust anchor. An entry used with certificate-based authentication MAY include additional data to facilitate certificate revocation status, e.g., a list of appropriate OCSP responders or CRL repositories, and associated authentication data. For authentication based on a pre-shared secret, the PAD contains the pre-shared secret to be used by IKE.

This document does not require that the IKE ID asserted by a peer be syntactically related to a specific field in an end entity certificate that is employed to authenticate the identity of that peer. However, it often will be appropriate to impose such a requirement, e.g., when a single entry represents a set of peers each of whom may have a distinct SPD entry. Thus, implementations MUST provide a means for an administrator to require a match between an asserted IKE ID and the subject name or subject alt name in a certificate. The former is applicable to IKE IDs expressed as distinguished names; the latter is appropriate for DNS names, RFC 822 e-mail addresses, and IP addresses. Since KEY ID is intended for identifying a peer authenticated via a pre-shared secret, there is no requirement to match this ID type to a certificate field.

See IKEv2 [Kau05] for details of how IKE performs peer authentication using certificates or pre-shared secrets.

This document does not mandate support for any other authentication

methods, although such methods MAY be employed.

4.4.3.3. Child SA Authorization Data

Once an IKE peer is authenticated, child SAs may be created. Each PAD entry contains data to constrain the set of IDs that can be asserted by an IKE peer, for matching against the SPD. Each PAD entry indicates whether the IKE ID is to be used as a symbolic name for SPD matching, or whether an IP address asserted in a traffic selector payload is to be used.

If the entry indicates that the IKE ID is to be used, then the PAD entry ID field defines the authorized set of IDs. If the entry indicates that child SAs traffic selectors are to be used, then an additional data element is required, in the form of IPv4 and/or IPv6 address ranges. (A peer may be authorized for both address types, so there MUST be provision for both a v4 and a v6 address range.)

4.4.3.4. How the PAD Is Used

During the initial IKE exchange, the initiator and responder each assert their identity via the IKE ID payload and send an AUTH payload to verify the asserted identity. One or more CERT payloads may be transmitted to facilitate the verification of each asserted identity.

When an IKE entity receives an IKE ID payload, it uses the asserted ID to locate an entry in the PAD, using the matching rules described above. The PAD entry specifies the authentication method to be employed for the identified peer. This ensures that the right method is used for each peer and that different methods can be used for different peers. The entry also specifies the authentication data that will be used to verify the asserted identity. This data is employed in conjunction with the specified method to authenticate the peer, before any CHILD SAs are created.

Child SAs are created based on the exchange of traffic selector payloads, either at the end of the initial IKE exchange or in subsequent CREATE_CHILD_SA exchanges. The PAD entry for the (now authenticated) IKE peer is used to constrain creation of child SAs; specifically, the PAD entry specifies how the SPD is searched using a traffic selector proposal from a peer. There are two choices: either the IKE ID asserted by the peer is used to find an SPD entry via its symbolic name, or peer IP addresses asserted in traffic selector payloads are used for SPD lookups based on the remote IP address field portion of an SPD entry. It is necessary to impose these constraints on creation of child SAs to prevent an authenticated peer from spoofing IDs associated with other, legitimate peers.

Note that because the PAD is checked before searching for an SPD entry, this safeguard protects an initiator against spoofing attacks. For example, assume that IKE A receives an outbound packet destined for IP address X, a host served by a security gateway. RFC 2401 [RFC2401] and this document do not specify how A determines the address of the IKE peer serving X. However, any peer contacted by A

as the presumed representative for X must be registered in the PAD in order to allow the IKE exchange to be authenticated. Moreover, when the authenticated peer asserts that it represents X in its traffic selector exchange, the PAD will be consulted to determine if the peer in question is authorized to represent X. Thus, the PAD provides a binding of address ranges (or name sub-spaces) to peers, to counter such attacks.

4.5. SA and Key Management

All IPsec implementations MUST support automated SA and cryptographic key management and MAY support manual SA and cryptographic key management. The IPsec protocol ESP, is largely independent of the associated SA management techniques, although the techniques involved do affect some of the security services offered by the protocol. For example, the granularity of key distribution employed with IPsec determines the granularity of authentication provided. In general, data origin authentication in ESP is limited by the extent to which secrets used with the integrity algorithm (or with a key management protocol that creates such secrets) are shared among multiple possible sources.

The following text describes the minimum requirements for both types of SA management.

4.5.1. Manual Techniques

The simplest form of management is manual management, in which a person manually configures each system with keying material and SA management data relevant to secure communication with other systems. Manual techniques are practical in small, static environments but they do not scale well. For example, a company could create a virtual private network (VPN) using IPsec in security gateways at several sites. If the number of sites is small, and since all the sites come under the purview of a single administrative domain, this might be a feasible context for manual management techniques. In this case, the security gateway might selectively protect traffic to and from other sites within the organization using a manually configured key, while not protecting traffic for other destinations. It also might be appropriate when only selected communications need to be secured. A similar argument might apply to use of IPsec entirely within an organization for a small number of hosts and/or gateways. Manual management techniques often employ statically configured, symmetric keys, though other options also exist.

4.5.2. Automated SA and Key Management

Widespread deployment and use of IPsec requires an Internet-standard, scalable, automated, SA management protocol. Such support is required to facilitate use of the anti-replay features of ESP, and to accommodate on-demand creation of SAs, e.g., for user- and session-oriented keying. (Note that the notion of "rekeying" an SA actually implies creation of a new SA with a new SPI, a process that generally implies use of an automated SA/key management protocol.)

The default automated key management protocol selected for use with IPsec is IKEv2 [Kau05]. Other automated SA management protocols MUST NOT be employed.

The output of the automated SA/key management protocol is used to generate multiple keys for a single SA. This also occurs because distinct keys are used for each of the two SAs created by IKE. If both integrity and confidentiality are employed, then a minimum of four keys are required.

The Key Management System may provide a separate string of bits for each key or it may generate one string of bits from which all keys are extracted. If a single string of bits is provided, care needs to be taken to ensure that the parts of the system that map the string of bits to the required keys do so in the same fashion at both ends of the SA. To ensure that the IPsec implementations at each end of the SA use the same bits for the same keys, and irrespective of which part of the system divides the string of bits into individual keys, the encryption keys MUST be taken from the first (left-most, high-order) bits and the integrity keys MUST be taken from the remaining bits. The number of bits for each key is defined in the relevant cryptographic algorithm specification RFC. In the case of multiple encryption keys or multiple integrity keys, the specification for the cryptographic algorithm must specify the order in which they are to be selected from a single string of bits provided to the cryptographic algorithm.

4.5.3. Locating a Security Gateway

This section discusses issues relating to how a host learns about the existence of relevant security gateways and, once a host has contacted these security gateways, how it knows that these are the correct security gateways. The details of where the required information is stored is a local matter, but the Peer Authorization Database (PAD) described in Section 4.4 is the most likely candidate. (Note: S* indicates a system that is running IPsec, e.g., SH1 and SG2 below.)

Consider a situation in which a remote host (SH1) is using the Internet to gain access to a server or other machine (H2) and there is a security gateway (SG2), e.g., a firewall, through which H1's traffic must pass. An example of this situation would be a mobile host crossing the Internet to his home organization's firewall (SG2). This situation raises several issues:

1. How does SH1 know/learn about the existence of the security gateway SG2?

2. How does it authenticate SG2, and once it has authenticated SG2, how does it confirm that SG2 has been authorized to represent H2?

3. How does SG2 authenticate SH1 and verify that SH1 is authorized to contact H2?

4. How does SH1 know/learn about any additional gateways that provide alternate paths to H2?

To address these problems, an IPsec-supporting host or security gateway MUST have an administrative interface that allows the user/administrator to configure the address of one or more security gateways for ranges of destination addresses that require its use. This includes the ability to configure information for locating and authenticating one or more security gateways and verifying the authorization of these gateways to represent the destination host. (The authorization function is implied in the PAD.) This document does not address the issue of how to automate the discovery/verification of security gateways.

4.6. SAs and Multicast

The receiver-orientation of the SA implies that, in the case of unicast traffic, the destination system will select the SPI value. By having the destination select the SPI value, there is no potential for manually configured SAs to conflict with automatically configured (e.g., via a key management protocol) SAs or for SAs from multiple sources to conflict with each other. For multicast traffic, there are multiple destination systems associated with a single SA. So some system or person will need to coordinate among all multicast groups to select an SPI or SPIs on behalf of each multicast group and then communicate the group's IPsec information to all of the legitimate members of that multicast group via mechanisms not defined here.

Multiple senders to a multicast group SHOULD use a single Security Association (and hence SPI) for all traffic to that group when a symmetric key encryption or integrity algorithm is employed. In such circumstances, the receiver knows only that the message came from a system possessing the key for that multicast group. In such circumstances, a receiver generally will not be able to authenticate which system sent the multicast traffic. Specifications for other, more general multicast approaches are deferred to the IETF Multicast Security Working Group.

5. IP Traffic Processing

As mentioned in Section 4.4.1, "The Security Policy Database (SPD)", the SPD (or associated caches) MUST be consulted during the processing of all traffic that crosses the IPsec protection boundary, including IPsec management traffic. If no policy is found in the SPD that matches a packet (for either inbound or outbound traffic), the packet MUST be discarded. To simplify processing, and to allow for very fast SA lookups (for SG/BITS/BITW), this document introduces the notion of an SPD cache for all outbound traffic (SPD-O plus SPD-S), and a cache for inbound, non-IPsec-protected traffic (SPD-I). (As mentioned earlier, the SAD acts as a cache for checking the selectors of inbound IPsec-protected traffic arriving on SAs.) There is nominally one cache per SPD. For the purposes of this specification,

it is assumed that each cached entry will map to exactly one SA. Note, however, exceptions arise when one uses multiple SAs to carry traffic of different priorities (e.g., as indicated by distinct DSCP values) but the same selectors. Note also, that there are a couple of situations in which the SAD can have entries for SAs that do not have corresponding entries in the SPD. Since this document does not mandate that the SAD be selectively cleared when the SPD is changed, SAD entries can remain when the SPD entries that created them are changed or deleted. Also, if a manually keyed SA is created, there could be an SAD entry for this SA that does not correspond to any SPD entry.

Since SPD entries may overlap, one cannot safely cache these entries in general. Simple caching might result in a match against a cache entry, whereas an ordered search of the SPD would have resulted in a match against a different entry. But, if the SPD entries are first decorrelated, then the resulting entries can safely be cached. Each cached entry will indicate that matching traffic should be bypassed or discarded, appropriately. (Note: The original SPD entry might result in multiple SAs, e.g., because of PFP.) Unless otherwise noted, all references below to the "SPD" or "SPD cache" or "cache" are to a decorrelated SPD (SPD-I, SPD-O, SPD-S) or the SPD cache containing entries from the decorrelated SPD.

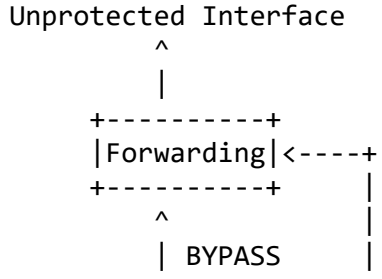
Note: In a host IPsec implementation based on sockets, the SPD will be consulted whenever a new socket is created to determine what, if any, IPsec processing will be applied to the traffic that will flow on that socket. This provides an implicit caching mechanism, and the portions of the preceding discussion that address caching can be ignored in such implementations.

Note: It is assumed that one starts with a correlated SPD because that is how users and administrators are accustomed to managing these sorts of access control lists or firewall filter rules. Then the decorrelation algorithm is applied to build a list of cache-able SPD entries. The decorrelation is invisible at the management interface.

For inbound IPsec traffic, the SAD entry selected by the SPI serves as the cache for the selectors to be matched against arriving IPsec packets, after ESP processing has been performed.

5.1. Outbound IP Traffic Processing (protected-to-unprotected)

First consider the path for traffic entering the implementation via a protected interface and exiting via an unprotected interface.



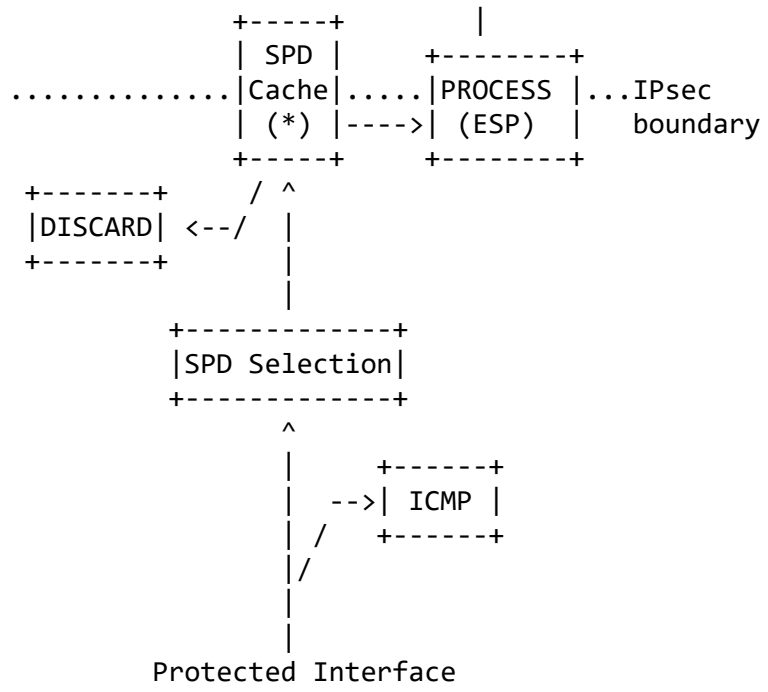


Figure 2. Processing Model for Outbound Traffic
(*) = The SPD caches are shown here. If there is a cache miss, then the SPD is checked. There is no requirement that an implementation buffer the packet if there is a cache miss.

IPsec MUST perform the following steps when processing outbound packets:

1. When a packet arrives from the subscriber (protected) interface, invoke the SPD selection function to obtain the SPD-ID needed to choose the appropriate SPD. (If the implementation uses only one SPD, this step is a no-op.)

2. Match the packet headers against the cache for the SPD specified by the SPD-ID from step 1. Note that this cache contains entries from SPD-O and SPD-S.

3a. If there is a match, then process the packet as specified by the matching cache entry, i.e., BYPASS, DISCARD, or PROTECT using ESP. If IPsec processing is applied, there is a link from the SPD cache entry to the relevant SAD entry (specifying the mode, cryptographic algorithms, keys, SPI, PMTU, etc.). IPsec processing is as previously defined, as specified in the RFC [Ken05a]. Note that the SA PMTU value, plus the value of the stateful fragment checking flag (and the DF bit in the IP header of the outbound packet) determine whether the packet can (must) be fragmented prior to or after IPsec processing, or if it must be discarded and an ICMP PMTU message is sent.

3b. If no match is found in the cache, search the SPD (SPD-S and SPD-O parts) specified by SPD-ID. If the SPD entry calls for

BYPASS or DISCARD, create one or more new outbound SPD cache entries and if BYPASS, create one or more new inbound SPD cache entries. (More than one cache entry may be created since a decorrelated SPD entry may be linked to other such entries that were created as a side effect of the decorrelation process.) If the SPD entry calls for PROTECT, i.e., creation of an SA, the key management mechanism (e.g., IKEv2) is invoked to create the SA. If SA creation succeeds, a new outbound (SPD-S) cache entry is created, along with outbound and inbound SAD entries, otherwise the packet is discarded. (A packet that triggers an SPD lookup MAY be discarded by the implementation, or it MAY be processed against the newly created cache entry, if one is created.) Since SAs are created in pairs, an SAD entry for the corresponding inbound SA also is created, and it contains the selector values derived from the SPD entry (and packet, if any PFP flags were "true") used to create the inbound SA, for use in checking inbound traffic delivered via the SA.

4. The packet is passed to the outbound forwarding function (operating outside of the IPsec implementation), to select the interface to which the packet will be directed.

Note: An SG, BITS, or BITW implementation MAY fragment packets before applying IPsec. (This applies only to IPv4. For IPv6 packets, only the originator is allowed to fragment them.) The device SHOULD have a configuration setting to disable this. The resulting fragments are evaluated against the SPD in the normal manner. Thus, fragments not containing port numbers (or ICMP message type and code, or Mobility Header type) will only match rules having port (or ICMP message type and code, or MH type) selectors of OPAQUE or ANY. (See Section 7 for more details.)

Note: With regard to determining and enforcing the PMTU of an SA, the IPsec system MUST follow the steps described in Section 8.2.

5.1.1. Handling an Outbound Packet That Must Be Discarded

If an IPsec system receives an outbound packet that it finds it must discard, it SHOULD be capable of generating and sending an ICMP message to indicate to the sender of the outbound packet that the packet was discarded. The type and code of the ICMP message will depend on the reason for discarding the packet, as specified below. The reason SHOULD be recorded in the audit log. The audit log entry for this event SHOULD include the reason, current date/time, and the selector values from the packet.

a. The selectors of the packet matched an SPD entry requiring the packet to be discarded.

IPv4 Type = 3 (destination unreachable) Code = 13
(Communication Administratively Prohibited)

IPv6 Type = 1 (destination unreachable) Code = 1
(Communication with destination administratively

prohibited)

b1. The IPsec system successfully reached the remote peer but was unable to negotiate the SA required by the SPD entry matching the packet because, for example, the remote peer is administratively prohibited from communicating with the initiator, the initiating peer was unable to authenticate itself to the remote peer, the remote peer was unable to authenticate itself to the initiating peer, or the SPD at the remote peer did not have a suitable entry.

IPv4 Type = 3 (destination unreachable) Code = 13 (Communication Administratively Prohibited)

IPv6 Type = 1 (destination unreachable) Code = 1 (Communication with destination administratively prohibited)

b2. The IPsec system was unable to set up the SA required by the SPD entry matching the packet because the IPsec peer at the other end of the exchange could not be contacted.

IPv4 Type = 3 (destination unreachable) Code = 1 (host unreachable)

IPv6 Type = 1 (destination unreachable) Code = 3 (address unreachable)

Note that an attacker behind a security gateway could send packets with a spoofed source address, W.X.Y.Z, to an IPsec entity causing it to send ICMP messages to W.X.Y.Z. This creates an opportunity for a denial of service (DoS) attack among hosts behind a security gateway. To address this, a security gateway SHOULD include a management control to allow an administrator to configure an IPsec implementation to send or not send the ICMP messages under these circumstances, and if this facility is selected, to rate limit the transmission of such ICMP responses.

5.1.2. Header Construction for Tunnel Mode

This section describes the handling of the inner and outer IP headers, extension headers, and options for an ESP tunnel, with regard to outbound traffic processing. This includes how to construct the encapsulating (outer) IP header, how to process fields in the inner IP header, and what other actions should be taken for outbound, tunnel mode traffic. The general processing described here is modeled after RFC 2003, "IP Encapsulation within IP" [Per96]:

- The outer IP header Source Address and Destination Address identify the "endpoints" of the tunnel (the encapsulator and decapsulator). The inner IP header Source Address and Destination Addresses identify the original sender and recipient of the datagram (from the perspective of this tunnel), respectively.

(See footnote 3 after the table in 5.1.2.1 for more details on the encapsulating source IP address.)

- The inner IP header is not changed except as noted below for TTL (or Hop Limit) and the DS/ECN Fields. The inner IP header otherwise remains unchanged during its delivery to the tunnel exit point.

- No change to IP options or extension headers in the inner header occurs during delivery of the encapsulated datagram through the tunnel.

Note: IPsec tunnel mode is different from IP-in-IP tunneling (RFC 2003 [Per96]) in several ways:

- IPsec offers certain controls to a security administrator to manage covert channels (which would not normally be a concern for tunneling) and to ensure that the receiver examines the right portions of the received packet with respect to application of access controls. An IPsec implementation MAY be configurable with regard to how it processes the outer DS field for tunnel mode for transmitted packets. For outbound traffic, one configuration setting for the outer DS field will operate as described in the following sections on IPv4 and IPv6 header processing for IPsec tunnels. Another will allow the outer DS field to be mapped to a fixed value, which MAY be configured on a per-SA basis. (The value might really be fixed for all traffic outbound from a device, but per-SA granularity allows that as well.) This configuration option allows a local administrator to decide whether the covert channel provided by copying these bits outweighs the benefits of copying.

- IPsec describes how to handle ECN or DS and provides the ability to control propagation of changes in these fields between unprotected and protected domains. In general, propagation from a protected to an unprotected domain is a covert channel and thus controls are provided to manage the bandwidth of this channel. Propagation of ECN values in the other direction are controlled so that only legitimate ECN changes (indicating occurrence of congestion between the tunnel endpoints) are propagated. By default, DS propagation from an unprotected domain to a protected domain is not permitted. However, if the sender and receiver do not share the same DS code space, and the receiver has no way of learning how to map between the two spaces, then it may be appropriate to deviate from the default. Specifically, an IPsec implementation MAY be configurable in terms of how it processes the outer DS field for tunnel mode for received packets. It may be configured to either discard the outer DS value (the default) OR to overwrite the inner DS field with the outer DS field. If offered, the discard vs. overwrite behavior MAY be configured on a per-SA basis. This configuration option allows a local administrator to decide whether the vulnerabilities created by copying these bits outweigh the benefits of copying. See [RFC2983] for further information on when each of these behaviors may be useful, and also for the possible need for diffserv traffic

conditioning prior or subsequent to IPsec processing (including tunnel decapsulation).

- o IPsec allows the IP version of the encapsulating header to be different from that of the inner header.

The tables in the following sub-sections show the handling for the different header/option fields ("constructed" means that the value in the outer field is constructed independently of the value in the inner).

5.1.2.1. IPv4: Header Construction for Tunnel Mode

IPv4	<-- How Outer Hdr Relates to Inner Hdr --> Outer Hdr at Encapsulator	Inner Hdr at Decapsulator
Header fields:		
version	4 (1)	no change
header length	constructed	no change
DS Field	copied from inner hdr (5)	no change
ECN Field	copied from inner hdr	constructed (6)
total length	constructed	no change
ID	constructed	no change
flags (DF,MF)	constructed, DF (4)	no change
fragment offset	constructed	no change
TTL	constructed (2)	decrement (2)
protocol	ESP	no change
checksum	constructed	constructed (2)(6)
src address	constructed (3)	no change
dest address	constructed (3)	no change
Options	never copied	no change

Notes:

(1) The IP version in the encapsulating header can be different from the value in the inner header.

(2) The TTL in the inner header is decremented by the encapsulator prior to forwarding and by the decapsulator if it forwards the packet. (The IPv4 checksum changes when the TTL changes.) Note: Decrementing the TTL value is a normal part of forwarding a packet. Thus, a packet originating from the same node as the encapsulator does not have its TTL decremented, since the sending node is originating the packet rather than forwarding it. This applies to BITS and native IPsec implementations in hosts and routers. However, the IPsec processing model includes an external forwarding capability. TTL processing can be used to prevent looping of packets, e.g., due to configuration errors, within the context of this processing model.

(3) Local and Remote addresses depend on the SA, which is used to determine the Remote address, which in turn determines which Local address (net interface) is used to forward the packet.

Note: For multicast traffic, the destination address, or source and destination addresses, may be required for demuxing. In that case, it is important to ensure consistency over the lifetime of the SA by ensuring that the source address that appears in the encapsulating tunnel header is the same as the one that was negotiated during the SA establishment process. There is an exception to this general rule, i.e., a mobile IPsec implementation will update its source address as it moves.

(4) Configuration determines whether to copy from the inner header (IPv4 only), clear, or set the DF.

(5) If the packet will immediately enter a domain for which the DSCP value in the outer header is not appropriate, that value MUST be mapped to an appropriate value for the domain [NiBlBaBL98]. See RFC 2475 [BBCDWW98] for further information.

(6) If the ECN field in the inner header is set to ECT(0) or ECT(1), where ECT is ECN-Capable Transport (ECT), and if the ECN field in the outer header is set to Congestion Experienced (CE), then set the ECN field in the inner header to CE; otherwise, make no change to the ECN field in the inner header. (The IPv4 checksum changes when the ECN changes.)

Note: IPsec does not copy the options from the inner header into the outer header, nor does IPsec construct the options in the outer header. However, post-IPsec code MAY insert/construct options for the outer header.

5.1.2.2. IPv6: Header Construction for Tunnel Mode

	<-- How Outer Hdr Relates	Inner Hdr --->
IPv6	Outer Hdr at	Inner Hdr at
Header fields:	Encapsulator	Decapsulator
	---	---
version	6 (1)	no change
DS Field	copied from inner hdr (5)	no change (9)
ECN Field	copied from inner hdr	constructed (6)
flow label	copied or configured (8)	no change
payload length	constructed	no change
next header	ESP,routing hdr	no change
hop limit	constructed (2)	decrement (2)
src address	constructed (3)	no change
dest address	constructed (3)	no change
Extension headers	never copied (7)	no change

Notes:

(1) - (6) See Section 5.1.2.1.

(7) IPsec does not copy the extension headers from the inner

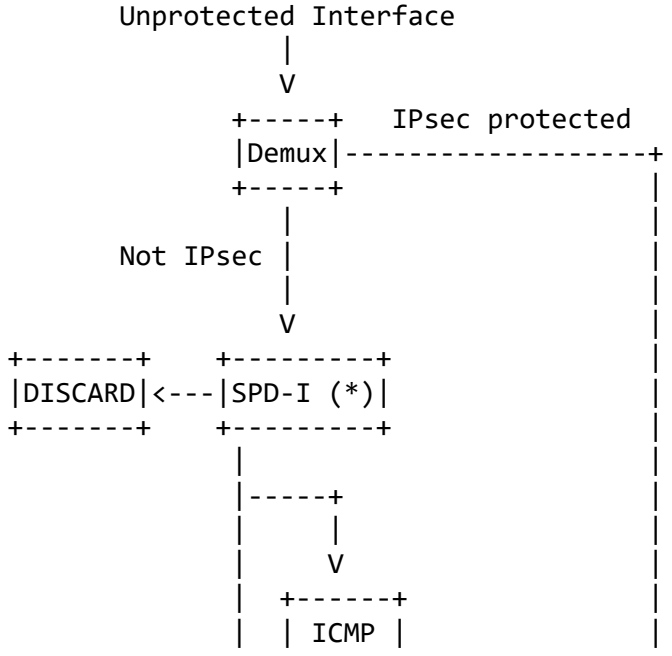
packet into outer headers, nor does IPsec construct extension headers in the outer header. However, post-IPsec code MAY insert/construct extension headers for the outer header.

(8) See [RaCoCaDe04]. Copying is acceptable only for end systems, not SGs. If an SG copied flow labels from the inner header to the outer header, collisions might result.

(9) An implementation MAY choose to provide a facility to pass the DS value from the outer header to the inner header, on a per-SA basis, for received tunnel mode packets. The motivation for providing this feature is to accommodate situations in which the DS code space at the receiver is different from that of the sender and the receiver has no way of knowing how to translate from the sender's space. There is a danger in copying this value from the outer header to the inner header, since it enables an attacker to modify the outer DSCP value in a fashion that may adversely affect other traffic at the receiver. Hence the default behavior for IPsec implementations is NOT to permit such copying.

5.2. Processing Inbound IP Traffic (unprotected-to-protected)

Inbound processing is somewhat different from outbound processing, because of the use of SPIs to map IPsec-protected traffic to SAs. The inbound SPD cache (SPD-I) is applied only to bypassed or discarded traffic. If an arriving packet appears to be an IPsec fragment from an unprotected interface, reassembly is performed prior to IPsec processing. The intent for any SPD cache is that a packet that fails to match any entry is then referred to the corresponding SPD. Every SPD SHOULD have a nominal, final entry that catches anything that is otherwise unmatched, and discards it. This ensures that non-IPsec-protected traffic that arrives and does not match any SPD-I entry will be discarded.



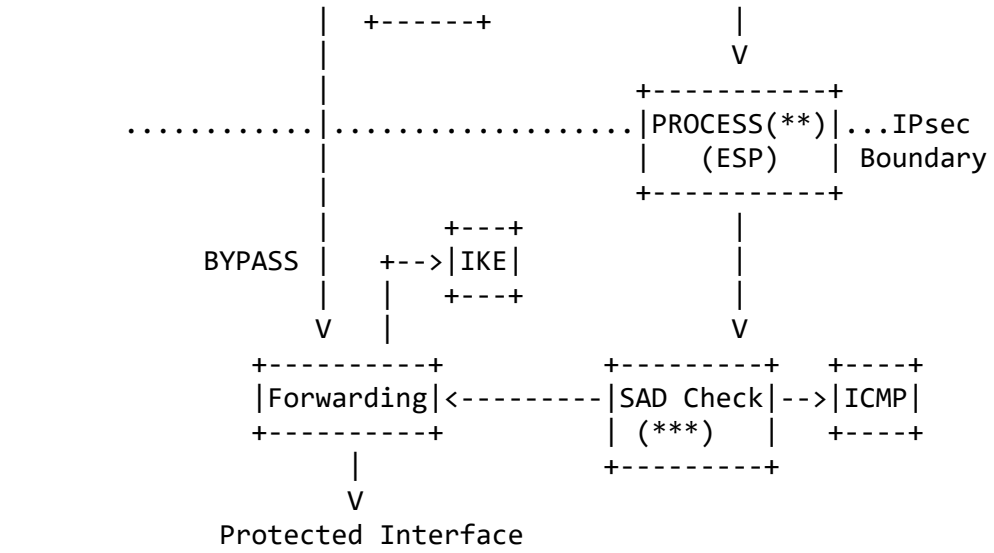


Figure 3. Processing Model for Inbound Traffic
(*) = The caches are shown here. If there is a cache miss, then the SPD is checked. There is no requirement that an implementation buffer the packet if there is a cache miss.
(**) = This processing includes using the packet's SPI, etc., to look up the SA in the SAD, which forms a cache of the SPD for inbound packets (except for cases noted in Sections 4.4.2 and 5). See step 3a below.
(***) = This SAD check refers to step 4 below.

Prior to performing ESP processing, any IP fragments that arrive via the unprotected interface are reassembled (by IP). Each inbound IP datagram to which IPsec processing will be applied is identified by the appearance of the ESP value in the IP Next Protocol field (or of ESP as a next layer protocol in the IPv6 context).

IPsec MUST perform the following steps:

1. When a packet arrives, it may be tagged with the ID of the interface (physical or virtual) via which it arrived, if necessary, to support multiple SPDs and associated SPD-I caches. (The interface ID is mapped to a corresponding SPD-ID.)

2. The packet is examined and demuxed into one of two categories:
   - If the packet appears to be IPsec protected and it is addressed to this device, an attempt is made to map it to an active SA via the SAD. Note that the device may have multiple IP addresses that may be used in the SAD lookup, e.g., in the case of protocols such as SCTP.
   - Traffic not addressed to this device, or addressed to this device and not ESP, is directed to SPD-I lookup. (This implies that IKE traffic MUST have an explicit BYPASS entry in the SPD.) If multiple SPDs are employed, the tag assigned to

the packet in step 1 is used to select the appropriate SPD-I (and cache) to search. SPD-I lookup determines whether the action is DISCARD or BYPASS.

3a. If the packet is addressed to the IPsec device and ESP is specified as the protocol, the packet is looked up in the SAD. For unicast traffic, use only the SPI (or SPI plus protocol). For multicast traffic, use the SPI plus the destination or SPI plus destination and source addresses, as specified in Section 4.1. In either case (unicast or multicast), if there is no match, discard the traffic. This is an auditable event. The audit log entry for this event SHOULD include the current date/time, SPI, source and destination of the packet, IPsec protocol, and any other selector values of the packet that are available. If the packet is found in the SAD, process it accordingly (see step 4).

3b. If the packet is not addressed to the device or is addressed to this device and is not ESP, look up the packet header in the (appropriate) SPD-I cache. If there is a match and the packet is to be discarded or bypassed, do so. If there is no cache match, look up the packet in the corresponding SPD-I and create a cache entry as appropriate. (No SAs are created in response to receipt of a packet that requires IPsec protection; only BYPASS or DISCARD cache entries can be created this way.) If there is no match, discard the traffic. This is an auditable event. The audit log entry for this event SHOULD include the current date/time, SPI if available, IPsec protocol if available, source and destination of the packet, and any other selector values of the packet that are available.

3c. Processing of ICMP messages is assumed to take place on the unprotected side of the IPsec boundary. Unprotected ICMP messages are examined and local policy is applied to determine whether to accept or reject these messages and, if accepted, what action to take as a result. For example, if an ICMP unreachable message is received, the implementation must decide whether to act on it, reject it, or act on it with constraints. (See Section 6.)

4. Apply ESP processing as specified, using the SAD entry selected in step 3a above. Then match the packet against the inbound selectors identified by the SAD entry to verify that the received packet is appropriate for the SA via which it was received.

5. If an IPsec system receives an inbound packet on an SA and the packet's header fields are not consistent with the selectors for the SA, it MUST discard the packet. This is an auditable event. The audit log entry for this event SHOULD include the current date/time, SPI, IPsec protocol(s), source and destination of the packet, any other selector values of the packet that are available, and the selector values from the relevant SAD entry. The system SHOULD also be capable of generating and sending an IKE notification of INVALID_SELECTORS to the sender (IPsec peer), indicating that the received packet was discarded because of

failure to pass selector checks.

To minimize the impact of a DoS attack, or a mis-configured peer, the IPsec system SHOULD include a management control to allow an administrator to configure the IPsec implementation to send or not send this IKE notification, and if this facility is selected, to rate limit the transmission of such notifications.

After traffic is bypassed or processed through IPsec, it is handed to the inbound forwarding function for disposition. Ultimately, the packet should be forwarded to the destination host or process for disposition.

6. ICMP Processing

This section describes IPsec handling of ICMP traffic. There are two categories of ICMP traffic: error messages (e.g., type = destination unreachable) and non-error messages (e.g., type = echo). This section applies exclusively to error messages. Disposition of non-error, ICMP messages (that are not addressed to the IPsec implementation itself) MUST be explicitly accounted for using SPD entries.

The discussion in this section applies to ICMPv6 as well as to ICMPv4. Also, a mechanism SHOULD be provided to allow an administrator to cause ICMP error messages (selected, all, or none) to be logged as an aid to problem diagnosis.

6.1. Processing ICMP Error Messages Directed to an IPsec Implementation

6.1.1. ICMP Error Messages Received on the Unprotected Side of the Boundary

Figure 3 in Section 5.2 shows a distinct ICMP processing module on the unprotected side of the IPsec boundary, for processing ICMP messages (error or otherwise) that are addressed to the IPsec device and that are not protected via ESP. An ICMP message of this sort is unauthenticated, and its processing may result in denial or degradation of service. This suggests that, in general, it would be desirable to ignore such messages. However, many ICMP messages will be received by hosts or security gateways from unauthenticated sources, e.g., routers in the public Internet. Ignoring these ICMP messages can degrade service, e.g., because of a failure to process PMTU message and redirection messages. Thus, there is also a motivation for accepting and acting upon unauthenticated ICMP messages.

To accommodate both ends of this spectrum, a compliant IPsec implementation MUST permit a local administrator to configure an IPsec implementation to accept or reject unauthenticated ICMP traffic. This control MUST be at the granularity of ICMP type and MAY be at the granularity of ICMP type and code. Additionally, an implementation SHOULD incorporate mechanisms and parameters for dealing with such traffic. For example, there could be the ability to establish a minimum PMTU for traffic (on a per destination basis),

to prevent receipt of an unauthenticated ICMP from setting the PMTU to a trivial size.

If an ICMP PMTU message passes the checks above and the system is configured to accept it, then there are two possibilities. If the implementation applies fragmentation on the ciphertext side of the boundary, then the accepted PMTU information is passed to the forwarding module (outside of the IPsec implementation), which uses it to manage outbound packet fragmentation. If the implementation is configured to effect plaintext side fragmentation, then the PMTU information is passed to the plaintext side and processed as described in Section 8.2.

6.1.2. ICMP Error Messages Received on the Protected Side of the Boundary

These ICMP messages are not authenticated, but they do come from sources on the protected side of the IPsec boundary. Thus, these messages generally are viewed as more "trustworthy" than their counterparts arriving from sources on the unprotected side of the boundary. The major security concern here is that a compromised host or router might emit erroneous ICMP error messages that could degrade service for other devices "behind" the security gateway, or that could even result in violations of confidentiality. For example, if a bogus ICMP redirect were consumed by a security gateway, it could cause the forwarding table on the protected side of the boundary to be modified so as to deliver traffic to an inappropriate destination "behind" the gateway. Thus, implementers MUST provide controls to allow local administrators to constrain the processing of ICMP error messages received on the protected side of the boundary, and directed to the IPsec implementation. These controls are of the same type as those employed on the unprotected side, described above in Section 6.1.1.

6.2. Processing Protected, Transit ICMP Error Messages

When an ICMP error message is transmitted via an SA to a device "behind" an IPsec implementation, both the payload and the header of the ICMP message require checking from an access control perspective. If one of these messages is forwarded to a host behind a security gateway, the receiving host IP implementation will make decisions based on the payload, i.e., the header of the packet that purportedly triggered the error response. Thus, an IPsec implementation MUST be configurable to check that this payload header information is consistent with the SA via which it arrives. (This means that the payload header, with source and destination address and port fields reversed, matches the traffic selectors for the SA.) If this sort of check is not performed, then, for example, anyone with whom the receiving IPsec system (A) has an active SA could send an ICMP Destination Unreachable message that refers to any host/net with which A is currently communicating, and thus effect a highly efficient DoS attack regarding communication with other peers of A. Normal IPsec receiver processing of traffic is not sufficient to protect against such attacks. However, not all contexts may require

such checks, so it is also necessary to allow a local administrator to configure an implementation to NOT perform such checks.

To accommodate both policies, the following convention is adopted. If an administrator wants to allow ICMP error messages to be carried by an SA without inspection of the payload, then configure an SPD entry that explicitly allows for carriage of such traffic. If an administrator wants IPsec to check the payload of ICMP error messages for consistency, then do not create any SPD entries that accommodate carriage of such traffic based on the ICMP packet header. This convention motivates the following processing description.

IPsec senders and receivers MUST support the following processing for ICMP error messages that are sent and received via SAs.

If an SA exists that accommodates an outbound ICMP error message, then the message is mapped to the SA and only the IP and ICMP headers are checked upon receipt, just as would be the case for other traffic. If no SA exists that matches the traffic selectors associated with an ICMP error message, then the SPD is searched to determine if such an SA can be created. If so, the SA is created and the ICMP error message is transmitted via that SA. Upon receipt, this message is subject to the usual traffic selector checks at the receiver. This processing is exactly what would happen for traffic in general, and thus does not represent any special processing for ICMP error messages.

If no SA exists that would carry the outbound ICMP message in question, and if no SPD entry would allow carriage of this outbound ICMP error message, then an IPsec implementation MUST map the message to the SA that would carry the return traffic associated with the packet that triggered the ICMP error message. This requires an IPsec implementation to detect outbound ICMP error messages that map to no extant SA or SPD entry, and treat them specially with regard to SA creation and lookup. The implementation extracts the header for the packet that triggered the error (from the ICMP message payload), reverses the source and destination IP address fields, extracts the protocol field, and reverses the port fields (if accessible). It then uses this extracted information to locate an appropriate, active outbound SA, and transmits the error message via this SA. If no such SA exists, no SA will be created, and this is an auditable event.

If an IPsec implementation receives an inbound ICMP error message on an SA, and the IP and ICMP headers of the message do not match the traffic selectors for the SA, the receiver MUST process the received message in a special fashion. Specifically, the receiver must extract the header of the triggering packet from the ICMP payload, and reverse fields as described above to determine if the packet is consistent with the selectors for the SA via which the ICMP error message was received. If the packet fails this check, the IPsec implementation MUST NOT forwarded the ICMP message to the destination. This is an auditable event.

7. Handling Fragments (on the protected side of the IPsec boundary)

Earlier sections of this document describe mechanisms for (a) fragmenting an outbound packet after IPsec processing has been applied and reassembling it at the receiver before IPsec processing and (b) handling inbound fragments received from the unprotected side of the IPsec boundary. This section describes how an implementation should handle the processing of outbound plaintext fragments on the protected side of the IPsec boundary. (See Appendix D, "Fragment Handling Rationale".) In particular, it addresses:

- mapping an outbound non-initial fragment to the right SA (or finding the right SPD entry)
- verifying that a received non-initial fragment is authorized for the SA via which it was received
- mapping outbound and inbound non-initial fragments to the right SPD-O/SPD-I entry or the relevant cache entry, for BYPASS/DISCARD traffic

Note: Note that in Section 4.4.1, two special values, ANY and OPAQUE, were defined for selectors and that ANY includes OPAQUE. The term "non-trivial" is used to mean that the selector has a value other than OPAQUE or ANY.

Note: The term "non-initial fragment" is used here to indicate a fragment that does not contain all the selector values that may be needed for access control. As observed in Section 4.4.1, depending on the Next Layer Protocol, in addition to Ports, the ICMP message type/code or Mobility Header type could be missing from non-initial fragments. Also, for IPv6, even the first fragment might NOT contain the Next Layer Protocol or Ports (or ICMP message type/code, or Mobility Header type) depending on the kind and number of extension headers present. If a non-initial fragment contains the Port (or ICMP type and code or Mobility Header type) but not the Next Layer Protocol, then unless there is an SPD entry for the relevant Local/Remote addresses with ANY for Next Layer Protocol and Port (or ICMP type and code or Mobility Header type), the fragment would not contain all the selector information needed for access control.

To address the above issues, three approaches have been defined:

- Tunnel mode SAs that carry initial and non-initial fragments (See Section 7.1.)
- Separate tunnel mode SAs for non-initial fragments (See Section 7.2.)
- Stateful fragment checking (See Section 7.3.)

7.1. Tunnel Mode SAs that Carry Initial and Non-Initial Fragments

All implementations MUST support tunnel mode SAs that are configured to pass traffic without regard to port field (or ICMP type/code or Mobility Header type) values. If the SA will carry traffic for specified protocols, the selector set for the SA MUST specify the port fields (or ICMP type/code or Mobility Header type) as ANY. An SA defined in this fashion will carry all traffic including initial

and non-initial fragments for the indicated Local/Remote addresses and specified Next Layer protocol(s). If the SA will carry traffic without regard to a specific protocol value (i.e., ANY is specified as the (Next Layer) protocol selector value), then the port field values are undefined and MUST be set to ANY as well. (As noted in 4.4.1, ANY includes OPAQUE as well as all specific values.)

7.2. Separate Tunnel Mode SAs for Non-Initial Fragments

An implementation MAY support tunnel mode SAs that will carry only non-initial fragments, separate from non-fragmented packets and initial fragments. The OPAQUE value will be used to specify port (or ICMP type/code or Mobility Header type) field selectors for an SA to carry such fragments. Receivers MUST perform a minimum offset check on IPv4 (non-initial) fragments to protect against overlapping fragment attacks when SAs of this type are employed. Because such checks cannot be performed on IPv6 non-initial fragments, users and administrators are advised that carriage of such fragments may be dangerous, and implementers may choose to NOT support such SAs for IPv6 traffic. Also, an SA of this sort will carry all non-initial fragments that match a specified Local/Remote address pair and protocol value, i.e., the fragments carried on this SA belong to packets that if not fragmented, might have gone on separate SAs of differing security. Therefore, users and administrators are advised to protect such traffic using ESP (with integrity) and the "strongest" integrity and encryption algorithms in use between both peers. (Determination of the "strongest" algorithms requires imposing an ordering of the available algorithms, a local determination at the discretion of the initiator of the SA.)

Specific port (or ICMP type/code or Mobility Header type) selector values will be used to define SAs to carry initial fragments and non-fragmented packets. This approach can be used if a user or administrator wants to create one or more tunnel mode SAs between the same Local/Remote addresses that discriminate based on port (or ICMP type/code or Mobility Header type) fields. These SAs MUST have non-trivial protocol selector values, otherwise approach #1 above MUST be used.

Note: In general, for the approach described in this section, one needs only a single SA between two implementations to carry all non-initial fragments. However, if one chooses to have multiple SAs between the two implementations for QoS differentiation, then one might also want multiple SAs to carry fragments-without-ports, one for each supported QoS class. Since support for QoS via distinct SAs is a local matter, not mandated by this document, the choice to have multiple SAs to carry non-initial fragments should also be local.

7.3. Stateful Fragment Checking

An implementation MAY support some form of stateful fragment checking for a tunnel mode SA with non-trivial port (or ICMP type/code or MH type) field values (not ANY or OPAQUE). Implementations that will transmit non-initial fragments on a tunnel mode SA that makes use of

non-trivial port (or ICMP type/code or MH type) selectors MUST notify a peer via the IKE NOTIFY NON_FIRST_FRAGMENTS_ALSO payload.

The peer MUST reject this proposal if it will not accept non-initial fragments in this context. If an implementation does not successfully negotiate transmission of non-initial fragments for such an SA, it MUST NOT send such fragments over the SA. This standard does not specify how peers will deal with such fragments, e.g., via reassembly or other means, at either sender or receiver. However, a receiver MUST discard non-initial fragments that arrive on an SA with non-trivial port (or ICMP type/code or MH type) selector values unless this feature has been negotiated. Also, the receiver MUST discard non-initial fragments that do not comply with the security policy applied to the overall packet. Discarding such packets is an auditable event. Note that in network configurations where fragments of a packet might be sent or received via different security gateways or BITW implementations, stateful strategies for tracking fragments may fail.

7.4. BYPASS/DISCARD Traffic

All implementations MUST support DISCARDing of fragments using the normal SPD packet classification mechanisms. All implementations MUST support stateful fragment checking to accommodate BYPASS traffic for which a non-trivial port range is specified. The concern is that BYPASS of a cleartext, non-initial fragment arriving at an IPsec implementation could undermine the security afforded IPsec-protected traffic directed to the same destination. For example, consider an IPsec implementation configured with an SPD entry that calls for IPsec protection of traffic between a specific source/destination address pair, and for a specific protocol and destination port, e.g., TCP traffic on port 23 (Telnet). Assume that the implementation also allows BYPASS of traffic from the same source/destination address pair and protocol, but for a different destination port, e.g., port 119 (NNTP). An attacker could send a non-initial fragment (with a forged source address) that, if bypassed, could overlap with IPsec-protected traffic from the same source and thus violate the integrity of the IPsec-protected traffic. Requiring stateful fragment checking for BYPASS entries with non-trivial port ranges prevents attacks of this sort. As noted above, in network configurations where fragments of a packet might be sent or received via different security gateways or BITW implementations, stateful strategies for tracking fragments may fail.

8. Path MTU/DF Processing

The application of ESP to an outbound packet increases the size of a packet and thus may cause a packet to exceed the PMTU for the SA via which the packet will travel. An IPsec implementation also may receive an unprotected ICMP PMTU message and, if it chooses to act upon the message, the result will affect outbound traffic processing. This section describes the processing required of an IPsec implementation to deal with these two PMTU issues.

8.1. DF Bit

All IPsec implementations MUST support the option of copying the DF bit from an outbound packet to the tunnel mode header that it emits, when traffic is carried via a tunnel mode SA. This means that it MUST be possible to configure the implementation's treatment of the DF bit (set, clear, copy from inner header) for each SA. This applies to SAs where both inner and outer headers are IPv4.

8.2. Path MTU (PMTU) Discovery

This section discusses IPsec handling for unprotected Path MTU Discovery messages. ICMP PMTU is used here to refer to an ICMP message for:

IPv4 (RFC 792 [Pos81b]):
- Type = 3 (Destination Unreachable)
- Code = 4 (Fragmentation needed and DF set)
- Next-Hop MTU in the low-order 16 bits of the second word of the ICMP header (labeled "unused" in RFC 792), with high-order 16 bits set to zero)

IPv6 (RFC 2463 [CD98]):
- Type = 2 (Packet Too Big)
- Code = 0 (Fragmentation needed)
- Next-Hop MTU in the 32-bit MTU field of the ICMP6 message

8.2.1. Propagation of PMTU

When an IPsec implementation receives an unauthenticated PMTU message, and it is configured to process (vs. ignore) such messages, it maps the message to the SA to which it corresponds. This mapping is effected by extracting the header information from the payload of the PMTU message and applying the procedure described in Section 5.2. The PMTU determined by this message is used to update the SAD PMTU field, taking into account the size of the ESP header that will be applied, any crypto synchronization data, and the overhead imposed by an additional IP header, in the case of a tunnel mode SA.

In a native host implementation, it is possible to maintain PMTU data at the same granularity as for unprotected communication, so there is no loss of functionality. Signaling of the PMTU information is internal to the host. For all other IPsec implementation options, the PMTU data must be propagated via a synthesized ICMP PMTU. In these cases, the IPsec implementation SHOULD wait for outbound traffic to be mapped to the SAD entry. When such traffic arrives, if the traffic would exceed the updated PMTU value the traffic MUST be handled as follows:

Case 1: Original (cleartext) packet is IPv4 and has the DF bit set. The implementation SHOULD discard the packet and send a PMTU ICMP message.

Case 2: Original (cleartext) packet is IPv4 and has the DF bit clear. The implementation SHOULD fragment (before or after encryption per its configuration) and then forward the fragments. It SHOULD NOT send a PMTU ICMP message.

Case 3: Original (cleartext) packet is IPv6. The implementation SHOULD discard the packet and send a PMTU ICMP message.

8.2.2. PMTU Aging

In all IPsec implementations, the PMTU associated with an SA MUST be "aged" and some mechanism is required to update the PMTU in a timely manner, especially for discovering if the PMTU is smaller than required by current network conditions. A given PMTU has to remain in place long enough for a packet to get from the source of the SA to the peer, and to propagate an ICMP error message if the current PMTU is too big.

Implementations SHOULD use the approach described in the Path MTU Discovery document (RFC 1191 [MD90], Section 6.3), which suggests periodically resetting the PMTU to the first-hop data-link MTU and then letting the normal PMTU Discovery processes update the PMTU as necessary. The period SHOULD be configurable.

9. Auditing

IPsec implementations are not required to support auditing. For the most part, the granularity of auditing is a local matter. However, several auditable events are identified in this document, and for each of these events a minimum set of information that SHOULD be included in an audit log is defined. Additional information also MAY be included in the audit log for each of these events, and additional events, not explicitly called out in this specification, also MAY result in audit log entries. There is no requirement for the receiver to transmit any message to the purported transmitter in response to the detection of an auditable event, because of the potential to induce denial of service via such action.

10. Conformance Requirements

All IPv4 IPsec implementations MUST comply with all requirements of this document. All IPv6 implementations MUST comply with all requirements of this document.

11. Security Considerations

The focus of this document is security; hence security considerations permeate this specification.

IPsec imposes stringent constraints on bypass of IP header data in both directions, across the IPsec barrier, especially when tunnel mode SAs are employed. Some constraints are absolute, while others are subject to local administrative controls, often on a per-SA basis. For outbound traffic, these constraints are designed to limit

covert channel bandwidth. For inbound traffic, the constraints are designed to prevent an adversary who has the ability to tamper with one data stream (on the unprotected side of the IPsec barrier) from adversely affecting other data streams (on the protected side of the barrier). The discussion in Section 5 dealing with processing DSCP values for tunnel mode SAs illustrates this concern.

If an IPsec implementation is configured to pass ICMP error messages over SAs based on the ICMP header values, without checking the header information from the ICMP message payload, serious vulnerabilities may arise. Consider a scenario in which several sites (A, B, and C) are connected to one another via ESP-protected tunnels: A-B, A-C, and B-C. Also assume that the traffic selectors for each tunnel specify ANY for protocol and port fields and IP source/destination address ranges that encompass the address range for the systems behind the security gateways serving each site. This would allow a host at site B to send an ICMP Destination Unreachable message to any host at site A, that declares all hosts on the net at site C to be unreachable. This is a very efficient DoS attack that could have been prevented if the ICMP error messages were subjected to the checks that IPsec provides, if the SPD is suitably configured, as described in Section 6.2.

12. IANA Considerations

13. Differences from RFC 2401

14. Acknowledgements

Appendix A: Glossary

This section provides definitions for several key terms that are employed in this document. Other documents provide additional definitions and background information relevant to this technology, e.g., [Shi00], [VK83], and [HA94]. Included in this glossary are generic security service and security mechanism terms, plus IPsec-specific terms.

Access Control
: A security service that prevents unauthorized use of a resource, including the prevention of use of a resource in an unauthorized manner. In the IPsec context, the resource to which access is being controlled is often:

  - for a host, computing cycles or data
  - for a security gateway, a network behind the gateway or bandwidth on that network.

Anti-replay
: See "Integrity" below.

Authentication
: Used informally to refer to the combination of two nominally distinct security services, data origin authentication and

connectionless integrity. See the definitions below for each of these services.

Availability
When viewed as a security service, addresses the security concerns engendered by attacks against networks that deny or degrade service. For example, in the IPsec context, the use of anti-replay mechanisms in ESP support availability.

Confidentiality
The security service that protects data from unauthorized disclosure. The primary confidentiality concern in most instances is unauthorized disclosure of application-level data, but disclosure of the external characteristics of communication also can be a concern in some circumstances. Traffic flow confidentiality is the service that addresses this latter concern by concealing source and destination addresses, message length, or frequency of communication. In the IPsec context, using ESP in tunnel mode, especially at a security gateway, can provide some level of traffic flow confidentiality. (See also "Traffic Analysis" below.)

Data Origin Authentication
A security service that verifies the identity of the claimed source of data. This service is usually bundled with connectionless integrity service.

Encryption
A security mechanism used to transform data from an intelligible form (plaintext) into an unintelligible form (ciphertext), to provide confidentiality. The inverse transformation process is designated "decryption". Often the term "encryption" is used to generically refer to both processes.

Integrity
A security service that ensures that modifications to data are detectable. Integrity comes in various flavors to match application requirements. IPsec supports two forms of integrity: connectionless and a form of partial sequence integrity. Connectionless integrity is a service that detects modification of an individual IP datagram, without regard to the ordering of the datagram in a stream of traffic. The form of partial sequence integrity offered in IPsec is referred to as anti-replay integrity, and it detects arrival of duplicate IP datagrams (within a constrained window). This is in contrast to connection-oriented integrity, which imposes more stringent sequencing requirements on traffic, e.g., to be able to detect lost or re-ordered messages. Although authentication and integrity services often are cited separately, in practice they are intimately connected and almost always offered in tandem.

Protected vs. Unprotected
"Protected" refers to the systems or interfaces that are inside the IPsec protection boundary, and "unprotected" refers to the

systems or interfaces that are outside the IPsec protection boundary. IPsec provides a boundary through which traffic passes. There is an asymmetry to this barrier, which is reflected in the processing model. Outbound data, if not discarded or bypassed, is protected via the application of ESP and the addition of the corresponding headers. Inbound data, if not discarded or bypassed, is processed via the removal of ESP headers. In this document, inbound traffic enters an IPsec implementation from the "unprotected" interface.
Outbound traffic enters the implementation via the "protected" interface, or is internally generated by the implementation on the "protected" side of the boundary and directed toward the "unprotected" interface. An IPsec implementation may support more than one interface on either or both sides of the boundary. The protected interface may be internal, e.g., in a host implementation of IPsec. The protected interface may link to a socket layer interface presented by the OS.

Security Association (SA)
A simplex (uni-directional) logical connection, created for security purposes. All traffic traversing an SA is provided the same security processing. In IPsec, an SA is an Internet-layer abstraction implemented through the use of ESP. State data associated with an SA is represented in the SA Database (SAD).

Security Gateway
An intermediate system that acts as the communications interface between two networks. The set of hosts (and networks) on the external side of the security gateway is termed unprotected (they are generally at least less protected than those "behind" the SG), while the networks and hosts on the internal side are viewed as protected. The internal subnets and hosts served by a security gateway are presumed to be trusted by virtue of sharing a common, local, security administration. In the IPsec context, a security gateway is a point at which ESP is implemented in order to serve a set of internal hosts, providing security services for these hosts when they communicate with external hosts also employing IPsec (either directly or via another security gateway).

Security Parameters Index (SPI)
An arbitrary 32-bit value that is used by a receiver to identify the SA to which an incoming packet should be bound. For a unicast SA, the SPI can be used by itself to specify an SA, or it may be used in conjunction with the IPsec protocol type. Additional IP address information is used to identify multicast SAs. The SPI is carried in the ESP protocol to enable the receiving system to select the SA under which a received packet will be processed. An SPI has only local significance, as defined by the creator of the SA (usually the receiver of the packet carrying the SPI); thus an SPI is generally viewed as an opaque bit string. However, the creator of an SA may choose to interpret the bits in an SPI to facilitate local processing.

Traffic Analysis

The analysis of network traffic flow for the purpose of deducing information that is useful to an adversary. Examples of such information are frequency of transmission, the identities of the conversing parties, sizes of packets, and flow identifiers [Sch94].

Appendix B: Decorrelation

This appendix is based on work done for caching of policies in the IP Security Policy Working Group by Luis Sanchez, Matt Condell, and John Zao.

Two SPD entries are correlated if there is a non-null intersection between the values of corresponding selectors in each entry. Caching correlated SPD entries can lead to incorrect policy enforcement. A solution to this problem, which still allows for caching, is to remove the ambiguities by decorrelating the entries. That is, the SPD entries must be rewritten so that for every pair of entries there exists a selector for which there is a null intersection between the values in both of the entries. Once the entries are decorrelated, there is no longer any ordering requirement on them, since only one entry will match any lookup. The next section describes decorrelation in more detail and presents an algorithm that may be used to implement decorrelation.

B.1. Decorrelation Algorithm

The basic decorrelation algorithm takes each entry in a correlated SPD and divides it into a set of entries using a tree structure. The nodes of the tree are the selectors that may overlap between the policies. At each node, the algorithm creates a branch for each of the values of the selector. It also creates one branch for the complement of the union of all selector values. Policies are then formed by traversing the tree from the root to each leaf. The policies at the leaves are compared to the set of already decorrelated policy rules. Each policy at a leaf is either completely overridden by a policy in the already decorrelated set and is discarded or is decorrelated with all the policies in the decorrelated set and is added to it.

The basic algorithm does not guarantee an optimal set of decorrelated entries. That is, the entries may be broken up into smaller sets than is necessary, though they will still provide all the necessary policy information. Some extensions to the basic algorithm are described later to improve this and improve the performance of the algorithm.

C A set of ordered, correlated entries (a correlated SPD).
Ci The ith entry in C.
U The set of decorrelated entries being built from C.
Ui The ith entry in U.
Sik The kth selection for policy Ci.
Ai The action for policy Ci.

A policy (SPD entry) P may be expressed as a sequence of selector values and an action (BYPASS, DISCARD, or PROTECT):

```
Ci = Si1 x Si2 x ... x Sik -> Ai
```

1) Put C1 in set U as U1

For each policy Cj (j > 1) in C

2) If Cj is decorrelated with every entry in U, then add it to U.

3) If Cj is correlated with one or more entries in U, create a tree rooted at the policy Cj that partitions Cj into a set of decorrelated entries. The algorithm starts with a root node where no selectors have yet been chosen.

A) Choose a selector in Cj, Sjn, that has not yet been chosen when traversing the tree from the root to this node. If there are no selectors not yet used, continue to the next unfinished branch until all branches have been completed. When the tree is completed, go to step D.

   T is the set of entries in U that are correlated with the entry at this node.

   The entry at this node is the entry formed by the selector values of each of the branches between the root and this node. Any selector values that are not yet represented by branches assume the corresponding selector value in Cj, since the values in Cj represent the maximum value for each selector.

B) Add a branch to the tree for each value of the selector Sjn that appears in any of the entries in T. (If the value is a superset of the value of Sjn in Cj, then use the value in Cj, since that value represents the universal set.) Also add a branch for the complement of the union of all the values of the selector Sjn in T. When taking the complement, remember that the universal set is the value of Sjn in Cj. A branch need not be created for the null set.

C) Repeat A and B until the tree is completed.

D) The entry to each leaf now represents an entry that is a subset of Cj. The entries at the leaves completely partition Cj in such a way that each entry is either completely overridden by an entry in U, or is decorrelated with the entries in U.

   Add all the decorrelated entries at the leaves of the tree to U.

4) Get next Cj and go to 2.

5) When all entries in C have been processed, then U will contain an decorrelated version of C.

There are several optimizations that can be made to this algorithm. A few of them are presented here.

It is possible to optimize, or at least improve, the amount of branching that occurs by carefully choosing the order of the selectors used for the next branch. For example, if a selector Sjn can be chosen so that all the values for that selector in T are equal to or a superset of the value of Sjn in Cj, then only a single branch needs to be created (since the complement will be null).

Branches of the tree do not have to proceed with the entire decorrelation algorithm. For example, if a node represents an entry that is decorrelated with all the entries in U, then there is no reason to continue decorrelating that branch. Also, if a branch is completely overridden by an entry in U, then there is no reason to continue decorrelating the branch.

An additional optimization is to check to see if a branch is overridden by one of the CORRELATED entries in set C that has already been decorrelated. That is, if the branch is part of decorrelating Cj, then check to see if it was overridden by an entry Cm, m < j. This is a valid check, since all the entries Cm are already expressed in U.

Along with checking if an entry is already decorrelated in step 2, check if Cj is overridden by any entry in U. If it is, skip it since it is not relevant. An entry x is overridden by another entry y if every selector in x is equal to or a subset of the corresponding selector in entry y.

Appendix C: ASN.1 for an SPD Entry

This appendix is included as an additional way to describe SPD entries, as defined in Section 4.4.1. It uses ASN.1 syntax that has been successfully compiled. This syntax is merely illustrative and need not be employed in an implementation to achieve compliance. The SPD description in Section 4.4.1 is normative.

SPDModule

```
 {iso(1) org (3) dod (6) internet (1) security (5) mechanisms (5)
  ipsec (8) asn1-modules (3) spd-module (1) }

    DEFINITIONS IMPLICIT TAGS ::=

    BEGIN

    IMPORTS
        RDNSequence FROM PKIX1Explicit88
          { iso(1) identified-organization(3)
            dod(6) internet(1) security(5) mechanisms(5) pkix(7)
            id-mod(0) id-pkix1-explicit(18) } ;

    -- An SPD is a list of policies in decreasing order of preference
```

```
SPD ::= SEQUENCE OF SPDEntry

SPDEntry ::= CHOICE {
    iPsecEntry       IPsecEntry,               -- PROTECT traffic
    bypassOrDiscard  [0] BypassOrDiscardEntry } -- DISCARD/BYPASS

IPsecEntry ::= SEQUENCE {       -- Each entry consists of
    name        NameSets OPTIONAL,
    pFPs        PacketFlags,    -- Populate from packet flags
                       -- Applies to ALL of the corresponding
                       -- traffic selectors in the SelectorLists
    condition   SelectorLists,  -- Policy "condition"
    processing  Processing      -- Policy "action"
    }

BypassOrDiscardEntry ::= SEQUENCE {
    bypass      BOOLEAN,        -- TRUE BYPASS, FALSE DISCARD
    condition   InOutBound }

InOutBound ::= CHOICE {
    outbound    [0] SelectorLists,
    inbound     [1] SelectorLists,
    bothways    [2] BothWays }

BothWays ::= SEQUENCE {
    inbound     SelectorLists,
    outbound    SelectorLists }

NameSets ::= SEQUENCE {
    passed      SET OF Names-R,  -- Matched to IKE ID by
                                 -- responder
    local       SET OF Names-I } -- Used internally by IKE
                                 -- initiator

Names-R ::= CHOICE {                   -- IKEv2 IDs
    dName       RDNSequence,           -- ID_DER_ASN1_DN
    fqdn        FQDN,                  -- ID_FQDN
    rfc822      [0] RFC822Name,        -- ID_RFC822_ADDR
    keyID       OCTET STRING }         -- KEY_ID

Names-I ::= OCTET STRING       -- Used internally by IKE
                               -- initiator

FQDN ::= IA5String

RFC822Name ::= IA5String

PacketFlags ::= BIT STRING {
            -- if set, take selector value from packet
            -- establishing SA
            -- else use value in SPD entry
    localAddr  (0),
    remoteAddr (1),
    protocol   (2),
```

```
    localPort  (3),
    remotePort (4)  }

SelectorLists ::= SET OF SelectorList

SelectorList ::= SEQUENCE {
    localAddr   AddrList,
    remoteAddr  AddrList,
    protocol    ProtocolChoice }

Processing ::= SEQUENCE {
    extSeqNum   BOOLEAN, -- TRUE 64 bit counter, FALSE 32 bit
    seqOverflow BOOLEAN, -- TRUE rekey, FALSE terminate & audit
    fragCheck   BOOLEAN, -- TRUE stateful fragment checking,
                         -- FALSE no stateful fragment checking
    lifetime    SALifetime,
    spi         ManualSPI,
    algorithms  ESPAlgs,
    tunnel      TunnelOptions }

SALifetime ::= SEQUENCE {
    seconds   [0] INTEGER OPTIONAL,
    bytes     [1] INTEGER OPTIONAL }

ManualSPI ::= SEQUENCE {
    spi     INTEGER,
    keys    KeyIDs }

KeyIDs ::= SEQUENCE OF OCTET STRING

ESPAlgs ::= CHOICE {
    both            [0] IntegrityConfidentialityAlgs,
    combined        [1] CombinedModeAlgs }

IntegrityConfidentialityAlgs ::= SEQUENCE {
    integrity       IntegrityAlgs,
    confidentiality ConfidentialityAlgs }

-- Integrity Algorithms, ordered by decreasing preference
IntegrityAlgs ::= SEQUENCE OF IntegrityAlg

-- Confidentiality Algorithms, ordered by decreasing preference
ConfidentialityAlgs ::= SEQUENCE OF ConfidentialityAlg

-- Integrity Algorithms
IntegrityAlg ::= SEQUENCE {
    algorithm   IntegrityAlgType,
    parameters  ANY -- DEFINED BY algorithm -- OPTIONAL }

IntegrityAlgType ::= INTEGER {
    none              (0),
    auth-HMAC-MD5-96  (1),
    auth-HMAC-SHA1-96 (2),
    auth-DES-MAC      (3),
```

```
    auth-KPDK-MD5     (4),
    auth-AES-XCBC-96  (5)
--  tbd (6..65535)
    }

-- Confidentiality Algorithms
ConfidentialityAlg ::= SEQUENCE {
    algorithm   ConfidentialityAlgType,
    parameters  ANY -- DEFINED BY algorithm -- OPTIONAL }

ConfidentialityAlgType ::= INTEGER {
    encr-DES-IV64   (1),
    encr-DES        (2),
    encr-3DES       (3),
    encr-RC5        (4),
    encr-IDEA       (5),
    encr-CAST       (6),
    encr-BLOWFISH   (7),
    encr-3IDEA      (8),
    encr-DES-IV32   (9),
    encr-RC4       (10),
    encr-NULL      (11),
    encr-AES-CBC   (12),
    encr-AES-CTR   (13)
--  tbd (14..65535)
    }

CombinedModeAlgs ::= SEQUENCE OF CombinedModeAlg

CombinedModeAlg ::= SEQUENCE {
    algorithm   CombinedModeType,
    parameters  ANY -- DEFINED BY algorithm} -- defined outside
                            -- of this document for AES modes.

CombinedModeType ::= INTEGER {
    comb-AES-CCM    (1),
    comb-AES-GCM    (2)
--  tbd (3..65535)
    }

TunnelOptions ::= SEQUENCE {
    dscp        DSCP,
    ecn         BOOLEAN,    -- TRUE Copy CE to inner header
    df          DF,
    addresses   TunnelAddresses }

TunnelAddresses ::= CHOICE {
    ipv4        IPv4Pair,
    ipv6        [0] IPv6Pair }

IPv4Pair ::= SEQUENCE {
    local       OCTET STRING (SIZE(4)),
    remote      OCTET STRING (SIZE(4)) }
```

```
IPv6Pair ::= SEQUENCE {
    local       OCTET STRING (SIZE(16)),
    remote      OCTET STRING (SIZE(16)) }

DSCP ::= SEQUENCE {
    copy      BOOLEAN, -- TRUE copy from inner header
                       -- FALSE do not copy
    mapping   OCTET STRING OPTIONAL} -- points to table
                                     -- if no copy

DF ::= INTEGER {
    clear   (0),
    set     (1),
    copy    (2) }

ProtocolChoice::= CHOICE {
    anyProt  AnyProtocol,              -- for ANY protocol
    noNext   [0] NoNextLayerProtocol,  -- has no next layer
                                       -- items
    oneNext  [1] OneNextLayerProtocol, -- has one next layer
                                       -- item
    twoNext  [2] TwoNextLayerProtocol, -- has two next layer
                                       -- items
    fragment FragmentNoNext }          -- has no next layer
                                       -- info

AnyProtocol ::= SEQUENCE {
    id          INTEGER (0),    -- ANY protocol
    nextLayer   AnyNextLayers }

AnyNextLayers ::= SEQUENCE {      -- with either
    first       AnyNextLayer,     -- ANY next layer selector
    second      AnyNextLayer }    -- ANY next layer selector

NoNextLayerProtocol ::= INTEGER (2..254)

FragmentNoNext ::= INTEGER (44)   -- Fragment identifier

OneNextLayerProtocol ::= SEQUENCE {
    id          INTEGER (1..254),   -- ICMP, MH, ICMPv6
    nextLayer   NextLayerChoice }   -- ICMP Type*256+Code
                                    -- MH   Type*256

TwoNextLayerProtocol ::= SEQUENCE {
    id          INTEGER (2..254),   -- Protocol
    local       NextLayerChoice,    -- Local and
    remote      NextLayerChoice }   -- Remote ports

NextLayerChoice ::= CHOICE {
    any         AnyNextLayer,
    opaque      [0] OpaqueNextLayer,
    range       [1] NextLayerRange }

-- Representation of ANY in next layer field
```

```
    AnyNextLayer ::= SEQUENCE {
        start       INTEGER (0),
        end         INTEGER (65535) }

    -- Representation of OPAQUE in next layer field.
    -- Matches IKE convention
    OpaqueNextLayer ::= SEQUENCE {
        start       INTEGER (65535),
        end         INTEGER (0) }

    -- Range for a next layer field
    NextLayerRange ::= SEQUENCE {
        start       INTEGER (0..65535),
        end         INTEGER (0..65535) }

    -- List of IP addresses
    AddrList ::= SEQUENCE {
        v4List      IPv4List OPTIONAL,
        v6List      [0] IPv6List OPTIONAL }

    -- IPv4 address representations
    IPv4List ::= SEQUENCE OF IPv4Range

    IPv4Range ::= SEQUENCE {    -- close, but not quite right ...
        ipv4Start   OCTET STRING (SIZE (4)),
        ipv4End     OCTET STRING (SIZE (4)) }

    -- IPv6 address representations
    IPv6List ::= SEQUENCE OF IPv6Range

    IPv6Range ::= SEQUENCE {    -- close, but not quite right ...
        ipv6Start   OCTET STRING (SIZE (16)),
        ipv6End     OCTET STRING (SIZE (16)) }

    END
```

Appendix D: Fragment Handling Rationale

There are three issues that must be resolved regarding processing of (plaintext) fragments in IPsec:

- mapping a non-initial, outbound fragment to the right SA (or finding the right SPD entry)
- verifying that a received, non-initial fragment is authorized for the SA via which it is received
- mapping outbound and inbound non-initial fragments to the right SPD/cache entry, for BYPASS/DISCARD traffic

The first and third issues arise because we need a deterministic algorithm for mapping traffic to SAs (and SPD/cache entries). All three issues are important because we want to make sure that non-initial fragments that cross the IPsec boundary do not cause the access control policies in place at the receiver (or transmitter) to be violated.

D.1. Transport Mode and Fragments

D.2. Tunnel Mode and Fragments

For tunnel mode SAs, it has always been the case that outbound fragments might arrive for processing at an IPsec implementation. The need to accommodate fragmented outbound packets can pose a problem because a non-initial fragment generally will not contain the port fields associated with a next layer protocol such as TCP, UDP, or SCTP. Thus, depending on the SPD configuration for a given IPsec implementation, plaintext fragments might or might not pose a problem.

For example, if the SPD requires that all traffic between two address ranges is offered IPsec protection (no BYPASS or DISCARD SPD entries apply to this address range), then it should be easy to carry non-initial fragments on the SA defined for this address range, since the SPD entry implies an intent to carry ALL traffic between the address ranges. But, if there are multiple SPD entries that could match a fragment, and if these entries reference different subsets of port fields (vs. ANY), then it is not possible to map an outbound non-initial fragment to the right entry, unambiguously. (If we choose to allow carriage of fragments on transport mode SAs for IPv6, the problems arises in that context as well.)

This problem largely, though not exclusively, motivated the definition of OPAQUE as a selector value for port fields in RFC 2401. The other motivation for OPAQUE is the observation that port fields might not be accessible due to the prior application of IPsec. For example, if a host applied IPsec to its traffic and that traffic arrived at an SG, these fields would be encrypted. The algorithm specified for locating the "next layer protocol" described in RFC 2401 also motivated use of OPAQUE to accommodate an encrypted next layer protocol field in such circumstances. Nonetheless, the primary use of the OPAQUE value was to match traffic selector fields in packets that did not contain port fields (non-initial fragments), or packets in which the port fields were already encrypted (as a result of nested application of IPsec). RFC 2401 was ambiguous in discussing the use of OPAQUE vs. ANY, suggesting in some places that ANY might be an alternative to OPAQUE.

We gain additional access control capability by defining both ANY and OPAQUE values. OPAQUE can be defined to match only fields that are not accessible. We could define ANY as the complement of OPAQUE, i.e., it would match all values but only for accessible port fields. We have therefore simplified the procedure employed to locate the next layer protocol in this document, so that we treat ESP as next layer protocol. As a result, the notion of an encrypted next layer protocol field has vanished, and there is also no need to worry about encrypted port fields either. And accordingly, OPAQUE will be applicable only to non-initial fragments.

Since we have adopted the definitions above for ANY and OPAQUE, we

need to clarify how these values work when the specified protocol does not have port fields, and when ANY is used for the protocol selector. Accordingly, if a specific protocol value is used as a selector, and if that protocol has no port fields, then the port field selectors are to be ignored and ANY MUST be specified as the value for the port fields. (In this context, ICMP TYPE and CODE values are lumped together as a single port field (for IKEv2 negotiation), as is the IPv6 Mobility Header TYPE value.) If the protocol selector is ANY, then this should be treated as equivalent to specifying a protocol for which no port fields are defined, and thus the port selectors should be ignored, and MUST be set to ANY.

D.3. The Problem of Non-Initial Fragments

For an SG implementation, it is obvious that fragments might arrive from end systems behind the SG. A BITW implementation also may encounter fragments from a host or gateway behind it. (As noted earlier, native host implementations and BITS implementations probably can avoid the problems described below.) In the worst case, fragments from a packet might arrive at distinct BITW or SG instantiations and thus preclude reassembly as a solution option. Hence, in RFC 2401 we adopted a general requirement that fragments must be accommodated in tunnel mode for all implementations. However, RFC 2401 did not provide a perfect solution. The use of OPAQUE as a selector value for port fields (a SHOULD in RFC 2401) allowed an SA to carry non-initial fragments.

Using the features defined in RFC 2401, if one defined an SA between two IPsec (SG or BITW) implementations using the OPAQUE value for both port fields, then all non-initial fragments matching the source/destination (S/D) address and protocol values for the SA would be mapped to that SA. Initial fragments would NOT map to this SA, if we adopt a strict definition of OPAQUE. However, RFC 2401 did not provide detailed guidance on this and thus it may not have been apparent that use of this feature would essentially create a "non-initial fragment only" SA.

In the course of discussing the "fragment-only" SA approach, it was noted that some subtle problems, problems not considered in RFC 2401, would have to be avoided. For example, an SA of this sort must be configured to offer the "highest quality" security services for any traffic between the indicated S/D addresses (for the specified protocol). This is necessary to ensure that any traffic captured by the fragment-only SA is not offered degraded security relative to what it would have been offered if the packet were not fragmented. A possible problem here is that we may not be able to identify the "highest quality" security services defined for use between two IPsec implementation, since the choice of security protocols, options, and algorithms is a lattice, not a totally ordered set. (We might safely say that BYPASS < AH < ESP w/integrity, but it gets complicated if we have multiple ESP encryption or integrity algorithm options.) So, one has to impose a total ordering on these security parameters to make this work, but this can be done locally.

However, this conservative strategy has a possible performance downside. If most traffic traversing an IPsec implementation for a given S/D address pair (and specified protocol) is bypassed, then a fragment-only SA for that address pair might cause a dramatic increase in the volume of traffic afforded crypto processing. If the crypto implementation cannot support high traffic rates, this could cause problems. (An IPsec implementation that is capable of line rate or near line rate crypto performance would not be adversely affected by this SA configuration approach. Nonetheless, the performance impact is a potential concern, specific to implementation capabilities.)

Another concern is that non-initial fragments sent over a dedicated SA might be used to effect overlapping reassembly attacks, when combined with an apparently acceptable initial fragment. (This sort of attack assumes creation of bogus fragments and is not a side effect of normal fragmentation.) This concern is easily addressed in IPv4, by checking the fragment offset value to ensure that no non-initial fragments have a small enough offset to overlap port fields that should be contained in the initial fragment. Recall that the IPv4 MTU minimum is 576 bytes, and the max IP header length is 60 bytes, so any ports should be present in the initial fragment. If we require all non-initial fragments to have an offset of, say, 128 or greater, just to be on the safe side, this should prevent successful attacks of this sort. If the intent is only to protect against this sort of reassembly attack, this check need be implemented only by a receiver.

IPv6 also has a fragment offset, carried in the fragmentation extension header. However, IPv6 extension headers are variable in length and there is no analogous max header length value that we can use to check non-initial fragments, to reject ones that might be used for an attack of the sort noted above. A receiver would need to maintain state analogous to reassembly state, to provide equivalent protection. So, only for IPv4 is it feasible to impose a fragment offset check that would reject attacks designed to circumvent port field checks by IPsec (or firewalls) when passing non-initial fragments.

Another possible concern is that in some topologies and SPD configurations this approach might result in an access control surprise. The notion is that if we create an SA to carry ALL (non-initial) fragments, then that SA would carry some traffic that might otherwise arrive as plaintext via a separate path, e.g., a path monitored by a proxy firewall. But, this concern arises only if the other path allows initial fragments to traverse it without requiring reassembly, presumably a bad idea for a proxy firewall. Nonetheless, this does represent a potential problem in some topologies and under certain assumptions with respect to SPD and (other) firewall rule sets, and administrators need to be warned of this possibility.

A less serious concern is that non-initial fragments sent over a non-initial fragment-only SA might represent a DoS opportunity, in that they could be sent when no valid, initial fragment will ever

arrive. This might be used to attack hosts behind an SG or BITW device. However, the incremental risk posed by this sort of attack, which can be mounted only by hosts behind an SG or BITW device, seems small.

If we interpret the ANY selector value as encompassing OPAQUE, then a single SA with ANY values for both port fields would be able to accommodate all traffic matching the S/D address and protocol traffic selectors, an alternative to using the OPAQUE value. But, using ANY here precludes multiple, distinct SAs between the same IPsec implementations for the same address pairs and protocol. So, it is not an exactly equivalent alternative.

Fundamentally, fragment handling problems arise only when more than one SA is defined with the same S/D address and protocol selector values, but with different port field selector values.

D.4. BYPASS/DISCARD Traffic

We also have to address the non-initial fragment processing issue for BYPASS/DISCARD entries, independent of SA processing. This is largely a local matter for two reasons:

1) We have no means for coordinating SPD entries for such traffic between IPsec implementations since IKE is not invoked.
2) Many of these entries refer to traffic that is NOT directed to or received from a location that is using IPsec. So there is no peer IPsec implementation with which to coordinate via any means.

However, this document should provide guidance here, consistent with our goal of offering a well-defined, access control function for all traffic, relative to the IPsec boundary. To that end, this document says that implementations MUST support fragment reassembly for BYPASS/DISCARD traffic when port fields are specified. An implementation also MUST permit a user or administrator to accept such traffic or reject such traffic using the SPD conventions described in Section 4.4.1. The concern is that BYPASS of a cleartext, non-initial fragment arriving at an IPsec implementation could undermine the security afforded IPsec-protected traffic directed to the same destination. For example, consider an IPsec implementation configured with an SPD entry that calls for IPsec-protection of traffic between a specific source/destination address pair, and for a specific protocol and destination port, e.g., TCP traffic on port 23 (Telnet). Assume that the implementation also allows BYPASS of traffic from the same source/destination address pair and protocol, but for a different destination port, e.g., port 119 (NNTP). An attacker could send a non-initial fragment (with a forged source address) that, if bypassed, could overlap with IPsec-protected traffic from the same source and thus violate the integrity of the IPsec-protected traffic. Requiring stateful fragment checking for BYPASS entries with non-trivial port ranges prevents attacks of this sort.

D.5. Just say no to ports?

It has been suggested that we could avoid the problems described above by not allowing port field selectors to be used in tunnel mode. But the discussion above shows this to be an unnecessarily stringent approach, i.e., since no problems arise for the native OS and BITS implementations. Moreover, some WG members have described scenarios where use of tunnel mode SAs with (non-trivial) port field selectors is appropriate. So the challenge is defining a strategy that can deal with this problem in BITW and SG contexts. Also note that BYPASS/DISCARD entries in the SPD that make use of ports pose the same problems, irrespective of tunnel vs. transport mode notions.

Some folks have suggested that a firewall behind an SG or BITW should be left to enforce port-level access controls and the effects of fragmentation. However, this seems to be an incongruous suggestion in that elsewhere in IPsec (e.g., in IKE payloads) we are concerned about firewalls that always discard fragments. If many firewalls don't pass fragments in general, why should we expect them to deal with fragments in this case? So, this analysis rejects the suggestion of disallowing use of port field selectors with tunnel mode SAs.

D.6. Other Suggested Solutions

One suggestion is to reassemble fragments at the sending IPsec implementation, and thus avoid the problem entirely. This approach is invisible to a receiver and thus could be adopted as a purely local implementation option.

A more sophisticated version of this suggestion calls for establishing and maintaining minimal state from each initial fragment encountered, to allow non-initial fragments to be matched to the right SAs or SPD/cache entries. This implies an extension to the current processing model (and the old one). The IPsec implementation would intercept all fragments; capture Source/Destination IP addresses, protocol, packet ID, and port fields from initial fragments; and then use this data to map non-initial fragments to SAs that require port fields. If this approach is employed, the receiver needs to employ an equivalent scheme, as it too must verify that received fragments are consistent with SA selector values. A non-initial fragment that arrives prior to an initial fragment could be cached or discarded, awaiting arrival of the corresponding initial fragment.

A downside of both approaches noted above is that they will not always work. When a BITW device or SG is configured in a topology that might allow some fragments for a packet to be processed at different SGs or BITW devices, then there is no guarantee that all fragments will ever arrive at the same IPsec device. This approach also raises possible processing problems. If the sender caches non-initial fragments until the corresponding initial fragment arrives, buffering problems might arise, especially at high speeds. If the non-initial fragments are discarded rather than cached, there

is no guarantee that traffic will ever pass, e.g., retransmission will result in different packet IDs that cannot be matched with prior transmissions. In any case, housekeeping procedures will be needed to decide when to delete the fragment state data, adding some complexity to the system. Nonetheless, this is a viable solution in some topologies, and these are likely to be common topologies.

The Working Group rejected an earlier version of the convention of creating an SA to carry only non-initial fragments, something that was supported implicitly under the RFC 2401 model via use of OPAQUE port fields, but never clearly articulated in RFC 2401. The (rejected) text called for each non-initial fragment to be treated as protocol 44 (the IPv6 fragment header protocol ID) by the sender and receiver. This approach has the potential to make IPv4 and IPv6 fragment handling more uniform, but it does not fundamentally change the problem, nor does it address the issue of fragment handling for BYPASS/DISCARD traffic. Given the fragment overlap attack problem that IPv6 poses, it does not seem that it is worth the effort to adopt this strategy.

D.7. Consistency

Earlier, the WG agreed to allow an IPsec BITS, BITW, or SG to perform fragmentation prior to IPsec processing. If this fragmentation is performed after SA lookup at the sender, there is no "mapping to the right SA" problem. But, the receiver still needs to be able to verify that the non-initial fragments are consistent with the SA via which they are received. Since the initial fragment might be lost en route, the receiver encounters all of the potential problems noted above. Thus, if we are to be consistent in our decisions, we need to say how a receiver will deal with the non-initial fragments that arrive.

D.8. Conclusions

There is no simple, uniform way to handle fragments in all contexts. Different approaches work better in different contexts. Thus, this document offers 3 choices -- one MUST and two MAYs. At some point in the future, if the community gains experience with the two MAYs, they may become SHOULDs or MUSTs or other approaches may be proposed.

Appendix E: Example of Supporting Nested SAs via SPD and Forwarding Table Entries

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