Lectures 5 and 6

INFS 766/INFT 865
Internet Security Protocols

Lectures 5 and 6
IPSEC

Prof. Ravi Sandhu

IPSEC ROADMAP

- Security Association
- IP AH (Authentication Header) Protocol
- IP ESP (Encapsulating Security Protocol)
- Authentication Algorithm
- Encryption Algorithm
- IKE (Key Exchange)
- [IP Compression Protocol and Algorithms]

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SECURITY DEPENDS UPON

secure protocols but also much more
  • cryptographic strength
  • implementation quality
  • good random number sources
  • end system security
  • system management
  • ..................

IPSEC TRAFFIC PROTOCOLS

security extensions for IPv4 and IPv6
IP Authentication Header (AH)
  • authentication and integrity of payload and header
IP Encapsulating Security Protocol (ESP)
  • confidentiality of payload
ESP with optional ICV (integrity check value)
  • confidentiality, authentication and integrity of payload
IPSEC TRAFFIC PROTOCOLS

◆ security services
  ● authentication and integrity
  ● confidentiality
  ● replay prevention
  ● partial traffic flow confidentiality
  ● compression
◆ algorithm-independent with standard defaults
◆ secret-key technology

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IPSEC TRAFFIC PROTOCOLS

◆ both IP AH and IP ESP can operate in
  ● transport mode
    ■ end-to-end
  ● tunnel mode
    ■ security-gateway to security-gateway
◆ transport mode and tunnel model can coexist

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IP TUNNELING

Internal Network 1  Public Internet  Internal Network 2

Security Gateway  Security Gateway

Source Address  Destination Address  Data Payload

outer header

Source Address  Destination Address

A  B  C  D

Tunneled

inner header

C  D

Source Address  Destination Address  Data Payload

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IPSEC
SECURITY ASSOCIATION (SA)

- SA is a one-directional relationship between sender and receiver
- SA applies to AH or ESP but not both
- two-way secure exchange of IP packets requires two (or more) SAs
- unicast (multicast will come later)
- SAs are established by
  - management protocols (IKE)
  - manually

IPSEC
SECURITY ASSOCIATION (SA)

- referenced by a 32 bit security parameter index (SPI) carried in each IPSEC packet
- SA for an IP packet is uniquely identified by
  - SPI
  - destination address
  - security protocol (AH or ESP)
IPSEC
SECURITY ASSOCIATION (SA)

- sequence number counter: 32 bit
- overflow flag: indicating abort or not on overflow
- anti-replay window
- AH information: algorithm, key, key lifetime
- ESP information:
  - encryption: algorithm, key, IV, key lifetime
  - authentication: algorithm, key, key lifetime
- lifetime of SA
- IPSEC protocol mode: transport, tunnel, wildcard
- path MTU (maximum transmission unit)

IPSEC KEYING (SA) GRANULARITY

Host Oriented

User Oriented

Session Unique

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IP AUTHENTICATION HEADER

- IPv4 and IPv6 packets
  - data origin authentication
  - data integrity
  - replay prevention (optional as per SA)
- MAC on IP packet header and data payload
- IP header fields that change hop-by-hop set to 0 for MAC computation

IP AH TRANSPORT MODE

- protocol field of IP header is 51 (for AH payload)
- AH in turn contains protocol field specifying protocol of actual payload, e.g., TCP or UDP or ICMP or IP
IP AH TUNNEL MODE

- IP AH is a single protocol
- transport or tunnel mode is determined by SA
  - actually SA can allow both

IP AUTHENTICATION HEADER FIELDS

- next header: 8 bit protocol field
- length: 8 bit field specifying length of authentication data in 32 bit words
- unused: 16 bit set to 0
- SPI: 32 bit
- sequence number: 32 bit
- integrity check value (ICV): some multiple of 32 bits, e.g., 96, 128, 160
  - must support HMAC-MD5-96, HMAC-SHA-1-96
IP AUTHENTICATION HEADER

- prevents IP spoofing attacks
  - at performance cost
- prevents replay attacks
  - sequence number added in revision
- can be widely and strongly deployed without concern of crypto-politics

ANTI-REPLAY MECHANISM

- Sequence number starts at 1 and cannot go past $2^{32}-1$
- receiver keeps a window of min size 32 (64 preferred, larger is ok)
  - packets to left of window are discarded
  - repeated packets within window are discarded
  - authentic packets to right of window cause window to move right
IP ENCAPSULATING SECURITY PAYLOAD (ESP)

- IPv4 and IPv6
  - ESP: data confidentiality
  - ESP w/Auth: data confidentiality, authentication, integrity
  - ESP w/Auth is an option within ESP
- ESP header (cleartext)
  - security parameter index (SPI)
  - sequence number: 32 bit
  - Initial Value for CBC
- ESP trailer (encrypted)
  - padding
  - next header (identifies payload protocol)
- ESP w/Auth authentication
  - ICV: for authentication option
  - applies only to encrypted payload and not to header

ESP TUNNELING MODE

original IP datagram

IP Header Payload

ENCRIPT

New IP Header ESP Header Original IP Header Payload ESP Trailer ICV

encrypted

authenticated

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ESP TRANSPORT MODE

- original IP datagram
- IP Header
- Payload
- ENCRYPT
- w/Auth
- encrypted
- authenticated

ESP

- protocol 50
  - ESP w/Auth determined by SA
- ESP header
  - SPI, IV in cleartext
- ESP trailer
  - padding info, payload protocol is encrypted
- tunnel mode provides partial traffic flow confidentiality
INTERNET KEY EXCHANGE (IKE)

- Hybrid protocol

ISAKMP
SKHEME
SKIP
MKMP
OAKLEY
IKE

ISAKMP

- Internet security association and key management protocol
- separates key management from key exchanges
- complex general protocol used in a specific way in IKE
  - can apply to protocols other than IPSEC
- for IPSEC uses UDP over IP
IKE

◆ ISAKMP phase 1: establishes ISAKMP SA
  - Main mode (DH with identity protection)
  - Aggressive mode (DH without identity protection)
◆ Between phases
  - New group mode
◆ ISAKMP phase 2: establishes SA for target protocol
  - Quick mode

DIFFIE-HELLMAN KEY ESTABLISHMENT

\[ y_A = a^{x_A} \mod p \quad \text{public key} \]
\[ y_B = a^{x_B} \mod p \quad \text{public key} \]

\[ k = y_B^{x_A} \mod p = y_A^{x_B} \mod p = a^{x_Ax_B} \mod p \]

System constants: \( p \): prime number, \( a \): integer
PERFECT FORWARD SECRECY

- Use a different DH key-pair on each exchange
- DH public keys need to be authenticated
  - Authentication can be done by many techniques
- Loss of long-term (authentication) keys does not disclose session keys

PHASE 1 AUTHENTICATION ALTERNATIVES

- Public-key signature
- Preshared-key
- Public-key encryption
- Revised public-key encryption
**COOKIE EXCHANGE**

- Phase 1 employs cookie exchange to thwart (not prevent) denial of service attacks
- A -> B: Cookie_Request
  - A’s cookie, 64 bit random number
- B -> A: Cookie_Response
  - includes A and B’s cookies
- all further Phase 1 and Phase 2 messages include both cookies
  - ISAKMP SA is identified by both cookies
  - IPSEC protocol SA is identified by SPI

**COOKIE GENERATION**

- hash over
  - IP Source and Destination Address
  - UDP Source and Destination Ports
  - a locally generated random secret
  - timestamp
IKE DEFAULT OAKLEY DH GROUPS

- **Group 1**
  - MODP, 768 bit prime p, g=2

- **Group 2**
  - MODP, 1024 bit prime p, g=2

- **Group 3**
  - EC2N, 155 bit field size

- **Group 4**
  - EC2N, 185 bit field size

- private groups can be used

IKE NOTATION

- **HDR** ISAKMP header whose exchange type is the mode
- **HDR** indicates payload encryption
- **SA** SA negotiation payload, initiator MAY provide multiple proposals, responder replies with one
- **<P>_b** body of payload <P>
- **SAi_b** body of the SA payload (minus generic headers)
- **CKY-I** Initiator's cookie
- **CKY-R** Responder's cookie
- **g^xi** initiator's DH public value
- **g^xr** responder's DH public value
- **g^xy** Diffie-Hellman shared secret
- **KE** key exchange containing DH public values
- **Ni** initiator nonce
- **Nr** responder nonce
- **Idii** identification payload for ISAKMP initiator
- **Idir** identification payload for ISAKMP responder
- **SIG** signature payload, data signed varies
- **CERT** certificate payload
- **HASH** hash payload

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### IPSEC IDs

<table>
<thead>
<tr>
<th>ID Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RESERVED</td>
<td>0</td>
</tr>
<tr>
<td>ID_IPV4_ADDR</td>
<td>1</td>
</tr>
<tr>
<td>ID_FQDN</td>
<td>2</td>
</tr>
<tr>
<td>ID_USER_FQDN</td>
<td>3</td>
</tr>
<tr>
<td>ID_IPV4_ADDR_SUBNET</td>
<td>4</td>
</tr>
<tr>
<td>ID_IPV6_ADDR</td>
<td>5</td>
</tr>
<tr>
<td>ID_IPV6_ADDR_SUBNET</td>
<td>6</td>
</tr>
<tr>
<td>ID_IPV4_ADDR_RANGE</td>
<td>7</td>
</tr>
<tr>
<td>ID_IPV6_ADDR_RANGE</td>
<td>8</td>
</tr>
<tr>
<td>ID_DER_ASN1_DN</td>
<td>9</td>
</tr>
<tr>
<td>ID_DER_ASN1_GN</td>
<td>10</td>
</tr>
<tr>
<td>ID_KEY_ID</td>
<td>11</td>
</tr>
</tbody>
</table>

---

### IKE NOTATION

- **prf(key, msg)** keyed pseudo-random function (often MAC)
- **SKEYID** string derived from secret material known only to the active players in the exchange
- **SKEYID_e** keying material used by the ISAKMP SA to protect confidentiality of its messages.
- **SKEYID_a** keying material used by the ISAKMP SA to protect authentication of its messages.
- **SKEYID_d** keying material used to derive keys for non-ISAKMP SAs

- `<x>y`  "x" is encrypted with the key "y"
- `-->` initiator to responder
- `<--` responder to initiator
- `|` concatenation of information
- `[x]` indicates that x is optional
### SKEYS, HASH AND SIG

\[
\begin{align*}
SKEYID_d &= \text{prf}(SKEYID, g^{xy} \mid CKY-I \mid CKY-R \mid 0) \\
SKEYID_a &= \text{prf}(SKEYID, SKEYID_d \mid g^{xy} \mid CKY-I \mid CKY-R \mid 1) \\
SKEYID_e &= \text{prf}(SKEYID, SKEYID_a \mid g^{xy} \mid CKY-I \mid CKY-R \mid 2) \\
\end{align*}
\]

\[
\begin{align*}
\text{HASH}_I &= \text{prf}(SKEYID, g^{xi} \mid g^{xr} \mid CKY-I \mid CKY-R \mid SA_i_b \mid ID_i_b) \\
\text{HASH}_R &= \text{prf}(SKEYID, g^{xr} \mid g^{xi} \mid CKY-R \mid CKY-I \mid SA_i_b \mid ID_i_b) \\
\end{align*}
\]

\text{HASH}_I and \text{HASH}_R used directly for MAC authentication OR digitally signed by SIG_I and SIG_R

### MAIN MODE WITH DIGITAL SIGNATURES

<table>
<thead>
<tr>
<th>Initiator</th>
<th>Responder</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDR, SA</td>
<td>&lt;!-- HDR, SA</td>
</tr>
<tr>
<td>HDR, KE, Ni</td>
<td>--&gt; HDR, KE, Nr</td>
</tr>
</tbody>
</table>

\[
\text{SKEYID} = \text{prf}(\text{Ni}_b \mid \text{Nr}_b, g^{xy})
\]
### AGGRESSIVE MODE WITH DIGITAL SIGNATURES

<table>
<thead>
<tr>
<th>Initiator</th>
<th>Responder</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDR, SA, KE, Ni, IDii</td>
<td>--- &gt; HDR, SA</td>
</tr>
<tr>
<td>HDR, [ CERT, ] SIG_I</td>
<td>--- &gt; HDR, SA, KE, Nr, IDir, [ CERT, ] SIG_R</td>
</tr>
</tbody>
</table>

\[ \text{SKEYID} = \text{prf}(Ni_b | Nr_b, g^xy) \]

### MAIN AND AGGRESSIVE MODE WITH PRE-SHARED KEY

#### MAIN MODE

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<td>--- &gt; HDR, SA</td>
</tr>
<tr>
<td>HDR, KE, Ni</td>
<td>--- &gt; HDR, KE, Nr</td>
</tr>
<tr>
<td>HDR*, IDii, HASH_I</td>
<td>--- &gt; HDR*, IDir, HASH_R</td>
</tr>
</tbody>
</table>

#### AGGRESSIVE MODE

<table>
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<th>Responder</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDR, SA, KE, Ni, IDii</td>
<td>--- &gt; HDR, SA, KE, Nr, IDir, HASH_R</td>
</tr>
<tr>
<td>HDR, HASH_I</td>
<td>--- &gt; HDR, SA, KE, Nr, IDir, HASH_R</td>
</tr>
</tbody>
</table>

\[ \text{SKEYID} = \text{prf}(\text{pre-shared-key, } Ni_b | Nr_b) \]
MAIN MODE WITH PUBLIC KEY ENCRYPTION

Initiator                                      Responder
---------------------------------------------
HDR, SA                                        -->    HDR, SA
HDR, KE, [ HASH(1), ]                        <--    HDR, SA
<IDii_b>PubKey_r,                             <--    <IDir_b>PubKey_i,
<Ni_b>PubKey_r                                 <Nr_b>PubKey_i
HDR*, HASH_I                                   <--    HDR*, HASH_R

HASH(1) is hash of responder’s certificate

SKEYID = prf(hash(Ni_b | Nr_b), CKY-I | CKY-R)

AGGRESSIVE MODE WITH PUBLIC KEY ENCRYPTION

Initiator                                      Responder
---------------------------------------------
HDR, SA, [ HASH(1), ] KE,                     -->    HDR, SA, KE, <IDir_b>PubKey_i,
<IDii_b>PubKey_r,                             <--    <Nr_b>PubKey_i, HASH_R
<Ni_b>PubKey_r                                 <Nr_b>PubKey_i
HDR, HASH_I                                    <--    HDR, HASH_R

Provides identity protection

HASH(1) is hash of responder’s certificate

SKEYID = prf(hash(Ni_b | Nr_b), CKY-I | CKY-R)
AUTHENTICATION WITH PUBLIC-KEY ENCRYPTION

- does not provide non-repudiation
- provides additional security since attacked must break both
  - DH key exchange
  - public-key encryption
- provides identity protection in aggressive mode
- revised protocol reduces public-key operations

MAIN MODE WITH REVISED PUBLIC KEY ENCRYPTION

<table>
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<th>Responder</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDR, SA</td>
<td>&lt;-- HDR, SA</td>
</tr>
<tr>
<td>HDR, [ HASH(1), ]&lt;Ni_b&gt;Pubkey_r,&lt;KE_b&gt;Ke_i,&lt;IDii_b&gt;Ke_i,&lt;Cert-I_b&gt;Ke_i] &lt;--&gt; HDR, &lt;Nr_b&gt;PubKey_i,&lt;KE_b&gt;Ke_r,&lt;IDir_b&gt;Ke_r</td>
<td></td>
</tr>
<tr>
<td>HDR*, HASH_I</td>
<td>&lt;-- HDR*, HASH_R</td>
</tr>
</tbody>
</table>
MAIN MODE WITH REVISED PUBLIC KEY ENCRYPTION

Ne_i = prf(Ni_b, CKY-I)
Ne_r = prf(Nr_b, CKY-R)

Ke_i is leftmost 320 bits of K1 | K2 | K3 where
K1 = prf(Ne_i, 0)
K2 = prf(Ne_i, K1)
K3 = prf(Ne_i, K2)

Similarly for Ke_r

AGGRESSIVE MODE WITH REVISED PUBLIC KEY ENCRYPTION

Initiator                        Responder
-------------------                      -------------------
HDR, SA, [ HASH(1), ]              HDR, SA, <Nr_b>PubKey_i,
<Ni_b>Pubkey_r,                  <KE_b>Ke_r, <IDir_b>Ke_r,
<KE_b>Ke_i, <IDii_b>Ke_i           [<--
[, <Cert-I_b>Ke_i ]               HDR, HASH_I]
        -->

HDR, HASH_I                      <--

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PHASE 2 QUICK MODE

Initiator
---------------
HDR*, HASH(1), SA, Ni
[, KE ] [, IDci, IDcr ]

Responder
---------------
<- HDR*, HASH(2), SA, Nr
[, KE ] [, IDci, IDcr ]

HDR*, HASH(3) -->

HASH(1) = prf(SKEYID\_a, M-ID | SA | Ni [, KE ] [, IDci, IDcr ])
HASH(2) = prf(SKEYID\_a, M-ID | Ni\_b | SA | Nr [, KE ] [, IDci, IDcr ])
HASH(3) = prf(SKEYID\_a, 0 | M-ID | Ni\_b | Nr\_b)

PHASE 2 QUICK MODE

If no PFS there is no KE payload and new keying material is

KEYMAT = prf(SKEYID\_d, protocol | SPI | Ni\_b | Nr\_b).

If PFS there is KE payload and new keying material is

KEYMAT = prf(SKEYID\_d, g(qm)^xy | protocol | SPI | Ni\_b | Nr\_b)

where g(qm)^xy is the shared secret from the ephemeral DH exchange of this Quick Mode (which must then be deleted)

In either case, "protocol" and "SPI" are from the ISAKMP Proposal Payload that contained the negotiated Transform.

Two SAs are established
One in each direction
Keys are different because of different SPIs
PHASE 2 QUICK MODE

Additional key material can be generated if needed as follows:

\[
\text{KEYMAT} = K_1 \mid K_2 \mid K_3 \mid \ldots
\]

where

\[
K_1 = \text{prf}(\text{SKEYID}_d, [ g(qm)^xy \mid \text{protocol} \mid \text{SPI} \mid N_{i_b} \mid N_{r_b} ])
\]

\[
K_2 = \text{prf}(\text{SKEYID}_d, K_1 \mid [ g(qm)^xy \mid \text{protocol} \mid \text{SPI} \mid N_{i_b} \mid N_{r_b} ])
\]

\[
K_3 = \text{prf}(\text{SKEYID}_d, K_2 \mid [ g(qm)^xy \mid \text{protocol} \mid \text{SPI} \mid N_{i_b} \mid N_{r_b} ])
\]

etc.

Multiple SA's and keys can be negotiated with one exchange as follows:

Initiator                        Responder
-----------                      -----------
HDR*, HASH(1), SA0, SA1, Ni,   HDR*, HASH(2), SA0, SA1, Nr,
[, KE ] [ , IDci, IDcr ] -->     [, KE ] [ , IDci, IDcr ]

Results in 4 security associations-- 2 each way for both SA0 and SA1
NEW GROUP MODE

- sandwiched between phase 1 and 2
- group can be negotiated in phase 1
- new group mode allows nature of group to be hidden
  - in phase 1 only group id is communicated in clear

Initiator                        Responder
-----------                      -----------
HDR*, HASH(1), SA        -->     HDR*, HASH(2), SA
HASH(1) = prf(SKEYID_a, M-ID | SA)
HASH(2) = prf(SKEYID_a, M-ID | SA)
VIRTUAL PRIVATE NETWORKS

VPNs

- VPNs are used to securely connect networks using tunnels (virtual circuits) over the Internet
- Secure remote access is used to securely connect a single computer using tunnels (virtual circuits) over the Internet
VPN TECHNOLOGIES

- **IPSEC**
  - layer 3 VPN (standards based), layer 2 VPN (proprietary)
- **PPTP (Point-to-point tunneling protocol)**
  - Microsoft layer 2 VPN, built in security with known flaws
- **L2F (layer 2 forwarding)**
  - Cisco layer 2 VPN, no security, phasing out
- **L2TP (layer 2 tunneling protocol)**
  - emerging IETF standard, needs IPSEC security
- **SSL (layer 4 tunnel)**
  - proprietary approaches, tunnel IP over SSL-protected TCP

VIRTUAL PRIVATE NETWORKS

Diagram showing the connection between Internal Network 1 (C), Public Internet (A), Internal Network 2 (D) with IPSEC tunnels and IP ESP with ICV or IP AH or both tunnel mode.
WHAT IS TUNNELED

- IPSEC tunnel can be used to tunnel
  - IP packets
    - IPSEC standard approach
  - Layer 2 packets
    - Virtual switched LAN (VSLAN)
    - Proprietary approaches

VIRTUAL PRIVATE NETWORKS

```
  Firewall
  C       Public Internet
    A     B
    |     |
  Internal Network 1  IP ESP w/ICV or IP AH or both tunnel mode  Internal Network 2
  |     |
  C     D
```

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SECURE REMOTE ACCESS

Public Internet

C

IPSEC tunnel

Internal Network 1

A

IP ESP w/ICV or IP AH or both tunnel mode

B

Remote Laptop

IPSEC tunnel

Firewall

C

PPTP VPNs

- Originally intended for secure remote access
- Enhancements for network to network VPNs
- Known security flaws
  - Remedied in version 2
PPTP VPNs

- Voluntary tunneling
  - PPTP tunnel from client to network

- Compulsory tunneling
  - PPTP tunnel from ISP to network
  - client to ISP dial-in via PPP is unprotected