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IP Encapsulating Security Payload (ESP)

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Abstract

This document describes an updated version of the Encapsulating Security Payload (ESP) protocol, which is designed to provide a mix of security services in IPv4 and IPv6. ESP is used to provide confidentiality, data origin authentication, connectionless integrity, an anti-replay service (a form of partial sequence integrity), and limited traffic flow confidentiality. This document obsoletes RFC 2406 (November 1998).

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1. Introduction

This document assumes that the reader is familiar with the terms and concepts described in the "Security Architecture for the Internet Protocol" [Ken-Arch], hereafter referred to as the Security Architecture document. In particular, the reader should be familiar with the definitions of security services offered by the Encapsulating Security Payload (ESP) and the IP Authentication Header (AH), the concept of Security Associations, the ways in which ESP can be used in conjunction with AH, and the different key management options available for ESP and AH.

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].

The Encapsulating Security Payload (ESP) header is designed to provide a mix of security services in IPv4 and IPv6 [DH98]. ESP may be applied alone, in combination with AH [Ken-AH], or in a nested fashion (see the Security Architecture document [Ken-Arch]). Security services can be provided between a pair of communicating hosts, between a pair of communicating security gateways, or between a security gateway and a host. For more details on how to use ESP and AH in various network environments, see the Security Architecture document [Ken-Arch].

The ESP header is inserted after the IP header and before the next layer protocol header (transport mode) or before an encapsulated IP header (tunnel mode). These modes are described in more detail below.

ESP can be used to provide confidentiality, data origin authentication, connectionless integrity, an anti-replay service (a form of partial sequence integrity), and (limited) traffic flow confidentiality. The set of services provided depends on options selected at the time of Security Association (SA) establishment and on the location of the implementation in a network topology.

Using encryption-only for confidentiality is allowed by ESP. However, it should be noted that in general, this will provide defense only against passive attackers. Using encryption without a strong integrity mechanism on top of it (either in ESP or separately via AH) may render the confidentiality service insecure against some forms of active attacks [Bel96, Kra01]. Moreover, an underlying integrity service, such as AH, applied before encryption does not necessarily protect the encryption-only confidentiality against active attackers [Kra01]. ESP allows encryption-only SAs because this may offer considerably better performance and still provide

adequate security, e.g., when higher-layer authentication/integrity protection is offered independently. However, this standard does not require ESP implementations to offer an encryption-only service.

Data origin authentication and connectionless integrity are joint services, hereafter referred to jointly as "integrity". (This term is employed because, on a per-packet basis, the computation being performed provides connectionless integrity directly; data origin authentication is provided indirectly as a result of binding the key used to verify the integrity to the identity of the IPsec peer. Typically, this binding is effected through the use of a shared, symmetric key.) Integrity-only ESP MUST be offered as a service selection option, e.g., it must be negotiable in SA management protocols and MUST be configurable via management interfaces. Integrity-only ESP is an attractive alternative to AH in many contexts, e.g., because it is faster to process and more amenable to pipelining in many implementations.

Although confidentiality and integrity can be offered independently, ESP typically will employ both services, i.e., packets will be protected with regard to confidentiality and integrity. Thus, there are three possible ESP security service combinations involving these services:

- confidentiality-only (MAY be supported)
- integrity only (MUST be supported)
- confidentiality and integrity (MUST be supported)

The anti-replay service may be selected for an SA only if the integrity service is selected for that SA. The selection of this service is solely at the discretion of the receiver and thus need not be negotiated. However, to make use of the Extended Sequence Number feature in an interoperable fashion, ESP does impose a requirement on SA management protocols to be able to negotiate this feature (see Section 2.2.1 below).

The traffic flow confidentiality (TFC) service generally is effective only if ESP is employed in a fashion that conceals the ultimate source and destination addresses of correspondents, e.g., in tunnel mode between security gateways, and only if sufficient traffic flows between IPsec peers (either naturally or as a result of generation of masking traffic) to conceal the characteristics of specific, individual subscriber traffic flows. (ESP may be employed as part of a higher-layer TFC system, e.g., Onion Routing [Syverson], but such systems are outside the scope of this standard.) New TFC features present in ESP facilitate efficient generation and discarding of dummy traffic and better padding of real traffic, in a backward-compatible fashion.

Section 7 provides a brief review of the differences between this document and RFC 2406.

2. Encapsulating Security Payload Packet Format

The (outer) protocol header (IPv4, IPv6, or Extension) that immediately precedes the ESP header SHALL contain the value 50 in its Protocol (IPv4) or Next Header (IPv6, Extension) field (see IANA web page at http://www.iana.org/assignments/protocol-numbers). Figure 1 illustrates the top-level format of an ESP packet. The packet begins with two 4-byte fields (Security Parameters Index (SPI) and Sequence Number). Following these fields is the Payload Data, which has substructure that depends on the choice of encryption algorithm and mode, and on the use of TFC padding, which is examined in more detail later. Following the Payload Data are Padding and Pad Length fields, and the Next Header field. The optional Integrity Check Value (ICV) field completes the packet.

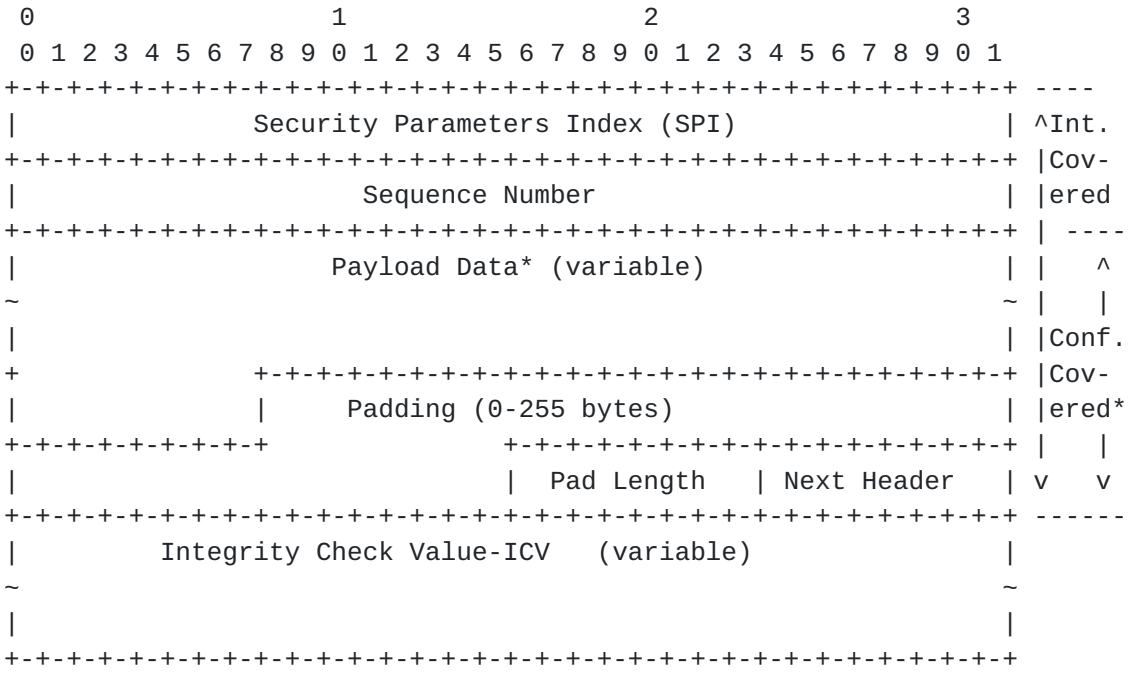


Figure 1. Top-Level Format of an ESP Packet

* If included in the Payload field, cryptographic synchronization data, e.g., an Initialization Vector (IV, see Section 2.3), usually is not encrypted per se, although it often is referred to as being part of the ciphertext.

The (transmitted) ESP trailer consists of the Padding, Pad Length, and Next Header fields. Additional, implicit ESP trailer data (which is not transmitted) is included in the integrity computation, as described below.

If the integrity service is selected, the integrity computation encompasses the SPI, Sequence Number, Payload Data, and the ESP trailer (explicit and implicit).

If the confidentiality service is selected, the ciphertext consists of the Payload Data (except for any cryptographic synchronization data that may be included) and the (explicit) ESP trailer.

As noted above, the Payload Data may have substructure. An encryption algorithm that requires an explicit Initialization Vector (IV), e.g., Cipher Block Chaining (CBC) mode, often prefixes the Payload Data to be protected with that value. Some algorithm modes combine encryption and integrity into a single operation; this document refers to such algorithm modes as "combined mode algorithms". Accommodation of combined mode algorithms requires that the algorithm explicitly describe the payload substructure used to convey the integrity data.

Some combined mode algorithms provide integrity only for data that is encrypted, whereas others can provide integrity for some additional data that is not encrypted for transmission. Because the SPI and Sequence Number fields require integrity as part of the integrity service, and they are not encrypted, it is necessary to ensure that they are afforded integrity whenever the service is selected, regardless of the style of combined algorithm mode employed.

When any combined mode algorithm is employed, the algorithm itself is expected to return both decrypted plaintext and a pass/fail indication for the integrity check. For combined mode algorithms, the ICV that would normally appear at the end of the ESP packet (when integrity is selected) may be omitted. When the ICV is omitted and integrity is selected, it is the responsibility of the combined mode algorithm to encode within the Payload Data an ICV-equivalent means of verifying the integrity of the packet.

If a combined mode algorithm offers integrity only to data that is encrypted, it will be necessary to replicate the SPI and Sequence Number as part of the Payload Data.

Finally, a new provision is made to insert padding for traffic flow confidentiality after the Payload Data and before the ESP trailer. Figure 2 illustrates this substructure for Payload Data. (Note: This

diagram shows bits-on-the-wire. So even if extended sequence numbers are being used, only 32 bits of the Sequence Number will be transmitted (see Section 2.2.1).)

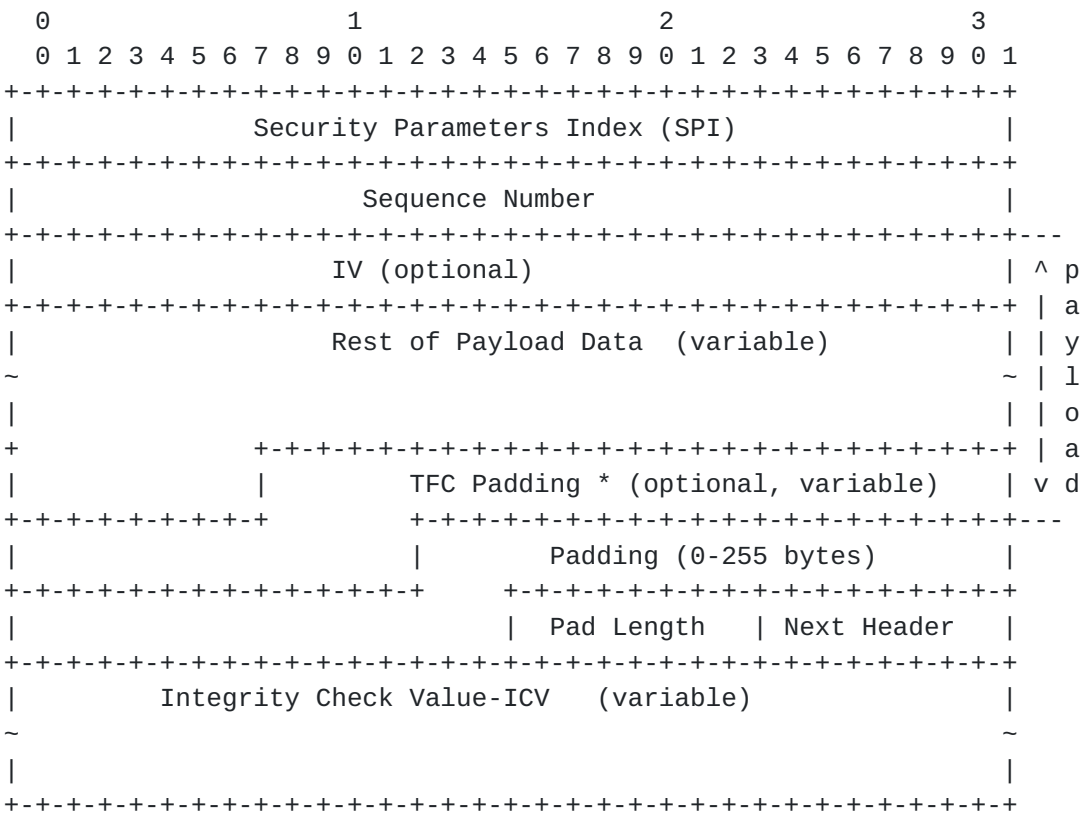


Figure 2. Substructure of Payload Data

* If tunnel mode is being used, then the IPsec implementation can add Traffic Flow Confidentiality (TFC) padding (see Section 2.4) after the Payload Data and before the Padding (0-255 bytes) field.

If a combined algorithm mode is employed, the explicit ICV shown in Figures 1 and 2 may be omitted (see Section 3.3.2.2 below). Because algorithms and modes are fixed when an SA is established, the detailed format of ESP packets for a given SA (including the Payload Data substructure) is fixed, for all traffic on the SA.

The tables below refer to the fields in the preceding figures and illustrate how several categories of algorithmic options, each with a different processing model, affect the fields noted above. The processing details are described in later sections.

Table 1. Separate Encryption and Integrity Algorithms

	# of bytes	Requ'd [1]	What Encrypt Covers	What Integ Covers	What is Xmtd	
SPI	4	M		Y	plain	
Seq# (low-order bits)	4	M		Y	plain	p
						a
IV	variable	O		Y	plain	y
IP datagram [2]	variable	M or D	Y	Y	cipher[3]	-l
TFC padding [4]	variable	O	Y	Y	cipher[3]	o
						a
Padding	0-255	M	Y	Y	cipher[3]	d
Pad Length	1	M	Y	Y	cipher[3]	
Next Header	1	M	Y	Y	cipher[3]	
Seq# (high-order bits)	4	if ESN [5]		Y	not xmtd	
ICV Padding	variable	if need		Y	not xmtd	
ICV	variable	M [6]			plain	

[1] M = mandatory; O = optional; D = dummy
[2] If tunnel mode -> IP datagram
If transport mode -> next header and data
[3] ciphertext if encryption has been selected
[4] Can be used only if payload specifies its "real" length
[5] See section 2.2.1
[6] mandatory if a separate integrity algorithm is used

Table 2. Combined Mode Algorithms

	# of bytes	Requ'd [1]	What Encrypt Covers	What Integ Covers	What is Xmtd	
SPI	4	M			plain	
Seq# (low-order bits)	4	M			plain	p
						--- a
IV	variable	O		Y	plain	| y
IP datagram [2]	variable	M or D	Y	Y	cipher	|-l
TFC padding [3]	variable	O	Y	Y	cipher	| o
						--- a
Padding	0-255	M	Y	Y	cipher	d
Pad Length	1	M	Y	Y	cipher	
Next Header	1	M	Y	Y	cipher	
Seq# (high-order bits)	4	if ESN [4]		Y	[5]	
ICV Padding	variable	if need		Y	[5]	
ICV	variable	O [6]			plain	

[1] M = mandatory; O = optional; D = dummy
[2] If tunnel mode -> IP datagram
If transport mode -> next header and data
[3] Can be used only if payload specifies its "real" length
[4] See Section 2.2.1
[5] The algorithm choices determines whether these are transmitted, but in either case, the result is invisible to ESP
[6] The algorithm spec determines whether this field is present

The following subsections describe the fields in the header format. "Optional" means that the field is omitted if the option is not selected, i.e., it is present in neither the packet as transmitted nor as formatted for computation of an ICV (see Section 2.7). Whether or not an option is selected is determined as part of Security Association (SA) establishment. Thus, the format of ESP packets for a given SA is fixed, for the duration of the SA. In contrast, "mandatory" fields are always present in the ESP packet format, for all SAs.

Note: All of the cryptographic algorithms used in IPsec expect their input in canonical network byte order (see Appendix of RFC 791 [Pos81]) and generate their output in canonical network byte order. IP packets are also transmitted in network byte order.

ESP does not contain a version number, therefore if there are concerns about backward compatibility, they MUST be addressed by using a signaling mechanism between the two IPsec peers to ensure compatible versions of ESP (e.g., Internet Key Exchange (IKEv2) [Kau05]) or an out-of-band configuration mechanism.

2.1. Security Parameters Index (SPI)

The SPI is an arbitrary 32-bit value that is used by a receiver to identify the SA to which an incoming packet is bound. The SPI field is mandatory.

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 (in this case ESP). Because the SPI value is generated by the receiver for a unicast SA, whether the value is sufficient to identify an SA by itself or whether it must be used in conjunction with the IPsec protocol value is a local matter. This mechanism for mapping inbound traffic to unicast SAs MUST be supported by all ESP implementations.

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 de-multiplexing algorithm.

In many secure multicast architectures (e.g., [RFC3740]), a central Group Controller/Key Server unilaterally assigns the group security association'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 comprise the group. Consequently, it is possible that a group security association and a unicast security association 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 Security Association Database (SAD) [Ken-Arch] must indicate whether the SA lookup makes use of the destination, or 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, or destination and source, address comparison (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 {SPI, destination address, source address}. If an SAD entry matches, then process the inbound ESP packet with that matching SAD entry. Otherwise, proceed to step 2.

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

3. Search the SAD for a match on only {SPI} if the receiver has chosen to maintain a single SPI space for AH and ESP, or on {SPI, protocol} otherwise. If an SAD entry matches, then process the inbound ESP packet with that matching SAD entry. Otherwise, discard the packet and log an auditable event.

In practice, an implementation MAY choose any method 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 are 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 are 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.

The set of SPI values in the range 1 through 255 are reserved by the Internet Assigned Numbers Authority (IANA) for future use; a reserved SPI value will not normally be assigned by IANA unless the use of the assigned SPI value is specified in an RFC. The SPI value of zero (0) is reserved for local, implementation-specific use and MUST NOT be sent on the wire. (For example, a key management implementation might use the zero SPI value to mean "No Security Association Exists"

during the period when the IPsec implementation has requested that its key management entity establish a new SA, but the SA has not yet been established.)

2.2. Sequence Number

This unsigned 32-bit field contains a counter value that increases by one for each packet sent, i.e., a per-SA packet sequence number. For a unicast SA or a single-sender multicast SA, the sender MUST increment this field for every transmitted packet. Sharing an SA among multiple senders is permitted, though generally not recommended. ESP provides no means of synchronizing packet counters among multiple senders or meaningfully managing a receiver packet counter and window in the context of multiple senders. Thus, for a multi-sender SA, the anti-replay features of ESP are not available (see Sections 3.3.3 and 3.4.3.)

The field is mandatory and MUST always be present even if the receiver does not elect to enable the anti-replay service for a specific SA. Processing of the Sequence Number field is at the discretion of the receiver, but all ESP implementations MUST be capable of performing the processing described in Sections 3.3.3 and 3.4.3. Thus, the sender MUST always transmit this field, but the receiver need not act upon it (see the discussion of Sequence Number Verification in the "Inbound Packet Processing" section (3.4.3) below).

The sender's counter and the receiver's counter are initialized to 0 when an SA is established. (The first packet sent using a given SA will have a sequence number of 1; see Section 3.3.3 for more details on how the sequence number is generated.) If anti-replay is enabled (the default), the transmitted sequence number must never be allowed to cycle. Thus, the sender's counter and the receiver's counter MUST be reset (by establishing a new SA and thus a new key) prior to the transmission of the 2^32nd packet on an SA.

2.2.1. Extended (64-bit) Sequence Number

To support high-speed IPsec implementations, Extended Sequence Numbers (ESNs) SHOULD be implemented, as an extension to the current, 32-bit sequence number field. Use of an ESN MUST be negotiated by an SA management protocol. Note that in IKEv2, this negotiation is implicit; the default is ESN unless 32-bit sequence numbers are explicitly negotiated. (The ESN feature is applicable to multicast as well as unicast SAs.)

The ESN facility allows use of a 64-bit sequence number for an SA. (See Appendix A, "Extended (64-bit) Sequence Numbers", for details.) Only the low-order 32 bits of the sequence number are transmitted in the plaintext ESP header of each packet, thus minimizing packet overhead. The high-order 32 bits are maintained as part of the sequence number counter by both transmitter and receiver and are included in the computation of the ICV (if the integrity service is selected). If a separate integrity algorithm is employed, the high order bits are included in the implicit ESP trailer, but are not transmitted, analogous to integrity algorithm padding bits. If a combined mode algorithm is employed, the algorithm choice determines whether the high-order ESN bits are transmitted or are included implicitly in the computation. See Section 3.3.2.2 for processing details.

2.3. Payload Data

Payload Data is a variable-length field containing data (from the original IP packet) described by the Next Header field. The Payload Data field is mandatory and is an integral number of bytes in length. If the algorithm used to encrypt the payload requires cryptographic synchronization data, e.g., an Initialization Vector (IV), then this data is carried explicitly in the Payload field, but it is not called out as a separate field in ESP, i.e., the transmission of an explicit IV is invisible to ESP. (See Figure 2.) Any encryption algorithm that requires such explicit, per-packet synchronization data MUST indicate the length, any structure for such data, and the location of this data as part of an RFC specifying how the algorithm is used with ESP. (Typically, the IV immediately precedes the ciphertext. See Figure 2.) If such synchronization data is implicit, the algorithm for deriving the data MUST be part of the algorithm definition RFC. (If included in the Payload field, cryptographic synchronization data, e.g., an Initialization Vector (IV), usually is not encrypted per se (see Tables 1 and 2), although it sometimes is referred to as being part of the ciphertext.)

Note that the beginning of the next layer protocol header MUST be aligned relative to the beginning of the ESP header as follows. For IPv4, this alignment is a multiple of 4 bytes. For IPv6, the alignment is a multiple of 8 bytes.

With regard to ensuring the alignment of the (real) ciphertext in the presence of an IV, note the following:

- For some IV-based modes of operation, the receiver treats the IV as the start of the ciphertext, feeding it into the algorithm directly. In these modes, alignment of the start of the (real) ciphertext is not an issue at the receiver.

- In some cases, the receiver reads the IV in separately from the ciphertext. In these cases, the algorithm specification MUST address how alignment of the (real) ciphertext is to be achieved.

2.4. Padding (for Encryption)

Two primary factors require or motivate use of the Padding field.

- If an encryption algorithm is employed that requires the plaintext to be a multiple of some number of bytes, e.g., the block size of a block cipher, the Padding field is used to fill the plaintext (consisting of the Payload Data, Padding, Pad Length, and Next Header fields) to the size required by the algorithm.

- Padding also may be required, irrespective of encryption algorithm requirements, to ensure that the resulting ciphertext terminates on a 4-byte boundary. Specifically, the Pad Length and Next Header fields must be right aligned within a 4-byte word, as illustrated in the ESP packet format figures above, to ensure that the ICV field (if present) is aligned on a 4-byte boundary.

Padding beyond that required for the algorithm or alignment reasons cited above could be used to conceal the actual length of the payload, in support of TFC. However, the Padding field described is too limited to be effective for TFC and thus should not be used for that purpose. Instead, the separate mechanism described below (see Section 2.7) should be used when TFC is required.

The sender MAY add 0 to 255 bytes of padding. Inclusion of the Padding field in an ESP packet is optional, subject to the requirements noted above, but all implementations MUST support generation and consumption of padding.

- For the purpose of ensuring that the bits to be encrypted are a multiple of the algorithm's block size (first bullet above), the padding computation applies to the Payload Data exclusive of any IV, but including the ESP trailer fields. If a combined algorithm mode requires transmission of the SPI and Sequence Number to effect integrity, e.g., replication of the SPI and Sequence Number in the Payload Data, then the replicated versions of these data items, and any associated, ICV-equivalent data, are included in the computation of the pad length. (If the ESN option is

selected, the high-order 32 bits of the ESN also would enter into the computation, if the combined mode algorithm requires their transmission for integrity.)

- For the purposes of ensuring that the ICV is aligned on a 4-byte boundary (second bullet above), the padding computation applies to the Payload Data inclusive of the IV, the Pad Length, and Next Header fields. If a combined mode algorithm is used, any replicated data and ICV-equivalent data are included in the Payload Data covered by the padding computation.

If Padding bytes are needed but the encryption algorithm does not specify the padding contents, then the following default processing MUST be used. The Padding bytes are initialized with a series of (unsigned, 1-byte) integer values. The first padding byte appended to the plaintext is numbered 1, with subsequent padding bytes making up a monotonically increasing sequence: 1, 2, 3, ... When this padding scheme is employed, the receiver SHOULD inspect the Padding field. (This scheme was selected because of its relative simplicity, ease of implementation in hardware, and because it offers limited protection against certain forms of "cut and paste" attacks in the absence of other integrity measures, if the receiver checks the padding values upon decryption.)

If an encryption or combined mode algorithm imposes constraints on the values of the bytes used for padding, they MUST be specified by the RFC defining how the algorithm is employed with ESP. If the algorithm requires checking of the values of the bytes used for padding, this too MUST be specified in that RFC.

2.5. Pad Length

The Pad Length field indicates the number of pad bytes immediately preceding it in the Padding field. The range of valid values is 0 to 255, where a value of zero indicates that no Padding bytes are present. As noted above, this does not include any TFC padding bytes. The Pad Length field is mandatory.

2.6. Next Header

The Next Header is a mandatory, 8-bit field that identifies the type of data contained in the Payload Data field, e.g., an IPv4 or IPv6 packet, or a next layer header and data. The value of this field is chosen from the set of IP Protocol Numbers defined on the web page of the IANA, e.g., a value of 4 indicates IPv4, a value of 41 indicates IPv6, and a value of 6 indicates TCP.

To facilitate the rapid generation and discarding of the padding traffic in support of traffic flow confidentiality (see Section 2.4), the protocol value 59 (which means "no next header") MUST be used to designate a "dummy" packet. A transmitter MUST be capable of generating dummy packets marked with this value in the next protocol field, and a receiver MUST be prepared to discard such packets, without indicating an error. All other ESP header and trailer fields (SPI, Sequence Number, Padding, Pad Length, Next Header, and ICV) MUST be present in dummy packets, but the plaintext portion of the payload, other than this Next Header field, need not be well-formed, e.g., the rest of the Payload Data may consist of only random bytes. Dummy packets are discarded without prejudice.

Implementations SHOULD provide local management controls to enable the use of this capability on a per-SA basis. The controls should allow the user to specify if this feature is to be used and also provide parametric controls; for example, the controls might allow an administrator to generate random-length or fixed-length dummy packets.

DISCUSSION: Dummy packets can be inserted at random intervals to mask the absence of actual traffic. One can also "shape" the actual traffic to match some distribution to which dummy traffic is added as dictated by the distribution parameters. As with the packet length padding facility for Traffic Flow Security (TFS), the most secure approach would be to generate dummy packets at whatever rate is needed to maintain a constant rate on an SA. If packets are all the same size, then the SA presents the appearance of a constant bit rate data stream, analogous to what a link crypto would offer at layer 1 or 2. However, this is unlikely to be practical in many contexts, e.g., when there are multiple SAs active, because it would imply reducing the allowed bandwidth for a site, based on the number of SAs, and that would undermine the benefits of packet switching. Implementations SHOULD provide controls to enable local administrators to manage the generation of dummy packets for TFC purposes.

2.7. Traffic Flow Confidentiality (TFC) Padding

As noted above, the Padding field is limited to 255 bytes in length. This generally will not be adequate to hide traffic characteristics relative to traffic flow confidentiality requirements. An optional field, within the payload data, is provided specifically to address the TFC requirement.

An IPsec implementation SHOULD be capable of padding traffic by adding bytes after the end of the Payload Data, prior to the beginning of the Padding field. However, this padding (hereafter referred to as TFC padding) can be added only if the Payload Data field contains a specification of the length of the IP datagram. This is always true in tunnel mode, and may be true in transport mode depending on whether the next layer protocol (e.g., IP, UDP, ICMP) contains explicit length information. This length information will enable the receiver to discard the TFC padding, because the true length of the Payload Data will be known. (ESP trailer fields are located by counting back from the end of the ESP packet.) Accordingly, if TFC padding is added, the field containing the specification of the length of the IP datagram MUST NOT be modified to reflect this padding. No requirements for the value of this padding are established by this standard.

In principle, existing IPsec implementations could have made use of this capability previously, in a transparent fashion. However, because receivers may not have been prepared to deal with this padding, the SA management protocol MUST negotiate this service prior to a transmitter employing it, to ensure backward compatibility. Combined with the convention described in Section 2.6 above, about the use of protocol ID 59, an ESP implementation is capable of generating dummy and real packets that exhibit much greater length variability, in support of TFC.

Implementations SHOULD provide local management controls to enable the use of this capability on a per-SA basis. The controls should allow the user to specify if this feature is to be used and also provide parametric controls for the feature.

2.8. Integrity Check Value (ICV)

The Integrity Check Value is a variable-length field computed over the ESP header, Payload, and ESP trailer fields. Implicit ESP trailer fields (integrity padding and high-order ESN bits, if applicable) are included in the ICV computation. The ICV field is optional. It is present only if the integrity service is selected and is provided by either a separate integrity algorithm or a combined mode algorithm that uses an ICV. The length of the field is

specified by the integrity algorithm selected and associated with the SA. The integrity algorithm specification MUST specify the length of the ICV and the comparison rules and processing steps for validation.

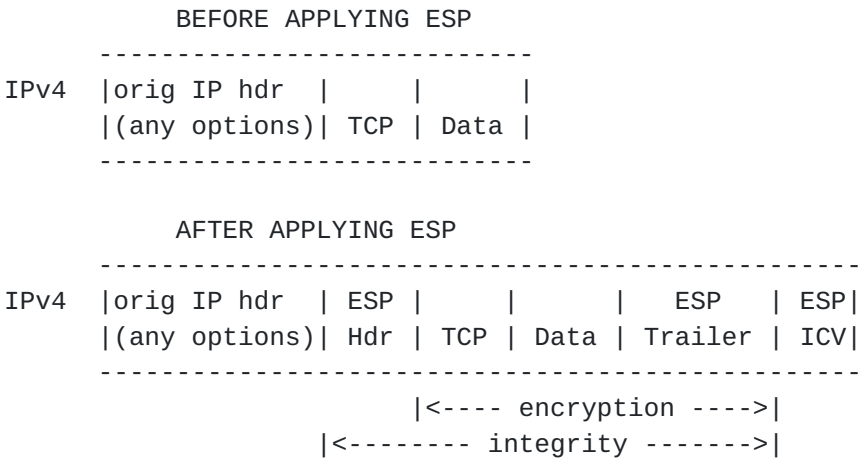
3. Encapsulating Security Protocol Processing

3.1. ESP Header Location

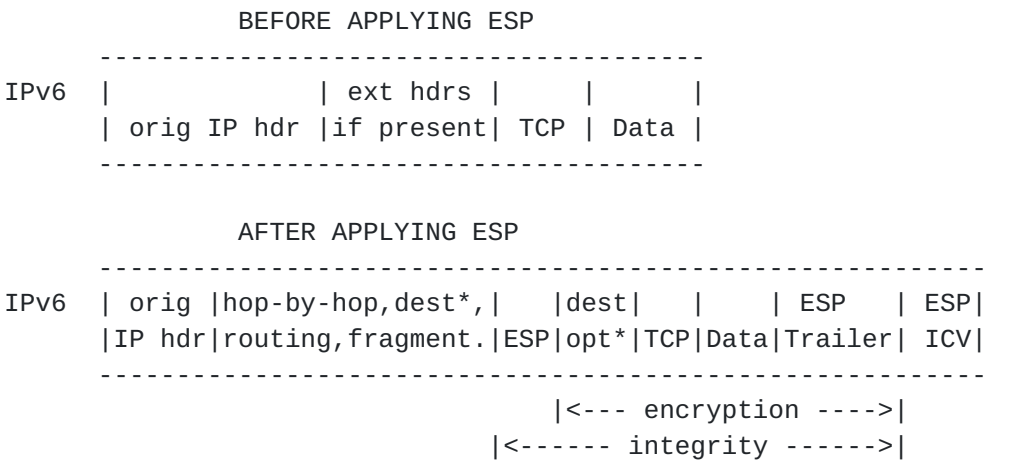
ESP may be employed in two ways: transport mode or tunnel mode.

3.1.1. Transport Mode Processing

In transport mode, ESP is inserted after the IP header and before a next layer protocol, e.g., TCP, UDP, ICMP, etc. In the context of IPv4, this translates to placing ESP after the IP header (and any options that it contains), but before the next layer protocol. (If AH is also applied to a packet, it is applied to the ESP header, Payload, ESP trailer, and ICV, if present.) (Note that the term "transport" mode should not be misconstrued as restricting its use to TCP and UDP.) The following diagram illustrates ESP transport mode positioning for a typical IPv4 packet, on a "before and after" basis. (This and subsequent diagrams in this section show the ICV field, the presence of which is a function of the security services and the algorithm/mode selected.)



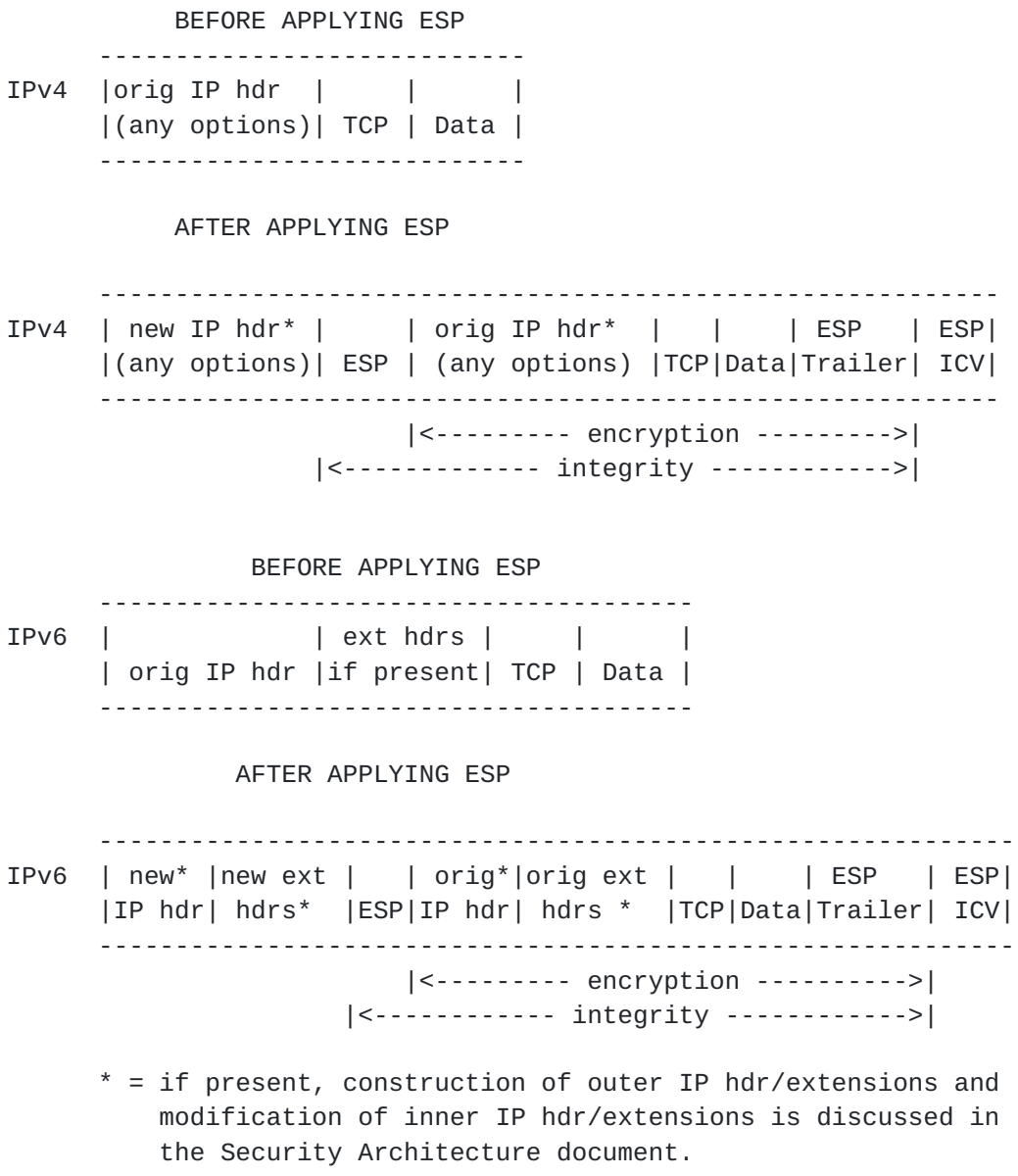
In the IPv6 context, ESP is viewed as an end-to-end payload, and thus should appear after hop-by-hop, routing, and fragmentation extension headers. Destination options extension header(s) could appear before, after, or both before and after the ESP header depending on the semantics desired. However, because ESP protects only fields after the ESP header, it generally will be desirable to place the destination options header(s) after the ESP header. The following diagram illustrates ESP transport mode positioning for a typical IPv6 packet.



Note that in transport mode, for "bump-in-the-stack" or "bump-in-the-wire" implementations, as defined in the Security Architecture document, inbound and outbound IP fragments may require an IPsec implementation to perform extra IP reassembly/fragmentation in order to both conform to this specification and provide transparent IPsec support. Special care is required to perform such operations within these implementations when multiple interfaces are in use.

3.1.2. Tunnel Mode Processing

In tunnel mode, the "inner" IP header carries the ultimate (IP) source and destination addresses, while an "outer" IP header contains the addresses of the IPsec "peers", e.g., addresses of security gateways. Mixed inner and outer IP versions are allowed, i.e., IPv6 over IPv4 and IPv4 over IPv6. In tunnel mode, ESP protects the entire inner IP packet, including the entire inner IP header. The position of ESP in tunnel mode, relative to the outer IP header, is the same as for ESP in transport mode. The following diagram illustrates ESP tunnel mode positioning for typical IPv4 and IPv6 packets.



* = if present, construction of outer IP hdr/extensions and modification of inner IP hdr/extensions is discussed in the Security Architecture document.

3.2. Algorithms

The mandatory-to-implement algorithms for use with ESP are described in a separate RFC, to facilitate updating the algorithm requirements independently from the protocol per se. Additional algorithms, beyond those mandated for ESP, MAY be supported. Note that although both confidentiality and integrity are optional, at least one of these services MUST be selected, hence both algorithms MUST NOT be simultaneously NULL.

3.2.1. Encryption Algorithms

The encryption algorithm employed to protect an ESP packet is specified by the SA via which the packet is transmitted/received. Because IP packets may arrive out of order, and not all packets may arrive (packet loss), each packet must carry any data required to allow the receiver to establish cryptographic synchronization for decryption. This data may be carried explicitly in the payload field, e.g., as an IV (as described above), or the data may be derived from the plaintext portions of the (outer IP or ESP) packet header. (Note that if plaintext header information is used to derive an IV, that information may become security critical and thus the protection boundary associated with the encryption process may grow. For example, if one were to use the ESP Sequence Number to derive an IV, the Sequence Number generation logic (hardware or software) would have to be evaluated as part of the encryption algorithm implementation. In the case of FIPS 140-2 [NIST01], this could significantly extend the scope of a cryptographic module evaluation.) Because ESP makes provision for padding of the plaintext, encryption algorithms employed with ESP may exhibit either block or stream mode characteristics. Note that because encryption (confidentiality) MAY be an optional service (e.g., integrity-only ESP), this algorithm MAY be "NULL" [Ken-Arch].

To allow an ESP implementation to compute the encryption padding required by a block mode encryption algorithm, and to determine the MTU impact of the algorithm, the RFC for each encryption algorithm used with ESP must specify the padding modulus for the algorithm.

3.2.2. Integrity Algorithms

The integrity algorithm employed for the ICV computation is specified by the SA via which the packet is transmitted/received. As was the case for encryption algorithms, any integrity algorithm employed with ESP must make provisions to permit processing of packets that arrive out of order and to accommodate packet loss. The same admonition noted above applies to use of any plaintext data to facilitate receiver synchronization of integrity algorithms. Note that because the integrity service MAY be optional, this algorithm may be "NULL".

To allow an ESP implementation to compute any implicit integrity algorithm padding required, the RFC for each algorithm used with ESP must specify the padding modulus for the algorithm.

3.2.3. Combined Mode Algorithms

If a combined mode algorithm is employed, both confidentiality and integrity services are provided. As was the case for encryption algorithms, a combined mode algorithm must make provisions for per-packet cryptographic synchronization, to permit decryption of packets that arrive out of order and to accommodate packet loss. The means by which a combined mode algorithm provides integrity for the payload, and for the SPI and (Extended) Sequence Number fields, may vary for different algorithm choices. In order to provide a uniform, algorithm-independent approach to invocation of combined mode algorithms, no payload substructure is defined. For example, the SPI and Sequence Number fields might be replicated within the ciphertext envelope and an ICV may be appended to the ESP trailer. None of these details should be observable externally.

To allow an ESP implementation to determine the MTU impact of a combined mode algorithm, the RFC for each algorithm used with ESP must specify a (simple) formula that yields encrypted payload size, as a function of the plaintext payload and sequence number sizes.

3.3. Outbound Packet Processing

In transport mode, the sender encapsulates the next layer protocol information between the ESP header and the ESP trailer fields, and retains the specified IP header (and any IP extension headers in the IPv6 context). In tunnel mode, the outer and inner IP header/extensions can be interrelated in a variety of ways. The construction of the outer IP header/extensions during the encapsulation process is described in the Security Architecture document.

3.3.1. Security Association Lookup

ESP is applied to an outbound packet only after an IPsec implementation determines that the packet is associated with an SA that calls for ESP processing. The process of determining what, if any, IPsec processing is applied to outbound traffic is described in the Security Architecture document.

3.3.2. Packet Encryption and Integrity Check Value (ICV) Calculation

In this section, we speak in terms of encryption always being applied because of the formatting implications. This is done with the understanding that "no confidentiality" is offered by using the NULL encryption algorithm (RFC 2410). There are several algorithmic options.

3.3.2.1. Separate Confidentiality and Integrity Algorithms

If separate confidentiality and integrity algorithms are employed, the Sender proceeds as follows:

1. Encapsulate (into the ESP Payload field):
   - for transport mode -- just the original next layer protocol information.
   - for tunnel mode -- the entire original IP datagram.

2. Add any necessary padding -- Optional TFC padding and (encryption) Padding

3. Encrypt the result using the key, encryption algorithm, and algorithm mode specified for the SA and using any required cryptographic synchronization data.
   - If explicit cryptographic synchronization data, e.g., an IV, is indicated, it is input to the encryption algorithm per the algorithm specification and placed in the Payload field.
   - If implicit cryptographic synchronization data is employed, it is constructed and input to the encryption algorithm as per the algorithm specification.
   - If integrity is selected, encryption is performed first, before the integrity algorithm is applied, and the encryption does not encompass the ICV field. This order of processing facilitates rapid detection and rejection of replayed or bogus packets by the receiver, prior to decrypting the packet, hence potentially reducing the impact of denial of service (DoS) attacks. It also allows for the possibility of parallel processing of packets at the receiver, i.e., decryption can take place in parallel with integrity checking. Note that because the ICV is not protected by encryption, a keyed integrity algorithm must be employed to compute the ICV.

4. Compute the ICV over the ESP packet minus the ICV field. Thus, the ICV computation encompasses the SPI, Sequence Number, Payload Data, Padding (if present), Pad Length, and Next Header. (Note that the last 4 fields will be in ciphertext form, because encryption is performed first.) If the ESN option is enabled for the SA, the high-order 32 bits of the sequence number are appended after the Next Header field for purposes of this computation, but are not transmitted.

For some integrity algorithms, the byte string over which the ICV computation is performed must be a multiple of a block size specified by the algorithm. If the length of ESP packet (as described above) does not match the block size requirements for the algorithm, implicit padding MUST be appended to the end of the ESP packet. (This padding is added after the Next Header field, or after the high-order 32 bits of the sequence number, if ESN is selected.) The block size (and hence the length of the padding) is specified by the integrity algorithm specification. This padding is not transmitted with the packet. The document that defines an integrity algorithm MUST be consulted to determine if implicit padding is required as described above. If the document does not specify an answer to this question, then the default is to assume that implicit padding is required (as needed to match the packet length to the algorithm's block size.) If padding bytes are needed but the algorithm does not specify the padding contents, then the padding octets MUST have a value of zero.

3.3.2.2. Combined Confidentiality and Integrity Algorithms

If a combined confidentiality/integrity algorithm is employed, the Sender proceeds as follows:

1. Encapsulate into the ESP Payload Data field:
   - for transport mode -- just the original next layer protocol information.
   - for tunnel mode -- the entire original IP datagram.

2. Add any necessary padding -- includes optional TFC padding and (encryption) Padding.

3. Encrypt and integrity protect the result using the key and combined mode algorithm specified for the SA and using any required cryptographic synchronization data.
   - If explicit cryptographic synchronization data, e.g., an IV, is indicated, it is input to the combined mode algorithm per the algorithm specification and placed in the Payload field.
   - If implicit cryptographic synchronization data is employed, it is constructed and input to the encryption algorithm as per the algorithm specification.
   - The Sequence Number (or Extended Sequence Number, as appropriate) and the SPI are inputs to the algorithm, as they must be included in the integrity check computation. The means by which these values are included in this computation are a function of

the combined mode algorithm employed and thus not specified in this standard.

- The (explicit) ICV field MAY be a part of the ESP packet format when a combined mode algorithm is employed. If one is not used, an analogous field usually will be a part of the ciphertext payload. The location of any integrity fields, and the means by which the Sequence Number and SPI are included in the integrity computation, MUST be defined in an RFC that defines the use of the combined mode algorithm with ESP.

3.3.3. Sequence Number Generation

The sender's counter is initialized to 0 when an SA is established. The sender increments the sequence number (or ESN) counter for this SA and inserts the low-order 32 bits of the value into the Sequence Number field. Thus, the first packet sent using a given SA will contain a sequence number of 1.

If anti-replay is enabled (the default), the sender checks to ensure that the counter has not cycled before inserting the new value in the Sequence Number field. In other words, the sender MUST NOT send a packet on an SA if doing so would cause the sequence number to cycle. An attempt to transmit a packet that would result in sequence number overflow is an auditable event. The audit log entry for this event SHOULD include the SPI value, current date/time, Source Address, Destination Address, and (in IPv6) the cleartext Flow ID.

The sender assumes anti-replay is enabled as a default, unless otherwise notified by the receiver (see Section 3.4.3). Thus, typical behavior of an ESP implementation calls for the sender to establish a new SA when the Sequence Number (or ESN) cycles, or in anticipation of this value cycling.

If the key used to compute an ICV is manually distributed, a compliant implementation SHOULD NOT provide anti-replay service. If a user chooses to employ anti-replay in conjunction with SAs that are manually keyed, the sequence number counter at the sender MUST be correctly maintained across local reboots, etc., until the key is replaced. (See Section 5.)

If anti-replay is disabled (as noted above), the sender does not need to monitor or reset the counter. However, the sender still increments the counter and when it reaches the maximum value, the counter rolls over back to zero. (This behavior is recommended for multi-sender, multicast SAs, unless anti-replay mechanisms outside

the scope of this standard are negotiated between the sender and receiver.)

If ESN (see Appendix) is selected, only the low-order 32 bits of the sequence number are transmitted in the Sequence Number field, although both sender and receiver maintain full 64-bit ESN counters. The high order 32 bits are included in the integrity check in an algorithm/mode-specific fashion, e.g., the high-order 32 bits may be appended after the Next Header field when a separate integrity algorithm is employed.

Note: If a receiver chooses to not enable anti-replay for an SA, then the receiver SHOULD NOT negotiate ESN in an SA management protocol. Use of ESN creates a need for the receiver to manage the anti-replay window (in order to determine the correct value for the high-order bits of the ESN, which are employed in the ICV computation), which is generally contrary to the notion of disabling anti-replay for an SA.

3.3.4. Fragmentation

If necessary, fragmentation is performed after ESP processing within an IPsec implementation. Thus, transport mode ESP is applied only to whole IP datagrams (not to IP fragments). An IP packet to which ESP has been applied may itself be fragmented by routers en route, and such fragments must be reassembled prior to ESP processing at a receiver. In tunnel mode, ESP is applied to an IP packet, which may be a fragment of an IP datagram. For example, a security gateway or a "bump-in-the-stack" or "bump-in-the-wire" IPsec implementation (as defined in the Security Architecture document) may apply tunnel mode ESP to such fragments.

NOTE: For transport mode -- As mentioned at the end of Section 3.1.1, bump-in-the-stack and bump-in-the-wire implementations may have to first reassemble a packet fragmented by the local IP layer, then apply IPsec, and then fragment the resulting packet.

NOTE: For IPv6 -- For bump-in-the-stack and bump-in-the-wire implementations, it will be necessary to examine all the extension headers to determine if there is a fragmentation header and hence that the packet needs reassembling prior to IPsec processing.

Fragmentation, whether performed by an IPsec implementation or by routers along the path between IPsec peers, significantly reduces performance. Moreover, the requirement for an ESP receiver to accept fragments for reassembly creates denial of service vulnerabilities. Thus, an ESP implementation MAY choose to not support fragmentation and may mark transmitted packets with the DF bit, to facilitate Path MTU (PMTU) discovery. In any case, an ESP implementation MUST

support generation of ICMP PMTU messages (or equivalent internal signaling for native host implementations) to minimize the likelihood of fragmentation. Details of the support required for MTU management are contained in the Security Architecture document.

3.4. Inbound Packet Processing

3.4.1. Reassembly

If required, reassembly is performed prior to ESP processing. If a packet offered to ESP for processing appears to be an IP fragment, i.e., the OFFSET field is non-zero or the MORE FRAGMENTS flag is set, the receiver MUST discard the packet; this is an auditable event. The audit log entry for this event SHOULD include the SPI value, date/time received, Source Address, Destination Address, Sequence Number, and (in IPv6) the Flow ID.

NOTE: For packet reassembly, the current IPv4 spec does NOT require either the zeroing of the OFFSET field or the clearing of the MORE FRAGMENTS flag. In order for a reassembled packet to be processed by IPsec (as opposed to discarded as an apparent fragment), the IP code must do these two things after it reassembles a packet.

3.4.2. Security Association Lookup

Upon receipt of a packet containing an ESP Header, the receiver determines the appropriate (unidirectional) SA via lookup in the SAD. For a unicast SA, this determination is based on the SPI or the SPI plus protocol field, as described in Section 2.1. If an implementation supports multicast traffic, the destination address is also employed in the lookup (in addition to the SPI), and the sender address also may be employed, as described in Section 2.1. (This process is described in more detail in the Security Architecture document.) The SAD entry for the SA also indicates whether the Sequence Number field will be checked, whether 32- or 64-bit sequence numbers are employed for the SA, and whether the (explicit) ICV field should be present (and if so, its size). Also, the SAD entry will specify the algorithms and keys to be employed for decryption and ICV computation (if applicable).

If no valid Security Association exists for this packet, the receiver MUST discard the packet; this is an auditable event. The audit log entry for this event SHOULD include the SPI value, date/time received, Source Address, Destination Address, Sequence Number, and (in IPv6) the cleartext Flow ID.

(Note that SA management traffic, such as IKE packets, does not need to be processed based on SPI, i.e., one can demultiplex this traffic separately based on Next Protocol and Port fields, for example.)

3.4.3. Sequence Number Verification

All ESP implementations MUST support the anti-replay service, though its use may be enabled or disabled by the receiver on a per-SA basis. This service MUST NOT be enabled unless the ESP integrity service also is enabled for the SA, because otherwise the Sequence Number field has not been integrity protected. Anti-replay is applicable to unicast as well as multicast SAs. However, this standard specifies no mechanisms for providing anti-replay for a multi-sender SA (unicast or multicast). In the absence of negotiation (or manual configuration) of an anti-replay mechanism for such an SA, it is recommended that sender and receiver checking of the sequence number for the SA be disabled (via negotiation or manual configuration), as noted below.

If the receiver does not enable anti-replay for an SA, no inbound checks are performed on the Sequence Number. However, from the perspective of the sender, the default is to assume that anti-replay is enabled at the receiver. To avoid having the sender do unnecessary sequence number monitoring and SA setup (see section 3.3.3), if an SA establishment protocol is employed, the receiver SHOULD notify the sender, during SA establishment, if the receiver will not provide anti-replay protection.

If the receiver has enabled the anti-replay service for this SA, the receive packet counter for the SA MUST be initialized to zero when the SA is established. For each received packet, the receiver MUST verify that the packet contains a Sequence Number that does not duplicate the Sequence Number of any other packets received during the life of this SA. This SHOULD be the first ESP check applied to a packet after it has been matched to an SA, to speed rejection of duplicate packets.

ESP permits two-stage verification of packet sequence numbers. This capability is important whenever an ESP implementation (typically the cryptographic module portion thereof) is not capable of performing decryption and/or integrity checking at the same rate as the interface(s) to unprotected networks. If the implementation is capable of such "line rate" operation, then it is not necessary to perform the preliminary verification stage described below.

The preliminary Sequence Number check is effected utilizing the Sequence Number value in the ESP Header and is performed prior to integrity checking and decryption. If this preliminary check fails,

the packet is discarded, thus avoiding the need for any cryptographic operations by the receiver. If the preliminary check is successful, the receiver cannot yet modify its local counter, because the integrity of the Sequence Number has not been verified at this point.

Duplicates are rejected through the use of a sliding receive window. How the window is implemented is a local matter, but the following text describes the functionality that the implementation must exhibit.

The "right" edge of the window represents the highest, validated Sequence Number value received on this SA. Packets that contain sequence numbers lower than the "left" edge of the window are rejected. Packets falling within the window are checked against a list of received packets within the window. If the ESN option is selected for an SA, only the low-order 32 bits of the sequence number are explicitly transmitted, but the receiver employs the full sequence number computed using the high-order 32 bits for the indicated SA (from his local counter) when checking the received Sequence Number against the receive window. In constructing the full sequence number, if the low-order 32 bits carried in the packet are lower in value than the low-order 32 bits of the receiver's sequence number, the receiver assumes that the high-order 32 bits have been incremented, moving to a new sequence number subspace. (This algorithm accommodates gaps in reception for a single SA as large as 2**32-1 packets. If a larger gap occurs, additional, heuristic checks for re-synchronization of the receiver sequence number counter MAY be employed, as described in the Appendix.)

If the received packet falls within the window and is not a duplicate, or if the packet is to the right of the window, and if a separate integrity algorithm is employed, then the receiver proceeds to integrity verification. If a combined mode algorithm is employed, the integrity check is performed along with decryption. In either case, if the integrity check fails, the receiver MUST discard the received IP datagram as invalid; this is an auditable event. The audit log entry for this event SHOULD include the SPI value, date/time received, Source Address, Destination Address, the Sequence Number, and (in IPv6) the Flow ID. The receive window is updated only if the integrity verification succeeds. (If a combined mode algorithm is being used, then the integrity protected Sequence Number must also match the Sequence Number used for anti-replay protection.)

A minimum window size of 32 packets MUST be supported when 32-bit sequence numbers are employed; a window size of 64 is preferred and SHOULD be employed as the default. Another window size (larger than the minimum) MAY be chosen by the receiver. (The receiver does NOT notify the sender of the window size.) The receive window size

should be increased for higher-speed environments, irrespective of assurance issues. Values for minimum and recommended receive window sizes for very high-speed (e.g., multi-gigabit/second) devices are not specified by this standard.

3.4.4. Integrity Check Value Verification

As with outbound processing, there are several options for inbound processing, based on features of the algorithms employed.

3.4.4.1. Separate Confidentiality and Integrity Algorithms

If separate confidentiality and integrity algorithms are employed processing proceeds as follows:

1. If integrity has been selected, the receiver computes the ICV over the ESP packet minus the ICV, using the specified integrity algorithm and verifies that it is the same as the ICV carried in the packet. Details of the computation are provided below.

   If the computed and received ICVs match, then the datagram is valid, and it is accepted. If the test fails, then the receiver MUST discard the received IP datagram as invalid; this is an auditable event. The log data SHOULD include the SPI value, date/time received, Source Address, Destination Address, the Sequence Number, and (for IPv6) the cleartext Flow ID.

   Implementation Note:

   Implementations can use any set of steps that results in the same result as the following set of steps. Begin by removing and saving the ICV field. Next check the overall length of the ESP packet minus the ICV field. If implicit padding is required, based on the block size of the integrity algorithm, append zero-filled bytes to the end of the ESP packet directly after the Next Header field, or after the high-order 32 bits of the sequence number if ESN is selected. Perform the ICV computation and compare the result with the saved value, using the comparison rules defined by the algorithm specification.

2. The receiver decrypts the ESP Payload Data, Padding, Pad Length, and Next Header using the key, encryption algorithm, algorithm mode, and cryptographic synchronization data (if any), indicated by the SA. As in Section 3.3.2, we speak here in terms of encryption always being applied because of

the formatting implications. This is done with the understanding that "no confidentiality" is offered by using the NULL encryption algorithm (RFC 2410).

- If explicit cryptographic synchronization data, e.g., an IV, is indicated, it is taken from the Payload field and input to the decryption algorithm as per the algorithm specification.

- If implicit cryptographic synchronization data is indicated, a local version of the IV is constructed and input to the decryption algorithm as per the algorithm specification.

3. The receiver processes any Padding as specified in the encryption algorithm specification. If the default padding scheme (see Section 2.4) has been employed, the receiver SHOULD inspect the Padding field before removing the padding prior to passing the decrypted data to the next layer.

4. The receiver checks the Next Header field. If the value is "59" (no next header), the (dummy) packet is discarded without further processing.

5. The receiver reconstructs the original IP datagram from:

   - for transport mode -- outer IP header plus the original next layer protocol information in the ESP Payload field
   - for tunnel mode -- the entire IP datagram in the ESP Payload field.

   The exact steps for reconstructing the original datagram depend on the mode (transport or tunnel) and are described in the Security Architecture document. At a minimum, in an IPv6 context, the receiver SHOULD ensure that the decrypted data is 8-byte aligned, to facilitate processing by the protocol identified in the Next Header field. This processing "discards" any (optional) TFC padding that has been added for traffic flow confidentiality. (If present, this will have been inserted after the IP datagram (or transport-layer frame) and before the Padding field (see Section 2.4).)

If integrity checking and encryption are performed in parallel, integrity checking MUST be completed before the decrypted packet is passed on for further processing. This order of processing facilitates rapid detection and rejection of replayed or bogus

packets by the receiver, prior to decrypting the packet, hence potentially reducing the impact of denial of service attacks.

Note: If the receiver performs decryption in parallel with integrity checking, care must be taken to avoid possible race conditions with regard to packet access and extraction of the decrypted packet.

3.4.4.2. Combined Confidentiality and Integrity Algorithms

If a combined confidentiality and integrity algorithm is employed, then the receiver proceeds as follows:

1. Decrypts and integrity checks the ESP Payload Data, Padding, Pad Length, and Next Header, using the key, algorithm, algorithm mode, and cryptographic synchronization data (if any), indicated by the SA. The SPI from the ESP header, and the (receiver) packet counter value (adjusted as required from the processing described in Section 3.4.3) are inputs to this algorithm, as they are required for the integrity check.

    - If explicit cryptographic synchronization data, e.g., an IV, is indicated, it is taken from the Payload field and input to the decryption algorithm as per the algorithm specification.

    - If implicit cryptographic synchronization data, e.g., an IV, is indicated, a local version of the IV is constructed and input to the decryption algorithm as per the algorithm specification.

2. If the integrity check performed by the combined mode algorithm fails, the receiver MUST discard the received IP datagram as invalid; this is an auditable event. The log data SHOULD include the SPI value, date/time received, Source Address, Destination Address, the Sequence Number, and (in IPv6) the cleartext Flow ID.

3. Process any Padding as specified in the encryption algorithm specification, if the algorithm has not already done so.

4. The receiver checks the Next Header field. If the value is "59" (no next header), the (dummy) packet is discarded without further processing.

5. Extract the original IP datagram (tunnel mode) or transport-layer frame (transport mode) from the ESP Payload Data field. This implicitly discards any (optional) padding

that has been added for traffic flow confidentiality. (If present, the TFC padding will have been inserted after the IP payload and before the Padding field (see Section 2.4).)

4. Auditing

Not all systems that implement ESP will implement auditing. However, if ESP is incorporated into a system that supports auditing, then the ESP implementation MUST also support auditing and MUST allow a system administrator to enable or disable auditing for ESP. For the most part, the granularity of auditing is a local matter. However, several auditable events are identified in this specification and for each of these events a minimum set of information that SHOULD be included in an audit log is defined.

- No valid Security Association exists for a session. The audit log entry for this event SHOULD include the SPI value, date/time received, Source Address, Destination Address, Sequence Number, and (for IPv6) the cleartext Flow ID.

- A packet offered to ESP for processing appears to be an IP fragment, i.e., the OFFSET field is non-zero or the MORE FRAGMENTS flag is set. The audit log entry for this event SHOULD include the SPI value, date/time received, Source Address, Destination Address, Sequence Number, and (in IPv6) the Flow ID.

- Attempt to transmit a packet that would result in Sequence Number overflow. The audit log entry for this event SHOULD include the SPI value, current date/time, Source Address, Destination Address, Sequence Number, and (for IPv6) the cleartext Flow ID.

- The received packet fails the anti-replay checks. The audit log entry for this event SHOULD include the SPI value, date/time received, Source Address, Destination Address, the Sequence Number, and (in IPv6) the Flow ID.

- The integrity check fails. The audit log entry for this event SHOULD include the SPI value, date/time received, Source Address, Destination Address, the Sequence Number, and (for IPv6) the Flow ID.

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 sender in response to the detection of an auditable event, because of the potential to induce denial of service via such action.

5. Conformance Requirements

Implementations that claim conformance or compliance with this specification MUST implement the ESP syntax and processing described here for unicast traffic, and MUST comply with all additional packet processing requirements levied by the Security Architecture document [Ken-Arch]. Additionally, if an implementation claims to support multicast traffic, it MUST comply with the additional requirements specified for support of such traffic. If the key used to compute an ICV is manually distributed, correct provision of the anti-replay service requires correct maintenance of the counter state at the sender (across local reboots, etc.), until the key is replaced, and there likely would be no automated recovery provision if counter overflow were imminent. Thus, a compliant implementation SHOULD NOT provide anti-replay service in conjunction with SAs that are manually keyed.

The mandatory-to-implement algorithms for use with ESP are described in a separate document [Eas04], to facilitate updating the algorithm requirements independently from the protocol per se. Additional algorithms, beyond those mandated for ESP, MAY be supported.

Because use of encryption in ESP is optional, support for the "NULL" encryption algorithm also is required to maintain consistency with the way ESP services are negotiated. Support for the confidentiality-only service version of ESP is optional. If an implementation offers this service, it MUST also support the negotiation of the "NULL" integrity algorithm. NOTE that although integrity and encryption may each be "NULL" under the circumstances noted above, they MUST NOT both be "NULL".

6. Security Considerations

Security is central to the design of this protocol, and thus security considerations permeate the specification. Additional security-relevant aspects of using the IPsec protocol are discussed in the Security Architecture document.

7. Differences from RFC 2406

This document differs from RFC 2406 in a number of significant ways.

- Confidentiality-only service -- now a MAY, not a MUST.

- SPI -- modified to specify a uniform algorithm for SAD lookup for unicast and multicast SAs, covering a wider range of multicast technologies. For unicast, the SPI may be used alone to select an SA, or may be combined with the protocol, at the option of the receiver. For multicast SAs, the SPI is combined with the destination address, and optionally the source address, to select an SA.
- Extended Sequence Number -- added a new option for a 64-bit sequence number for very high-speed communications. Clarified sender and receiver processing requirements for multicast SAs and multi-sender SAs.
- Payload data -- broadened model to accommodate combined mode algorithms.
- Padding for improved traffic flow confidentiality -- added requirement to be able to add bytes after the end of the IP Payload, prior to the beginning of the Padding field.
- Next Header -- added requirement to be able to generate and discard dummy padding packets (Next Header = 59)
- ICV -- broadened model to accommodate combined mode algorithms.
- Algorithms -- Added combined confidentiality mode algorithms.
- Moved references to mandatory algorithms to a separate document.
- Inbound and Outbound packet processing -- there are now two paths: (1) separate confidentiality and integrity algorithms and (2) combined confidentiality mode algorithms. Because of the addition of combined mode algorithms, the encryption/decryption and integrity sections have been combined for both inbound and outbound packet processing.

8. Backward-Compatibility Considerations

There is no version number in ESP and no mechanism enabling IPsec peers to discover or negotiate which version of ESP each is using or should use. This section discusses consequent backward-compatibility issues.

First, if none of the new features available in ESP v3 are employed, then the format of an ESP packet is identical in ESP v2 and v3. If a combined mode encryption algorithm is employed, a feature supported only in ESP v3, then the resulting packet format may differ from the ESP v2 spec. However, a peer who implements only ESP v2 would never negotiate such an algorithm, as they are defined for use only in the ESP v3 context.

Extended Sequence Number (ESN) negotiation is supported by IKE v2 and has been addressed for IKE v1 by the ESN Addendum to the IKE v1 Domain of Interpretation (DOI).

In the new ESP (v3), we make two provisions to better support traffic flow confidentiality (TFC):

- arbitrary padding after the end of an IP packet
- a discard convention using Next Header = 59

The first feature is one that should not cause problems for a receiver, since the IP total length field indicates where the IP packet ends. Thus, any TFC padding bytes after the end of the packet should be removed at some point during IP packet processing, after ESP processing, even if the IPsec software does not remove such padding. Thus, this is an ESP v3 feature that a sender can employ irrespective of whether a receiver implements ESP v2 or ESP v3.

The second feature allows a sender to send a payload that is an arbitrary string of bytes that do not necessarily constitute a well-formed IP packet, inside of a tunnel, for TFC purposes. It is an open question as to what an ESP v2 receiver will do when the Next Header field in an ESP packet contains the value "59". It might discard the packet when it finds an ill-formed IP header, and log this event, but it certainly ought not to crash, because such behavior would constitute a DoS vulnerability relative to traffic received from authenticated peers. Thus this feature is an optimization that an ESP v3 sender can make use of irrespective of whether a receiver implements ESP v2 or ESP v3.

9. Acknowledgements

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Appendix A: Extended (64-bit) Sequence Numbers

A1. Overview

This appendix describes an extended sequence number (ESN) scheme for use with IPsec (ESP and AH) that employs a 64-bit sequence number, but in which only the low-order 32 bits are transmitted as part of each packet. It covers both the window scheme used to detect replayed packets and the determination of the high-order bits of the sequence number that are used both for replay rejection and for computation of the ICV. It also discusses a mechanism for handling loss of synchronization relative to the (not transmitted) high-order bits.

A2. Anti-Replay Window

The receiver will maintain an anti-replay window of size W. This window will limit how far out of order a packet can be, relative to the packet with the highest sequence number that has been authenticated so far. (No requirement is established for minimum or recommended sizes for this window, beyond the 32- and 64-packet values already established for 32-bit sequence number windows. However, it is suggested that an implementer scale these values consistent with the interface speed supported by an implementation that makes use of the ESN option. Also, the algorithm described below assumes that the window is no greater than 2^31 packets in width.) All 2^32 sequence numbers associated with any fixed value for the high-order 32 bits (Seqh) will hereafter be called a sequence number subspace. The following table lists pertinent variables and their definitions.

Var. Name	Size (bits)	Meaning
W	32	Size of window
T	64	Highest sequence number authenticated so far, upper bound of window
Tl	32	Lower 32 bits of T
Th	32	Upper 32 bits of T
B	64	Lower bound of window
Bl	32	Lower 32 bits of B
Bh	32	Upper 32 bits of B
Seq	64	Sequence Number of received packet
Seql	32	Lower 32 bits of Seq
Seqh	32	Upper 32 bits of Seq

When performing the anti-replay check, or when determining which high-order bits to use to authenticate an incoming packet, there are two cases:

+ Case A: Tl >= (W - 1). In this case, the window is within one sequence number subspace. (See Figure 1)
+ Case B: Tl < (W - 1). In this case, the window spans two sequence number subspaces. (See Figure 2)

In the figures below, the bottom line ("----") shows two consecutive sequence number subspaces, with zeros indicating the beginning of each subspace. The two shorter lines above it show the higher-order bits that apply. The "====" represents the window. The "****" represents future sequence numbers, i.e., those beyond the current highest sequence number authenticated (ThTl).

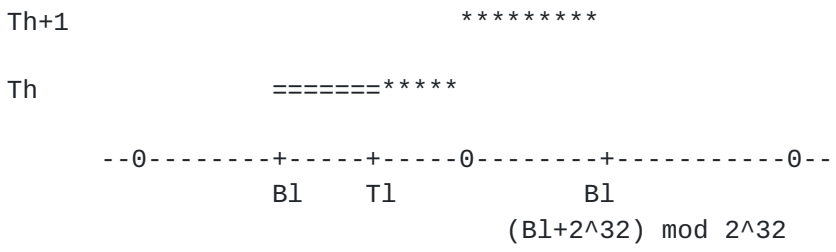

Figure 1 -- Case A

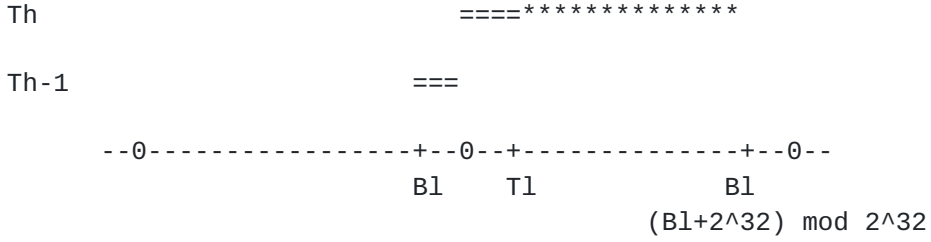

Figure 2 -- Case B

A2.1. Managing and Using the Anti-Replay Window

The anti-replay window can be thought of as a string of bits where `W' defines the length of the string. W = T - B + 1 and cannot exceed 2^32 - 1 in value. The bottom-most bit corresponds to B and the top-most bit corresponds to T, and each sequence number from Bl through Tl is represented by a corresponding bit. The value of the bit indicates whether or not a packet with that sequence number has been received and authenticated, so that replays can be detected and rejected.

When a packet with a 64-bit sequence number (Seq) greater than T is received and validated,

+ B is increased by (Seq - T)
+ (Seq - T) bits are dropped from the low end of the window
+ (Seq - T) bits are added to the high end of the window
+ The top bit is set to indicate that a packet with that sequence number has been received and authenticated
+ The new bits between T and the top bit are set to indicate that no packets with those sequence numbers have been received yet.
+ T is set to the new sequence number

In checking for replayed packets,

+ Under Case A: If Seql >= Bl (where Bl = Tl - W + 1) AND Seql <= Tl, then check the corresponding bit in the window to see if this Seql has already been seen. If yes, reject the packet. If no, perform integrity check (see Appendix A2.2. below for determination of Seqh).

+ Under Case B: If Seql >= Bl (where Bl = Tl - W + 1) OR Seql <= Tl, then check the corresponding bit in the window to see if this Seql has already been seen. If yes, reject the packet. If no, perform integrity check (see Appendix A2.2. below for determination of Seqh).

A2.2. Determining the Higher-Order Bits (Seqh) of the Sequence Number

Because only `Seql' will be transmitted with the packet, the receiver must deduce and track the sequence number subspace into which each packet falls, i.e., determine the value of Seqh. The following equations define how to select Seqh under "normal" conditions; see Section A3 for a discussion of how to recover from extreme packet loss.

+ Under Case A (Figure 1):
  If Seql >= Bl (where Bl = Tl - W + 1), then Seqh = Th
  If Seql < Bl (where Bl = Tl - W + 1), then Seqh = Th + 1

+ Under Case B (Figure 2):
  If Seql >= Bl (where Bl = Tl - W + 1), then Seqh = Th - 1
  If Seql < Bl (where Bl = Tl - W + 1), then Seqh = Th

A2.3. Pseudo-Code Example

The following pseudo-code illustrates the above algorithms for anti-replay and integrity checks. The values for `Seql', `Tl', `Th' and `W' are 32-bit unsigned integers. Arithmetic is mod 2^32.

```
     If (Tl >= W - 1)                          Case A
         If (Seql >= Tl - W + 1)
             Seqh = Th
             If (Seql <= Tl)
                 If (pass replay check)
                     If (pass integrity check)
                         Set bit corresponding to Seql
                         Pass the packet on
                     Else reject packet
                 Else reject packet
             Else
                 If (pass integrity check)
                     Tl = Seql (shift bits)
                     Set bit corresponding to Seql
                     Pass the packet on
                 Else reject packet
         Else
             Seqh = Th + 1
             If (pass integrity check)
                 Tl = Seql (shift bits)
                 Th = Th + 1
                 Set bit corresponding to Seql
                 Pass the packet on
             Else reject packet
     Else                                      Case B
         If (Seql >= Tl - W + 1)
             Seqh = Th - 1
             If (pass replay check)
                 If (pass integrity check)
                     Set the bit corresponding to Seql
                     Pass packet on
                 Else reject packet
             Else reject packet
         Else
             Seqh = Th
             If (Seql <= Tl)
                 If (pass replay check)
                     If (pass integrity check)
                         Set the bit corresponding to Seql
                         Pass packet on
                     Else reject packet
                 Else reject packet
```

```
            Else
                If (pass integrity check)
                    Tl = Seql (shift bits)
                    Set the bit corresponding to Seql
                    Pass packet on
                Else reject packet
```

A3. Handling Loss of Synchronization due to Significant Packet Loss

If there is an undetected packet loss of 2^32 or more consecutive packets on a single SA, then the transmitter and receiver will lose synchronization of the high-order bits, i.e., the equations in Section A2.2. will fail to yield the correct value. Unless this problem is detected and addressed, subsequent packets on this SA will fail authentication checks and be discarded. The following procedure SHOULD be implemented by any IPsec (ESP or AH) implementation that supports the ESN option.

Note that this sort of extended traffic loss is likely to be detected at higher layers in most cases, before IPsec would have to invoke the sort of re-synchronization mechanism described in A3.1 and A3.2. If any significant fraction of the traffic on the SA in question is TCP, the source would fail to receive ACKs and would stop sending long before 2^32 packets had been lost. Also, for any bi-directional application, even ones operating above UDP, such an extended outage would likely result in triggering some form of timeout. However, a unidirectional application, operating over UDP, might lack feedback that would cause automatic detection of a loss of this magnitude, hence the motivation to develop a recovery method for this case. Note that the above observations apply to SAs between security gateways, or between hosts, or between host and security gateways.

The solution we've chosen was selected to:

+ minimize the impact on normal traffic processing

+ avoid creating an opportunity for a new denial of service attack such as might occur by allowing an attacker to force diversion of resources to a re-synchronization process

+ limit the recovery mechanism to the receiver -- because anti-replay is a service only for the receiver, and the transmitter generally is not aware of whether the receiver is using sequence numbers in support of this optional service, it is preferable for recovery mechanisms to be local to the receiver. This also allows for backward compatibility.

A3.1. Triggering Re-synchronization

For each SA, the receiver records the number of consecutive packets that fail authentication. This count is used to trigger the re-synchronization process, which should be performed in the background or using a separate processor. Receipt of a valid packet on the SA resets the counter to zero. The value used to trigger the re-synchronization process is a local parameter. There is no requirement to support distinct trigger values for different SAs, although an implementer may choose to do so.

A3.2. Re-synchronization Process

When the above trigger point is reached, a "bad" packet is selected for which authentication is retried using successively larger values for the upper half of the sequence number (Seqh). These values are generated by incrementing by one for each retry. The number of retries should be limited, in case this is a packet from the "past" or a bogus packet. The limit value is a local parameter. (Because the Seqh value is implicitly placed after the ESP (or AH) payload, it may be possible to optimize this procedure by executing the integrity algorithm over the packet up to the endpoint of the payload, then compute different candidate ICVs by varying the value of Seqh.) Successful authentication of a packet via this procedure resets the consecutive failure count and sets the value of T to that of the received packet.

This solution requires support only on the part of the receiver, thereby allowing for backward compatibility. Also, because re-synchronization efforts would either occur in the background or utilize an additional processor, this solution does not impact traffic processing and a denial of service attack cannot divert resources away from traffic processing.

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