Network Security

Chapter 8
Security Protocols of the Data Link Layer

Acknowledgments

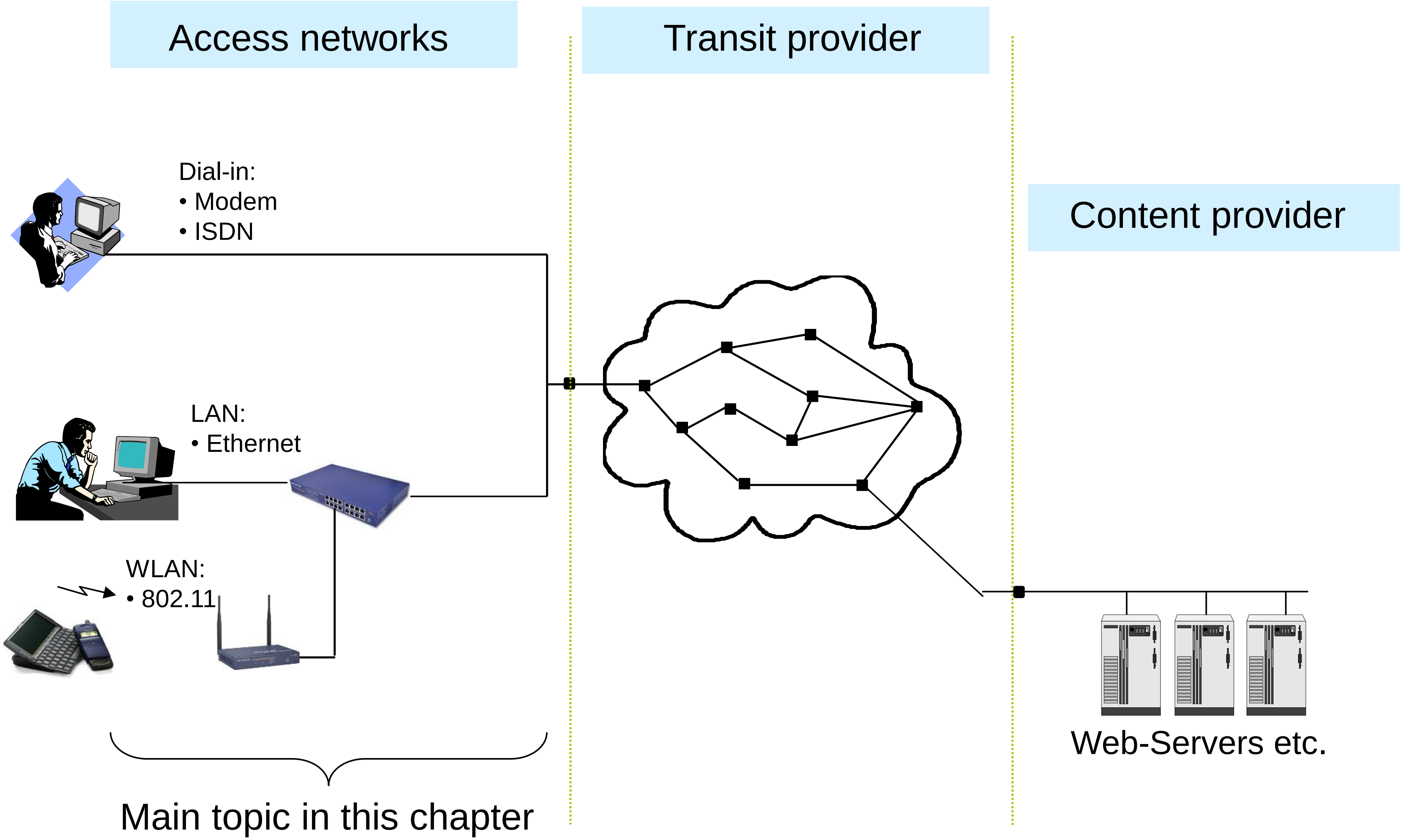
This course is based to a significant extend on slides provided by Günter Schäfer, author of the **book "Netzsicherheit - Algorithmische Grundlagen und Protokolle"**, available in German from **dpunkt Verlag**. The English version of the book is entitled “Security in Fixed and Wireless Networks: An Introduction to Securing Data Communications” and is published by Wiley is also available. We gratefully acknowledge his support.

The slides by Günter Schäfer have been partially reworked by Heiko Niedermayer, Ali Fessi, Ralph Holz and Georg Carle.

Overview

- Introduction
- Point-to-Point Protocol (PPP)
- Extensible Authentication Protocol (EAP)
- IEEE 802.1x
- AAA Protocols
- Wireless LAN Security
  - WEP Security Flaws, WPA, WPA2
- Conclusions

Localization of Access Networks within the Internet-Based IT-Infrastructure



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- ❑ **Point-to-Point Protocol (PPP)**
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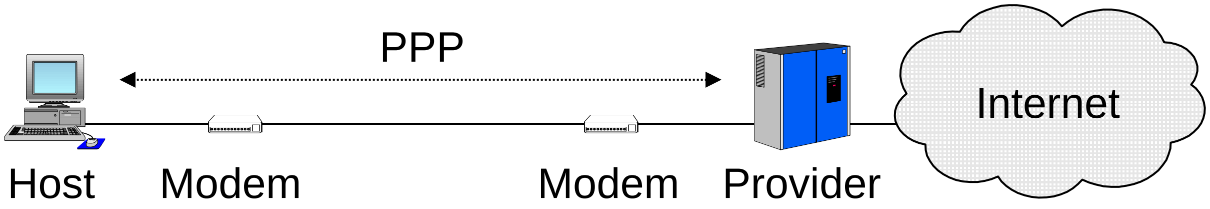
- ❑ Conclusions

Point-to-Point Protocol: Purpose and Tasks

- Large parts of the Internet rely on point-to-point connections:
  - Wide area network (WAN) connections between routers
  - Dial-up connections of hosts using (DSL) modems and telephone lines
- Protocols for this purpose:
  - Serial Line IP (SLIP): no error detection, supports only IP, no dynamic address assignment, no authentication [RFC 1055]
  - Point-to-Point Protocol (PPP): successor to SLIP, supports IP, IPX, ...



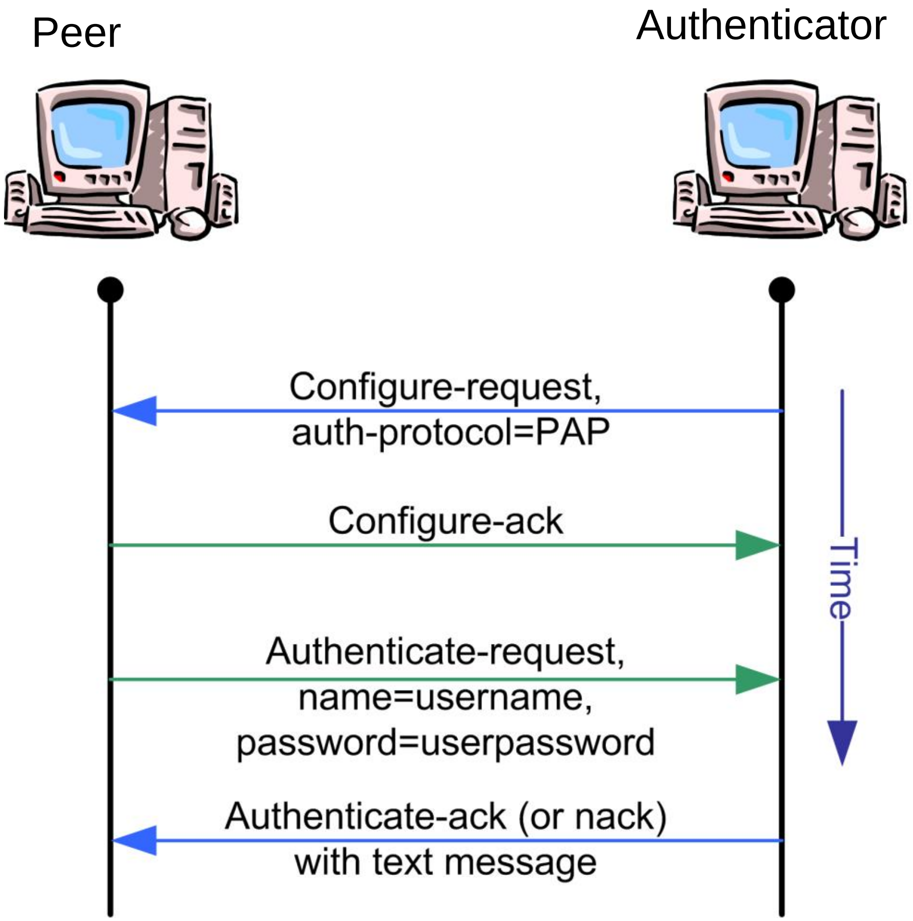
- PPP [RFC 1661/1662]:
  - Layer-2 frame format with frame delimitation and error detection
  - Control protocol *(Link Control Protocol, LCP)* for connection establishment, test, negotiation, and release

Point-to-Point Protocol: Security Services

- Entity authentication
  - The original version of PPP [RFC 1661] suggests the optional use of an authentication protocol after the link establishment phase:
    - If required, authentication is demanded by one peer entity via a LCP (Link Control Protocol) message at the end of the link establishment phase
    - Originally, two authentication protocols have been defined:
      - *Password Authentication Protocol (PAP)*
      - *Challenge Handshake Authentication Protocol (CHAP)*
    - Meanwhile, an extensible protocol has been defined:
      - *Extensible Authentication Protocol (EAP)*
- Encryption
  - PPP allows to negotiate data encryption after entity authentication with the *Encryption Control Protocol (ECP)*
  - However, ECP does not provide a mechanism for key management
  - Currently nobody uses ECP because there is no non-manual means of keying it.
- Message authentication
  - PPP does not provide message authentication

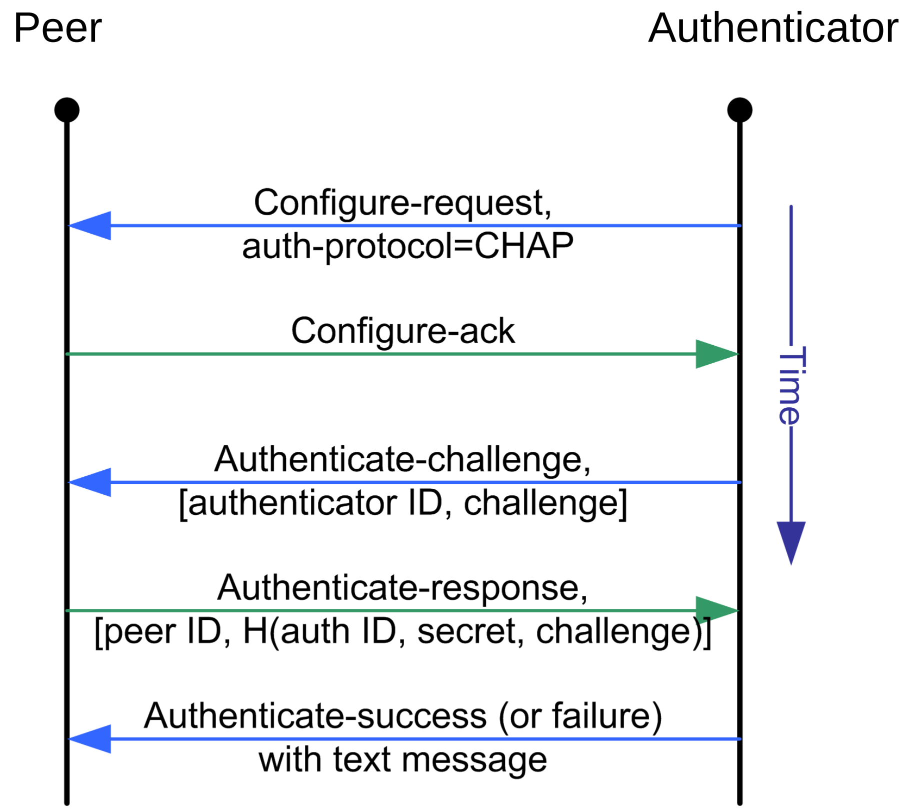
Point-to-Point Protocol: Password-based Authentication – PAP

- Password Authentication Protocol (PAP):
  - PAP was defined 1992 [RFC 1334]



Point-to-Point Protocol: Password-based Authentication (better) – CHAP

- Challenge Handshake Authentication Protocol (CHAP):



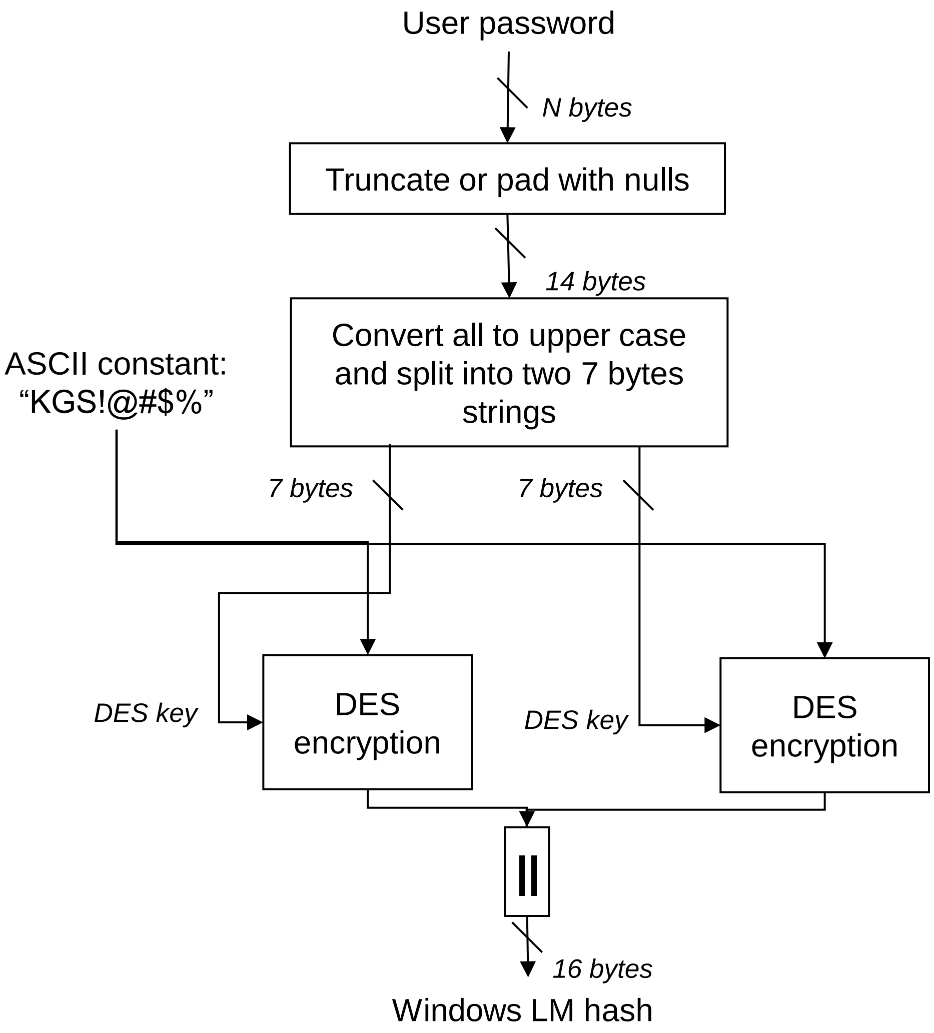
PPP Security – Reality Check (1)

- The lack of key management for PPP has lead to proprietary protocols with some security holes
  - Microsoft implemented CHAP with a home-made hash function
  - The Microsoft PPP authentication protocol was standardized as MSCHAP [RFC2433]
  - MSCHAP was accompanied with a proprietary key derivation mechanism.
    - The session key can be derived from the user's password.
    - The so-called Microsoft Point-to-Point Encryption (MPPE) was published in [RFC3078]
  - A security analysis of MSCHAP and MPPE was published by Schneier, *et al,* in 1998 [SMW99a] and show ed that MSCHAP and MPPE can be easily compromised
  - As a response to [SMW99a] Microsoft updated MSCHAP (➔ MSCHAP2) and MPPE

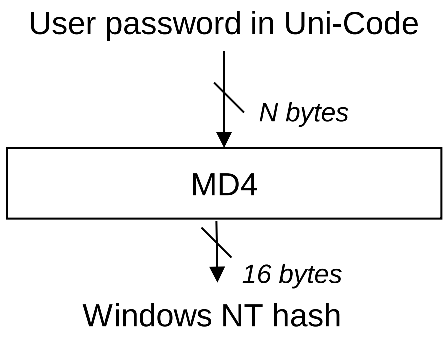
Issues with Password-based Authentication: MSCHAP (1)

- MSCHAP uses
  - the Windows LAN Manager hash function
  - and the Windows NT hash function
- Windows LAN Manager Hash function:
  1. Turn the password into a 14-character string, either by truncating longer passwords or padding shorter passwords with nulls.
  2. Convert all lowercase characters to uppercase. Numbers and non-alphanumerics remain unaffected.
  3. Split the 14-byte string into two seven-byte halves.
  4. Using each seven-byte string as a DES key, encrypt a fixed constant with each key, yielding two 8-byte encrypted strings.
  5. Concatenate the two strings together to create a single 16-byte hash value.
- Windows NT Hash function:
  1. Convert the password case sensitive up to 14 bytes into Uni-Code
  2. The password is hashed using MD4, yielding a 16 byte hash value

Issues with Password-based Authentication: MSCHAP (2)


User password
N bytes
Truncate or pad with nulls
14 bytes
Convert all to upper case and split into two 7 bytes strings
ASCII constant: “KGS!@#$%”
7 bytes
7 bytes
DES key
DES encryption
DES key
DES encryption
||
16 bytes
Windows LM hash

Windows LAN Manager Hash Function



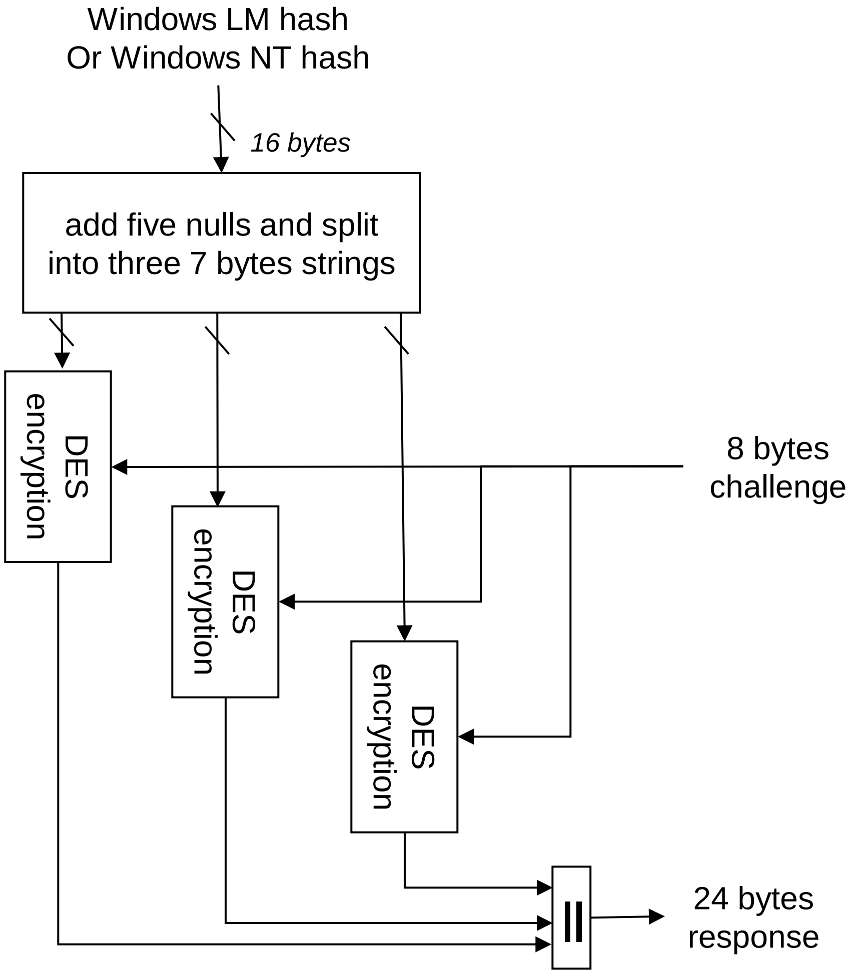
Windows NT Hash Function

Issues with Password-based Authentication: MSCHAP (3)

- Weaknesses of the Windows LAN Manager hash function
  - Users typically choose poor passwords with small entropy
  - All characters are converted to upper case, making the number of possible passwords even smaller
  - The two seven-byte “halves" of the password are hashed independently
    - Thus, the two halves can be brute-forced independently, and the complexity of the attack is at most the complexity against a seven-byte password. Passwords longer than seven characters are no stronger than seven-character passwords.
  - Passwords of seven characters or less can be immediately recognized since the second half of the hash is always the same constant

Issues with Password-based Authentication: MSCHAP (4)

- MSCHAP authentication dialogue
  1. Client requests a login challenge.
  2. Server sends back an 8-byte random challenge
  3. The client calculates the LAN Manager hash, and adds 5 nulls to create a 21-byte string, and partitions the string into three 7-byte keys. Each key is used to encrypt the challenge, resulting in a 24-byte encrypted value which is returned to the server
  - The client does the same with the Windows NT hash.
  - Given a challenge and the corresponding response that is computed with the Windows LM hash function, a dictionary attack can be performed within few minutes



MSCHAP Function Block

PPP Security – Reality Check (2)

- A security analysis of MSCHAP2 and the update of MPPE was published by Schneier in [SMW99a]
  - *„the fundamental weakness of the authentication and encryption protocol is that it is only as secure as the password chosen by the user“*
- MSCHAP2 and MPPE are still widely used [Mar12]
  - For IPSec with Pre-shared key over PPTP
  - With Radius and WPA2 (protocols mentioned later in this chapter)
- In order to cope with the security weaknesses of legacy or password-based authentication methods, it can be performed in 2 phases:
  - a TLS tunnel is established to the Authenticator first

    (Note: the client needs to verify the certificate of the Authenticator here)
  - then legacy (weak) authentication method is performed, e.g. PAP, CHAP, MSCHAP2
- Other alternative: use certificate instead of pre-shared key auth.
- A funny and interesting attack in practice can be found in [heise07]

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- ❑ IEEE 802.1x
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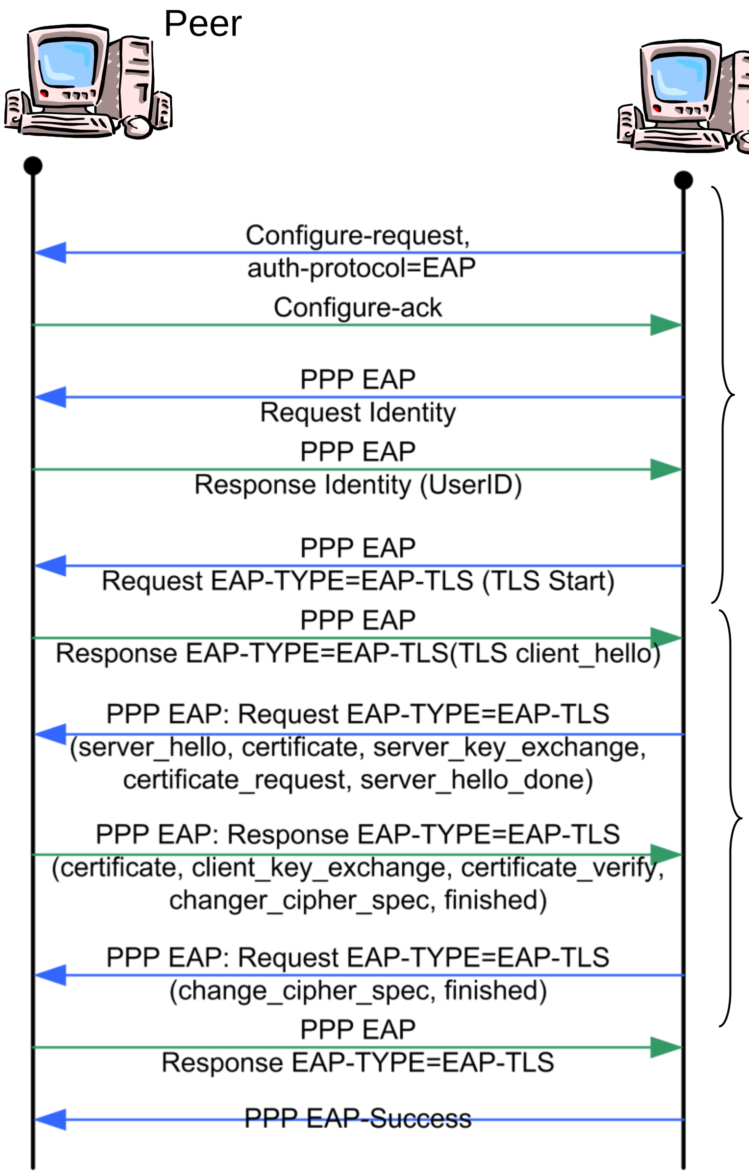
- ❑ Wireless LAN Security
- ❑ Conclusions

Extensible Authentication Protocol (1)

- EAP is a general protocol for PPP authentication which supports multiple authentication methods [RFC2284]
- The main idea behind EAP is to provide a common protocol to run more elaborated authentication methods than “1 question + 1 answer”
- The protocol provides basic primitives:
  - Request, Response: further refined by *type field* + *type specific data*
  - Success, Failure: to indicate the result of an authentication exchange
- As EAP provides a generic framework for authentication, it supports several EAP methods, e.g.
  - EAP-MD5 Challenge (this is equivalent to CHAP)
  - EAP-TLS

Extensible Authentication Protocol (2)

- e.g. EAP-TLS:



Peer

Authenticator

Configure-request,
auth-protocol=EAP

Configure-ack

PPP EAP
Request Identity

PPP EAP
Response Identity (UserID)

PPP EAP
Request EAP-TYPE=EAP-TLS (TLS Start)

PPP EAP
Response EAP-TYPE=EAP-TLS(TLS client_hello)

PPP EAP: Request EAP-TYPE=EAP-TLS
(server_hello, certificate, server_key_exchange,
certificate_request, server_hello_done)

PPP EAP: Response EAP-TYPE=EAP-TLS
(certificate, client_key_exchange, certificate_verify,
changer_cipher_spec, finished)

PPP EAP: Request EAP-TYPE=EAP-TLS
(change_cipher_spec, finished)

PPP EAP
Response EAP-TYPE=EAP-TLS

PPP EAP-Success

Negotiate EAP-TLS for authentication and exchange UserID

TLS handshake:
TLS messages are carried within an EAP message envelopes

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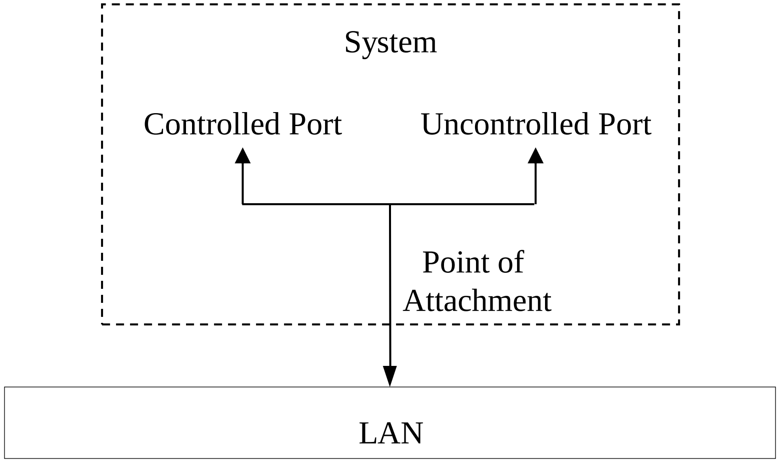
IEEE 802.1x: Controlled and Uncontrolled Ports



- IEEE 802.1x introduces the notion of two ***logical*** ports:
  - the uncontrolled port allows to authenticate a device
  - the controlled port allows an authenticated device to access LAN services
- Accessing a LAN with IEEE 802.1x security measures:
  - Prior to successful authentication the client can access the uncontrolled port:
    - The port is uncontrolled in the sense that it allows access prior to authentication
    - However, this port allows only restricted access
  - Authentication can be initiated by the client or the authenticator (e.g. LAN switch or WLAN access point)
  - After successful authentication the controlled port is opened

IEEE 802.1x: Roles

- Three principal roles are distinguished:
  - A device that wants to use the service offered by an IEEE 802.1x LAN acts as a ***supplicant*** requesting access to the controlled port
  - The point of attachment to the LAN infrastructure (e.g. a MAC bridge) acts as the ***authenticator*** demanding the supplicant to authenticate itself
  - The authenticator does not check the credentials presented by the supplicant itself, but passes them to his ***authentication server*** for verification
- *Authenticator* and *authentication server* communicate together using a so-called AAA protocol.

IEEE 802.1x Security Protocols & Message Exchange

- IEEE 802.1x does not define its own security protocols, but advocates the use of existing protocols:
  - The *Extensible Authentication Protocol (EAP)* may realize basic device authentication [RFC 2284]
  - If negotiation of a session key during authentication is required, the use of the *PPP EAP TLS Authentication Protocol* is recommended [RFC 2716]
  - Note however that newer methods might be appropriate, e.g. EAP-TTLS or PEAP
  - Furthermore, the *authentication server* is recommended to be realized with a AAA protocol such as RADIUS [RFC 2865] or DIAMETER [RFC 3588]

    (Diameter is the successor of the Radius protocol)
- Exchange of EAP messages between supplicant and authenticator is realized with the *EAP over LANs (EAPoL)* protocol:
  - EAPoL defines the encapsulation techniques that shall be used in order to carry EAP packets between the *supplicant* and the *Authenticator* in a LAN environment.

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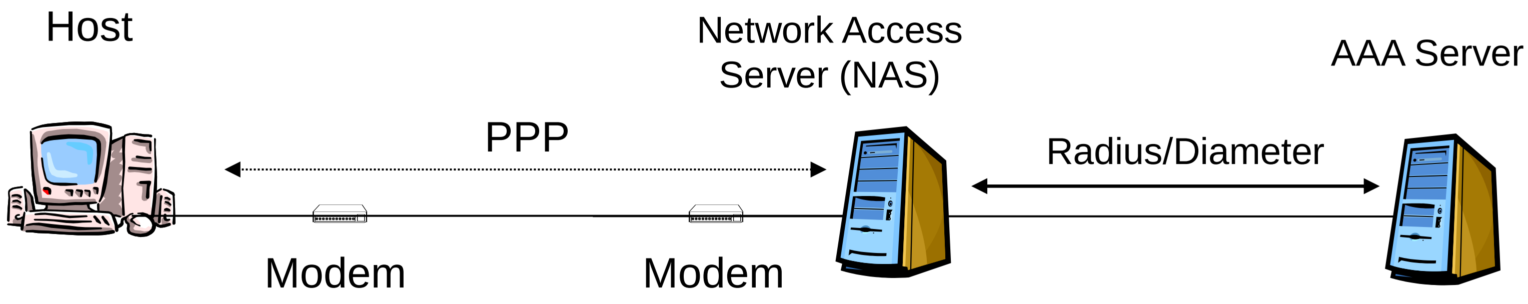
Authentication, Authorization and Accounting (AAA) Protocols

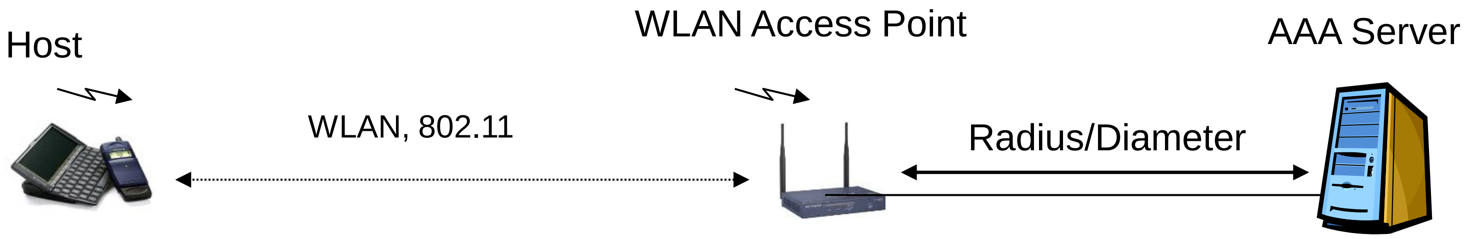
- Motivation
  - Provide a generic architecture for Authentication, Authorization and Accounting
  - Delegate AAA tasks (e.g. verification of user credentials such as passwords) to dedicated AAA servers.
  - AAA data (e.g. login/passwords) do not need to be stored at each *authenticator* device, e.g. Ethernet switch or wireless LAN access point.
  - The user database (e.g. login/passwords) can be re-used for several purposes and does not need to be duplicated (duplication can lead to inconsistency)

AAA Application Scenarios

- Authentication for dial-in services



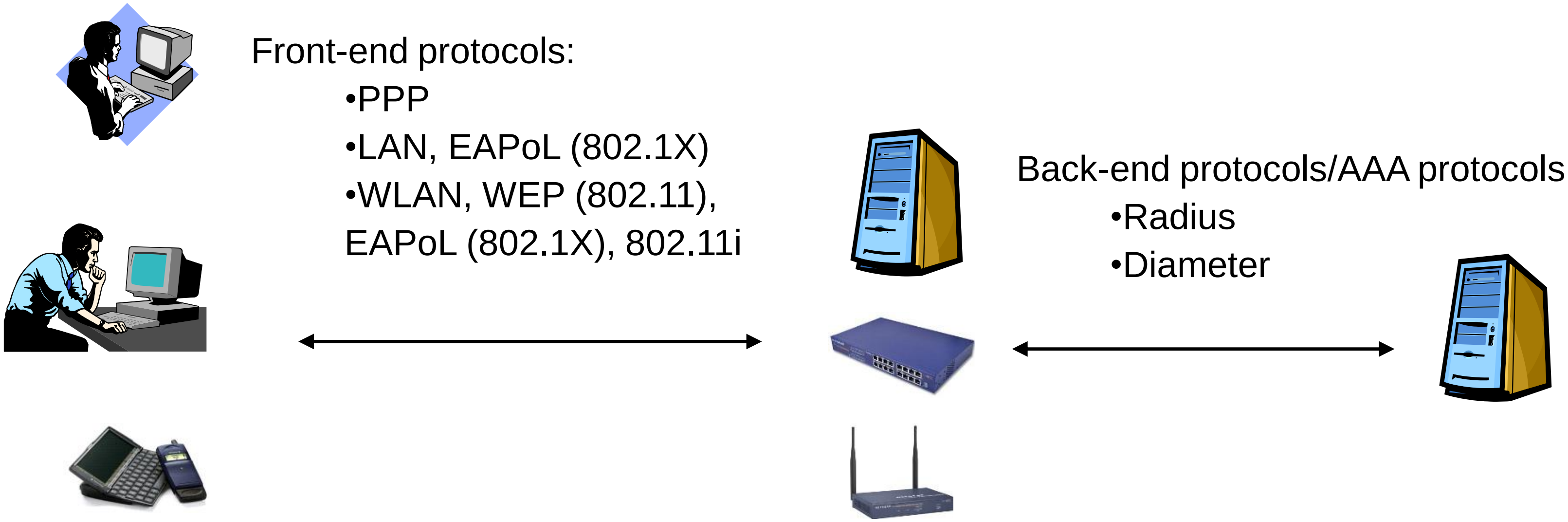
- Authentication for access to a wireless LAN network:



- AAA protocols can be also used between an Ethernet switch and a AAA server for access control with 802.1X
- Another application for AAA protocols (at the application layer) is the authenticating of users in Voice over IP (VoIP) networks

Back-End and Front-End Protocols

- ❑ Protocols between Supplicant and Authenticator are also called *Front-end protocols*
- ❑ Protocols between Authenticator and AS are also called *Back-end protocols*



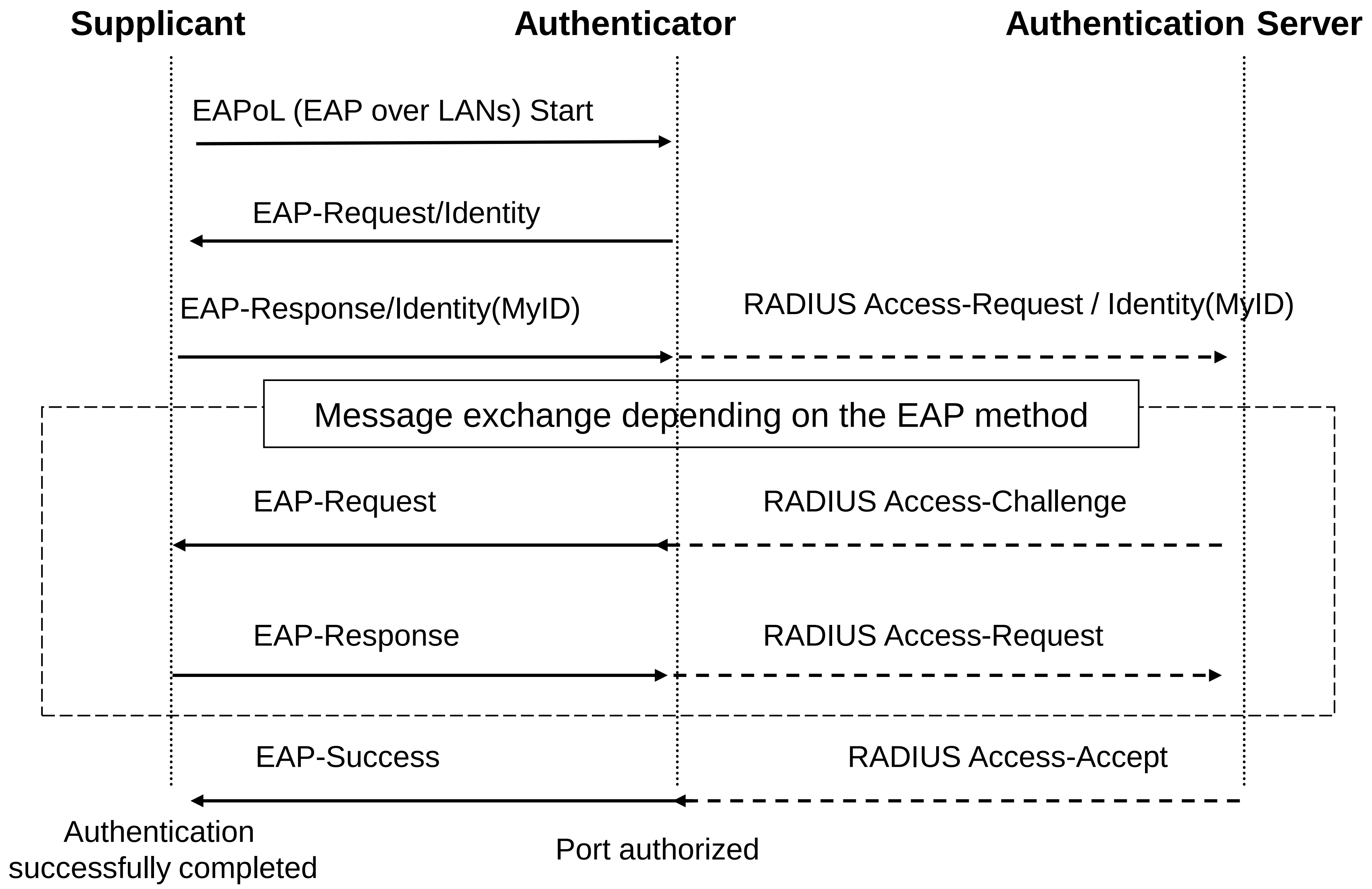
Front-end protocols:

- •PPP
- •LAN, EAPoL (802.1X)
- •WLAN, WEP (802.11), EAPoL (802.1X), 802.11i

Back-end protocols/AAA protocols

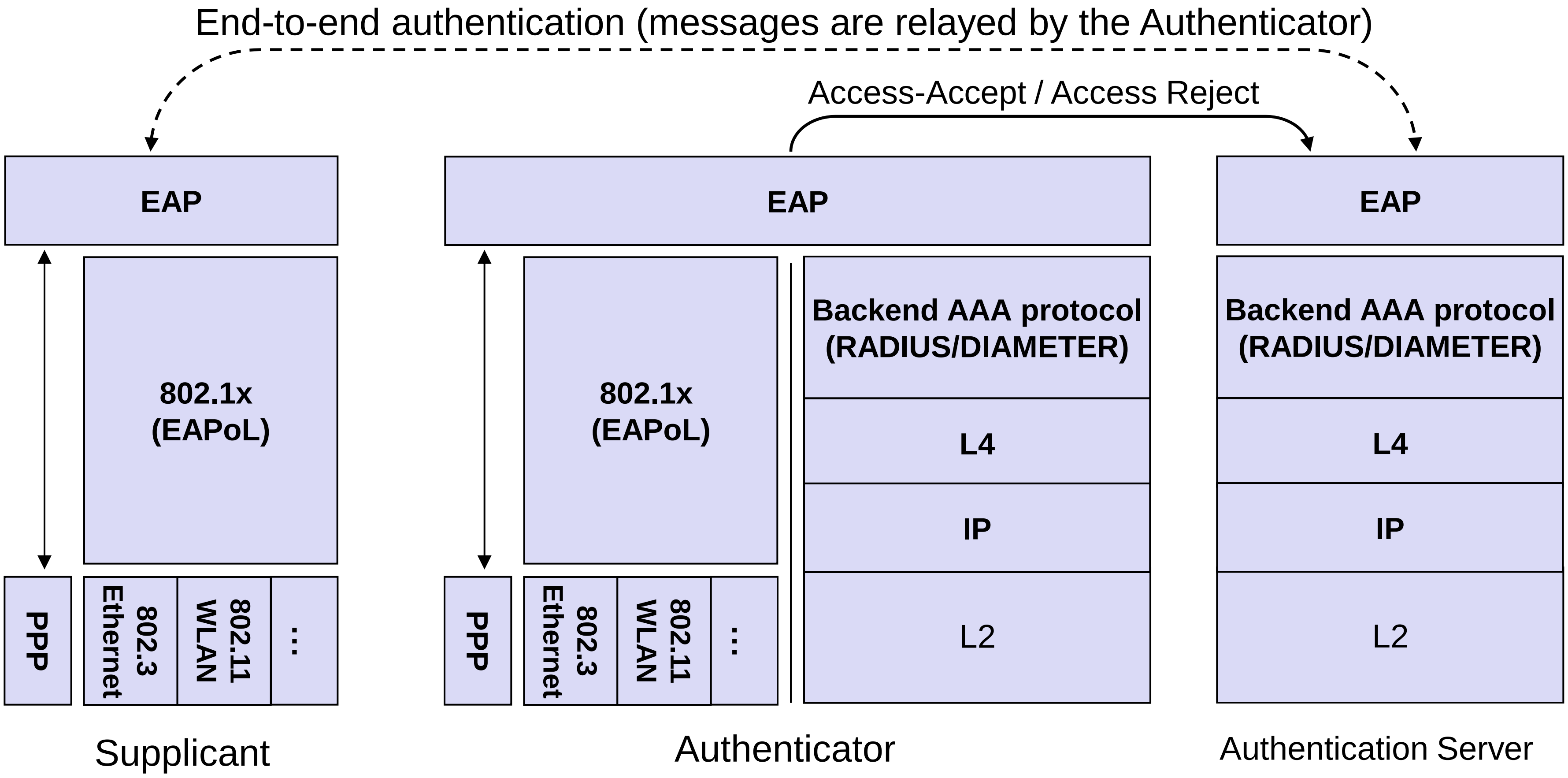
- •Radius
- •Diameter

Putting the pieces together: Network Access Control with 802.1X, EAP and a AAA backend server



Putting the pieces together: EAP, 802.1X and AAA Protocols

- EAP was originally designed for PPP
- EAPoL encapsulates EAP messages within Ethernet or WLAN frames
- Between the authenticator and the authentication server, EAP messages are encapsulated within RADIUS/DIAMETER messages


End-to-end authentication (messages are relayed by the Authenticator)
Access-Accept / Access Reject
EAP
802.1x (EAPoL)
PPP
802.3 Ethernet
802.11 WLAN
…
EAP
802.1x (EAPoL)
PPP
802.3 Ethernet
802.11 WLAN
…
Backend AAA protocol (RADIUS/DIAMETER)
L4
IP
L2
EAP
Backend AAA protocol (RADIUS/DIAMETER)
L4
IP
L2
Supplicant
Authenticator
Authentication Server

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Wireless Security - Overview

- IEEE 802.11
- Wired Equivalent Privacy (WEP)
  - Security Flaws
- Access Control with 802.1X
- Wi-Fi Protected Access (WPA)
  - Temporal Key Integrity Protocol
- WPA2

IEEE 802.11

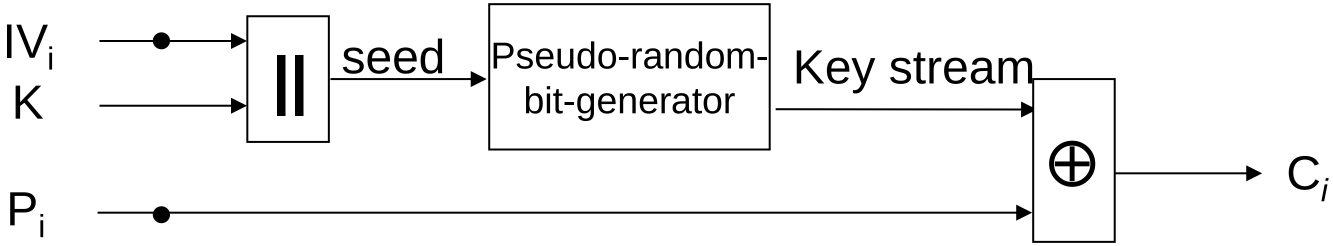
- IEEE 802.11 standardizes medium access control (MAC) and physical characteristics of a wireless *local area network (LAN)*
- Transmission occurs in the license-free 2.4 GHz band
- The medium access control (MAC) supports operation under control of an access point as well as between independent stations
- In this class we will mainly focus on the standard's security aspects:
  - Some equipment vendors claimed that IEEE 802.11 is as secure as a wired network (more on this below...)

Security Services of IEEE 802.11

- Security services of IEEE 802.11 are realized by:
  - Entity authentication service
  - *Wired Equivalent Privacy (WEP)* mechanism
- WEP is supposed to provide the following security services:
  - Confidentiality
  - Data origin authentication / data integrity
- WEP makes use of the following algorithms:
  - The RC4 stream cipher (please refer to chapter 3)
  - The Cyclic Redundancy Code (CRC) checksum for detecting errors

The Stream Cipher Algorithm RC4

- RC4 is a *stream cipher* that has been invented by Ron Rivest in 1987
- It was proprietary until 1994 when someone posted it anonymously to a mailing list
- RC4 works in Output Feedback (OFB) mode
  - The RC4 algorithm generates a pseudo-random sequence RC4(*IV*, *K*), that depends only on an initialization vector *IV* concatenated with the key *K*
  - The plaintext P_i is then XORed with the pseudo-random sequence to obtain the ciphertext and vice versa:
    - $C_i = P_i \oplus \text{RC4}(IV_i, K)$
    - $P_i = C_i \oplus \text{RC4}(IV_i, K)$



RC4 Encryption Block Diagram

Security of RC4 (1)

- RC4 uses a variable length key up to 2048 bit
  - The key serves as the seed for a pseudo-random-bit-generator
  - The variable key length of up to 2048 bit allows to make brute force attacks impractical (at least with the resources available in our universe)
  - However, by reducing the key length RC4 can also be made arbitrarily insecure!

- Known-Plain-Text Attacks on RC4:
  - It is crucial to the security of the RC4 that the initialization vector is never re-used!
    - If the plain text P_1 of a given ciphertext C_1 can be guessed and it happens that the initialization vector IV_1 is re-used later (i.e. $IV_1 = IV_2$ with the same K), then we have the same keystream RC4(IV_1, K) = RC4(IV_2, K), then C_2 can be easily decrypted :

$$P_2 = C_2 \oplus \text{RC4}(IV_2, K) = C_2 \oplus \text{RC4}(IV_1, K) = C_2 \oplus (C_1 \oplus P_1)$$

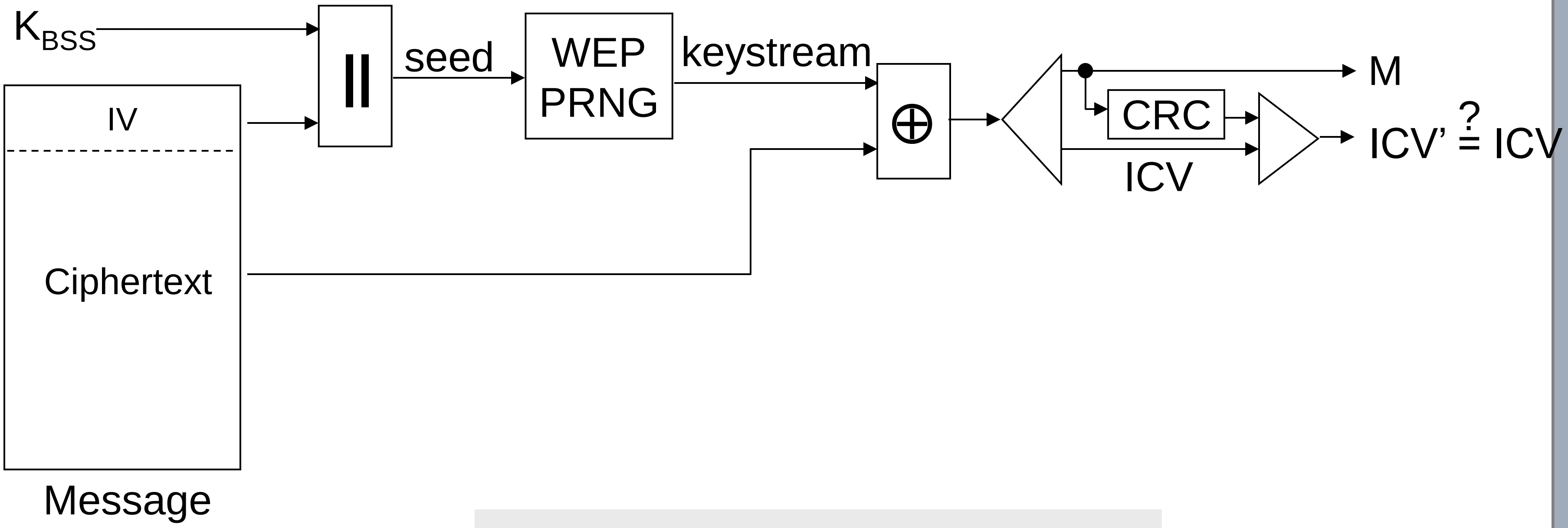
  - This means if all possible IVs has been used, key re-negotiation is necessary before proceeding.
  - However, if no key management is provided (*K* is constant) and the *IV* is short, a repetition of the same IV, and therefore a repetition of the keystream, can occur quickly.

Security of RC4 (3)

- In 2001 a new and surprising discovery was made by Fluhrer, Mantin and Shamir [FMS01a] :
  - Over all possible RC4 keys, the statistics for the first few bytes of output keystream are strongly non-random, leaking information about the key.
  - If the long-term key and nonce are simply concatenated to generate the RC4 key, this long-term key can be discovered by analyzing a large number of messages encrypted with this key.
  - This and related effects were then used to break the WEP ("wired equivalent privacy") encryption
- Applications using RC4 could defend against this attack by discarding the initial portion of the keystream (say the first 1024 bytes) before using it.

IEEE 802.11's Wired Equivalence Privacy (2)

- As *IV* is send in clear with every message, every receiver who knows K_{BSS} can produce the appropriate keystream to decrypt a message
  - This assures the important *self-synchronization property* of WEP
- The decryption process is basically the inverse of encryption:



WEP Decryption Block Diagram

Weakness #1: The Keys

- IEEE 802.11 does not specify any key management:
  - Manual management is error prone and insecure
  - Shared use of one key for all stations of a BSS introduces additional security problems
  - As a consequence of manual key management, keys are rarely changed

- Key Length:
  - The key length of 40 bit specified in the original standard provides only poor security
  - The reason for this was exportability
  - Note that
    - today’s wireless LAN cards often also allow keys of length 128 bit
    - However, WEP is still insecure even with 128 bits key length due to the reasons explained in the next slides.

Weakness #2: WEP Confidentiality is Insecure

- Even with well distributed and long keys WEP is insecure
- The reason for this is the reuse of keystream:
  - Recall that encryption is re-synchronized with every message by pre-pending an *IV* of length 24 bit to K_{BSS} and re-initializing the PRNG
  - Consider two plaintexts M_1 and M_2 encrypted using the same IV_1:
    - $C_1 = P_1 \oplus \text{RC4}(IV_1, K_{BSS})$
    - $C_2 = P_2 \oplus \text{RC4}(IV_1, K_{BSS})$
  - If an attacker knows, for example, P_1 and C_1 he can recover P_2 from C_2 without knowledge of the key K_{BSS}
    - $P_2 = C_1 \oplus C_2 \oplus P_1$
- How often does reuse of IV occur?
  - In practice quite often, as many implementations choose *IV* poorly
  - Even with optimum random choice, as IV's length is 24 bit, according the Birthday-Paradox it is expected that IV will be repeated after ~ 2^{12} WLAN frames

The Cyclic Redundancy Code (1)

- The cyclic redundancy code (CRC) is an error detection code
- Mathematical basis:
  - Treat bit strings as representations of polynomials with coefficients 0 and 1 ⇒ a bit string representing message *M* is interpreted as *M(x)*
  - Polynomial arithmetic is performed modulo 2

    ⇒ addition and subtraction are identical to XOR
- CRC computation for a message M(x):
  - A and B agree upon a polynomial *G(x);* usually *G(x)* is standardized
  - Let *n* be the degree of *G(x)*, i.e. the length of *G(x)* is *n* + 1
  - Then if $\frac{M(x)\times 2^n}{G(x)} = Q(x) + \frac{R(x)}{G(x)}$ it holds $\frac{M(x)\times 2^n + R(x)}{G(x)} = Q(x)$

    where *R(x)* is the remainder of *M(x)* divided by *G(x)*
  - Usually, R(x) is appended to M(x) before transmission and Q(x) is not of interest, as it is only checked if $\frac{M(x)\times 2^n + R(x)}{G(x)}$ divides with remainder 0

The Cyclic Redundancy Code (2)

- Consider now two Messages M_1 and M_2 with CRCs R_1 and R_2:
  - As $\frac{M_1(x) \times 2^n + R_1(x)}{G(x)}$ and $\frac{M_2(x) \times 2^n + R_2(x)}{G(x)}$ divide with remainder 0

    also $\frac{M_1(x) \times 2^n + R_1(x) + M_2(x) \times 2^n + R_2(x)}{G(x)} = \frac{\left(M_1(x) + M_2(x)\right) \times 2^n + \left(R_1(x) + R_2(x)\right)}{G(x)}$

    divides with remainder 0

  $\Rightarrow$ CRC is additive, that is CRC($M_1 \oplus M_2$) = CRC(M_1) $\oplus$ CRC(M_2)

- i.e. if a message *M* is modified to a message *M‘*

  where M‘ = (M $\oplus$ Δ)

  then CRC(M‘) = CRC(M + Δ) = CRC (M) + CRC(Δ)

- Due to this property CRC is not appropriate for cryptographic purposes! (more on this below...)

Weakness #3: WEP Data Integrity is Insecure

- Recall that CRC is an additive function and RC4 is additive as well
- Consider *A* sending an encrypted message to *B* which is intercepted by an attacker *E*:
  - A → B: (IV, C) with $C = RC4(IV, K_{BSS}) \oplus (M, CRC(M))$
- The attacker *E* can construct a new ciphertext *C'* that will decrypt to a message *M'* with a valid checksum CRC(M'):
  - *E* chooses an arbitrary message Δ of the same length as M
  - $C' = C \oplus (\Delta, CRC(\Delta)) = RC4(IV, K_{BSS}) \oplus (M, CRC(M)) \oplus (\Delta, CRC(\Delta))$

    $= RC4(IV, K_{BSS}) \oplus (M \oplus \Delta, CRC(M) \oplus CRC(\Delta))$

    $= RC4(IV, K_{BSS}) \oplus (M \oplus \Delta, CRC(M \oplus \Delta))$

    $= RC4(IV, K_{BSS}) \oplus (M', CRC(M'))$
  - Note, that *E* does not know *M'* as it does not know *M*
  - Nevertheless, a “1” at position *n* in Δ results in a flipped bit at position *n* in *M'*, so *E* can make controlled changes to *M*

    $\Rightarrow$ Data origin authentication / data integrity of WEP is insecure!
- Recall that CRC is used for WEP as integrity function and it is computed without any key!

Weakness #5: Weakness in RC4 Key Scheduling

- In early August 2001 a new attack to WEP was discovered:
  - The shared key can be retrieved in less than 15 minutes provided that about 4 to 6 million packets have been recovered
  - The attack is basically a known-plaintext attack, that makes use of the following properties of RC4 and WEP's usage of RC4:
    - RC4 is vulnerable to deducing bits of a key if:
      - many messages are encrypted with keystream generated from a variable initialization vector and a fixed key, and
      - the initialization vectors and the plaintext of the first two octets are known for the encrypted messages
    - The IV for the keystream is transmitted in clear with every packet
    - The first two octets of an encrypted data packet can be guessed
  - The attack is described in [SMF01a] and [SIR01a]
  - R. Rivest comments on this [Riv01a]:

> *"Those who are using the RC4-based WEP or WEP2 protocols to provide confidentiality of their 802.11 communications should consider these protocols to be broken [...]"*

Summary of WEP weaknesses

- Missing key management makes use of the security mechanisms tedious and leads to rarely changed keys or even security switched off
- Entity authentication as well as encryption rely on a key shared by all stations of a basic service set
- 40 bit keys are too short to provide any security
- Re-use of keystream makes known-plaintext attacks possible
- Additive integrity function allows to forge ICVs
- Unkeyed integrity function allows to circumvent access control by creating valid messages from a known plaintext-ciphertext pair
- Weakness in RC4 key scheduling allows to crypto-analyze keys
- Even with IEEE 802.1x and individual keys the protocol remains weak

Evolution of WLAN Security (1)

- 802.11, which dates from 1997, helped to kick off the present adoption of WLANs, but was primarily concerned with connectivity and not with security.
- In June 2001 802.1X was ratified.
  - 802.1X provides Access Control, recommends the use of EAP with AAA servers for authentication.
  - However, 802.1X does not solve the confidentiality and integrity problems of WEP
- An IEEE Task Group had been working on a secure standard for WLANs: 802.11i. This was published in June 2004.
- In the mean time, (in October 2002), the Wi-Fi Alliance (a consortium of about 170 WLAN vendors) announced a security solution that counters the known weaknesses of WEP, called

  Wi-Fi Protected Access (WPA).

Evolution of WLAN Security (2)

- WPA was a snapshot of 802.11i.
- It was announced earlier than 802.11i due to the urgent need for a security solution for WLANs on the market and due to the slow process of standardization.
- However, WPA was only a short-term solution to patch WEP and re-uses the same hardware
- The long-term solution, also called ***WPA2***, uses
  - AES CTR mode for encryption instead of RC4
  - AES-CBC-MAC for data integrity

Wi-Fi Protected Access (WPA)

- WPA Authentication:
  - WPA incorporates the 802.1X standard with stations (Supplicant), access points (Authenticators) and authentication servers.
- Data Privacy (Encryption)
  - The Temporal Key Integrity Protocol (TKIP) for encryption is a rapid re-keying solution to patch WEP
  - TKIP provides a key management system with a *per-packet key* for WEP encryption to fix the WEP flaws
  - TKIP is a “work-around” to use the same WEP hardware while achieving a stronger encryption
- Data integrity:
  - TKIP includes also Message Integrity Code called MIC or „Michael“ at the end of each plaintext message to ensure messages are not being spoofed or altered.
  - Note: the IEEE uses the acronym MIC instead of MAC (Message Authentication Code) for the simple reason that MAC is reserved for „Medium Access Control“.
- TKIP is a work around WEP to correct its weaknesses while still using the same hardware

The improved Wireless LAN Security Standard: 802.11i

- ***WPA2***
  - Counter-Mode/CBC-MAC Protocol (CCMP):
    - Provides confidentiality, data integrity and replay protection
    - Uses AES in CTR mode for confidentiality
    - Uses AES-CBC-MAC (with a different key!) for data integrity
- Both WPA and WPA2 utilize
  - 802.1X for access control
  - EAP for authentication
- In both WPA and WPA2 the Authenticator can operate in
  - Stand-alone mode:
    - The Authenticator plays the role of the Authentication Server
  - Pass-through mode
    - The Authenticator relays authentication messages between the Supplicant and the Authentication Server.
    - When the authentication exchange is completed, the Authentication Server informs the Authenticator whether the Authentication was successful

Wireless LAN Security - Conclusions

- IEEE 802.11 does not provide sufficient security
- WPA uses TKIP for data encryption and integrity and 801.1X for access control
- 801.1X enables the use of different authentication methods by using EAP
- WPA2 uses CCMP which uses AES in CTR mode for encryption and AES-CBC-MAC for data integrity

Overview

- ❑ Introduction
- ❑ Point-to-Point Protocol (PPP)
- ❑ Extensible Authentication Protocol (EAP)
- ❑ IEEE 802.1x
- ❑ AAA Protocols
- ❑ Wireless LAN Security

- ❑ Conclusions

Link Layer Security – Summary and Conclusions (1)

- Mechanisms and protocols for *link layer security* aim at providing
  - Authentication of end hosts
  - Access control at the link layer
  - Data origin authentication at the link layer
  - Message integrity at the link layer
  - Confidentiality at the link layer
- Bad design and abuse of cryptography showed that these goals have been missed several times, e.g. MSCHAP, MSCHAP2, WEP
- Even though the introduction of EAP provided a basis for integrating stronger methods for authentication, initial EAP methods (e.g. EAP-MD5) do not provide keying material for a secure channel between the Supplicant and the Authenticator

Link Layer Security – Summary and Conclusions (2)

- IEEE/IETF standardization committees have learned lessons from other security protocols, e.g. IPSec and TLS
- However, requirements for link layer security are different
  - e.g. security have often to be implemented at the hardware interface with limited resources
  - Layer 2 frame properties and message overhead have to be considered
- Link layer security is still work-in-progress and it is expected to have many advancements and updates in the near future, e.g.
  - IEEE 802.1AE which is a standard for integrating security services, such as data integrity and confidentiality in Ethernet switches
  - Improvement of EAP methods, also with respect to latency in handover scenarios

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