



Network Security

Chapter 6 Security Protocols of the Data Link Layer

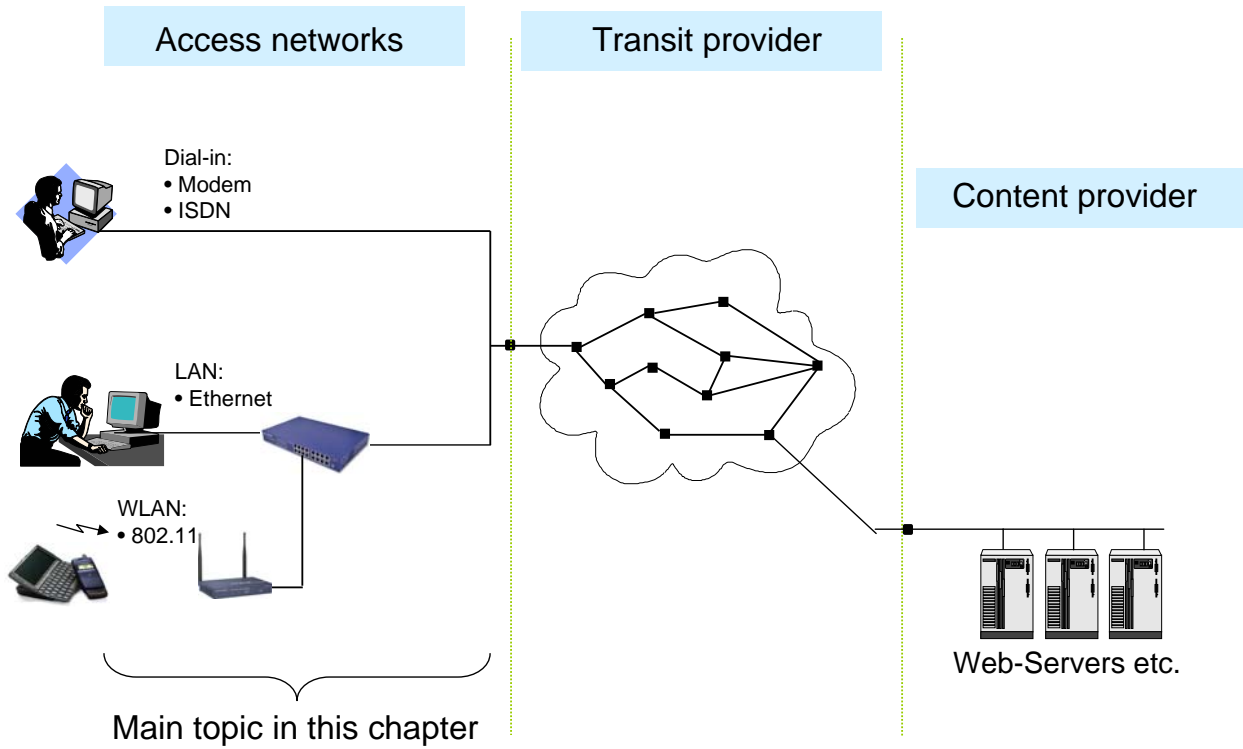


Overview

- ❑ 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



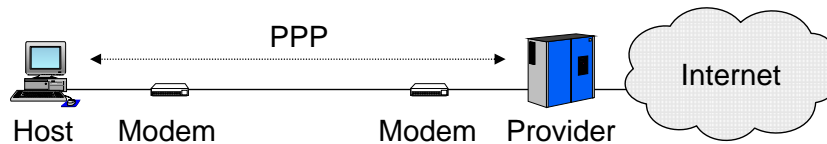
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Point-to-Point Protocol: Purpose and Tasks

- ❑ 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



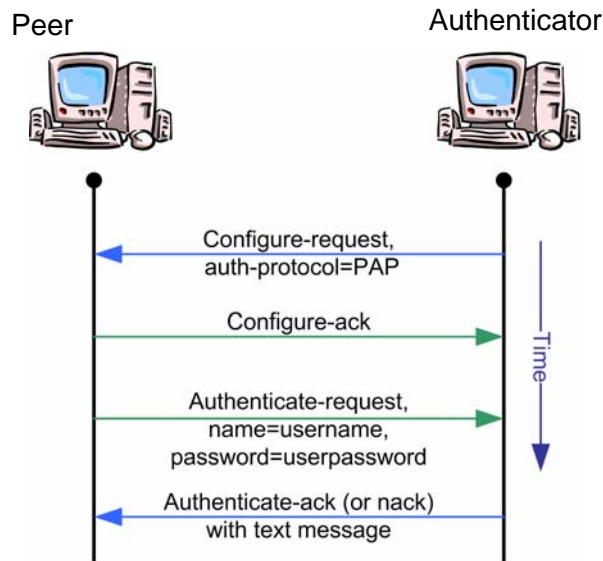
Point-to-Point Protocol: Security Services

- ❑ 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



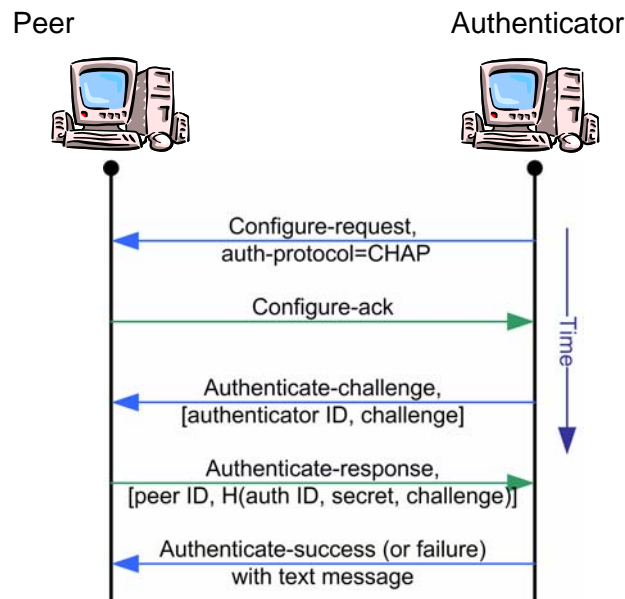
Point-to-Point Protocol: Authentication Protocols (1)

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



Point-to-Point Protocol: Authentication Protocols (2)

- Challenge Handshake Authentication Protocol (CHAP):





PPP Security – Reality Check (1)

- ❑ The lack of key management for PPP has led 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 showed that MSCHAP and MPPE can be easily compromised
 - As a response to [SMW99a] Microsoft updated MSCHAP (→ MSCHAP2) and MPPE

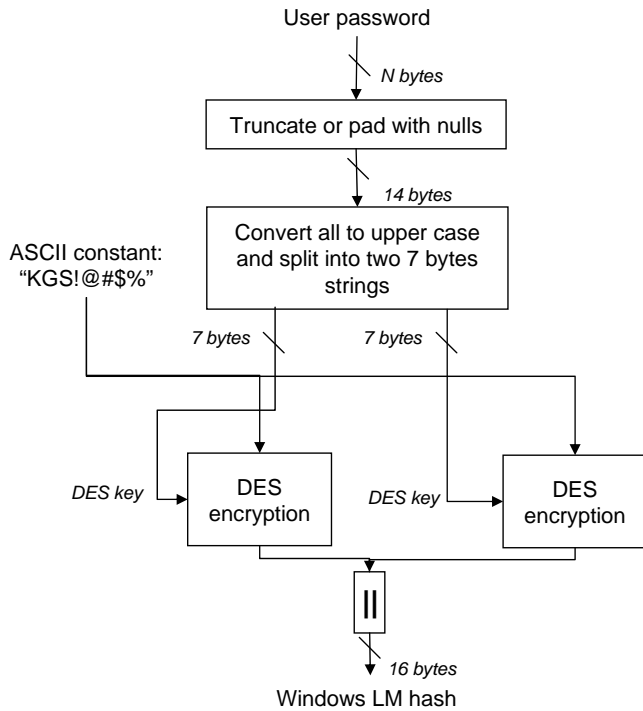


MSCHAP (1)

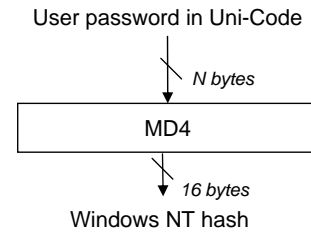
- ❑ MSCHAP uses
 - the Windows LAN Manager hash function
 - and the Windows NT hash function
- ❑ Windows LAN Manager Hash function:
 1. Turn the password into a 14-character string, either by truncating longer passwords or padding shorter passwords with nulls.
 2. Convert all lowercase characters to 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



MSCHAP (2)



Windows LAN Manager Hash Function



Windows NT Hash Function



MSCHAP (3)

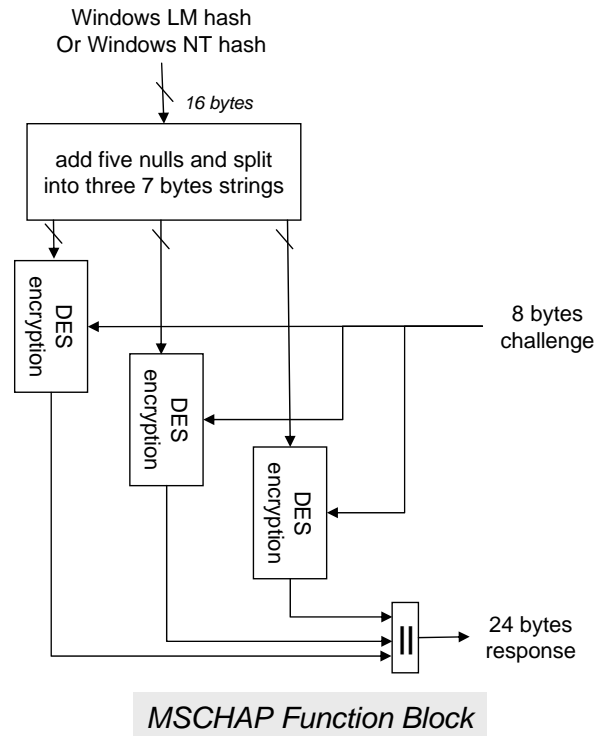
- Weaknesses of the Windows LAN Manager hash function
 - Users typically choose poor passwords with small entropy
 - All characters are converted to upper case, making the number of possible passwords even smaller
 - The two seven-byte “halves” of the password are hashed independently
 - Thus, the two 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



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



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
- ❑ However, in order to cope with the security weaknesses of legacy authentication methods, such as MSCHAP2, the authentication 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
- ❑ Nevertheless, misconfigured Internet provider networks can lead to the hijacking of DSL connections
- ❑ A funny and interesting attack in practice can be found in [heise07]



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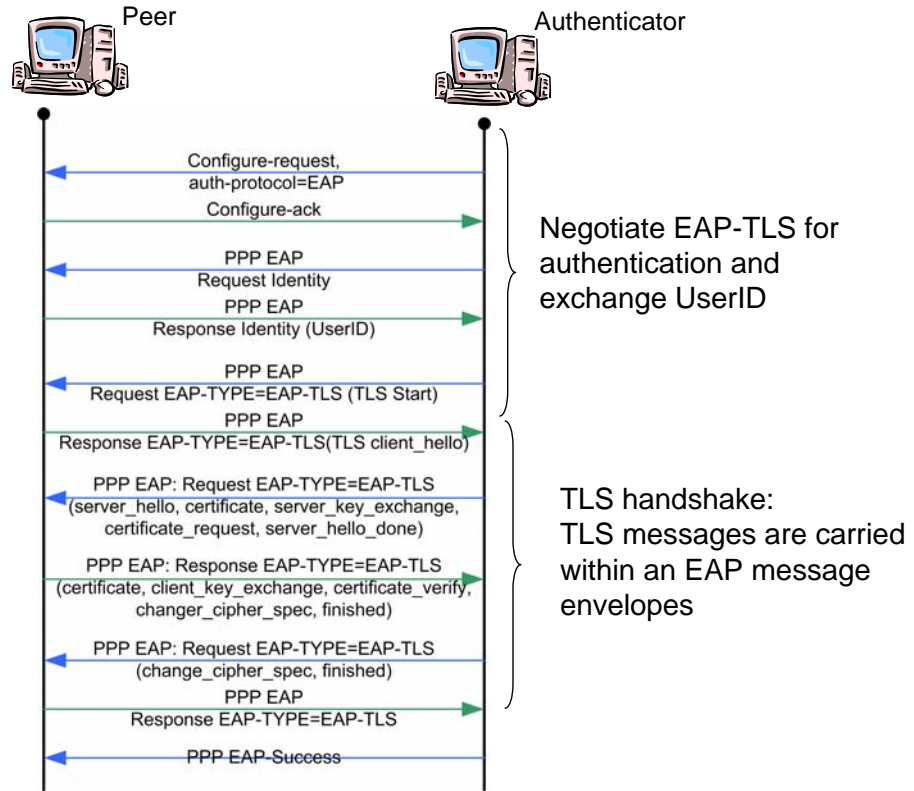
Extensible Authentication Protocol (1)

- 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:

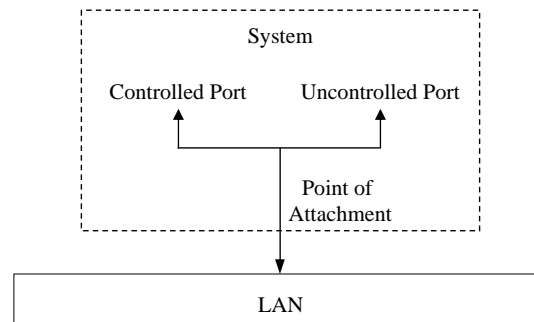


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IEEE 802.1x: Controlled and Uncontrolled Ports



- 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 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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- ❑ IEEE 802.1x

- ❑ **AAA Protocols**
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- ❑ Conclusions



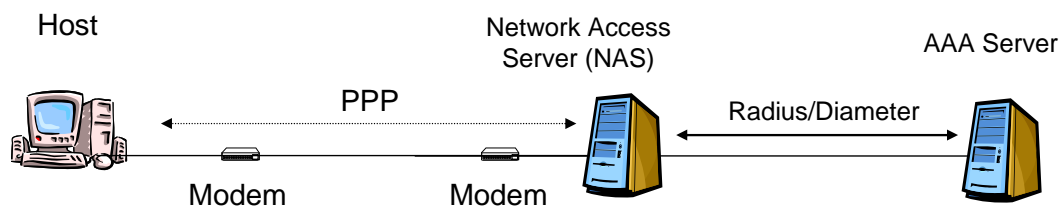
□ Motivation

- 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)

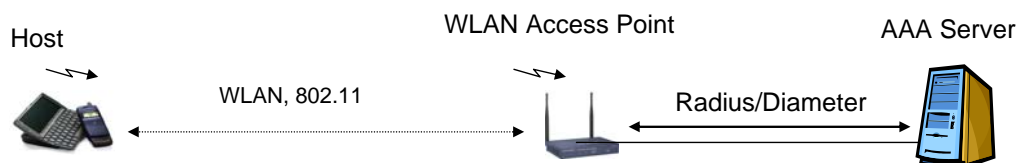


AAA Application Scenarios

□ Authentication for dial-in services



□ Authentication for access to a wireless LAN network:

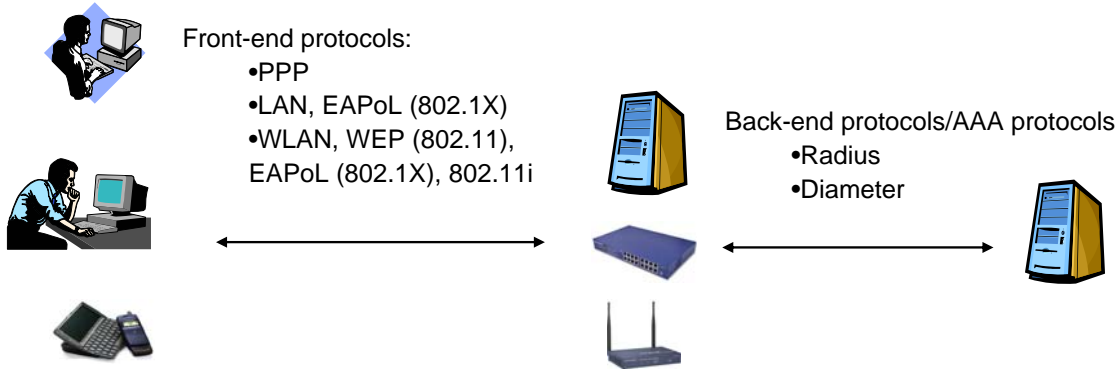


- AAA protocols can be also used between an Ethernet switch and a AAA server for access control with 802.1X
- Another application for AAA protocols (at the application layer) is the authenticating of users in Voice over IP (VoIP) networks

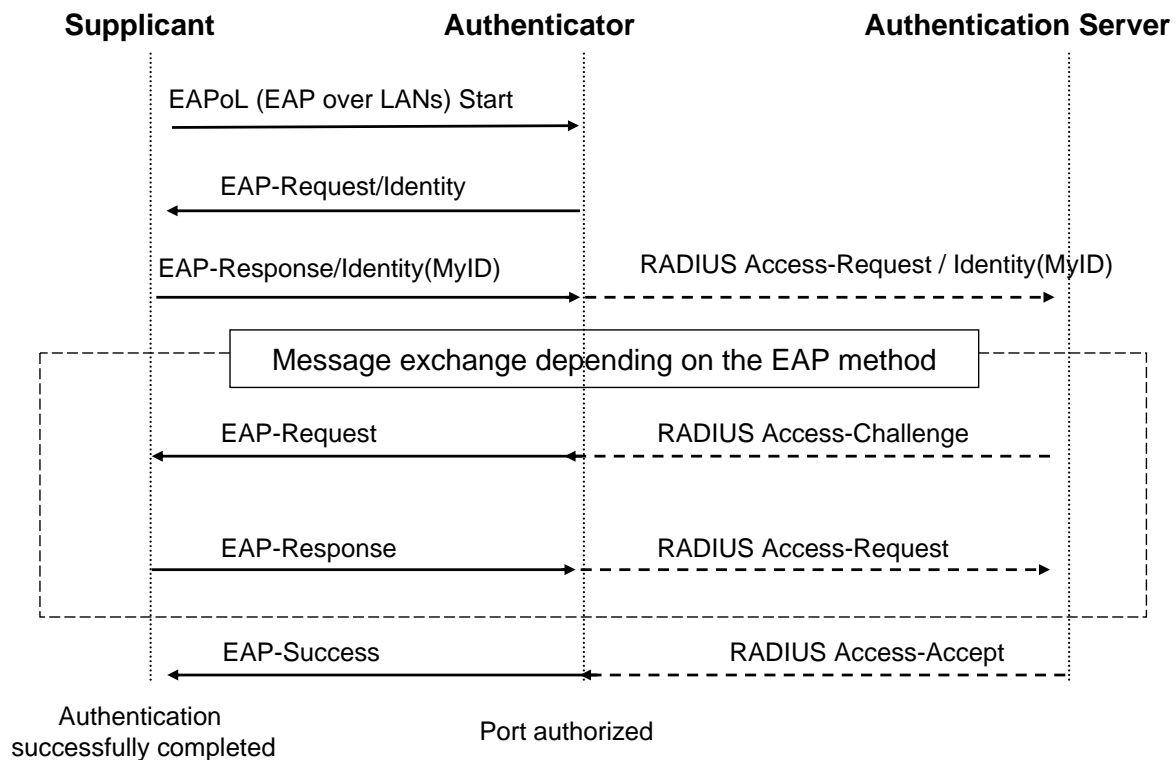


Back-End and Front-End Protocols

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



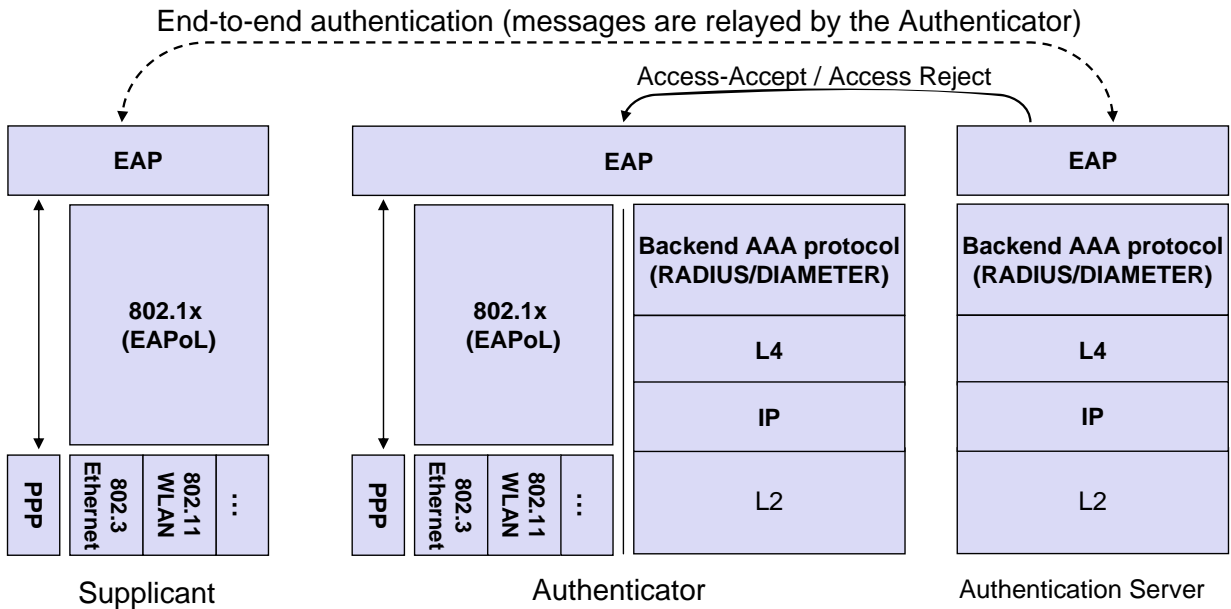
Putting the pieces together: Network Access Control with 802.1X, EAP and a AAA backend server





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



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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...)



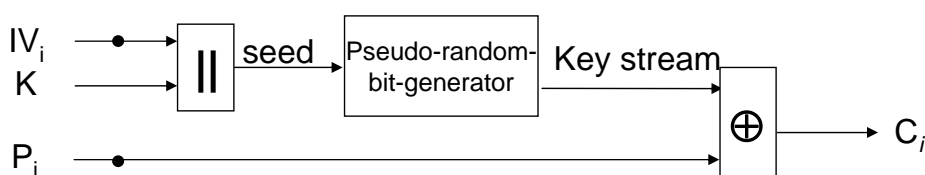
Security Services of IEEE 802.11

- 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:
 - $C_i = P_i \oplus RC4(IV_i, K)$
 - $P_i = C_i \oplus RC4(IV_i, K)$



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 :
$$P_2 = C_2 \oplus RC4(IV_2, K) = C_2 \oplus RC4(IV_1, K) = C_2 \oplus (C_1 \oplus P_1)$$
 - 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)

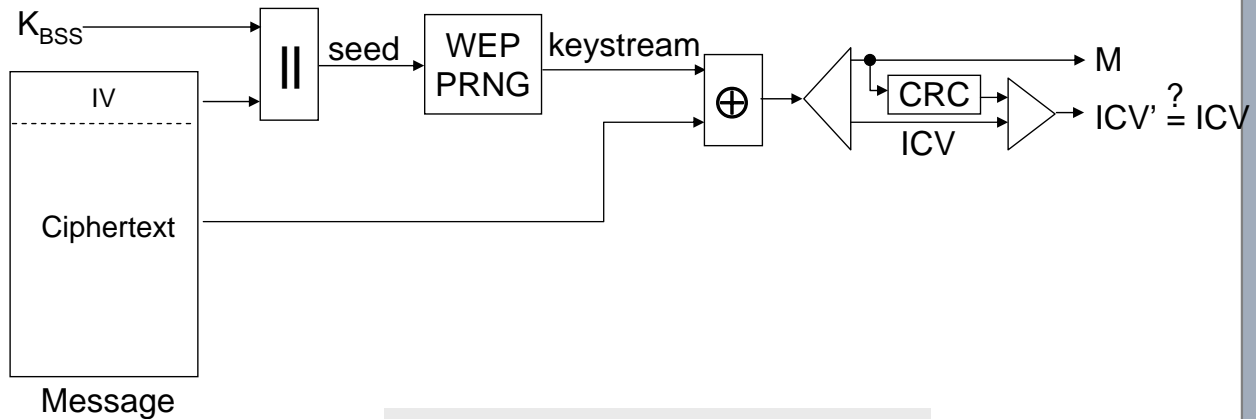
- In 2001 a new and surprising discovery was made by Fluhrer, Mantin and Shamir [FMS01a] :
 - Over all possible RC4 keys, the statistics for the first few bytes of output keystream are strongly non-random, leaking information about the key.
 - If the long-term key and nonce are simply concatenated to 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 sent 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 prepending 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 :
 - $C_1 = P_1 \oplus RC4(IV_1, K_{BSS})$
 - $C_2 = P_2 \oplus RC4(IV_1, K_{BSS})$
 - 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 $\sim 2^{12}$ WLAN frames



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 :
 - $A \rightarrow B: (IV, C)$ 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



TKIP Rekeying (1)

- ❑ TKIP uses a key hierarchy to generate temporal keys that have a short lifetime and are frequently refreshed.
- ❑ The key hierarchy has three layers:
 - 1. Master key:**
 - The master key is the highest key in the hierarchy.
 - The master key is generated by the 802.1X authentication server during the authentication and is provided to the station (via the AP).
 - The master key is used to secure the distribution of the key-encryption keys.
 - A session structure can be formed based on this key, spanning from authentication until the key is revoked, expires, or the station loses contact with the infrastructure.
 - Note: if an attacker compromise the master key then he can trivially compromise the key-encryption keys and temporal keys, thus voiding any TKIP privacy claims.
 - 2. Key-encryption keys:**
 - The key-encryption keys are used to protect the transport of the temporal keys.
 - There are 2 key-encryption keys: one to encrypt the distributed keying material, and a second to protect the “rekey key” messages from forgery.



TKIP Rekeying (2)

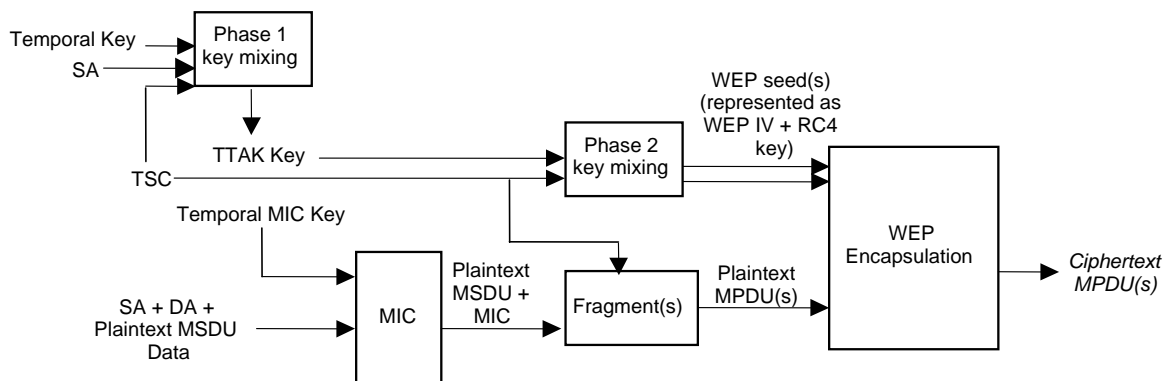
3. Temporal keys:

- TKIP employs a pair of temporary key types:
 - a 128-bit encryption key
 - a 64-bit key for data integrity
- TKIP uses a separate key pair for each direction of an association.
- Hence, each association has a total of 4 temporal keys.
- **Temporal keys** are refreshed with a „rekey key“ message.
- The „rekey key“ message distributes keying material from which both the station and the Access Point derive the next set of temporal keys. This exchange is secured by the **key encryption keys**.



TKIP Function Block on Sender Side

□ Putting everything together:



- DA – Destination Address
- ICV – Integrity Check Value
- MPDU – Message Protocol Data Unit
- MSDU – MAC Service Data Unit
- SA – Source Address
- TSC – TKIP Sequence Counter
- TTAKey – result of phase 1 key mixing of Temporal Key and Transmitter Address (Intermediate Key)



The improved Wireless LAN Security Standard: 802.11i

- The long term solution – also called **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



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- Wireless LAN Security

- **Conclusions**



- 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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Appendix



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 \Rightarrow a bit string representing message M is interpreted as $M(x)$
 - Polynomial arithmetic is performed modulo 2
 \Rightarrow 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 $\frac{M_1(x) \times 2^n + R_1(x) + M_2(x) \times 2^n + R_2(x)}{G(x)} = \frac{(M_1(x) + M_2(x)) \times 2^n + (R_1(x) + R_2(x))}{G(x)}$ divides with remainder 0
- ⇒ CRC is additive, that is $\text{CRC}(M_1 \oplus M_2) = \text{CRC}(M_1) \oplus \text{CRC}(M_2)$
- i.e. if a message M is modified to a message M'
 - where $M' = \text{CRC}(M \oplus \Delta)$
 - then $\text{CRC}(M') = \text{CRC}(M \oplus \Delta) = \text{CRC}(M) \oplus \text{CRC}(\Delta)$
- Due to this property CRC is not appropriate for cryptographic purposes! (more on this below...)



TKIP Key Mixing

- The temporal encryption keys are used to generate a *per-packet key* for WEP encryption.
- Note: this is not a new sophisticated method for encryption. It is designed just to correct the WEP's misuse of RC4.
- TKIP uses a function called the TKIP mixing function to transform the temporal key and a packet sequence number into a per-packet key and IV.
- The mixing function operates in 2 phases:
 - Phase 1 generates an intermediate key where:
 - intermediate key := S (MAC address, temporal key)
 - S is a non linear function which is a combination of table-look-ups and XOR.

Note here that involving the MAC address avoids that 2 different stations could use the same key.
 - Phase 2 uses a cipher function to "encrypt" the packet sequence number under the intermediate key, producing a 128-bit per-packet WEP key (24 bits IV and 104 bits RC4 key).
 - The cipher function used here has a Feistel structure and is a combination of XOR, shift, rotate and table look-ups (all cheap CPU operations common on 802.11 devices).