"Security, like correctness, is not an add-on feature."
-- Andrew S. Tanenbaum

SSH – Secure Shell

- SSH Transport Layer Protocol
  - Binary Packet Protocol
  - key exchange
  - server authentication
- SSH User Authentication Protocol
- SSH Connection Protocol

What is SSH?

- SSH – Secure Shell
- SSH is a protocol for secure remote login and other secure network services over an insecure network
- developed by SSH Communications Security Corp., Finland
- two distributions are available:
  - commercial version
  - freeware (www.openssh.com)
- specified in a set of Internet drafts

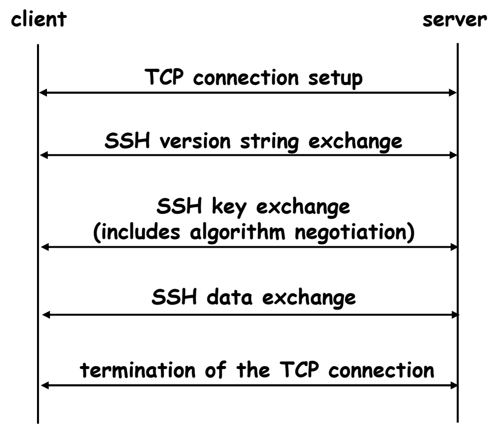
Major SSH components

- SSH Transport Layer Protocol
  - provides server authentication, confidentiality, and integrity services (may provide compression too)
  - runs on top of any reliable transport layer (e.g., TCP)
- SSH User Authentication Protocol
  - provides client-side user authentication
  - runs on top of the SSH Transport Layer Protocol
- SSH Connection Protocol
  - multiplexes the secure tunnel provided by the SSH Transport Layer and User Authentication Protocols into several logical channels
  - these logical channels can be used for a wide range of purposes
    - secure interactive shell sessions
    - TCP port forwarding
    - carrying X11 connections

SSH security features

- strong algorithms
  - uses well established strong algorithms for encryption, integrity, key exchange, and public key management
- large key size
  - requires encryption to be used with at least 128 bit keys
  - supports larger keys too
- algorithm negotiation
  - encryption, integrity, key exchange, and public key algorithms are negotiated
  - it is easy to switch to some other algorithm without modifying the base protocol

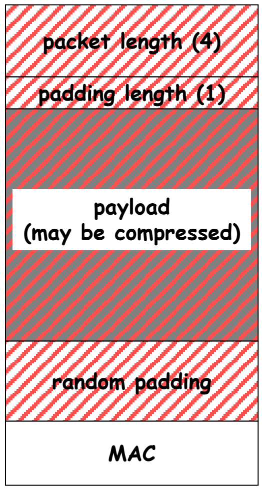
SSH TLP – Overview



Connection setup and version string exchange

- TCP connection setup
  - the server listens on port 22
  - the client initiates the connection
- SSH version string exchange
  - both side must send a version string of the following form:
    "SSH-protoversion-softwareversion comments" \CR \LF
  - used to indicate the capabilities of an implementation
  - triggers compatibility extensions
  - current protocol version is 2.0
  - all packets that follow the version string exchange is sent using the Binary Packet Protocol

Binary Packet Protocol



- packet length:
  - length of the packet not including the MAC and the packet length field
- padding length:
  - length of padding
- payload:
  - useful contents
  - might be compressed
  - max payload size is 32768
- random padding:
  - 4 – 255 bytes
  - total length of packet not including the MAC must be multiple of max(8, cipher block size)
  - even if a stream cipher is used
- MAC:
  - message authentication code
  - computed over the clear packet and an implicit sequence number

encryption

compression

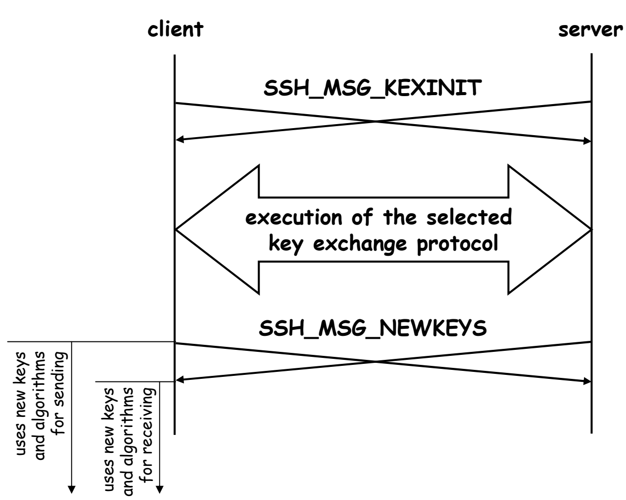
Encryption

- the encryption algorithm is negotiated during the key exchange
- supported algorithms
  - 3des-cbc (required) (168 bit key)
  - blowfish-cbc (recommended)
  - twofish256-cbc (opt) / twofish192-cbc (opt) / twofish128-cbc (recomm)
  - aes256-cbc (opt) / aes192-cbc (opt) / aes128-cbc (recomm)
  - serpent256-cbc (opt) / serpent192-cbc (opt) / serpent128-cbc (opt)
  - arcfour (opt) (RC4)
  - idea-cbc (opt) / cast128-cbc (opt)
- key and IV are also established during the key exchange
- all packets sent in one direction is considered a single data stream
  - IV is passed from the end of one packet to the beginning of the next one
- encryption algorithm can be different in each direction

MAC

- MAC algorithm and key are negotiated during the key exchange
- supported algorithms
  - hmac-sha1 (required) [MAC length = key length = 160 bits]
  - hmac-sha1-96 (recomm) [MAC length = 96, key length = 160 bits]
  - hmac-md5 (opt) [MAC length = key length = 128 bits]
  - hmac-md5-96 (opt) [MAC length = 96, key length = 128 bits]
- MAC algorithms used in each direction can be different
- MAC = mac(key, seq. number | clear packet)
  - sequence number is implicit, not sent with the packet
  - sequence number is represented on 4 bytes
  - sequence number initialized to 0 and incremented after each packet
  - it is never reset (even if keys and algs are renegotiated later)

Key exchange - Overview



Algorithm negotiation

- SSH_MSG_KEXINIT
  - kex_algorithms (comma separated list of names)
  - server_host_key_algorithms
  - encryption_algorithms_client_to_server
  - encryption_algorithms_server_to_client
  - mac_algorithms_client_to_server
  - mac_algorithms_server_to_client
  - compression_algorithms_client_to_server
  - compression_algorithms_server_to_client
  - first_kex_packet_follows (boolean)
  - random cookie (16 bytes)
- algorithm lists
  - the server lists the algorithms it supports
  - the client lists the algorithms that it is willing to accept
  - algorithms are listed in order of preference
  - selection: first algorithm on the client's list that is also on the server's list

Deriving keys and IVs

- any key exchange algorithm produces two values
  - a shared secret K
  - an exchange hash H
- H from the first key exchange is used as the session ID
- keys and IVs are derived from K and H as follows:
  - IV client to server = HASH(K | H | "A" | session ID)
  - IV server to client = HASH(K | H | "B" | session ID)
  - encryption key client to server = HASH(K | H | "C" | session ID)
  - encryption key server to client = HASH(K | H | "D" | session ID)
  - MAC key client to server = HASH(K | H | "E" | session ID)
  - MAC key server to client = HASH(K | H | "F" | session ID)

  where HASH is the hash function specified by the key exchange method (e.g., diffie-hellman-group1-sha1)
- if the key length is longer than the output of HASH…
  - K1 = HASH(K | H | X | session ID)
  - K2 = HASH(K | H | K1)
  - K3 = HASH(K | H | K1 | K2)
  - …
  - key = K1 | K2 | K3 | …

SSH Transport Layer Protocol

Diffie-Hellman key exchange

1.
   - the client generates a random number x and computes $e = g^x \bmod p$
   - the client sends e to the server
2.
   - the server generates a random number y and computes $f = g^y \bmod p$
   - the server receives e from the client
   - it computes $K = e^y \bmod p = g^{xy} \bmod p$ and H = HASH(client version string | server version string | client kex init msg | server kex init msg | server host key K_{srv} | e | f | K)
   - it generates a signature σ on H using the private part of the server host key (may involve additional hash computation on H)
   - it sends (K_{srv} | f | σ) to the client
3.
   - the client verifies that K_{srv} is really the host key of the server
   - the client computes $K = f^x \bmod p = g^{xy} \bmod p$ and the exchange hash H
   - the client verifies the signature σ on H

SSH Transport Layer Protocol

Server authentication

- based on the server's host key K_{srv}
- the client must check that K_{srv} is really the host key of the server
- models
  - the client has a local database that associates each host name with the corresponding public host key
  - the host name – to – key association is certified by a trusted CA and the server provides the necessary certificates or the client obtains them from elsewhere
  - check fingerprint of the key over an external channel (e.g., phone)
  - best effort:
    - accept host key without check when connecting the first time to the server
    - save the host key in a local database, and
    - check against the saved key on all future connections to the same server

Key re-exchange

- either party may initiate a key re-exchange
  - sending an SSH_MSG_KEXINIT packet when not already doing a key exchange
- key re-exchange is processed identically to the initial key exchange
  - except for the session ID, which will remain unchanged
- algorithms may be changed
- keys and IVs are recomputed
- encryption contexts are reset
- it is recommended to change keys after each gigabyte of transmitted data or after each hour of connection time

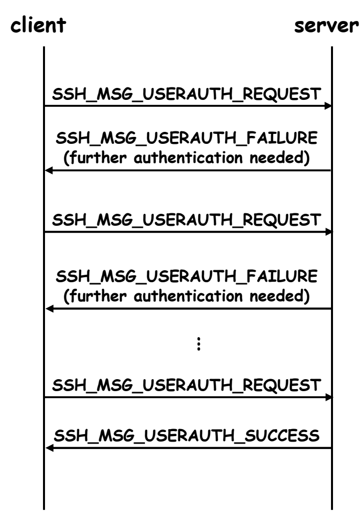
Service request

- after key exchange the client requests a service
- services
  - ssh-userauth
  - ssh-connection
- when the service starts, it has access to the session ID established during the first key exchange

SSH – User Authentication Protocol

- the protocol assumes that the underlying transport protocol provides integrity and confidentiality (e.g., SSH Transport Layer Protocol)
- the protocol has access to the session ID
- the server should have a timeout for authentication and disconnect if the authentication has not been accepted within the timeout period
  - recommended value is 10 minutes
- the server should limit the number of failed authentication attempts a client may perform in a single session
  - recommended value is 20 attempts
- three authentication methods are supported
  - publickey
  - password
  - hostbased

User authentication overview



- USERAUTH_REQUEST
  - user name
  - service name
  - method name
  - … method specific fields …
- USERAUTH_FAILURE
  - list of authentication methods that can continue
  - partial success flag
    - TRUE: previous request was successful, but further authentication is needed
    - FALSE: previous request was not successful
- USERAUTH_SUCCESS
  (authentication is complete, the server starts the requested service)

The "publickey" method

- all implementations must support this method
- however, most local policies will not require authentication with this method in the near future, as users don't have public keys
- authentication is based on demonstration of the knowledge of the private key (the client signs with the private key)
- the server verifies that
  - the public key really belongs to the user specified in the authentication request
  - the signature is correct

The "publickey" method cont'd

- SSH_MSG_USERAUTH_REQUEST
  - user name
  - service name
  - "publickey"
  - TRUE (a flag set to TRUE)
  - public key algorithm name (e.g., ssh-dss)
  - public key
  - signature (computed over the session ID and the data in the request)
- the server responds with SSH_MSG_USERAUTH_FAILURE if the request failed or more authentication is needed, or SSH_MSG_USERAUTH_SUCCESS otherwise

The "publickey" method cont'd

- using the private key
  - involves expensive computations
  - may require the user to type a password if the private key is stored in encrypted form on the client machine
- in order to avoid unnecessary processing, the client may check whether authentication using the public key would be acceptable
  - SSH_MSG_USERAUTH_REQUEST
    - user name
    - service name
    - "publickey"
    - FALSE
    - public key algorithm name
    - public key
  - if OK then the server responds with SSH_MSG_USERAUTH_PK_OK

The "password" method

- all implementations should support this method
- this method is likely the most widely used
- SSH_MSG_USERAUTH_REQUEST
  - user name
  - service name
  - "password"
  - FALSE (a flag set to FALSE)
  - password (plaintext)
- the server may respond with SSH_MSG_USERAUTH_FAILURE, SSH_MSG_USERAUTH_SUCCESS, or SSH_MSG_USERAUTH_PASSWD_CHANGEREQ

The "password" method cont'd

- changing the password
  - SSH_MSG_USERAUTH_REQUEST
    - user name
    - service name
    - "password"
    - TRUE
    - old password (plaintext)
    - new password (plaintext)

The "hostbased" method

- authentication is based on the host where the user is coming from
- this method is optional
- the client sends a signature that has been generated with the private host key of the client
- the server verifies that
  - the public key really belongs to the host specified in the authentication request
  - the signature is correct

The "hostbased" method cont'd

- SSH_MSG_USERAUTH_REQUEST
  - user name
  - service name
  - "hostbased"
  - public key algorithm name
  - public key and certificates for client host
  - client host name
  - user name on client host
  - signature (computed over the session ID and the data in the request)

SSH – Connection Protocol

- provides
  - interactive login sessions
  - remote execution of commands
  - forwarded TCP/IP connections
  - forwarded X11 connections
- all these applications are implemented as "channels"
- all channels are multiplexed into the single encrypted tunnel provided by the SSH Transport Layer Protocol
- channels are identified by channel numbers at both ends of the connection
- channel numbers for the same channel at the client and server sides may differ

Channel mechanisms

- opening a channel
  - SSH_MSG_CHANNEL_OPEN
    - channel type
    - sender channel number
    - initial window size
    - maximum packet size
    - … channel type specific data …
  - SSH_MSG_CHANNEL_OPEN_CONFIRMATION
    - recipient channel number (sender channel number from the open request)
    - sender channel number
    - initial window size
    - maximum packet size
    - … channel type specific data …
  - SSH_MSG_CHANNEL_OPEN_FAILURE
    - recipient channel number (sender channel number from the open request)
    - reason code and additional textual information

Channel mechanisms cont'd

- data transfer over a channel
  - SSH_MSG_CHANNEL_DATA
    - recipient channel number
    - data
  - SSH_MSG_CHANNEL_WINDOW_ADJUST
    - recipient channel number
    - bytes to add to the window size
- closing a channel
  - SSH_MSG_CHANNEL_EOF
    - recipient channel number

    (sent if the party doesn't want to send more data)
  - SSH_MSG_CHANNEL_CLOSE
    - recipient channel

    (receiving party must respond with an SSH_MSG_CHANNEL_CLOSE, the channel is closed if the party has sent and received the closing msg)

Channel mechanisms cont'd

SSH Connection Protocol

- channel type specific requests
  - SSH_MSG_CHANNEL_REQUEST
    - recipient channel number
    - request type
    - want reply flag (TRUE if reply is needed)
    - … request type specific data …
  - SSH_MSG_CHANNEL_SUCCESS
    - recipient channel
  - SSH_MSG_CHANNEL_FAILURE
    - recipient channel

Example: Starting a remote shell

SSH Connection Protocol

C → S: SSH_MSG_CHANNEL_OPEN
- channel type = "session"
- sender channel number = 5
- initial window size
- maximum packet size

C ← S: SSH_MSG_CHANNEL_OPEN_CONFIRMATION
- recipient channel number = 5
- sender channel number = 21
- initial window size
- maximum packet size

Example: Starting a remote shell cont'd

C → S: SSH_MSG_CHANNEL_REQUEST

- recipient channel number = 21
- request type = "pty-req" (pseudo terminal request)
- want reply flag = TRUE
- TERM environment variable value (e.g., vt100)
- terminal width in characters (e.g., 80)
- terminal height in rows (e.g., 24)
- …

C ← S: SSH_MSG_CHANNEL_SUCCESS

- recipient channel number = 5

Example: Starting a remote shell cont'd

C → S: SSH_MSG_CHANNEL_REQUEST

- recipient channel number = 21
- request type = "shell"
- want reply flag = TRUE

C ← S: SSH_MSG_CHANNEL_SUCCESS

- recipient channel number = 5

C ←→ S: SSH_MSG_CHANNEL_DATA,
SSH_MSG_CHANNEL_WINDOW_ADJUST
…

SSH Connection Protocol

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Recommended readings

- Internet drafts available at http://www.ietf.org/html.charters/secsh-charter.html
  - SSH Protocol Architecture
  - SSH Transport Layer Protocol
  - SSH User Authentication Protocol
  - SSH Connection Protocol