Protocol Security

Protocol Design – S-38.3157

Why Protocol Security?

- Expectation on ICT systems: Dependability
  - More and more mission-critical tasks are moved to ICT
- Problem: Bugs, Crashes, Failures, Malfunctions
- Problem: Malice
  - Protection against Malice may also help against bad coincidences
How much security?

Cost

Most likely, you are here

Cost for security

Total cost

Potential Damage

System security

Some terminology

- A **system** is designed with **security objectives** in mind
- Real systems have **weaknesses**
- **Vulnerabilities** allow circumvention (or misuse!) of security mechanisms

- A **threat** is the potential for an **attack**
- Attacks may create **damage**
- **Risk** = \( p(\text{attack}) \times \text{cost(damage)} \)
Security systems

- Security systems control attacks by:
  - prevention
  - detection
  - containment
- This is based on an underlying security policy
  - Rules and regulations, training of employees
  - Emergency planning, training
  - Management support (including protection of security personnel)

Who are the attackers?

- Insiders (lazy, frustrated, criminal)
  - Possibly implicated in Social Engineering
- „Hackers“ (Crackers), „script kiddies“
  - Pure curiosity, Fun/Suspense/Addiction, Craving for recognition!
- Professional Attackers (espionage, secret services)
- Organized Crime
  - E.g., blackmail
  - E.g., damaging a competitor
Security Objectives

- Confidentiality, access control (read), Privacy
  - Special case: Anonymity
- Integrity/Authenticity, access control (write)
- Accountability/Non-repudiability
- Availability

Confidentiality, access control (read), Privacy

- **secrecy**: restricting (read) access to authorized principals
- **confidentiality**: (often used in the sense of secrecy) obligation to keep secret
- **privacy**: right to secrecy of personal information

Special case: The fact that communication occurred at all is often also a subject of confidentiality (vs. *traffic analysis*)

Special case: **Anonymity**: Principal can act without giving away identity
  - Possibly giving away a pseudonym
Integrity/Authenticity, access control (write)

- **Integrity** of data: protection against **unauthorized** and **unnoticed** modification
  
  (cf. integrity in databases)

- **Authenticity**: Information is **integrity-protected** and **fresh**;
  
  clearly associated to the **identity** of a principal

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Accountability/Non-repudiability

- **Accountability**: An action can be reliability associated with the identity of the principal responsible for the action

- **Non-repudiability**: An action cannot be denied after the fact

  Necessary for:
  
  - Digital contracts
  
  - Digital interaction with government authorities
Availability

- **Availability**: protect the system against unauthorized impairment of function
  - vs. Denial of Service (DoS) attacks

- Availability + Correctness:
  - *dependability*: soundness; *reliability* in providing the service

Where are the weaknesses?

- **Bad Design**
  - E.g., missing security mechanisms, bad security model

- **Bad Implementation**
  - E.g., buffer overflows, avenues for circumvention

- **Bad Administration**
  - E.g., leaving accounts with standard password, open ports in firewalls, using inappropriate systems and tools

- **Bad Management**
  - E.g., leaving the security policy less than well-defined, not investing in training, no funds for security audits, no management support for the organizational cost of security measures
Design principles for secure systems (1)

- **Principle of Economy of Mechanism**
  The protection mechanism should have a simple and small design.

- **Principle of Fail-safe Defaults**
  The protection mechanism should deny access by default, and grant access only when explicit permission exists.

- **Principle of Complete Mediation**
  The protection mechanism should check every access to every object.

[Saltzer/Schroeder 1975]

Design principles for secure systems (2)

- **Principle of Open Design**
  The protection mechanism should not depend on attackers being ignorant of its design to succeed (no security by obscurity).
  It may however be based on the attacker's ignorance of specific information such as passwords or cipher keys.

- **Principle of Separation of Privilege**
  The protection mechanism should grant access only based on more than one piece of information.
Design principles for secure systems (3)

- **Principle of Least Privilege**
  The protection mechanism should force every process to operate with the minimum privileges needed to perform its task.

- **Principle of Least Common Mechanism**
  The protection mechanism should be shared as little as possible among users.

- **Principle of Psychological Acceptability**
  The protection mechanism should be easy to use (at least as easy as not using it).

Design principles for secure systems (4)

- **Principle of Defense in Depth**
  There should be multiple layers of defense before a high-value target is compromised. (No Maginot lines.)

- **Principle of Securing the Weakest Link**
  The protection mechanism should not have weak spots that allow circumventing the well-secured parts. (Security often is a chain.)

- **Principle of Reluctance to Trust**
  The protection mechanism should not give unwarranted trust to any mechanism or entity. (Healthy skepticism.)

(Beyond the 8 principles listed by Saltzer/Schroeder)
Examples: Layer 1 attacks

- Ethernet Repeaters, most kinds of communication lines:
  - Eavesdropping (attacking confidentiality)
  - Data Modification, Injection
    - (usually simpler on higher layers)

- Countermeasure: Quantum cryptography
  - Observation changes phenomena
    - Eavesdropping attack can be reliably detected
  - Low bitrate: mainly useful for transferring keying material

Examples: Layer 2 attacks

- Ethernet Switches: Poisoning the Switch database
  - E.g., make the switch send traffic to all ports

- ARP Spoofing
  - Eavesdropping (attacking confidentiality), data modification/suppression
  - Tools: Dsniff, Ettercap

- Spoofing MAC Adresses
  - E.g., to circumvent WLAN acces control
  - Tools: ifconfig … ether …
Examples: Layer 3 attacks

- Router: Poisoning Routing Protocols
  - Traffic is diverted
  - Eavesdropping (attacking confidentiality)
  - Traffic suppression (creating black holes so victim cannot be heard)

- Spoofing IP addresses
  - E.g., to circumvent NFS access control
  - Injection of data (e.g., for Session Hijacking)

- Loose Source Routing
  - Packets are returned via reversed source route
  - Circumvents TCP Handshake
    - Loose Source Route is heavily filtered throughout the Internet

Finding victims: Scanning

- Reconnaissance: Finding potentially vulnerable Hosts

- IPv4 address space is densely populated
  - Of ~ 4.3E9 IPv4 addresses, ~ 3.7E9 can be used as unicast addresses; of these ~ 2.4E9 are allocated (63.7 %)
  - Of these, ~ 1.4E9 are routed globally (37.8 % of the usable, 59.4 % of the allocated address space)
  - > 0.3E9 of these have a web server (netcraft.com), which is nearly 10 %!

- IPv6 makes scanning much harder
  - 1.3E33 addresses are allocated (0.0031 % of the currently usable space)
  - Enumerating these at 1 Gbit/s takes ~ 1.3E19 years
  - However, there are other ways to collect IPv6 addresses, e.g.
    - DNS analysis
    - Snooping traffic
Internet Background Radiation

- Worms such as SQL-Slammer are always active somewhere
- There is also backscatter from random spoofed source addresses
- „Background radiation“: ~ 0.5–4 Bytes/s/IP-Address
- Connecting an unpatched Windows-System to the Internet?
  - Infections within minutes (seconds?)
  - Usually crashes completely after ~ 30 minutes
- Add the intentionally targeted attacks
- Corporate networks may not need full Internet connectivity
  - Firewalls ➔ next segment

Examples: Layer 4 attacks

- RST-Attacks
  - Aborting a TCP connection between victim hosts
  - Can seriously damage Routing System (BGP) ➔ DoS

- SYN-Flooding
  - Create state
  - Overload prevents the creation of normal connections (DoS)
Examples: Layer 7 attacks

- DNS Spoofing
  - Poison the Caches of DNS Servers
- Email Spoofing
- Web Spoofing, Phishing
- Attacking programs: Buffer Overflows etc.

Commonalities

- On-Path attackers can eavesdrop
  - Certain active attacks can divert the path to make the attacker "on-path"
  - Countermeasure: Encryption (Cryptography)
- Identity assertions (e.g., source addresses) can be faked
  - Countermeasure: Authentication
  - Must be resistant against eavesdropping and replay
    - Cryptographic authentication
The Internet threat model

- Assumption: The end-systems are not compromised
  - There are ways to minimize damage even in this case, e.g., perfect forward secrecy
- However, the communications channel is completely compromised, i.e., attacker can:
  - Read any PDU
  - Undetectably remove, modify, inject any PDU
    - Including PDUs that appear to be from a "trusted" machine

Types of attacks

- Passive attacks:
  - Attacker only reads packets ("sniffing")
  - Extremely easy on wireless
  - Relatively easy on shared media such as Ethernet
  - Can only really be excluded by quantum cryptography
- Active attacks:
  - Attacker also injects new packets into the network
  - Source address can be spoofed
    - Egress/ingress filtering can make this harder
  - Blind attacks: can only write, not read
  - Replay attacks: inject copy of previous good packet ("launch rocket now")
Combinations

- **Passive followed by active attack:**
  - Password sniffing (passive) + login using sniffed password (active)
  - Can be supported by an offline attack, e.g. dictionary attack
    - If sniffed information can be used offline to determine whether guessed password is correct

- **Active attack to facilitate passive attack:**
  - Subvert forwarding/routing system to divert traffic via attacker
  - Quite easy at layer 2 (tools: dsniff, ettercap)
  - Subverting routing at layer 3 may be harder
  - Compromised router/switch can be used as tool

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Man-in-the-middle (middleperson) attack

- **Special form of active attack:**
- Man-in-the-middle creates the illusion for each communicating partner to be the other communicating partner:
  - Messages can be copied and modified

```
Alice ▷ Charlie ▷ Bob
  "Bob"  "Alice"
```

- **Countermeasure: Cryptography (Authentication/Encryption)**
On-path vs. off-path attacks

- On-path attacker can easily eavesdrop, spoof, suppress, inject
- Off-path attacker typically is limited to blind attacks
  - Unless topology can be subverted to convert off-path into on-path situation

- Many protocols protect well against off-path attackers, not so well against on-path
  - E.g., TCP random sequence numbers are worthless if overheard by on-path attackers

- (Note that real Internet paths are often asymmetric.)

Special case: link-local attacks

- Link-local peers may enjoy special trust (e.g., home network)
- Packets with TTL 1 will only reach link-local peers
- Packets with TTL 255 can only have been originated by link-local peers
- Warning: Some tunneling systems don’t decrement TTL
Key Management

- Keys “wear off”
  - Each usage increases amount of material available for cryptanalysis
  - The longer (in time) a key is in use, the more time an attacker has for cryptanalysis
  - Some modes of operation only allow limited number of uses before IV repeats

- Rekeying
  - After some time / some amount of data exchanged, rerun key management
  - **Key derivation**: Use “master key” to derive the actual keys in use
    - Needs cryptographically secure derivation function
    - Per-application keys: compromise in one application does not affect other application

Case Study: IEEE 802.11 WEP

- “Wired Equivalent Privacy”: Encryption designed under serious fear of export control problems
- Key too short (40 bits, this one remedied in products)
- Bad crypto usage (24-bit IV, RC4 problems)
  - Product flaws often made IV reuse even more likely
- No replay protection
- RIDICULOUS integrity check (CRC32 allows bit flipping attacks)
- The really bad problem:
  - There is only one key for each WLAN
  - The long-term key is directly used as encryption key
  - Once cracked, there is no security left
Case Study: IEEE 802.11i (“WPA”)

- 802.11i: Completely redesigned security algorithms
- Pairwise master key (PMK)
  - Derived from secure authentication protocol (e.g., EAP-TLS, EAP-TTLS)
  - PMK is not used directly for encryption/authentication of data
- PMK can alternatively be per-WLAN shared secret (“Pre-shared key”, WAP-PSK)
  - Intended for SOHO use (no EAP authentication server available)
  - Well-defined Password-based Key Derivation Function (PBKDF2, RFC2898) to convert passphrase into fixed-size key (usability!)
  - Unfortunately, still vulnerable to passive offline dictionary attack
    - But passphrase can be long and hard to guess, thwarting dictionary attacks
    - I.e., need to choose passphrase wisely

WPA: 4-Way-Handshake and PTK

- Do not use PMK for actual data transfer
- Instead:
  create Pairwise Transient Key PTK (512 bits) from the PMK and two Nonces
  - ANonce (authenticator nonce) and SNonce (supplicant nonce) ensure freshness of PTK
  - Principle: Joint Key Control (both parties contribute to key)
- This is then divided up into 4 parts of 128 bit each:
  - Encryption key, Integrity protection key
  - EAPOL-Key Encryption, EAPOL-Key Integrity
  - I.e., a part of the PTK is used for protecting rekeying
- The four-way handshake also establishes that both Station and AP know PMK
  - Principle: Mutual Authentication
4 Way Handshake und PTK

**Supplicant**
- PMK
- Create SNonce
- EAPOL Key (ANonce)
- EAPOL Key (SNonce, MIC, RSN IE)
- EAPOL Key (ANonce, MIC, RSN IE)
- EAPOL Key (SNonce, MIC)
- Install keys
- Install keys
- PTK
- EAPOL Key (ANonce)
- Install keys
- PTK
- EAPOL Key (ANonce)

**Authenticator**
- PMK
- Create ANonce
- EAPOL Key (ANonce)
- EAPOL Key (ANonce, MIC, RSN IE)
- EAPOL Key (ANonce, MIC, RSN IE)
- EAPOL Key (ANonce, MIC)
- Install keys
- Install keys
- PTK
- EAPOL Key (ANonce)
- Install keys
- PTK
- EAPOL Key (ANonce)

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**4 Way Handshake und PTK**

Pairwise Master Key (PMK) 256 bits

Pairwise Transient Key (PTK) 512 bits

<table>
<thead>
<tr>
<th>EAPOL Key MIC Key</th>
<th>EAPOL Key Encryption Key</th>
<th>Data MIC Key</th>
<th>Temporal Key</th>
</tr>
</thead>
<tbody>
<tr>
<td>128 bits</td>
<td>128 bits</td>
<td>128 bits</td>
<td>128 bits</td>
</tr>
</tbody>
</table>
Group Keys

- So far, all keys are pairwise (except PSK)
- Problem: Broadcasts (AP to Station) cannot use pairwise key
  - However: Broadcast packets from the Stations are unicast to APs first
  - For unicast Station→AP, the normal PTK is used

- Separate Group Transient Key (GTK)
- Sent from AP to each Station
  - via pairwise security association, once this has been established
- Needs to be recreated after each disassociation!
  - The old WEP Key-ID field is used to indicate a key serial
  - Allows seamless transition from old to new GTK

Generalizing the Terminology:
Multicast Data Confidentiality

- GTK == use a shared session key in the group:
  Traffic Encryption Key (TEK)
- To be deployed with a symmetric encryption algorithm
- Straightforward

- In addition:
  - Initial key distribution
  - Rekeying due to membership changes

- PTK == one or more Key Encryption Keys (KEK)
Data Confidentiality and Re-Keying

A joins

Data accessible to A

Group data transmission

A leaves

Backward access control

Forward access control

Immediate: 
\[ K \]

Batching: 
\[ K \rightarrow K' \]

Periodic: 
\[ K \]

Group Authentication

- Apply shared group key also to authentication
- Calculate hashed message authentication code (HMAC)
  - Hash over the message + key + nonce (e.g. timestamp)
  - E.g. Message Digest 5 (MD5, RFC 1321)
- Allows to identify the originator of a message as one of the group
  - But: does not provide source authentication
  - And does not support integrity protection
    - Message may have been altered by another group member
- Different for point-to-point communications
  - There are only two peers sharing a secret
Source Authentication (1)

- Prove the origination of a message / packet
- Must work for multicasting

- Digital signatures?
  - Public-key cryptography too expensive
  - Would require PKI

- Possibly operate on blocks of packets
  - Hash over a group of packets, then sign
  - Application-specific authentication support
    - E.g. file transfer: Calculate signatures only once over the entire contents
    - Entire transmission is lost if only a single packet is faked
    - Delays verification of contents!

Source Authentication (2)

- Authenticating individual packets
  - Tree hashing / hash chaining
  - Hash a sequence of packets
  - E.g. Packet P1 validates the hash of P2, P2 that of P3, etc.
  - Only one packet (e.g. P1) is signed per run of packets

- Issues with packet losses: verification may get impossible
  - Multi-chaining: include a hash in several other packets
  - Still may lead to extra packet drops of unauthenticated packets

- MAC-based authentication of unreliable streams: TESLA
  Timed Efficient Stream Loss-tolerant Authentication
TESLA (1)

- Basic idea: Hash key chain
  - Select an initial key
  - Then calculate derived keys using a one-way function $f$
  - Generate keys $k_0, \ldots, k_t$ – starting with $k_t$ as initial random key $k_{t-1} = f(k_t)$
  - Use another hash function to derive $k'_j$ from $k_j$: $k'_j = g(k_j)$
  - Use keys in backwards order, starting with $k_0$

```
k'_1  k'_2  k'_{t-1}  k'_t
  \downarrow g   \downarrow g   \downarrow g   \downarrow g
k_0   k_1   k_2   \ldots   k_{t-1}   k_t
f   f   \ldots   f
```

TESLA (2)

- Requirement: rough time synchronization of senders & receivers
- Subdivide time axis into $t$ intervals
  - All data packets per interval $i = \{1, \ldots, t\}$ are authenticated with $k'_i$
  - Choose a disclosure interval $d$ (equals authentication / processing delay)
- Sender transmits a digitally signed packet to initialize
  - Include “commitment to key chain” by means of signed $k_0$
- Sender transmits data packet $P_j$ in interval $i$ containing
  - Data $D_j$, the revealed key $k_{j-d}$ of interval $j-d$, auth MAC using $k'_j$

```
\text{d=3}  \\
\text{5}   \text{6}   \text{7}   \text{8}   \text{9}
```

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Group Security Association (GSA)

Group Management

- Initial setup of a Category 1 SA to the KD
  - (Several KDs may operate in a distributed fashion)
  - Point for access control policy enforcement
    - Authenticate the new group member
    - Verify its authorization to participate in the group
  - Configure member
  - Bootstrap Category 2 SA
  - Initialize Category 3 SA(s)

- Group management involves rekeying
  - Via push mechanisms using Category 2 SA
  - Via pull mechanisms through Category 1 SA
Group Key Management

- Provide a shared group key to all members: TEK
- Update group key during the group’s lifetime
  - Periodically to “prevent” cryptoanalysis
  - For membership changes
- Group key management architectures
  - E.g. IKAM
  - Hierarchical approach to key management and distribution
- Group key distribution protocols
  - GKMP, GSAM (derived from ISAKMP), GDOI
  - MIKEY (Multimedia Internet Keying; used for RTP)

Group Key Management Algorithms

- Initialization and re-keying
- Re-keying: immediate, periodic, batching
- Simplest variant for group changes
  - Re-key each group member individually using Cat 1 SA
  - O(n) for rekeying
  - Does not really scale to large groups
- Periodic re-keying: use a different group key from Cat 2 SA
  - Helps for stable membership
- Use hierarchical schemes to achieve better scalability
Example: **Logical Key Trees (LKH)**

- Create a (balanced) binary tree
  - As many leaves as group members (each leaf represents a member)
  - Adjusted dynamically by adding nodes (possibly splitting existing ones) and removing nodes
- Each node (including leaves) represents a KEK
- KEKs are used to distribute TEKs and new KEK when membership changes
- A group member A knows all the keys (KEKs) on the path from its corresponding leaf node up to the root
- Rekeying is done by distributing new keys (TEKs, KEKs) using the KEKs that are known to as many members possible
- Complexity $O(2 \log n)$ for join and leave group operations

**LKH Example**

1. **Create a (balanced) binary tree**
   - As many leaves as group members (each leaf represents a member)
   - Adjusted dynamically by adding nodes (possibly splitting existing ones) and removing nodes

2. **Each node (including leaves) represents a KEK**

3. **KEKs are used to distribute TEKs and new KEK when membership changes**

4. **A group member A knows all the keys (KEKs) on the path from its corresponding leaf node up to the root**

5. **Rekeying is done by distributing new keys (TEKs, KEKs) using the KEKs that are known to as many members possible**

6. **Complexity** $O(2 \log n)$ for join and leave group operations
LKH Example: Periodic Re-keying

LKH Example: H joining
Multicast Security Review

- No surprise: Adding Multicast makes life harder
  - Multicast Key Management = Security + Multicast
  - In practice, needs to interact with membership management

- LKH: Adding (even artificial) structure to a group can reduce effort required for state management algorithms significantly

- Scalable, efficient source authentication is really hard
  - TESLA is a nice "out of the box" idea with a limited field of application
Security: Take-away message

- Study security best practices
  - Key management usually is the complex part
  - Most security algorithms have a **limited field of applicability**
  - Often, security mechanisms need to be combined to hold water
    - But, in combinations, one algorithm can be used to attack another in surprising ways

- Reuse existing protocols, frameworks, algorithms as much as possible
  - But make sure you are using them **within** their field of applicability!
  - Communication security vs. object security

- Most important:
  Submit security protocols to early review (open design!)