Set 7
Network Security

Goals:

- understand principles of network security:
  - cryptography and its many uses beyond “confidentiality”
  - authentication
  - message integrity
- security in practice:
  - firewalls and intrusion detection systems
  - security in application, transport, network, link layers
Chapter 8 roadmap

8.1 What is network security?
8.2 Principles of cryptography
8.3 Message integrity, authentication
8.4 Securing e-mail
8.5 Securing TCP connections: SSL
8.6 Network layer security: IPsec
8.7 Securing wireless LANs
8.8 Operational security: firewalls and IDS
What is network security?

**Confidentiality:** only sender, intended receiver should “understand” message contents
- sender encrypts message
- receiver decrypts message

**Authentication:** sender, receiver want to confirm identity of each other

**Message Integrity:** sender, receiver want to ensure message not altered (in transit, or afterwards) without detection

**Access and Availability:** services must be accessible and available to users
Friends and enemies: Alice, Bob, Trudy

- well-known in network security world
- Bob, Alice (lovers!) want to communicate “securely”
- Trudy (intruder) may intercept, delete, add messages
Who might Bob, Alice be?

- ... well, *real-life* Bobs and Alices!
- Web browser/server for electronic transactions (e.g., on-line purchases)
- on-line banking client/server
- DNS servers
- routers exchanging routing table updates
- other examples?
There are bad guys (and girls) out there!

**Q:** What can a “bad guy” do?

**A:** A lot! See section 1.6

- **eavesdrop:** intercept messages
- actively **insert** messages into connection
- **impersonation:** can fake (spoof) source address in packet (or any field in packet)
- **hijacking:** “take over” ongoing connection by removing sender or receiver, inserting himself in place
- **denial of service:** prevent service from being used by others (e.g., by overloading resources)
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The language of cryptography

$m$ plaintext message
$K_A(m)$ ciphertext, encrypted with key $K_A$
$m = K_B(K_A(m))$
Breaking an encryption scheme

- **cipher-text only attack:** Trudy has ciphertext she can analyze
  - **two approaches:**
    - brute force: search through all keys
    - statistical analysis

- **known-plaintext attack:** Trudy has plaintext corresponding to ciphertext
  - e.g., in monoalphabetic cipher, Trudy determines pairings for a,l,i,c,e,b,o,

- **chosen-plaintext attack:** Trudy can get ciphertext for chosen plaintext
Symmetric key cryptography

plaintext message, \( m \) \( \rightarrow \) encryption algorithm \( \rightarrow \) ciphertext \( \rightarrow \) decryption algorithm \( \rightarrow \) plaintext

\[ m = K_S(K_S(m)) \]

**symmetric key crypto**: Bob and Alice share same (symmetric) key: \( K_S \)

- e.g., key is knowing substitution pattern in mono alphabetic substitution cipher

**Q**: how do Bob and Alice agree on key value?
Simple encryption scheme

**substitution cipher**: substituting one thing for another

- monoalphabetic cipher: substitute one letter for another

```
plaintext:  abcdefghijklmnopqrstuvwxyz
```
```
ciphertext: mnbvcxzasdfghjklpoiuytrewq
```

**e.g.:** Plaintext: bob. i love you. alice
```
ciphertext: nkn. s gktc wky. mgsbc
```

**Encryption key**: mapping from set of 26 letters to set of 26 letters
A more sophisticated encryption approach

- n substitution ciphers, $M_1, M_2, \ldots, M_n$
- cycling pattern:
  - e.g., $n=4$: $M_1, M_3, M_4, M_3, M_2; \quad M_1, M_3, M_4, M_3, M_2; \ldots$
- for each new plaintext symbol, use subsequent substitution pattern in cyclic pattern
  - dog: d from $M_1$, o from $M_3$, g from $M_4$

Encryption key: n substitution ciphers, and cyclic pattern
- key need not be just n-bit pattern
Symmetric key crypto: DES

DES: Data Encryption Standard

- US encryption standard [NIST 1993]
- 56-bit symmetric key, 64-bit plaintext input
- block cipher with cipher block chaining
- how secure is DES?
  - DES Challenge: 56-bit-key-encrypted phrase decrypted (brute force) in less than a day
  - no known good analytic attack
- making DES more secure:
  - 3DES: encrypt 3 times with 3 different keys
Symmetric key crypto: DES

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**DES operation**

- initial permutation
- 16 identical “rounds” of function application, each using different 48 bits of key
- final permutation
AES: Advanced Encryption Standard

- symmetric-key NIST standard, replaced DES (Nov 2001)
- processes data in 128 bit blocks
- 128, 192, or 256 bit keys
- brute force decryption (try each key) taking 1 sec on DES, takes 149 trillion years for AES
Public Key Cryptography

**symmetric key crypto**
- requires sender, receiver know shared secret key
- Q: how to agree on key in first place (particularly if never “met”)?

**public key crypto**
- radically different approach [Diffie-Hellman76, RSA78]
- sender, receiver do *not* share secret key
- *public* encryption key known to *all*
- *private* decryption key known only to receiver
Public key cryptography

- Bob’s public key: $K_B^+$
- Bob’s private key: $K_B^-$

plaintext message, $m$ \rightarrow \text{encryption algorithm} \rightarrow \text{ciphertext, } K_B^+(m) \rightarrow \text{decryption algorithm} \rightarrow \text{plaintext message, } m = K_B^-(K_B^+(m))
Public key encryption algorithms

requirements:

1. need $K_B^+(\cdot)$ and $K_B^-(\cdot)$ such that
   $$K_B^-(K_B^+(m)) = m$$

2. given public key $K_B^+$, it should be impossible to compute private key $K_B^-$

RSA: Rivest, Shamir, Adelson algorithm
Prerequisite: modular arithmetic

- $x \mod n =$ remainder of $x$ when divide by $n$
- facts:
  \[(a \mod n) + (b \mod n)] \mod n = (a+b) \mod n\]
  \[(a \mod n) - (b \mod n)] \mod n = (a-b) \mod n\]
  \[(a \mod n) \times (b \mod n)] \mod n = (a\times b) \mod n\]
- thus
  \[(a \mod n)^d \mod n = a^d \mod n\]
- example: $x=14$, $n=10$, $d=2$:
  \[(x \mod n)^d \mod n = 4^2 \mod 10 = 6\]
  \[x^d = 14^2 = 196 \quad x^d \mod 10 = 6\]
RSA: getting ready

- message: just a bit pattern
- bit pattern can be uniquely represented by an integer number
- thus, encrypting a message is equivalent to encrypting a number.

**example:**

- \( m = 10010001 \). This message is uniquely represented by the decimal number 145.
- to encrypt \( m \), we encrypt the corresponding number, which gives a new number (the ciphertext).
RSA: Creating public/private key pair

1. choose two large prime numbers \( p, q \). (e.g., 1024 bits each)
2. compute \( n = pq, \ z = (p-1)(q-1) \)
3. choose \( e \) (with \( e < n \)) that has no common factors with \( z \) (\( e, z \) are “relatively prime”).
4. choose \( d \) such that \( ed - 1 \) is exactly divisible by \( z \). (in other words: \( ed \mod z = 1 \)).
5. public key is \( (n,e) \). private key is \( (n,d) \).
RSA: encryption, decryption

0. given \((n,e)\) and \((n,d)\) as computed above

1. to encrypt message \(m (< n)\), compute
   \[ c = m^e \mod n \]

2. to decrypt received bit pattern, \(c\), compute
   \[ m = c^d \mod n \]

\[ m = (m^e \mod n)^d \mod n \]

\textit{magic happens!}
RSA example:


e=5 (so $e$, $z$ relatively prime).

d=29 (so $ed-1$ exactly divisible by $z$).

encrypting 8-bit messages.

\[
\text{encrypt: } \begin{array}{cccc}
\text{bit pattern} & m & m^e & c = m^e \mod n \\
\hline
00001000 & 12 & 24832 & 17
\end{array}
\]

\[
\text{decrypt: } \begin{array}{cccc}
\text{c} & \text{c}^d & m = \text{c}^d \mod n \\
\hline
17 & 481968572106750915091411825223071697 & 12
\end{array}
\]
Why does RSA work?

- must show that \( c^d \mod n = m \)
  where \( c = m^e \mod n \)
- fact: for any \( x \) and \( y \): \( x^y \mod n = x^{(y \mod z)} \mod n \)
  - where \( n = pq \) and \( z = (p-1)(q-1) \)
- thus,
  \[
  c^d \mod n = (m^e \mod n)^d \mod n \\
  = m^{ed} \mod n \\
  = m^{(ed \mod z)} \mod n \\
  = m^l \mod n \\
  = m
  \]
RSA: another important property

The following property will be very useful later:

\[ K_B^{-1}(K_B^+(m)) = m = K_B^+(K_B^-(m)) \]

use public key first, followed by private key
use private key first, followed by public key

result is the same!
Why \( K_B(K_B^+(m)) = m = K_B^+(K_B^-(m)) \) ?

follows directly from modular arithmetic:

\[
(m^e \mod n)^d \mod n = m^{ed} \mod n \\
= m^{de} \mod n \\
= (m^d \mod n)^e \mod n
\]
Why is RSA secure?

✓ suppose you know Bob’s public key (n,e). How hard is it to determine d?
✓ essentially need to find factors of n without knowing the two factors p and q
  ▪ fact: factoring a big number is hard
RSA in practice: session keys

- Exponentiation in RSA is computationally intensive
- DES is at least 100 times faster than RSA
- Use public key crypto to establish secure connection, then establish second key – symmetric session key – for encrypting data

Session key, $K_S$

- Bob and Alice use RSA to exchange a symmetric key $K_S$
- Once both have $K_S$, they use symmetric key cryptography
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**Authentication**

**Goal:** Bob wants Alice to “prove” her identity to him

**Protocol ap1.0:** Alice says “I am Alice”

Failure scenario??
Authentication

**Goal:** Bob wants Alice to “prove” her identity to him

**Protocol ap1.0:** Alice says “I am Alice”

in a network, Bob can not “see” Alice, so Trudy simply declares herself to be Alice
Authentication: another try

*Protocol ap2.0:* Alice says “I am Alice” in an IP packet containing her source IP address

Failure scenario??
Authentication: another try

Protocol ap2.0: Alice says “I am Alice” in an IP packet containing her source IP address

Trudy can create a packet “spoofing” Alice’s address
Protocol ap3.0: Alice says “I am Alice” and sends her secret password to “prove” it.

Authentication: another try

Failure scenario??
Authentication: another try

*Protocol ap3.0:* Alice says “I am Alice” and sends her secret password to “prove” it.

- Alice’s IP addr
- Alice’s password
- “I’m Alice”

*Playback attack:* Trudy records Alice’s packet and later plays it back to Bob.
Authentication: yet another try

Protocol ap3.1: Alice says “I am Alice” and sends her encrypted secret password to “prove” it.

Failure scenario??
Authentication: yet another try

**Protocol ap3.1:** Alice says “I am Alice” and sends her *encrypted* secret password to “prove” it.

Alice’s IP addr  | encrypted password  | “I’m Alice”  
--- | --- | ---

record and playback *still* works!
Authentication: yet another try

**Goal:** avoid playback attack

**nonce:** number (R) used only *once-in-a-lifetime*

**ap4.0:** to prove Alice “live”, Bob sends Alice *nonce*, R. Alice must return R, encrypted with shared secret key

---

Failures, drawbacks?
Authentication: ap5.0

ap4.0 requires shared symmetric key

- can we authenticate using public key techniques?

**ap5.0**: use nonce, public key cryptography

```
“I am Alice”

R

K_A^-(R)

“send me your public key”

K_A^+

Bob computes

K_A^+(K_A^-(R)) = R

and knows only Alice could have the private key, that encrypted R such that

K_A^+(K_A^-(R)) = R
```
ap5.0: security hole

**man (or woman) in the middle attack:** Trudy poses as Alice (to Bob) and as Bob (to Alice)

I am Alice

R

\[ K_A^-(R) \]

Send me your public key

\[ K_A^+ \]

I am Alice

R

\[ K_T^-(R) \]

Send me your public key

\[ K_T^+ \]

Trudy gets

\[ m = K_T^-(K_T^+(m)) \]

sends \( m \) to Alice

encrypted with Alice’s public key

\[ m = K_A^-(K_A^+(m)) \]
**ap5.0: security hole**

*man (or woman) in the middle attack:* Trudy poses as Alice (to Bob) and as Bob (to Alice)

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difficult to detect:

- Bob receives everything that Alice sends, and vice versa. (e.g., so Bob, Alice can meet one week later and recall conversation!)
- problem is that Trudy receives all messages as well!
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Digital signatures

cryptographic technique analogous to hand-written signatures:

- sender (Bob) digitally signs document, establishing he is document owner/creator.
- verifiable, nonforgeable: recipient (Alice) can prove to someone that Bob, and no one else (including Alice), must have signed document
simple digital signature for message m:

- Bob signs m by encrypting with his private key $K_B^-$, creating “signed” message, $K_B^-(m)$
Digital signatures

- suppose Alice receives msg m, with signature: m, $K_B^-(m)$
- Alice verifies m signed by Bob by applying Bob’s public key $K_B^+$ to $K_B^-(m)$ then checks $K_B^+(K_B^-(m)) = m$.
- If $K_B^+(K_B^-(m)) = m$, whoever signed m must have used Bob’s private key.

Alice thus verifies that:

- Bob signed m
- no one else signed m
- Bob signed m and not m ‘

non-repudiation:

- Alice can take m, and signature $K_B^-(m)$ to court and prove that Bob signed m
computationally expensive to public-key-encrypt long messages

**goal:** fixed-length, easy-to-compute digital “fingerprint”

- apply hash function $H$ to $m$, get fixed size message digest, $H(m)$.

**Hash function properties:**
- many-to-1
- produces fixed-size msg digest (fingerprint)
- given message digest $x$, computationally infeasible to find $m$ such that $x = H(m)$
Internet checksum: poor crypto hash function

Internet checksum has some properties of hash function:

- produces fixed length digest (16-bit sum) of message
- is many-to-one

But given message with given hash value, it is easy to find another message with same hash value:

<table>
<thead>
<tr>
<th>message</th>
<th>ASCII format</th>
<th>message</th>
<th>ASCII format</th>
</tr>
</thead>
<tbody>
<tr>
<td>I O U 1</td>
<td>49 4F 55 31</td>
<td>I O U 9</td>
<td>49 4F 55 39</td>
</tr>
<tr>
<td>0 0 . 9</td>
<td>30 30 2E 39</td>
<td>0 0 . 1</td>
<td>30 30 2E 31</td>
</tr>
<tr>
<td>9 B O B</td>
<td>39 42 D2 42</td>
<td>9 B O B</td>
<td>39 42 D2 42</td>
</tr>
</tbody>
</table>

B2 C1 D2 AC  different messages  B2 C1 D2 AC
but identical checksums!
Digital signature = signed message digest

Bob sends digitally signed message:

- Large message \( m \)
- Hash function \( H \):
  \[ H(m) \]
- Digital signature (encrypt): \( K_B^-(H(m)) \)
- Bob’s private key \( K_B^- \)

Alice verifies signature, integrity of digitally signed message:

- Large message \( m \)
- Hash function \( H \):
  \[ H(m) \]
- Encrypted msg digest: \( K_B^-(H(m)) \)
- Bob’s public key \( K_B^+ \)

Bob’s private key: \( K_B^- \)

Digital signature = signed message digest
Hash function algorithms

- MD5 hash function widely used (RFC 1321)
  - computes 128-bit message digest in 4-step process.
  - arbitrary 128-bit string $x$, appears difficult to construct
    msg $m$ whose MD5 hash is equal to $x$

- SHA-1 is also used
  - US standard [NIST, FIPS PUB 180-1]
  - 160-bit message digest
Recall: ap5.0 security hole

*man (or woman) in the middle attack:* Trudy poses as Alice (to Bob) and as Bob (to Alice)

\[
m = K_A^-(K_A^+(m))
\]

\[
Tm = K_T(K_T(m))
\]

Trudy gets \(m\) encrypted with Alice’s public key. She then sends \(m\) to Alice.
Public-key certification

- motivation: Trudy plays pizza prank on Bob
  - Trudy creates e-mail order:
    Dear Pizza Store, Please deliver to me four pepperoni pizzas. Thank you, Bob
  - Trudy signs order with her private key
  - Trudy sends order to Pizza Store
  - Trudy sends to Pizza Store her public key, but says it’s Bob’s public key
  - Pizza Store verifies signature; then delivers four pepperoni pizzas to Bob
  - Bob doesn’t even like pepperoni
Certification authorities

- **certification authority (CA):** binds public key to particular entity, E.

- E (person, router) registers its public key with CA.
  - E provides “proof of identity” to CA.
  - CA creates certificate binding E to its public key.
  - certificate containing E’s public key digitally signed by CA – CA says “this is E’s public key”
Certification authorities

- when Alice wants Bob’s public key:
  - gets Bob’s certificate (Bob or elsewhere).
  - apply CA’s public key to Bob’s certificate, get Bob’s public key
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8.3 Message integrity, authentication
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Secure e-mail

- Alice wants to send confidential e-mail, m, to Bob.

Alice:
- generates random symmetric private key, $K_S$
- encrypts message with $K_S$ (for efficiency)
- also encrypts $K_S$ with Bob’s public key
- sends both $K_S(m)$ and $K_B(K_S)$ to Bob
Secure e-mail

Alice wants to send confidential e-mail, m, to Bob.

Bob:
- uses his private key to decrypt and recover $K_S$
- uses $K_S$ to decrypt $K_S(m)$ to recover m
Secure e-mail (continued)

- Alice wants to provide sender authentication message integrity

- Alice digitally signs message
  - sends both message (in the clear) and digital signature
Secure e-mail (continued)

- Alice wants to provide secrecy, sender authentication, message integrity.

Alice uses three keys: her private key, Bob’s public key, newly created symmetric key.
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SSL: Secure Sockets Layer

- widely deployed security protocol
  - supported by almost all browsers, web servers
  - https
  - billions $/year over SSL
- mechanisms: [Woo 1994], implementation: Netscape
- variation - TLS: transport layer security, RFC 2246
- provides
  - confidentiality
  - integrity
  - authentication
- original goals:
  - Web e-commerce transactions
  - encryption (especially credit-card numbers)
  - Web-server authentication
  - optional client authentication
  - minimum hassle in doing business with new merchant
- available to all TCP applications
  - secure socket interface
SSL and TCP/IP

SSL provides application programming interface (API) to applications
C and Java SSL libraries/classes readily available
Could do something like PGP:

- but want to send byte streams & interactive data
- want set of secret keys for entire connection
- want certificate exchange as part of protocol: handshake phase
Toy SSL: a simple secure channel

- **handshake**: Alice and Bob use their certificates, private keys to authenticate each other and exchange shared secret
- **key derivation**: Alice and Bob use shared secret to derive set of keys
- **data transfer**: data to be transferred is broken up into series of records
- **connection closure**: special messages to securely close connection
Toy: a simple handshake

**MS**: master secret

**EMS**: encrypted master secret
Toy: key derivation

- considered bad to use same key for more than one cryptographic operation
  - use different keys for message authentication code (MAC) and encryption
- four keys:
  - $K_c = \text{encryption key for data sent from client to server}$
  - $M_c = \text{MAC key for data sent from client to server}$
  - $K_s = \text{encryption key for data sent from server to client}$
  - $M_s = \text{MAC key for data sent from server to client}$
- keys derived from key derivation function (KDF)
  - takes master secret and (possibly) some additional random data and creates the keys
Toy: data records

- why not encrypt data in constant stream as we write it to TCP?
  - where would we put the MAC? If at end, no message integrity until all data processed.
  - e.g., with instant messaging, how can we do integrity check over all bytes sent before displaying?
- instead, break stream in series of records
  - each record carries a MAC
  - receiver can act on each record as it arrives
- issue: in record, receiver needs to distinguish MAC from data
  - want to use variable-length records

```
length  data   MAC
```
Toy: sequence numbers

- **Problem**: attacker can capture and replay record or re-order records
- **Solution**: put sequence number into MAC:
  - $\text{MAC} = \text{MAC}(M_x, \text{sequence}||\text{data})$
  - note: no sequence number field

- **Problem**: attacker could replay all records
- **Solution**: use nonce
Toy: control information

- **Problem**: truncation attack:
  - attacker forges TCP connection close segment
  - one or both sides thinks there is less data than there actually is.

- **Solution**: record types, with one type for closure
  - type 0 for data; type 1 for closure

- MAC = MAC(M_x, sequence||type||data)
Toy SSL: summary

- hello
- certificate, nonce
- $K_B^+(MS) = EMS$
- type 0, seq 1, data
- type 0, seq 2, data
- type 0, seq 1, data
  encrypted

- type 0, seq 3, data
- type 1, seq 4, close
- type 1, seq 2, close

bob.com
Toy SSL isn’t complete

- how long are fields?
- which encryption protocols?
- want negotiation?
  - allow client and server to support different encryption algorithms
  - allow client and server to choose together specific algorithm before data transfer
SSL cipher suite

- cipher suite
  - public-key algorithm
  - symmetric encryption algorithm
  - MAC algorithm

- SSL supports several cipher suites

- negotiation: client, server agree on cipher suite
  - client offers choice
  - server picks one

common SSL symmetric ciphers
- DES – Data Encryption Standard: block
- 3DES – Triple strength: block
- RC2 – Rivest Cipher 2: block
- RC4 – Rivest Cipher 4: stream

SSL Public key encryption
- RSA
Real SSL: handshake (1)

Purpose

1. server authentication
2. negotiation: agree on crypto algorithms
3. establish keys
4. client authentication (optional)
Real SSL: handshake (2)

1. client sends list of algorithms it supports, along with client nonce
2. server chooses algorithms from list; sends back: choice + certificate + server nonce
3. client verifies certificate, extracts server’s public key, generates pre_master_secret, encrypts with server’s public key, sends to server
4. client and server independently compute encryption and MAC keys from pre_master_secret and nonces
5. client sends a MAC of all the handshake messages
6. server sends a MAC of all the handshake messages
Real SSL: handshaking (3)

last 2 steps protect handshake from tampering

- client typically offers range of algorithms, some strong, some weak
- man-in-the-middle could delete stronger algorithms from list
- last 2 steps prevent this
  - last two messages are encrypted
Real SSL: handshaking (4)

- why two random nonces?
- suppose Trudy sniffs all messages between Alice & Bob
- next day, Trudy sets up TCP connection with Bob, sends exact same sequence of records
  - Bob (Amazon) thinks Alice made two separate orders for the same thing
  - solution: Bob sends different random nonce for each connection. This causes encryption keys to be different on the two days
  - Trudy’ s messages will fail Bob’ s integrity check
SSL record protocol

record header: content type; version; length

MAC: includes sequence number, MAC key $M_x$

fragment: each SSL fragment $2^{14}$ bytes (~16 Kbytes)
SSL record format

<table>
<thead>
<tr>
<th>1 byte</th>
<th>2 bytes</th>
<th>3 bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>content type</td>
<td>SSL version</td>
<td>length</td>
</tr>
</tbody>
</table>

data

MAC

data and MAC encrypted (symmetric algorithm)
Real SSL connection

- Handshake: ClientHello
- Handshake: ServerHello
- Handshake: Certificate
- Handshake: ServerHelloDone
- Handshake: ClientKeyExchange
- ChangeCipherSpec
- Handshake: Finished
- ChangeCipherSpec
- Handshake: Finished
- Application data
- Application data
- Alert: warning, close_notify

Everything henceforth is encrypted

TCP FIN follows
Key derivation

- client nonce, server nonce, and pre-master secret input into pseudo random-number generator.
  - produces master secret
- master secret and new nonces input into another random-number generator: “key block”
  - because of resumption: TBD
- key block sliced and diced:
  - client MAC key
  - server MAC key
  - client encryption key
  - server encryption key
  - client initialization vector (IV)
  - server initialization vector (IV)
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8.1 What is network security?
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What is network-layer confidentiality?

between two network entities:

- sending entity encrypts datagram payload, payload could be:
  - TCP or UDP segment, ICMP message, OSPF message ...
- all data sent from one entity to other would be hidden:
  - web pages, e-mail, P2P file transfers, TCP SYN packets ...
- “blanket coverage”
Virtual Private Networks (VPNs)

*motivation:*

- institutions often want private networks for security.
  - costly: separate routers, links, DNS infrastructure.
- **VPN:** institution’s inter-office traffic is sent over public Internet instead
  - encrypted before entering public Internet
  - logically separate from other traffic
Virtual Private Networks (VPNs)
IPsec services

- data integrity
- origin authentication
- replay attack prevention
- confidentiality

- two protocols providing different service models:
  - AH
  - ESP
IPsec transport mode

- IPsec datagram emitted and received by end-system
- protects upper level protocols
IPsec – tunneling mode

- edge routers IPsec-aware
- hosts IPsec-aware
Two IPsec protocols

- Authentication Header (AH) protocol
  - provides source authentication & data integrity but *not* confidentiality

- Encapsulation Security Protocol (ESP)
  - provides source authentication, data integrity, *and* confidentiality
  - more widely used than AH
Four combinations are possible!

<table>
<thead>
<tr>
<th>Host mode with AH</th>
<th>Host mode with ESP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel mode with AH</td>
<td>Tunnel mode with ESP</td>
</tr>
</tbody>
</table>

Most common and most important.
Security associations (SAs)

- before sending data, “security association (SA)” established from sending to receiving entity
  - SAs are simplex: for only one direction
- ending, receiving entitles maintain state information about SA
  - recall: TCP endpoints also maintain state info
  - IP is connectionless; IPsec is connection-oriented!
- how many SAs in VPN w/ headquarters, branch office, and n traveling salespeople?
Example SA from R1 to R2

R1 stores for SA:

- 32-bit SA identifier: Security Parameter Index (SPI)
- origin SA interface (200.168.1.100)
- destination SA interface (193.68.2.23)
- type of encryption used (e.g., 3DES with CBC)
- encryption key
- type of integrity check used (e.g., HMAC with MD5)
- authentication key
Security Association Database (SAD)

- endpoint holds SA state in *security association database (SAD)*, where it can locate them during processing.
- with n salespersons, $2 + 2n$ SAs in R1’s SAD
- when sending IPsec datagram, R1 accesses SAD to determine how to process datagram.
- when IPsec datagram arrives to R2, R2 examines SPI in IPsec datagram, indexes SAD with SPI, and processes datagram accordingly.
focus for now on tunnel mode with ESP

new IP header  ESP hdr  original IP hdr  Original IP datagram payload  ESP trl  ESP auth

SPI  Seq #  padding  pad length  next header

“enchilada” authenticated  encrypted
What happens?

encrypted

“enchilada” authenticated

network security

new IP header
ESP hdr
original IP hdr
Original IP datagram payload
ESP trl
ESP auth

SPI
Seq #

padding
pad length
next header

headquarters
Internet
branch office

172.16.1/24
200.168.1.100
193.68.2.23
172.16.2/24

R1
security association
R2
R1: convert original datagram to IPsec datagram

- appends to back of original datagram (which includes original header fields!) an “ESP trailer” field.
- encrypts result using algorithm & key specified by SA.
- appends to front of this encrypted quantity the “ESP header, creating “enchilada”.
- creates authentication MAC over the whole enchilada, using algorithm and key specified in SA;
- appends MAC to back of enchilada, forming payload;
- creates brand new IP header, with all the classic IPv4 header fields, which it appends before payload.
Inside the enchilada:

- ESP trailer: Padding for block ciphers
- ESP header:
  - SPI, so receiving entity knows what to do
  - Sequence number, to thwart replay attacks
- MAC in ESP auth field is created with shared secret key
IPsec sequence numbers

- For new SA, sender initializes seq. # to 0
- Each time datagram is sent on SA:
  - Sender increments seq # counter
  - Places value in seq # field
- Goal:
  - Prevent attacker from sniffing and replaying a packet
  - Receipt of duplicate, authenticated IP packets may disrupt service
- Method:
  - Destination checks for duplicates
  - Doesn’t keep track of all received packets; instead uses a window
Security Policy Database (SPD)

- policy: For a given datagram, sending entity needs to know if it should use IPsec.
- needs also to know which SA to use:
  - may use: source and destination IP address; protocol number
- info in SPD indicates “what” to do with arriving datagram.
- info in SAD indicates “how” to do it.
Summary: IPsec services

- suppose Trudy sits somewhere between R1 and R2. She doesn’t know the keys.
  - will Trudy be able to see original contents of datagram? How about source, dest IP address, transport protocol, application port?
  - flip bits without detection?
  - masquerade as R1 using R1’s IP address?
  - replay a datagram?
**IKE: Internet Key Exchange**

- *previous examples*: manual establishment of IPsec SAs in IPsec endpoints:
  
  **Example SA**
  
  - SPI: 12345
  - Source IP: 200.168.1.100
  - Dest IP: 193.68.2.23
  - Protocol: ESP
  - Encryption algorithm: 3DES-cbc
  - HMAC algorithm: MD5
  - Encryption key: 0x7aeaca…
  - HMAC key: 0xc0291f…

- manual keying is impractical for VPN with 100s of endpoints
- instead use *IPsec IKE (Internet Key Exchange)*
IKE: PSK and PKI

- authentication (prove who you are) with either
  - pre-shared secret (PSK) or
  - with PKI (public/private keys and certificates).

- PSK: both sides start with secret
  - run IKE to authenticate each other and to generate IPsec SAs (one in each direction), including encryption, authentication keys

- PKI: both sides start with public/private key pair, certificate
  - run IKE to authenticate each other, obtain IPsec SAs (one in each direction).
  - similar with handshake in SSL.
IKE phases

- IKE has two phases
  - *phase 1*: establish bi-directional IKE SA
    - note: IKE SA different from IPsec SA
    - aka ISAKMP security association
  - *phase 2*: ISAKMP is used to securely negotiate IPsec pair of SAs
- phase 1 has two modes: aggressive mode and main mode
  - aggressive mode uses fewer messages
  - main mode provides identity protection and is more flexible
IPsec summary

- IKE message exchange for algorithms, secret keys, SPI numbers
- either AH or ESP protocol (or both)
  - AH provides integrity, source authentication
  - ESP protocol (with AH) additionally provides encryption
- IPsec peers can be two end systems, two routers/firewalls, or a router/firewall and an end system
Chapter 8 roadmap

8.1 What is network security?
8.2 Principles of cryptography
8.3 Message integrity
8.4 Securing e-mail
8.5 Securing TCP connections: SSL
8.6 Network layer security: IPsec
8.7 Securing wireless LANs
8.8 Operational security: firewalls and IDS
IEEE 802.11 Wireless LAN

- **802.11b**
  - 2.4-2.485 GHz unlicensed radio spectrum
  - up to 11 Mbps
  - direct sequence spread spectrum (DSSS) in physical layer: all hosts use same chipping code

- **802.11a**
  - 5-6 GHz range
  - up to 54 Mbps
  - Physical layer: orthogonal frequency division multiplexing (OFDM)

- **802.11g**
  - 2.4-2.485 GHz range
  - up to 54 Mbps
  - OFDM

- All use CSMA/CA for multiple access
- All have base-station and ad-hoc versions
- All allow for reducing bit rate for longer range
802.11 LAN architecture

- Wireless host communicates with base station
  - Base station = access point (AP)

- Basic Service Set (BSS) (aka "cell") in infrastructure mode contains:
  - Wireless hosts
  - Access point (AP): base station
  - Ad hoc mode: hosts only
Channels, beacon frames & association

- 802.11b: 2.4GHz-2.485GHz spectrum divided into 11 channels at different frequencies; 3 non-overlapping
  - AP admin chooses frequency for AP
  - interference possible: channel can be same as that chosen by neighboring AP!
- AP regularly sends beacon frame
  - Includes SSID, beacon interval (often 0.1 sec)
- host: must associate with an AP
  - scans channels, listening for beacon frames
  - selects AP to associate with; initiates association protocol
  - may perform authentication
  - After association, host will typically run DHCP to get IP address in AP’s subnet
### 802.11 frame: addressing

**Address 1:** MAC address of wireless host or AP to receive this frame

**Address 2:** MAC address of wireless host or AP transmitting this frame

**Address 3:** MAC address of router interface to which AP is attached

**Address 4:** used only in ad hoc mode

<table>
<thead>
<tr>
<th>Field</th>
<th>Size</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame Control</td>
<td>2</td>
<td>Contains frame control information</td>
</tr>
<tr>
<td>Duration</td>
<td>2</td>
<td>Specifies the duration of the frame in microseconds</td>
</tr>
<tr>
<td>Address 1</td>
<td>6</td>
<td>MAC address of wireless host or AP to receive this frame</td>
</tr>
<tr>
<td>Address 2</td>
<td>6</td>
<td>MAC address of wireless host or AP transmitting this frame</td>
</tr>
<tr>
<td>Address 3</td>
<td>6</td>
<td>MAC address of router interface to which AP is attached</td>
</tr>
<tr>
<td>Address 4</td>
<td>2</td>
<td>Used only in ad hoc mode</td>
</tr>
<tr>
<td>Sequence Control</td>
<td>6</td>
<td>Contains sequence control information</td>
</tr>
<tr>
<td>Address 4 (cont.)</td>
<td>6</td>
<td>MAC address of router interface to which AP is attached</td>
</tr>
<tr>
<td>Payload</td>
<td>0 - 2312</td>
<td>Data payload content</td>
</tr>
<tr>
<td>CRC</td>
<td>4</td>
<td>Cyclic redundancy check</td>
</tr>
</tbody>
</table>
802.11 frame: addressing

802.3 frame

802.11 frame
802.11 frame: addressing

802.3 frame

802.11 frame
802.11 frame (more)

- **Type/subtype** distinguishes beacon, association, ACK, RTS, CTS, etc frames.
- **To/From AP** defines meaning of address fields
- **802.11** allows for fragmentation at the link layer
- **802.11** allows stations to enter sleep mode
- **Seq number** identifies retransmitted frames (eg, when ACK lost)
- **WEP = 1** if encryption is used
802.11 Sniffing

- Requires wireless card that supports raw monitoring mode (rfmon)
  - Grabs all frames including management frames
- Tools:
  - There are many. Dump packets into Wireshark; interfaces with GPS devices, storing physical location

**Access control lists based on MAC addresses**

- Do they work?
  - Attacker sniffs channel, obtains valid MAC address
  - Attacker modifies its MAC address to valid address
Firewalled Networks with Wi-Fi (1)

- Firewall blocks traceroutes,…
- Traffic sent by wireless hosts/APs not blocked by firewall
  - Leaking of internal information
- Trudy can traceroute and port scan through AP
  - Establish connections
  - Attempt to overtake
Firewalled Networks with Wi-Fi (2)

- Move AP outside of firewall?
  - Trudy can no longer tracert route internal network via AP
  - But Trudy still gets everything sent/received by wireless hosts
Firewalled Networks with Wi-Fi (3)

- Crypto at link layer between wireless hosts and AP
  - Trudy doesn’t hear anything
  - Trudy can not port scan
  - Wireless hosts can access internal services
Sniffing Encrypted 802.11 traffic

**Suppose:**
- Traffic encrypted with symmetric crypto
- Attacker can sniff but can’t break crypto

**What’s the damage?**
- SSID, Mac addresses
- Manufacturers of cards from MAC addr
- Count # of devices

**Traffic analysis:**
- Size of packets
- Timing of messages
- Determine apps being used

**But cannot see anything really useful**
**Attacker needs the keys!**
Attacks on keys

- Attacker can get keys from disgruntled employee or sloppy administration.
- Possible solution: put key in hardware or software & don’t make key visible to humans.

Problems:

- Attacker gets access to equipment with key
- With good technical skills, attacker can extract key
- Ex: large corporation puts key in flash memory of all its devices
- Someone clever extracts key, publishes it on Web, destroying corporate security solution
WEP Feature Goals:

- **Authentication**
  - AP only allows authorized stations to associate

- **Data integrity**
  - Data received is the data sent

- **Confidentiality**
  - Symmetric encryption
WEP Design Goals

- Symmetric key crypto
  - Confidentiality
  - Station authorization
  - Data integrity

- Self synchronizing: each packet separately encrypted
  - Given encrypted packet and key, can decrypt; can continue to decrypt packets when preceding packet was lost
  - Unlike Cipher Block Chaining (CBC) in block ciphers

- Efficient
  - Can be implemented in hardware or software
WEP Keys

- 104 bits
- Key distribution not covered in standard
- Configure manually:
  - At home
  - Small organization with tens of users
  - Nightmare in company >100 users

Four default keys: 0,1,2,3

- Key 0 is initially active at AP and hosts.

- Administrator tells users: “must change to key 1 before date Z”
  - During transition: old key users and new key users.
  - AP encrypts with old key but decrypts with both old and new.
  - Node advertises its key ID in keyID field

- At deadline, AP encrypts and decrypts only with new key

- Four keys allow for directional key use
  - AP can use different key than hosts
Review: symmetric stream ciphers

- combine each byte of keystream with byte of plaintext to get ciphertext:
  - \( m(i) = \text{ith unit of message} \)
  - \( ks(i) = \text{ith unit of keystream} \)
  - \( c(i) = \text{ith unit of ciphertext} \)
  - \( c(i) = ks(i) \oplus m(i) \) (\( \oplus \) = exclusive or)
  - \( m(i) = ks(i) \oplus c(i) \)
- WEP uses RC4
Stream cipher and packet independence

- recall design goal: each packet separately encrypted
- if for frame n+1, use keystream from where we left off for frame n, then each frame is not separately encrypted
  - need to know where we left off for packet n
- WEP approach: initialize keystream with key + new IV for each packet:
WEP encryption (1)

- Sender calculates Integrity Check Value (ICV) over data
  - Four-byte hash/CRC for data integrity
- Each side has 104-bit shared key
- Sender creates 24-bit initialization vector (IV), appends to key: gives 128-bit key
- Sender also appends keyID (in 8-bit field)
- 128-bit key inputted into pseudo random number generator to get keystream
- Data in frame + ICV is encrypted with RC4:
  - B\bytes of keystream are XORed with bytes of data & ICV
  - IV & keyID are appended to encrypted data to create payload
  - Payload inserted into 802.11 frame
WEP encryption (2)

- IV (per frame)
- $K_s$: 104-bit secret symmetric key sequence generator (for given $K_s$, IV)
- plaintext frame data plus CRC
- 802.11 header
- IV
- WEP-encrypted data plus ICV

new IV for each frame
WEP decryption overview

- receiver extracts IV
- inputs IV, shared secret key into pseudo random generator, gets keystream
- XORs keystream with encrypted data to decrypt data + ICV
- verifies integrity of data with ICV
  - note: message integrity approach used here is different from MAC (message authentication code) and signatures (using PKI).
End-point authentication w/ nonce

**Nonce**: number (R) used only once – *in-a-lifetime*

**How to prove Alice “live”:** Bob sends Alice nonce, R. Alice must return R, encrypted with shared secret key

Alice is live, and only Alice knows key to encrypt nonce, so it must be Alice!
WEP authentication

authentication request

nonce (128 bytes)

nonce encrypted shared key

success if decrypted value equals nonce

Notes:
- not all APs do it, even if WEP is being used
- AP indicates if authentication is necessary in beacon frame
- done before association
WEP is flawed

- Message integrity problems
- Message privacy problems
WEP Flaws

- Two basic flaws undermined its use for protection against other than the casual browser - eavesdropper
  - No defined method for encryption key refresh or distribution
    - Pre-shared keys were set once at installation and rarely if ever changed
  - Use of RC4 which was designed to be a one-time cipher not intended for multiple message use
    - But because the pre-shared key is rarely changed, same key used over and over
    - Attacker monitors traffic and finds enough examples to work out the plaintext from message context
    - With knowledge of the ciphertext and plaintext, can compute the key
Encryption

- **WEP Flaw**
  - Takes about 10,000 packets to discover the key
  - Large amounts of known data is the fastest way of determining as many keystreams as possible
  - The information may be as innocuous as the fields in the protocol header or the DNS name query
  - Monitoring is passive so undetectable
  - Simple tools and instructions freely available to spit out the key
  - Legal experts postulate this type of monitoring may not be illegal
Other Problems

- **SSID (service set identifier)**
  - Identifies the 802.11 devices that belong to a Basic Service Set (BSS).
  - A BSS is analogous to a LAN segment in wired terms.
  - SSID is meant as a method to identify what Service Set you want to communicate with; **not as a security layer authentication**
  - Even when using WEP, the SSID remains fully visible.
  - Some mgfr even allow the WLAN cards to poll for the SSID and self configure.
Other Problems

- **MAC (media access control)**
  - Possible to restrict access by MAC address on many AP (access points) by means of an ACL
  - All standards compliant NIC cards, including WLAN cards, should have unique MAC, some software allow this address to be ‘spoofed’

- **Spoofing Wireless**
  - Is easy
  - Unlike internet devices which have routing issues to overcome, IP addresses of wireless devices can be manually changed at will
  - Some networks systems serve up the IP address dynamically
WEP authentication problems

Plaintext attack

- Attacker sniffs nonce, m, sent by AP
- Attacker sniffs response sent by station:
  - IV in clear
  - Encrypted nonce, c
- Attacker calculates keystream $ks = m \oplus c$, which is the keystream for the IV.
- Attacker then requests access to channel, receives nonce $m'$
- Attacker forms response $c' = ks \oplus m'$ and IV
- Server decrypts, matches $m'$ and declares attacker authenticated!
Problems with Message Integrity

- ICV (Integrity Check Value) supposed to provide data integrity
  - ICV is a hash/CRC calculation
  - But a flawed one.

- Can predict which bits in ICV change if you change single bit in data.
  - Suppose attacker knows that flipping bit 3244 of plaintext data causes bits 2, 7, 23 of plaintext ICV to flip

- Suppose attacker intercepts a frame:
  - In intercepted encrypted frame, attacker flips bit 3244 in data payload and ICV bits 2, 7, 23

- Will ICV match after decryption at the receiver?
  - After decryption, cleartext bit 3244 is flipped (stream cipher)
  - Also after decryption, cleartext bits 2, 7, 23 also flipped.
  - So cleartext ICV will match up with data!
Problems with WEP confidentiality (1)

- IV is 24 bits; incremented by 1 for each packet
  - $2^{24}$ (approx 17 million) different IV values
- If you know keystream for every IV, can decrypt all frames
  - 1500-byte keystream for all possible IVs: 23 Gybytes of storage – feasible
- How do you get the keystream for an IV?
Problems with WEP confidentiality (2)

- IV reuse
  - With 17 million IVs and 500 full-length frames/sec, collisions start after 7 hours
  - Worse when multiple hosts start with IV=0

- IV reuse:
  - Trudy guesses some of Alice’s plaintext $d_1 \ d_2 \ d_3 \ d_4 \ ...$
  - Trudy sniffs: $c_i = d_i \oplus k_i^{IV}$
  - Trudy computes keystream $k_i^{IV} = c_i \oplus d_i$
  - Trudy knows encrypting keystream $k_1^{IV} \ k_2^{IV} \ k_3^{IV} \ ...$
  - Next time IV is used, Trudy can decrypt!

- Worse: Weak Key Attack
  - Mathematical, complicated,
  - For certain key values (weak keys), disproportionate number of bits in first few bytes of the keystream are determined by just a few key bits.
  - As the IV cycles, wait for weak keys
  - Exploit weak keys to crack the key
  - Effort is only linear in key size!
  - Cracker script tool available
Summary of WEP flaws

**One common shared key**
- If any device is stolen or compromised, must change shared key in all devices
- No key distribution mechanism
- Infeasible for large organization: approach doesn’t scale

**Crypto is flawed**
- Early 2001: Integrity and authentication attacks published
- August 2001 (weak-key attack): can deduce RC4 key after observing several million packets
- AirSnort application allows casual user to decrypt WEP traffic

**Crypto problems**
- 24 bit IV to short
- Same key for encryption and message integrity
- ICV flawed, does not prevent adversarial modification of intercepted packets
- Cryptanalytic attack allows eavesdroppers to learn key after observing several millions of packets
Breaking 802.11 WEP encryption

security hole:
- 24-bit IV, one IV per frame, -> IV’s eventually reused
- IV transmitted in plaintext -> IV reuse detected

attack:
- Trudy causes Alice to encrypt known plaintext $d_1 \ d_2 \ d_3 \ d_4 \ ...
- Trudy sees: $c_i = d_i \ XOR \ k_i^{IV}$
- Trudy knows $c_i \ d_i$, so can compute $k_i^{IV}$
- Trudy knows encrypting key sequence $k_1^{IV} \ k_2^{IV} \ k_3^{IV} \ ...$
- Next time IV is used, Trudy can decrypt!
802.11i: improved security

- numerous (stronger) forms of encryption possible
- provides key distribution
- uses authentication server separate from access point
Improved Security Standards

- 802.1x Authentication (2001)
- WPA (Wi-Fi Protected Access) (2002)
- 802.11i (2003-4)
802.1X Authentication and EAP

- **802.1X**
  - Framework to control port access between devices, AP, and servers
- **Uses Extensible Authentication Protocol (EAP)** (RFC 2284)
  - Uses dynamic keys instead of the WEP authentication static key
  - Requires mutual authentication protocol
  - User’s transmission must go thru WLAN AP to reach authentication server performing the authentication
  - Permits number of authentication methods
  - RADIUS is the market de facto standard
EAP Types

- EAP-TLS (RFC 2716)
  - EAP is extension of PPP providing for additional authentication methods
  - TLS provides for mutual authentication and session key exchange
  - Negotiated mutual key becomes Master-Key for 802.11 TKIP
  - Requires client & server certificates (PKI based)
  - Deployed by Microsoft for its corporate network
  - Shipping in Windows 2000 and XP
Other EAP Types

- **EAP-TTLS**
  - “Tunneled” TLS -- uses two TLS sessions
    - Outer--TLS session with Server certificate for server authentication
    - Inner--TLS session using certificates at both ends and password
  - Protects user’s identity from intermediary entities

- **PEAP**
  - Similar to EAP-TTLS, but only allows EAP for authentication
  - Server authentication via Server certificate
    - User’s password delivered through SSL protected channel
    - Session continues when user’s password verified
  - Client-side certificate optional
WPA Interim 802.11 Security

- Wi-Fi Protected Access (WPA)
- Interim Solution between WEP and 802.11i
  - Plugs holes in legacy 802.11 devices; typically requires firmware or driver upgrade, but not new hardware
  - Subset of the 802.11i and is forward compatible
- Sponsored by the Wi-Fi Alliance
  - Will require WPA for current certifications
- Support announced by Microsoft, Intel, others
  - Agere
  - Atheros
  - Athnel
  - Colubris
  - Funk Sftw
  - Intesil
  - Proxim
  - Resonext
  - TI
WPA

- Improves WEP encryption
- Based on TKIP protocol and algorithm
  - Changes the way keys are derived
  - Refreshes keys more often
  - Adds message integrity control to prevent packet forgeries
- Benefits
  - Encryption weakness improved but not solved
  - Some concern that TKIP may degrade WLAN performance without hardware accelerator
  - But protects current device investment
  - Will be available sooner than 802.11i
WPA

- Works similarly to 802.1X authentication
  - Both Clients and AP must be WPA enabled for encryption to and from 802.1X EAP server
  - Key in a pass phrase (master key) in both client and AP
  - If pass phrase matches, then AP allows entry to the network
  - Pass phrase remains constant, but a new encryption key is generated for each session
TKIP

- Temporal Key Integrity Protocol
  - Quick fix to overcome the reuse of encryption key problem with WEP
  - Combines the pre-shared key with the client’s MAC and larger IV to ensure each client uses different key stream
  - Still uses WEP RC4, but changes temporal key every 10K packets
  - Mandates use of MIC (Michael) to prevent packet forgery

- Benefits
  - Uses existing device calculation capabilities to perform the encryption operations
  - Improves security, but is still only a short-term fix
New 802.11i Security

- Addresses the main problems of WEP and Shared-Key Authentication
  - Temporal Key Integrity Protocol (TKIP)
  - Message Integrity Control ~ Michael
  - AES Encryption replacement for RC4
  - Robust Security Network (RSN)
- Require new wireless hardware
- Ratification ~ YE 2003
IEEE 802.11i

- Much stronger encryption
  - TKIP (temporal key integrity protocol)
  - But use RC4 for compatibility with existing WEP hardware

- Extensible set of authentication mechanisms
  - Employs 802.1X authentication

- Key distribution mechanism
  - Typically public key cryptography
  - RADIUS authentication server
    - distributes different keys to each user
    - also there’s a less secure pre-shared key mode

- WPA: Wi-Fi Protected Access
  - Pre-standard subset of 802.11i
802.11i: four phases of operation

1. Discovery of security capabilities

2. STA and AS mutually authenticate, together generate Master Key (MK). *AP serves as “pass through”*

3. STA derives Pairwise Master Key (PMK)

4. STA, AP use PMK to derive Temporal Key (TK) used for message encryption, integrity
EAP: extensible authentication protocol

- EAP: end-end client (mobile) to authentication server protocol
- EAP sent over separate “links”
  - mobile-to-AP (EAP over LAN)
  - AP to authentication server (RADIUS over UDP)

![EAP TLS diagram]

<table>
<thead>
<tr>
<th>EAP TLS</th>
<th>EAP over LAN (EAPoL)</th>
<th>RADIUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAP</td>
<td>IEEE 802.11</td>
<td>UDP/IP</td>
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8.8 Operational security: firewalls and IDS
Firewalls

isolates organization’s internal net from larger Internet, allowing some packets to pass, blocking others
Firewalls: why

prevent denial of service attacks:
  - SYN flooding: attacker establishes many bogus TCP connections, no resources left for “real” connections

prevent illegal modification/access of internal data
  - e.g., attacker replaces CIA’s homepage with something else

allow only authorized access to inside network
  - set of authenticated users/hosts

three types of firewalls:
  - stateless packet filters
  - stateful packet filters
  - application gateways
Stateless packet filtering

- internal network connected to Internet via router firewall
- router filters packet-by-packet, decision to forward/drop packet based on:
  - source IP address, destination IP address
  - TCP/UDP source and destination port numbers
  - ICMP message type
  - TCP SYN and ACK bits

Should arriving packet be allowed in? Departing packet let out?
Stateless packet filtering: example

- **example 1**: block incoming and outgoing datagrams with IP protocol field = 17 and with either source or destination port = 23
  - **result**: all incoming, outgoing UDP flows and telnet connections are blocked

- **example 2**: block inbound TCP segments with ACK=0.
  - **result**: prevents external clients from making TCP connections with internal clients, but allows internal clients to connect to outside.
### Stateless packet filtering: more examples

<table>
<thead>
<tr>
<th>Policy</th>
<th>Firewall Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>No outside Web access.</td>
<td>Drop all outgoing packets to any IP address, port 80</td>
</tr>
<tr>
<td>No incoming TCP connections, except those for institution’s public Web server only.</td>
<td>Drop all incoming TCP SYN packets to any IP except 130.207.244.203, port 80</td>
</tr>
<tr>
<td>Prevent Web-radios from eating up the available bandwidth.</td>
<td>Drop all incoming UDP packets - except DNS and router broadcasts.</td>
</tr>
<tr>
<td>Prevent your network from being used for a smurf DoS attack.</td>
<td>Drop all ICMP packets going to a “broadcast” address (e.g. 130.207.255.255).</td>
</tr>
<tr>
<td>Prevent your network from being tracerouted</td>
<td>Drop all outgoing ICMP TTL expired traffic</td>
</tr>
</tbody>
</table>
## Access Control Lists

**ACL:** table of rules, applied top to bottom to incoming packets: (action, condition) pairs

<table>
<thead>
<tr>
<th>action</th>
<th>source address</th>
<th>dest address</th>
<th>protocol</th>
<th>source port</th>
<th>dest port</th>
<th>flag bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>allow</td>
<td>222.22/16</td>
<td>outside of 222.22/16</td>
<td>TCP</td>
<td>&gt; 1023</td>
<td>80</td>
<td>any</td>
</tr>
<tr>
<td>allow</td>
<td>outside of 222.22/16</td>
<td>222.22/16</td>
<td>TCP</td>
<td>80</td>
<td>&gt; 1023</td>
<td>ACK</td>
</tr>
<tr>
<td>allow</td>
<td>222.22/16</td>
<td>outside of 222.22/16</td>
<td>UDP</td>
<td>&gt; 1023</td>
<td>53</td>
<td>---</td>
</tr>
<tr>
<td>allow</td>
<td>outside of 222.22/16</td>
<td>222.22/16</td>
<td>UDP</td>
<td>53</td>
<td>&gt; 1023</td>
<td>----</td>
</tr>
<tr>
<td>deny</td>
<td>all</td>
<td>all</td>
<td>all</td>
<td>all</td>
<td>all</td>
<td>all</td>
</tr>
</tbody>
</table>
Stateful packet filtering

- **stateless packet filter**: heavy handed tool
  - admits packets that “make no sense,” e.g., dest port = 80, ACK bit set, even though no TCP connection established:
    - | action | source address | dest address | protocol | source port | dest port | flag bit |
    - | allow | outside of 222.22/16 | 222.22/16 | TCP | 80 | > 1023 | ACK |

- **stateful packet filter**: track status of every TCP connection
  - track connection setup (SYN), teardown (FIN): determine whether incoming, outgoing packets “makes sense”
  - timeout inactive connections at firewall: no longer admit packets
## Stateful packet filtering

- ACL augmented to indicate need to check connection state table before admitting packet

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<th>dest address</th>
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<th>source port</th>
<th>dest port</th>
<th>flag bit</th>
<th>check conxion</th>
</tr>
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<td>&gt; 1023</td>
<td>ACK</td>
<td>X</td>
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Application gateways

- filters packets on application data as well as on IP/TCP/UDP fields.
- **example:** allow select internal users to telnet outside.

1. require all telnet users to telnet through gateway.
2. for authorized users, gateway sets up telnet connection to dest host. Gateway relays data between 2 connections
3. router filter blocks all telnet connections not originating from gateway.
Application gateways

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Limitations of firewalls, gateways

- **IP spoofing**: router can’t know if data “really” comes from claimed source
- if multiple app’s. need special treatment, each has own app. gateway
- client software must know how to contact gateway.
  - e.g., must set IP address of proxy in Web browser
- filters often use all or nothing policy for UDP
- tradeoff: degree of communication with outside world, level of security
- many highly protected sites still suffer from attacks
Intrusion detection systems

- packet filtering:
  - operates on TCP/IP headers only
  - no correlation check among sessions

- **IDS: intrusion detection system**
  - *deep packet inspection*: look at packet contents (e.g., check character strings in packet against database of known virus, attack strings)
  - examine correlation among multiple packets
    - port scanning
    - network mapping
    - DoS attack
Intrusion detection systems

- multiple IDSs: different types of checking at different locations
Network Security (summary)

basic techniques……

- cryptography (symmetric and public)
- message integrity
- end-point authentication

….. used in many different security scenarios

- secure email
- secure transport (SSL)
- IP sec
- 802.11

operational security: firewalls and IDS