IPsec

- brief overview
- security associations (SAs)
- Authentication Header (AH) protocol
- Encapsulated Security Payload (ESP) protocol
- examples for combining SAs
- Internet Key Exchange (IKE) version 2

Overview

- IPsec is an Internet standard for network layer security
  - provides protection for IP and protocols above (ICMP, TCP, …)
  - allows selection of the required security services and algorithms
  - puts in place the necessary cryptographic keys
  - can be applied between a pair of hosts, between a pair of security gateways (e.g., firewalls), and between a host and a gateway
- components:
  - an authentication protocol (Authentication Header – AH)
  - a combined encryption and authentication protocol (Encapsulated Security Payload – ESP)
  - Security Assoc. and key establishment protocol (IKEv2)
- possible ways to implement IPsec:
  - integration into the native IP stack implementation
  - bump-in-the-stack (BITS): between IP and the network driver
  - bump-in-the-wire (BITW): a separate HW device (security gateway)

IPsec services

	AH	ESP (encryption only)	ESP (encryption and authentication)
integrity	✓		✓
data origin authentication	✓		✓
replay detection	✓	✓	✓
confidentiality		✓	✓
limited traffic flow confidentiality		✓	✓

Modes of operation (both AH and ESP)

- transport mode
  - provides protection primarily for upper layer protocols
  - protection is applied to the payload of the IP packet
    - ESP in transport mode encrypts and optionally authenticates the IP payload but not the IP header
    - AH in transport mode authenticates the IP payload and selected fields of the IP header
  - typically used between end-systems
- tunnel mode
  - provides protection to the entire IP packet
  - the entire IP packet is considered as payload and encapsulated in another IP packet (with potentially different source and destination addresses)
    - ESP in tunnel mode encrypts and optionally authenticates the entire inner IP packet
    - AH in tunnel mode authenticates the entire inner IP packet and selected fields of the outer IP header
  - usually used between two security gateways, or between a host and a security gateway

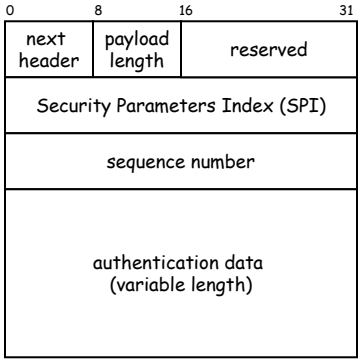
Security Associations (SA)

- the IPsec state shared by two systems (hosts, gateways) is represented by SAs
- an SA is always one-way, and it is either created for AH or for ESP (or IKE)
- an SA includes the following information:
  - end-point identifiers (e.g., IP addresses)
  - protocol information (algorithms, keys, and related parameters)
  - operational mode (tunnel or transport)
  - sending sequence number (for the sender of this SA)
  - anti-replay window (for the receiver of this SA)
    - a counter and a bit-map (or equivalent)
    - used to determine whether an inbound packet is a replay
  - lifetime (a time interval or byte count)
  - …
- SAs are referenced by an SPI (Security Parameter Index)
  - a bit string carried in AH and ESP headers to allow the receiving party to select the SA which must be used to process the packet

Selecting SAs

- Security Policy Database (SPD)
  - two separate databases for inbound and outbound traffic
  - each entry defines a subset of IP traffic and a set of SAs to be applied for that traffic
  - subset of IP traffic is defined in terms of selectors (header fields)
    - destination IP address (single, enumerated list, range, or mask)
    - source IP address (single, enumerated list, range, or mask)
    - transport layer protocol (single, enumerated list, or range)
    - source or destination port (single, enumerated list, range, or wildcard)
    - …
- outbound processing
  - compare the selector fields of the packet to the values in the SPD
  - determine which SAs should be used for the packet and their SPIs
  - do the requiered IPsec processing
- inbound processing
  - retrieve the SA that should be used based on the SPI in the inbound packet
  - do the IPsec processing
  - verify in the SPD if the right SAs have been applied

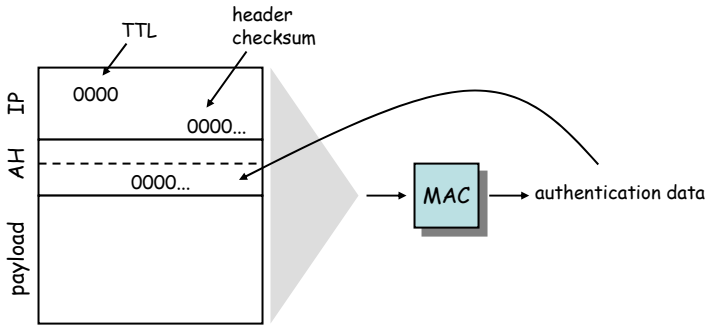
Authentication Header – AH



- next header
  - type of header immediately following this header (e.g., TCP, IP, etc.)
- payload length
  - length of AH (in 32 bit words) minus 2
  - e.g., 4 if Authentication data is 3x32 bits long
- Security Parameters Index
  - identifies the SA used to generate this header
- sequence number
  - sequence number of the packet
- authentication data
  - a (truncated) MAC (default length is 3x32 bits)

MAC

- the MAC is calculated over
  - IP header fields that do not change in transit
  - the AH header fields (authentication data field is set to 0)
  - entire upper layer protocol data
- the fields not covered by the MAC are set to 0 for the calculation



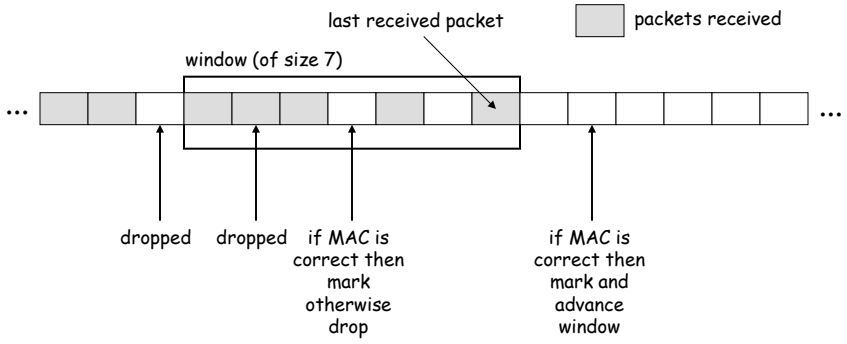
Supported MAC algorithms

Requirement	Algorithm (notes)
MUST	HMAC-SHA1-96 [RFC2404]
SHOULD+	AES-XCBC-MAC-96 [RFC3566]
MAY	HMAC-MD5-96 [RFC2403] (1)

Note:
(1) Weaknesses have become apparent in MD5; however, these should not affect the use of MD5 with HMAC.

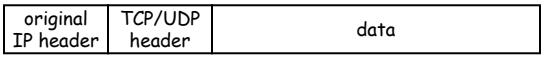
Replay detection

- replay: the attacker obtains an authenticated packet and later transmits (replays) it to the intended destination
- receiver has an anti-replay window of default size W = 64

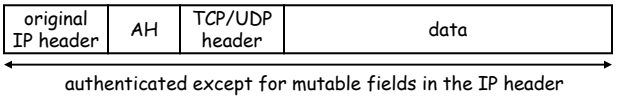


AH in transport and tunnel mode

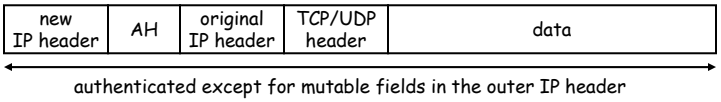
original IPv4 packet



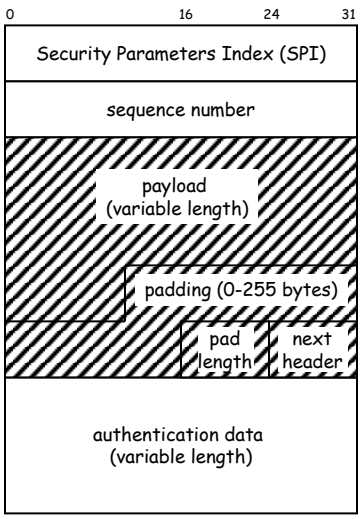
AH in transport mode



AH in tunnel mode



Encapsulating Security Payload – ESP



- Security Parameters Index
  - identifies the SA used to generate this encrypted packet
- sequence number
- payload
  - transport level segment (transfer mode) or encapsulated IP packet (tunnel mode)
- padding
  - variable length padding
- pad length
- next header
  - identifies the type of data contained in the payload
- authentication data
  - a (truncated) MAC computed over the ESP packet (SPI ... next header)

Encryption and MAC

- encryption
  - applied to the payload, padding, pad length, and next header fields
  - if an IV is needed, then it is explicitly carried at the beginning of the payload data (the IV is not encrypted)
- MAC
  - default length is 3x32 bits
  - MAC is computed over the SPI, sequence number, and encrypted payload, padding, pad length, and next header fields
  - unlike in AH, here the MAC does not cover the preceding IP header

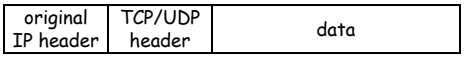
Supported encryption and MAC algorithms

Requirement	Encryption Algorithm
MUST	NULL
MUST-	TripleDES-CBC [RFC2451]
SHOULD+	AES-CBC with 128-bit keys [RFC3602]
SHOULD	AES-CTR [RFC3686]
SHOULD NOT	DES-CBC [RFC2405]

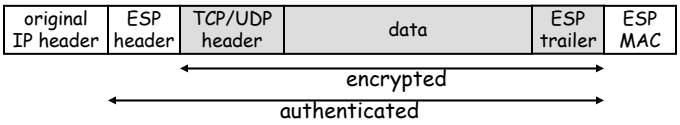
Requirement	Authentication Algorithm
MUST	HMAC-SHA1-96 [RFC2404]
MUST	NULL
SHOULD+	AES-XCBC-MAC-96 [RFC3566]
MAY	HMAC-MD5-96 [RFC2403]

ESP in transport and tunnel mode

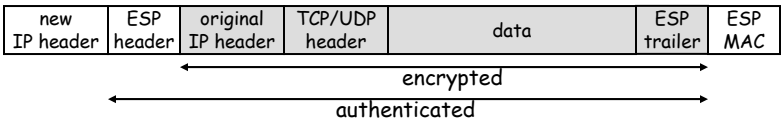
original IPv4 packet



ESP in transport mode

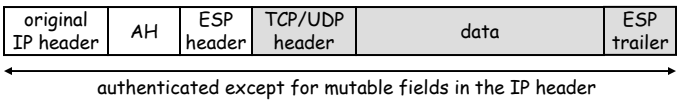


ESP in tunnel mode



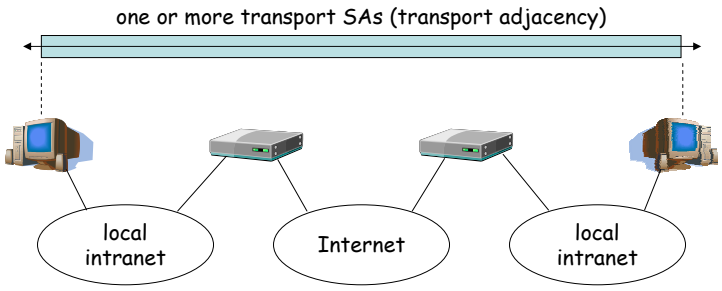
Combining SAs

- transport adjacency (basic ESP-AH combination)
  - first apply ESP in transport mode without authentication
  - then apply AH in transport mode

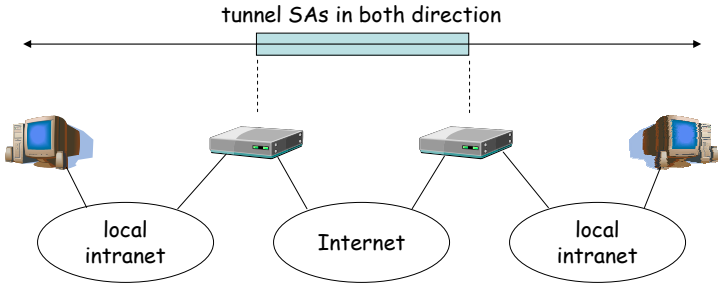


- iterated tunneling (multiple nested tunnels)
  - both end-points of the two tunnels are the same
  - one end-point of the two tunnels is the same
  - neither endpoint of the two tunnels is the same
- transport within tunnel

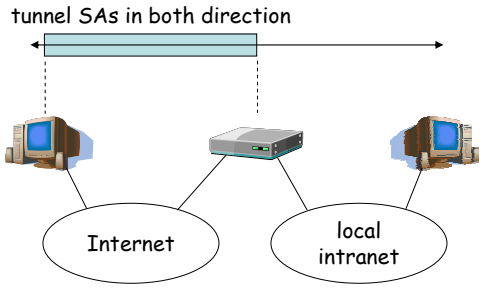
Example: secure end-to-end communications



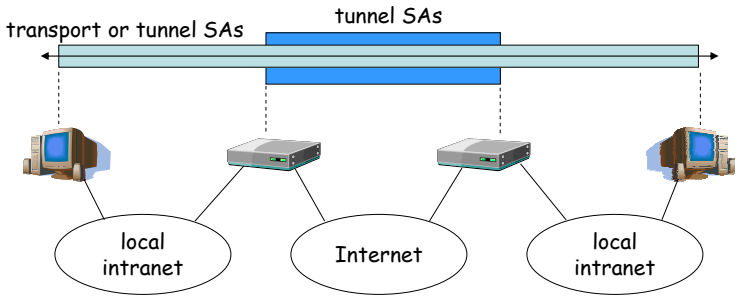
Example: corporate VPN with tunneling



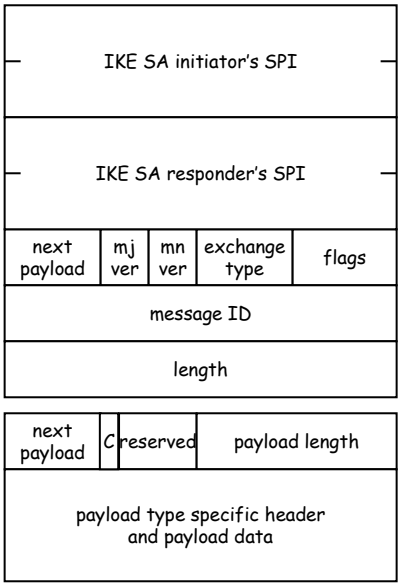
Example: remote access



Example: private connection within a corporate VPN



IKEv2 generic message format



- initiator's SPI
  - an 8 byte value chosen by the initiator to identify the IKE SA
- reponder's SPI
  - an 8 byte value chosen by the responder to identify the IKE SA
- major and minor version
  - 2.0
- exchange type
  - IKE_SA_INIT
  - IKE_AUTH
  - CREATE_CHILD_SA
  - INFORMATIONAL
- flags
  - I(nitiator) – set in messages sent by the original initiator
  - R(esponse) – indicates that this message is a response to a previous message with the same msg ID
- message ID
  - used to match responses and requests, and to detect retransmissions

Message IDs

- every IKE message contains a Message ID as part of its fixed header
- this Message ID is used
  - to match up requests and responses (responses always contain the same message ID as the corresponding request)
  - to identify retransmissions of messages
- each endpoint in the IKE SA maintains two "current" Message IDs:
  - the next one to be used for a request it initiates and
  - the next one it expects to see in a request from the other end
- counters are incremented as requests are generated and received
- thus, each integer n may appear as the message ID in four distinct messages:
  - the n-th request from the original IKE initiator,
  - the corresponding response,
  - the n-th request from the original IKE responder, and
  - the corresponding response
- there is no ambiguity in the messages, because the (I)nitiator and (R)esponse bits in the message header specify which of the four messages a particular one is

Payload types

- Security Association (SA)
- Key Exchange (KE)
- Identification - Initiator (IDi)
- Identification - Responder (IDr)
- Certificate (CERT)
- Certificate Request (CERTREQ)
- Authentication (AUTH)
- Nonce (Ni, Nr)
- Notify (N)
- Delete (D)
- Vendor ID (V)
- Traffic Selector - Initiator (TSi)
- Traffic Selector - Responder (TSr)
- Encrypted (E)
- Configuration (CP)
- Extensible Authentication (EAP)

IKE exchange types

- all IKE exchanges consist of request/response pairs
- IKE_SA_INIT
  - negotiation of cryptographic algorithms (for the IKE SA)
  - exchange of nonces
  - execution of a Diffie-Hellman key exchange
- IKE_AUTH
  - authenticates the previous (IKE_SA_INIT) messages
  - exchange of identities and certificates
  - establishment of the first CHILD_SA (for AH and ESP)
- CREATE_CHILD_SA
  - may be initiated by either end of the IKE_SA after the initial exchanges are completed
  - establishes further SAs between the two ends if needed (for AH and ESP)

The IKE_SA_INIT exchange

messages:

I → R : HDR; SAi1, KEi, Ni

R → I : HDR; SAr1, KEr, Nr

where

SAi1 – proposed cryptographic algorithms for the IKE SA

- encryption alg
- integrity alg
- prf (pseudo-random function)
- DH group

SAr1 – cryptographic algorithms chosen by the responder

KEi – initiator's ephemeral DH value

KEr – responder's ephemeral DH value

Ni, Nr - nonces

Supported algorithms

- encryption
  - ENCR_DES_IV64 (RFC1827)
  - ENCR_DES (RFC2405)
  - ENCR_3DES (RFC2451)
  - ENCR_RC5 (RFC2451)
  - ENCR_IDEA (RFC2451)
  - ENCR_CAST (RFC2451)
  - ENCR_BLOWFISH (RFC2451)
  - ENCR_3IDEA (RFC2451)
  - ENCR_DES_IV32
  - ENCR_AES_CBC (RFC3602)
  - ENCR_AES_CTR (RFC3664)
- integrity
  - AUTH_HMAC_MD5_96 (RFC2403)
  - AUTH_HMAC_SHA1_96 (RFC2404)
  - AUTH_DES_MAC
  - AUTH_KPDK_MD5 (RFC1826)
  - AUTH_AES_XCBC_96 (RFC3566)
- prf
  - PRF_HMAC_MD5 (RFC2104)
  - PRF_HMAC_SHA1 (RFC2104)
  - PRF_HMAC_TIGER (RFC2104)
  - PRF_AES128_XCBC (RFC3664)

Key derivation - preliminaries

- keying material is derived as the output of the negotiated prf algorithm

  prf+ (K,S) = T1 | T2 | T3 | ...

  where:

  T1 = prf (K, S | 0x01)
  T2 = prf (K, T1 | S | 0x02)
  T3 = prf (K, T2 | S | 0x03)

- keys are taken from the output string T1|T2|T3|... without regard to boundaries

Key derivation

SKEYSEED = prf(Ni | Nr, g^{XiXr})

→ SK_d | SK_ai | SK_ar | SK_ei | SK_er | SK_pi | SK_pr =
= prf+ (SKEYSEED, Ni | Nr | SPIi | SPIr)

→ KEYMAT = prf+(SK_d, Ni|Nr) // key material
// for child SAs

- SK_ei, SK_er – message encryption keys for the IKE SA
- SK_ai, SK_ar – message integrity (authentication) keys
- SK_pi, SK_pr – keys used to generate the AUTH payloads

The IKE_AUTH exchange

messages:

I → R : HDR; { IDi, [CERT,] AUTHi, SAi2, TSi, TSr }

R → I : HDR; { IDr, [CERT,] AUTHr, SAr2, TSi, TSr }

where

IDi – identifier of the initiator (e.g., its IP address)

IDr – identifier of the responder (e.g., its IP address)

CERT – public key certificate (optional)

AUTH – authentication payload used to authenticate the messages of the IKE_SA_INIT exchange

SAi1 – proposals for the first child SA

SAr1 – algorithms chosen by the responder for the child SA

TSi, TSr – traffic selectors

{ … } denotes cryptographic protection (encryption and integrity) with the keys SK_ai, SK_ar, SK_ei, SK_er

The AUTH payload

- AUTH authenticates the IKE_SA_INIT exchange
- two options are supported:
  - signature based authentication
  - authentication with a pre-shared secret
- in case of signature based authentication:
  - AUTHi : sig(msg1_of_IKE_SA_INIT | Nr | prf(SK_pi, IDi))
  - AUTHr : sig(msg2_of_IKE_SA_INIT | Ni | prf(SK_pr, IDr))
  - the signature can be an RSA or a DSS signature
  - CERT contains the public signature verification key
- in case of shared secret based authentication:
  - AUTH = prf(prf(secret,"Key Pad for IKEv2"), msg_octets)
- AUTHi and AUTHr may not necessarily computed with the same authentication approach

Protection against DoS attacks

messages:

I → R : HDR; SAi1, KEi, Ni
R → I : HDR; N(cookie)
I → R : HDR; N(cookie), SAi1, KEi, Ni
R → I : HDR; SAr1, KEr, Nr
I → R : HDR; { IDi, [CERT,] AUTHi, SAi2, TSi, TSr }
R → I : HDR; { IDr, [CERT,] AUTHr, SAr2, TSi, TSr }

- the responder sends a random cookie to the IP address from which the first message was received
- the initiator must repeat its first message with the cookie included
- an attacker cannot initiate an IKE exchange from a spoofed IP address

Protection against DoS attacks

- the responder shouldn't keep state for the purpose of verifying a previously sent cookie (because that could be exploited by a DoS attack)
- possible solution:

  cookie = <VersionIDofSecret> | Hash(Ni | IPi | SPIi | <secret>)

  where
  - <secret> is a randomly generated secret known only to the responder and periodically changed
  - <VersionIDofSecret> is changed whenever <secret> is regenerated

- in this way, the cookie can be re-computed when the IKE_SA_INIT request arrives the second time and compared to the cookie in the received message
- in order to avoid problems when <secret> is changed to a new value during a pending IKE_SA_INIT, the responder may keep the old value of <secret> around for a short time and accept cookies computed from either value

The CREATE_CHILD_SA exchange

messages:

I → R : HDR; { SAi, Ni, TSi, TSr }
R → I : HDR; { SAr, Nr, TSi, TSr }

where

SAi – contains proposals for the child SA to be created

SAr – contains a single accepted offer

Ni, Nr – nonces (used in key derivation)

TSi, TSr – traffic selectors (specify which packets should be protected by the new SA)

Recommended readings

- RFC 4301: an overview of the IPSec security architecture
- RFC 4302: specification of AH
- RFC 4303: specification of ESP
- RFC 4305: specification of algorithms for AH and ESP
- RFC 4306: specification of IKEv2